Distributed Intelligence in Critical Infrastructures for Sustainable Power

ENK5-CT-2002-00673

Distributed Intelligence for Distributed Energy Resources: Selected Publications from the CRISP Project

Hans Akkermans, editor

Identifier:	**CRISP Project Deliverable D4.3 (EC submission version v1.0)**
Date:	**21 October 2005**
Annexes:	**None**
Distribution:	**Public**
Overview:	**Dissemination Compilation Report of Selected CRISP Publications**

The CRISP consortium consists of:

ECN	Principal Contractor & Coordinator	The Netherlands
ABB AB	Principal Contractor	Sweden
Blekinge Institute of Technology	Principal Contractor	Sweden
EnerSearch AB	Principal Contractor	Sweden
IDEA	Principal Contractor	France
Sydkraft AB	Principal Contractor	Sweden

Control Versions:

Version	Date	Author	Description of Changes
Draft version v0.1	02 October 2005	Hans Akkermans	Initial draft for consortium
Submission version v1.0	21 October 2005	Hans Akkermans	Addition of articles, small updates; Complete final version for submission to EC
Final version v2.0	p.m.	Hans Akkermans	Toward the end of CRISP, an update with the latest publications will take place

Document Description

This deliverable D4.3 is a compilation report of CRISP dissemination publications. It offers a major selection of articles published by CRISP project members in journals and conferences in the period 2003-2005.

The intention of this volume is to be helpful as a reference source and service for all readers, researchers, engineers, and projects that will be involved in the development of the intelligent electricity networks of the future, and accordingly will find the scientific and technical results of the CRISP project valuable to their work.

Table of Contents:

Introduction

This deliverable D4.3 is a compilation report of CRISP dissemination publications. It offers a major selection of articles published by all CRISP project partners and members in journals and conferences. Together, the articles give a representative cross-section of the many results of the CRISP project. The credits belong, of course, to the multitude of authors of all the partners as they are listed in the bibliography below.

The order of the publications included in this volume is to some extent arbitrary, but the following characterization may be useful as a guide to the reader:

- Papers 1-4 give general overviews, from different angles, concerning the role of ICT in power and energy network issues.
- Papers 5-12 discuss several different applications of power engineering with the help of ICT, with a special emphasis on the role and importance of distributed generation.
- Papers 13-18 discuss advanced intelligent ICT methods in depth, particularly software agents and electronic market methods, and their power applications in a strongly distributed setting.
- Finally, paper 19 describes, in the educational and entertaining form of a game, basic underlying ideas of the CRISP project concerning how distributed intelligence may function to help manage the electricity networks of the future.

The intention of this volume is to be helpful as a reference source and service for all readers, researchers, engineers, and projects that will be involved in the development of the intelligent electricity networks of the future, and accordingly will find the scientific and technical results of the CRISP project valuable to their work.

Hans Akkermans

Amsterdam, October 2005

Bibliography of Selected CRISP Publications

Paper 1
B. Tornqvist, M. Fontela, P. Mellstrand, R. Gustavsson, C. Andrieu, S, Bacha, N. Hadjsaid, and Y. Besanger: *Overview of ICT components and its application in electric power systems*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Paper 2
D. Karlsson, M. Hemmingsson, and S. Lindahl: *Wide area system monitoring and control - terminology, phenomena, and solution implementation strategies*, IEEE Power and Energy Magazine, Volume 2, No. 5, September-October 2004, pages 68 – 76.

Paper 3
J.M. Akkermans: *Trends in intelligent systems, the Web, and e-services in energy*, in M. Hoppe-Kilpper (Ed.), Proceedings 8th Kasseler Symposium Energie-Systemtechnik, (Keynote 8th Energy and Communication Symposium, Kassel, 13-14 November 2003), pages 7-17, ISET, Kassel, Germany, 2003.

Paper 4
M. Kockott, D. Karlsson, and S. Lindahl: *System Protection Schemes Revisited – Experiences from Recent Power System Blackouts*, in Proceedings Fifth CIGRE Southern Africa Regional Conference, 24-27 October 2005, Somerset West, Western Cape, South Africa. (See also http://www.cigre.org/publications).

Paper 5
D. Andersson, P. Elmersson, Å. Juntti, P. Carlsson, Z. Gajić, D. Karlsson, and S. Lindahl: *Intelligent Load Shedding to Counteract Power System Instability*, in Proceedings CIGRE Conference, Paris, France, 29 August – 3 September 2004, paper No. 207-04. (See also http://www.cigre.org/publications).

Paper 6
M. Fontela, B. Enacheanu, C. Andrieu, S. Bacha, N. Hadjsaid, and Y. Besanger: *On the use of distributed generation to increase EPS robustness*, IEEE General Meeting 2005, June 2005, San Francisco, USA.

Paper 7
Ha Pham, Y. Besanger, C. Andrieu, N. Hadjsaid, M. Fontela, and B. Enacheanu: *A new restoration process following a blackout in a power system with large scale of dispersed generation*, IEEE PES T&D Conference 2005, October 2005, New Orleans, USA.

Paper 8
M. Fontela, P. Mellstrand, B. Stahl, C. Andrieu, R. Gustavsson, B. Enacheanu, and A. Martin: *Integration of new ICTs for EPS in the scope of utilities services*, CIRED 2005 conference, June 2005, Turin, Italy, Paper 373.

Paper 9
M. Fontela, C. Andrieu, S. Bacha, N. Hadjsaid, and Y. Besanger: *Limiting the DG insertion: a deterministic criterion*, CIRED 2005 conference, June 2005, Turin, Italy, Paper 371

Paper 10
B. Enacheanu, M. Fontela, C. Andrieu, P. Ha, A. Martin, and Y. Besanger: *New control strategies to prevent blackouts: intentional islanding operation in distribution networks*, CIRED 2005 conference, June 05, Turin, Italy, Paper 372

Paper 11
Z. Gajić, D. Karlsson, and M. Kockott: *Advanced online tap changer control to counteract power system voltage instability*, in Proceedings Fifth CIGRE Southern Africa Regional Conference, October 24-27, 2005, Somerset West, Western Cape, South Africa. (See also http://www.cigre.org/publications).

Paper 12
D. Penkov, B. Raison, C. Andrieu, L. Stoyanov, and J.-P. Rognon: *Simulation study of DG effect on fault location methods in distribution networks*, ELMA 2005 Conference, September 2005, Sofia, Bulgaria

Paper 13
J.M. Akkermans, J. Schreinemakers, and J.K. Kok: *Microeconomic distributed control: Theory and application of multi-agent electronic markets*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Paper 14
I.G. Kamphuis, P. Carlsson, C.J. Warmer, J.C.P. Kester, and J.K. Kok: *Distributed intelligence for supply/demand matching to improve embedding of distributed renewable energy sources*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Paper 15
P. Mellstrand and R. Gustavsson: *Dynamic protection of software execution environment*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Paper 16
P. Carlsson, A. Andersson, and F. Ygge: *A tractable mechanism for time dependent markets*, in Jen Yao Chung and Liang-Jie Zhang (Eds.), Proceedings CEC-2003 – IEEE International Conference on E-Commerce, pages 31-34. IEEE Computer Society, Los Alamitos, CA, June 2003 (http://www.computer.org).

Paper 17
P. Carlsson and A. Andersson: *A flexible model for tree-structured multi-commodity markets*, Electronic Commerce Research journal, to appear (2005).

Paper 18
J.K. Kok, C.J. Warmer, and I.G. Kamphuis: *PowerMatcher: multiagent control in the electricity infrastructure*, in Proceedings of the Fourth International Joint Conference on Autonomous Agents & Multi- Agent Systems AAMAS'05, ACM, New York, NY, July 2005 (ACM Order nr. 607054), Industrial Track Volume, pages 75 – 82.

Paper 19

J.M. Akkermans, C.J. Warmer, J.K. Kok, J.C.P. Kester, I.G. Kamphuis, and P. Carlsson: *ELEKTRA: the DER electronic market power game - an interactive experience with advanced Information and Communication Technologies for DER management*, in Proceedings First International Conference on the Integration of Renewable Energy Sources and Distributed Energy Resources, OTTI, Brussels, December 2004, pages 198-203.
(See also www.conference-on-integration.com and www.IRED-cluster.org).

Paper 1: *Overview of ICT components and its application in electric power systems*

Full bibliographic reference:

B. Tornqvist, M. Fontela, P. Mellstrand, R. Gustavsson, C. Andrieu, S, Bacha, N. Hadjsaid, and Y. Besanger: *Overview of ICT components and its application in electric power systems*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

OVERVIEW OF ICT COMPONENTS AND ITS APPLICATION IN ELECTRIC POWER SYSTEMS

Bjorn Tornqvist (*), M.Fontela (+), Per Mellstrand (*), R.Gustavsson (*), C.Andrieu (++), S,Bacha (+) , N. Hadjsaid (+) and Y.Besanger (+)

(*) Blekinge Institute of Technology, Ronneby, Sweden, (+)IDEA&Laboratoire d`Electrotechnique de Grenoble, St.Martin d`Heres, France, (++) IDEA, St.Martin d`Heres, France

Introduction

The recent deregulation of the electric power system has facilitated the apparition of new actors (producers, market agents…) and the split of the old national entities, which controlled the different parts of the system (generation, transmission and distribution), in new companies and operators that are responsible of the system operation.

Thus, the system is changing day by day in a metamorphosis process with the integration of the new elements. The network and market management represents a complicated task which needs the acquisition, communication, share of data for equal terms for market competitors and analysis of information. These information and communication requirements of the EPS (Electric Power System), under different states are described in detail in the paper.

The traditional EPS communication system was slightly adapted to accomplish the new required functions. This traditional EPS communication system is detailed as well in the article.

New developments in ICT components can improve the system but an adaptation of the EPS communication system is necessary to response to the traditional and innovative communication requirements. The recent terrorist plans and attacks (11-S and 11-M) have emphasized the concept of the EPS as a critical infrastructure for the normal life of a country. So, the new ICTs into EPS must be gone with a high security of the associated communication media and data integrity.

The paper analyses some practical uses of the new ICTs networks, which could appear in the tomorrow's system. The works included in the article are integrated in the CRISP[1] project and in the EURODOC program (PhD mobility) of the French Rhone-Alpes Region.

[1] ***CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power.*** Project funded by the European Community under the Fifth RTD Framework Programme (2002-2005). Project Co-ordinator: ECN. Partners: ABB, BTH, IDEA, ECN, ENECO, EnerSearch and Sydkraft. Contract No. ENK5-CT-2002-00673.

ICT definition

Information and Communication Technology can be defined as:

The technology involved acquiring, storing, processing and distributing information by electronics means (including radio, television, telephone, and computers).

Three processes are involved inside the ICT definition: information acquisition, communication of the information between different entities and information computerization (it includes information analysis, storing and visualization).

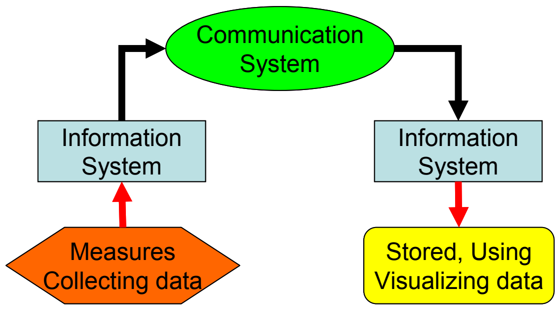


Figure 1: *Information vs Communication vs Computerization*

Communication is the fact of transmitting information between two or more points/agents of the system. The information and communication processes are related very closely. The information system is responsible of obtaining or measuring the parameters/variables that the systems need to control for a normal operation. So, at this step the information exists and can be transmitted from this point of measure to other points of the system for further utilization.

The communication system is responsible of this transmission and different communication media are used to transfer the information. The information transformed into different signals (analog or digital) is transmitted by the communication media to different centers where these signals are converted into other formats (data formats exploitable by the centers) and finally the communication process is finished when these data (information) are stored

The computerization consists in the use of the information or data in order to analyze the system or to establish a help for taking conclusions and so elaborating decisions. The computerization can be carried out there where there is the information (with or without communication between two entities because a same entity can obtain the information and computerized it). This computerization system refers mainly to the different computer tools and operating systems that can be applied in a computer, PLC or Control unit.

Current communication media in EPS

The use of communication media in SCADA (Supervisory Control and Data Acquisition) systems or EMS (Energy Management Systems) for EPS depends on different factors such as the nature of the media, possibility of interference or electromagnetic distortion, investment cost for installation or the requirement of special licenses. For example, the use of wireless media is not adequate for substations communications because the electromagnetic distortion that can appear especially during faults.

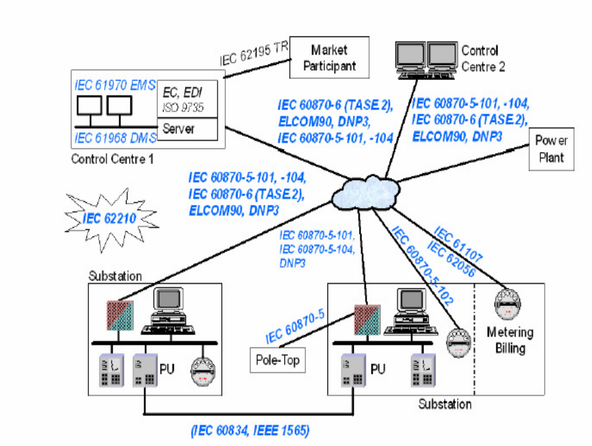


Figure 2: *Some Standards of Electric Power System Communication*

The International Standard Associations like IEC or IEEE have been working to establish standards and recommended practice for the communication between different agents and for different tasks in EPS (market, substation automation, communications inside SCADA…) [1]. In figure 2, some standards of EPS communications are cited.

The main component of the EPS communication system is the SCADA system. Basically, it is the architecture to acquire, store and process the parameters needed to control the system. The SCADA of TSOs or utilities is normally composed of several types of communication systems such as [2]:

- Fixed networks including public switched telephone and data networks
- Wireless networks including cellular telephones and wireless ATM (Asynchronous Transfer Mode), radio systems, microwave (radio signals operating n the 150 MHz to 20 GHz frequency range)
- Power line carrier is the most commonly used communication media for protection function. However, this medium does not offer a reliable solution for wide area data transmission. Communication with remote sites can not be maintained during a disturbance.
- Computer networks including various dedicated LANs, WANs, and the Internet.
- The satellite network is another segment of the communications system that can provide important services which are difficult to carry out with normal communication techniques. These services include detailed earth imaging, remote monitoring of dispersed locations and time synchronization using signal from GPS (Global Positioning System).

The delays or latencies and data rate of such communication media differ from a system to another. In table 1, a comparison is carried out in the case of wide area measurement networks [3]:

Communication link	Associated delay-one way (milliseconds)
Fiber-optic cables	100-150
Digital microwave links	100-150
Power line (PLC)	150-350
Telephone lines	200-300
Satellite link	500-700

Table.1.*-Communication delays of some communication in wide area measurement networks*

The different data rate of the currently media used in the power system are compared in Table 2 [4]:

Transmission media	Data Rate
T1	1Mbps. Effective bandwidth considering network traffic, data collision etc is 125 kbps
Frame Relay	280 kbps
ISDN	140 kbps
T1 fractional	62.5 kbps
56k leased line	565 kbps (effective bandwidth lower than this)
Internet	Effective rate 40 kbps depends on network traffic
Radio frequency	9.6 kbps
Power line carrier	1.2 kbps

Table.2.*-Data rate of currently media used in the power system*

SCADA usually processes discrete and continuous information coming from measurements done in the field for the normal operation of the EPS [5]:

- Measurements: active and reactive power flows, bus voltages and network frequencies, for transmission networks at 2 or 4 seconds periodic update and for sub-transmission network at 20 seconds periodic update.

- Signals: breaker positions with max. 1s delay, tap changer and isolator positions with max. 4 s delay

- Chronological registration of events, consisting in changes of status of protection systems, as well as switching and regulating devices, coming from each transmission bus and incident branches. Binary information associated to the component operating configuration is locally refreshed in terms of milliseconds.

- Analog registration of significant quantities in instantaneous form (sampling time about 1 ms) or in RMS form (sampling time of about 100ms), including a subset of logical quantities to recognise protection system interventions.

The operation of SCADA is split in several hierarchical levels:

- Level 1 is composed by the local points which pick up the information at the substations and generators by means of IEDs (Intelligent Electronic Devices) or PMUs (Phase Measurement Units). The substation of level 1 can be controlled from the bigger substations of level 2.

- Level 2 is composed by big substations and this level represents a collection of data from different points in the distribution system (they are normally called RTU, remote terminal units)

- Level 3 corresponds to the regional control centers. They have the mission of control the voltage at the distribution (20kV), sub-transmission (90 kV, 63 kV) and transmission system (only 225kV). They do some functions of back-up of the level 4 as well.

- Level 4 is the main national center that has information of everything in the system and control the system as a whole through the transmission network (400 kV). One of its most important functions is the interconnection with other countries and so the frequency control in the system and the voltage control of the 400 kV.

The links between the different hierarchical levels in the French system are as follows [6]:

- Level 1-Level 2: The speed of these links is low. Transmission always takes place by asynchronous transfer mode (ATM). It uses telephone lines, power line carriers or radio links.

- Level 1-Level 3: A few direct links exist between level 1 and level 3, especially for remote controlled gas turbines or pumping hydro plants with the same characteristics as previous mentioned.

- Level 2-Level 3: The speed depends upon the size of the level 2 (data accumulators or collecting centers), with synchronous or asynchronous modes. It uses rented telephone lines or power line carriers.

- Level 3-Level 4: This part is a packet switch data transmission system. It uses telephone wire of superior quality with a very low probability of loss or error (10^{-9}). It links the computers of the regional centers with the national center computers.

- Level 4-Foreign countries: This is a link between the different national control centers of a country with its neighbour's countries. They have dedicated communication, and it is normally used the telephone connection.

Different studies are allowed by the SCADA data collection such as: state estimation, load frequency control (LFC), security dispatch, security and contingency analysis.

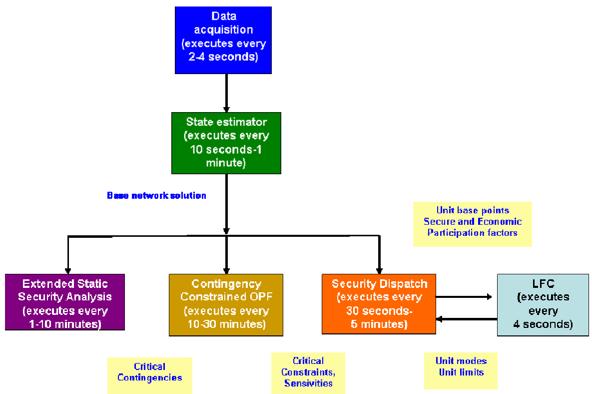


***Figure 3:** Computer analysis of SCADA data*

Protocols are the language that allows the communication between the different devices presents in the system. Different protocols can be sited: ICCP, TCP/IP, Modbus, Profibus, LON, UCA by EPRI... There are a wide variety of protocols because every device manufacturer usually uses its own protocol. The variety of protocols can be solved by means of the gateways, protocol converters or translators.

Application area	Protocol
IED to RTU	DNP3, EPRI UCA2, Modbus,
RTU to Utility SCADA	DNP, DNP3,ELCOM90, IEC-870-5
Utility SCADAs to TSO SCADA	ICCP, ELCOM90
TSO SCADA to TSO SCADA	ICCP

Table 3: *Some protocol examples in Electric Power System Communication*

The choice of the protocol depends on different parameters [7]:

- System area, RTU to IED, RTU to master SCADA, SCADA utility to SCADA TSO, SCADA national TSO to SCADA national TSO center…
- Time to develop the installation

ICT components requirements of EPS

The communication requirements of EPS correspond to the different tasks that EPS realize to control the the system under normal, emergency or restoration operations.

In normal operation. The different tasks of the power system have different amount of data to be transmitted, that is the bandwidth needs for each task are different and with a current time response related to the nature of the task. Some tasks like the monitoring of the system are carried out in a real time operation. Others are not critical for the normal operation and real time operation is not necessary, such as metering or data statistics and store.

Power System Task	Bandwidth requirement	Current response time
Load shedding(local decision)	Low	Seconds
Adaptive Relaying (i.e. Blocking relaying)	Low	Not available
Hierarchical Data Acquisition and Transfer	High	Seconds
Line/ Bus reconfiguration	Low	Minutes (by manual)
Control devices (e.g. FACTS, Transformer)	Medium	Seconds (by manual
Fault Event Recorder Information	Medium	Minutes
Generator Control	Low	Seconds
National Strategic Power Defense Plan	High	Not applicable

Table.4*.-Bandwidth requirements and response time for different power system tasks*

Table 4 introduces the requirements of bandwidth and time response of some significant actions [8].

In emergency operation. The emergency situations in the EPS correspond to violations of the current security criteria. These emergency situations can be classified from two points of view: the electric point of view in one hand and the communication point of view in other hand.

The electric point of view deals with pre-black-out events and extremely critical operation of the EPS. The result of such events depends on its duration, automatic consequences and the disturbance nature. Information must be shared and given to the different actors in order to optimize its operation and be prepared to major disturbances. Thus, the coordination of SCADA upper levels is one of the main actions to avoid the propagation of blackouts. If the entities could have enough time to react, the disturbance propagation can be completely or partially stopped. Otherwise, the system shut down and then the restoration procedure will be started.

The communications point of view refers to the loss of communications, wrong operations of software (data verification, unavailable alarms…) and intrusion of external agents. The loss of a communication in the EPS should not provoke a variation or high influence in the operation of the system as a result of the (n-1) criteria. It is why, it exists a redundancy in the communication links to ensure the information transmission in emergency situations and some dedicated links are reserved only for emergency operation. E.g. SCADA system contains back-up control centers (national and regional) which guarantee the operation in case of loss of the main control center.

In Restoration operation. The restoration of supply after a major disturbance is a heavy task due to the different parameters involving the event: determination of damaged network, existing communication links, generation capacity, available black-start capability, and coordination of control centers…The most important communications during this operation are the next ones:

- Communication for the detection of undamaged parts in the network.
- Detection, synchronization and interconnection of existing autonomous sub-areas
- Communication between re-energized areas to the utility or DSO, between utilities, customers and TSOs.

- Emergency communication facilities in case of loss of main and back-up links.

Basis for an ICT network

The ICT networks are a mean to establish the transmission of information communication between nodes on the electrical power grid. These nodes can be substations, relays, control devices or other equipment that collect information, or should be controllable from remote. The standard TCP/IP protocol is used on the Internet and essentially all private networks, Intranets. By using the TCP/IP protocols, a variety of different underlying link level protocols are enabled, such as Ethernet for the local communication within a substation, different type of fibre for fast long distance communications, and even dial up communications to remote locations.

These ICT networks based on TCP/IP could have a special interest in the utilities environment. The different tasks that the utilities are supposed to carry out could be done through the TCP/IP networks, e.g. protections using communications, telecontrol of generators and system coordination when faced to disturbances. The EPS requirements are addressed to the correct reception of messages and in the required latencies (the protection system communication requirements are the fastest because its typical response time and with the highest requirement in bit errors)

When building an ICT network, many lower-level communication problems are handled by the protocols. E.g. Bit errors that may occur during transmission are handled by the link level protocol, such as Ethernet, or by the IP protocol. The cost of this automatic error correction, and other features offered by the communication protocols, is that it is not possible to guarantee the maximum time it will take to deliver a piece of data from one node to another. Smaller transmission errors or small overloads of the communication channel are handled transparently by the communication protocols resulting in longer transmission times for the data transmitted.

The automatic error handling in the communication protocols is useful when connecting devices active on the electrical power grid to an ICT network, but the non-deterministic transmission times and occasional loss of transmitted data is an issue when transferring critical data over the information network. In addition, by default there is no prioritizing of traffic, so critical control messages have the same priority as arbitrary log messages and should traffic congestion occur either message has the same risk of being dropped by the network for later retransmission.

The messages in EPS do not have the same priority, thus the response time depends on the tasks as it was mentioned in the table 4. From the ICT point of view, there are a number of techniques for prioritizing different network traffic, typically based on which node sent the message or the message destination. It is also possible to prioritize traffic of higher-level properties such as TCP and UDP port numbers. As these prioritization criterions are rather coarse, it is likely that a high level of cooperation from the different nodes and applications is required to make a good prioritization of network traffic.

ICT networks as a tool to enhance EPS coordination

The mentioned ICT infrastructure can enable coordinated control of the power grids. Coordination of System Protection Systems (SPS) is one application area that has been raised as an interesting research area. Coordination of the components in the ICT network can be handled by a coordination middleware, a layer within the application layer in the ISO-OSI model. This enables an analysis of the coordination criteria in the context of the full system instead of just for a single application [9], and as it is the case in the power grids, the coordination criteria of an application changes along with the state of the system.

Traditional coordination research is focused on techniques for coordination given a specific context. Some fundamental research in this area is models and middleware for coordination of control-oriented tasks [10] which supports low latency coordination with weak robustness, and blackboard-oriented tasks [11] which are more robust at the cost of higher latency. However, the power network isn't controlled by technology alone. Consequently, coordination models that account for human agents [12] are of interest.

As it is known, the power grid will evolve at a faster pace in the future; as distributed generators are added, command and control of facilities is changed when businesses are sold, and when Grid- and Business- Operations software is updated, just to name a few scenarios. Different operators may have different incentives and priorities to invest in different parts of their networks – for economical and political reasons. Consequently, the networks will become heterogeneous and it is necessary to plan the issue from the start so that the heterogeneity is an enabling and not a disabling factor. An operator should be able to upgrade its system without requiring that all operators in the system implement the same upgrade.

No single coordination technique can account for the diverse requirements of the power grid. Several factors, such as the real-time requirements, prevent the coordination layer from enforcing a common base model. Instead, the best suitable coordination technique for the task at hand should be used. To that end, meta-coordination could be a tool [13].

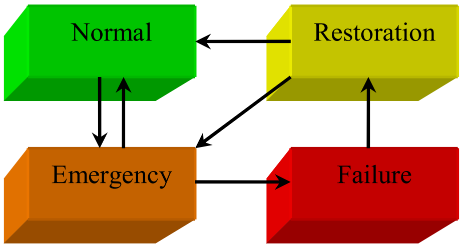


Figure 4: *State based coordination*

The state of the power grid affects which information is needed where and what actions should be coordinated. The main phases are normal operation, emergency (e.g. the loss of a line), failure (blackout), and restoration, as depicted in figure 4. The coordination requirements differ between these states, in that normal operation is focused on coordinating wide-area measurement data, emergency operations need quick reactions (e.g. load shedding), in failure the network may be incommunicable, and in restoration wide area consensus and planning is needed so that the system can safely be brought back into normal operation.

Conclusions

The paper analyses the current ICT uses in EPS. The introduction of new ICT network could enhance the EPS operation, notably when faced to major disturbances. These new ICT networks could represent valuable tools in the system for utilities, TSOs and DSOs to acquire information, communicate it for further utilisation (computerization, analysis…) in order to improve the coordination in the EPS and avoid resulting blackouts.

In this article we propose the use of an ICT network based on the TCP/IP, which is a wide-spread protocol on the Internet, and Intranets, worldwide. The use of TCP/IP avoids the problems of the variety of protocols. However, the latencies depend on the ICT network and some tasks such as protection are very sensitive to the messages time propagation and bit errors and so, higher requirements are needed in the routing of its messages. So, special ICT methods should be considered for the different messages in the EPS in order to guarantee the QoS (Quality of Service) required by EPS tasks.

References

[1] CIGRE B5.11, "The automation of new and existing substations: why and how". Draft. August 2003.

[2] Donald.G. Fink and H.Wayne Beaty, "Standard Handbook for Electrical Engineers". Section 10, Supervisory Control and Data Acquisition, pp-10-147 to 10-168. Ed.Mc-Graw Hill, 2000.

[3] Biju Naduvathuparambil et al, "Communication Delays in Wide Area Measurement Systems", Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory, 18-19 March 2002, Pages: 118 - 122

[4] Bin Qiu, "Next Generation Information Communication Infrastructure and Case Studies for Future Power Systems" Ph.D dissertation Virginia Tech, April 2002.

[5]: Project ExAMINE, **http://www.examine.ree.es**

[6]: Carpentier.J "The French National Control Center ". IEEE on Power Systems, Vol.PWRS-1,No.4, November 1986.

[7] John McDonald "Managing the Data and choosing the right protocol", IEEE/PES Transmission and Distribution Conference and Exposition, 2001, Pages:970 - 973 vol.2, 28 Oct.-2 Nov. 2001.

[8]Amin.M.,http://www.citris.berkeley.edu/defense/slides/Amin-Feb-04.PDF

[9] Janssens, N., Steegmans, E., Holvoet, T., Verbaeten, P., "An agent design method promoting separation between computation and coordination", Proceedings of the 2004 ACM sym-posium on Applied computing, 2004.

[10] Hsieh, C. S., Unger, E. A., "Manifolds: A very high-level conceptual framework of inter-process synchronization and communication", Proceedings of the 15th annual conference on Computer Science, pp196-204, ACM Press, 1987.

[11] Gelernter, D., "Generative communication in Linda", ACM Transactions on Programming Languages and Systems (TOPLAS), Volume 7, Issue 1, ACM Press, 1985.

[12] Wagner, T., Guralnik, V., Phelps, J., "A key-based coordination algorithm for dynamic readiness and repair service coordination", Proceedings of the second international joint conference on Autonomous agents and multiagent systems, 2003.

[13] Tornqvist, B., Gustavsson, R., "On adaptive aspect-oriented coordination for critical infrastructures", accepted for publication in WCAT04, June 2004.

Paper 2: *Wide area system monitoring and control - terminology, phenomena, and solution implementation strategies*

Full bibliographic reference:

D. Karlsson, M. Hemmingsson, and S. Lindahl: *Wide area system monitoring and control - terminology, phenomena, and solution implementation strategies*, IEEE Power and Energy Magazine, Volume 2, No. 5, September-October 2004, pages 68 – 76.

Wide Area System Monitoring and Control

Terminology, phenomena, and solution implementation strategies

by Daniel Karlsson, Morten Hemmingsson, and Sture Lindahl

 1540-7977/04/$20.00©2004 IEEE

THIS ARTICLE DESCRIBES THE TRANSITION FROM PHASOR-BASED WIDE area measurements to real time monitoring, control, and protection. The power system phenomena to deal with are reviewed, and key concepts in control and protection are addressed along with different design principles and architectures. Examples of analysis tools, monitoring tools and concepts for control and protection are given.

Basic Facts

There are a few basic facts and technological developments that have pushed the utility needs and the vendors' offers in wide area monitoring, control and protection.

- ✔ Economical pressure on the electricity market and on grid operators forces them to maximize the utilization of the high voltage equipment, which very often means operation closer to the limits of the system and its components. For the same reason there is also a desire to "push" the limits.
- ✔ Reliable electricity supply is continually becoming more and more essential for society, and blackouts are becoming more and more costly whenever they occur.
- ✔ Technical developments in communication technology and measurement synchronization, e.g., for reliable voltage phasor measurements, have made the design of system wide protection solutions possible. The use of phasor measurements also provides new possibilities for state estimator functions. Their main use so far has been for wide area measurement system (WAMS) applications.
- ✔ The deregulated electricity market causes rather quick changes in the system's operational conditions. New, unknown, load flow patterns show up more frequently for the system operator.
- ✔ There is a general trend to include both normal operation issues and disturbance handling into power system automation.
- ✔ Wide-area disturbances during the last decade, particularly during 2003, have forced/encouraged power companies to design system protection schemes to counteract voltage instability, angular instability, frequency instability, to improve damping properties or for other specific purposes, e.g., to avoid cascaded line trip.
- ✔ Much research and development within universities and industry have significantly increased our knowledge about the power system phenomena causing widespread blackouts. Methods to counteract them have been or are being developed (see the Web site http://www.epri.com/attachments/231875_CINSI _ GOP_BAC_Feb_2000.PDF).
- ✔ There is a heightened concern for physical security of power grids due to acts of coordinated sabotage, which traditionally were not considered in grid planning. Fast and efficient controls/protections are needed to stop the disruption from spreading.

Power System Phenomena to Counteract

Utility needs and problems are often formulated in very loose terms, such as "intelligent load shedding," "protection system against major disturbances," and "counteract cascaded line tripping." These needs have to be broken down to physical phenomena, such as protection against

- ✔ transient angle instability (first swing)
- ✔ small signal angle instability (damping)
- ✔ frequency instability
- ✔ short-term voltage instability
- ✔ long-term voltage instability
- ✔ cascading outages.

A detailed description of the different phenomena can be found in Cigre in the "For Further Reading" section.

Transient Angle Instability

Offline design studies are normally made to ensure the transient angle stability for credible contingencies. Parameters, which are required to be influenced during the design stage, are line circuit impedance, trip time, autoreclosing, inertia constants, and additional equipment

> The difference between normal and emergency control is the consequence for the power system if the control action is not performed.

such as series capacitors and breaking resistors. In the operational stage certain power flow levels must not be exceeded. Phasor measurement units (PMUs) allow for direct and fast angle measurement, instead of indirect power measurement, and more accurate control algorithms for emergency control or protective actions can be designed.

Small Signal Angle Instability

Offline studies, such as eigenfrequency analysis and time simulations, have to be done to check the damping conditions for different frequencies. Static var compensators (SVCs) in the network and power system stabilizers on the generators are common means to counteract power oscillations. Again PMUs in the power system can provide accurate angle measurements.

Frequency Instability

Frequency instability is most commonly the result of a sudden, large generation deficit. Automatic underfrequency controlled load shedding is the widely used measure to counteract a system breakdown in such situations. Also the time derivative of the frequency is used in some applications. In case of overfrequency, due to sudden loss of load, generators can be shed. Frequency instability may occur during the last phase of a major power system disturbance.

Short-Term Voltage Instability

Short-term voltage instability is normally associated with an extremely severe reduction of the network capacity, e.g., caused by the trip of several parallel lines due to a bush fire. Characteristic for the short-term voltage instability is that there is no stable equilibrium point immediately after the clearance of the initial fault(s). Remedial actions to save the system in such a situation therefore have to be fast (a few seconds or fractions of a second) and powerful (e.g., large amount of load shedding).

Long-Term Voltage Instability

When a power system is in transition towards a "long-term voltage instability," the power system "survived" the initial disturbance, i.e., there was a stable equilibrium point immediately after the clearance of the disturbance. However, load recovery and tap-changer operation cause the transmission system voltage to decrease and the collapse occurs in the time-scale of ten seconds to 30 minutes. Without any initial disturbance, a long-term voltage instability might occur due to a very large and rapid load increase.

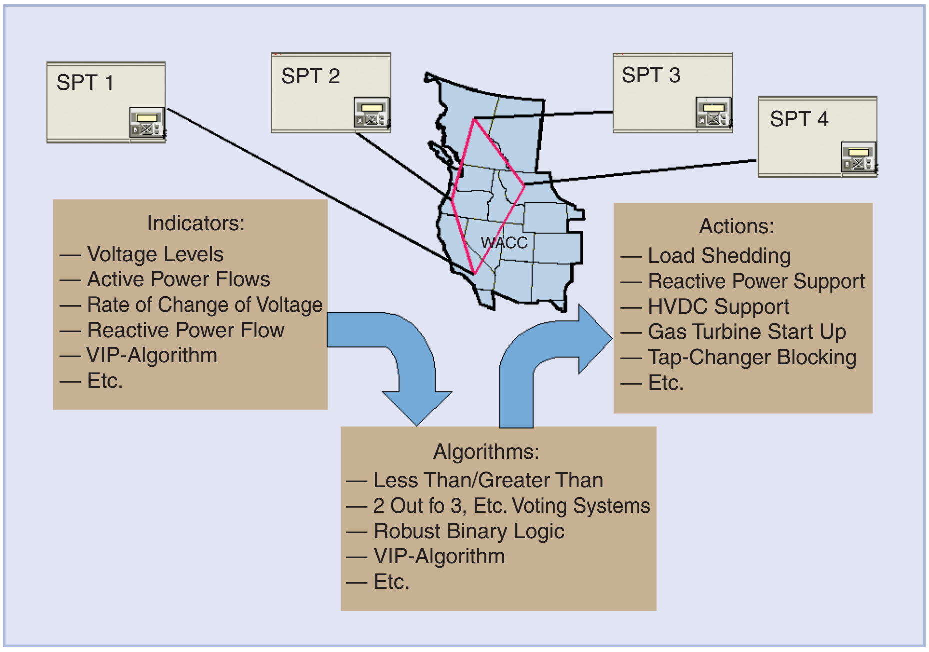


figure 1. Terminal-based wide area protection system against voltage instability.

Cascading Outages

Cascading outages of lines or generators might have different origins but are mainly associated with some kind of overload, followed by trip of one line or generator unit, which cause an increased overload on the remaining units, and so on. In such situations load shedding or generation rejection might be required to preserve the integrity of the power system.

More Detailed

For each phenomenon a reliable (based on redundancy and robustness) protection system has to be designed, with respect to input variables, decision criteria, and output actions, acording to Kundur. Parallel systems counteracting different phenomena and different layers of safety nets can be designed and coordinated.

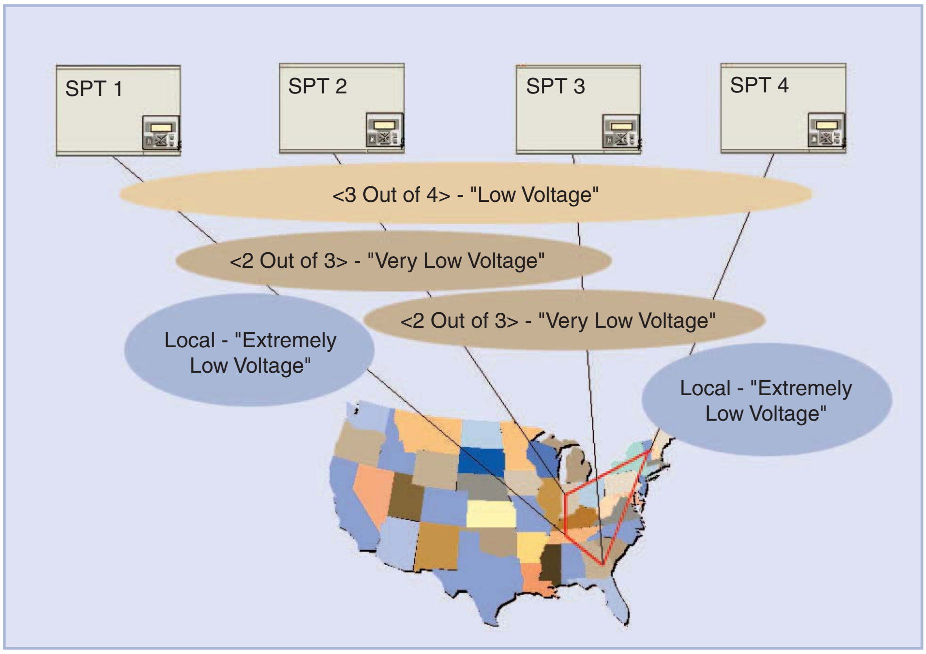


figure 2. Different layers of redundant protection levels.

Key Concepts in Protection and Control

Protection is very closely related to circuit-breaker trip signals to disconnect faulty or overloaded equipment from the network, to save components, and to reestablish normal operation of the healthy part of the power system and thereby continue electricity supply to the customers. Protection equipment is also aimed at protecting people, animals, and property from injury and damage due to electric faults. The situation when a protection device triggers should be so severe that if the equipment is not tripped, it will be damaged or the surrounding will be exposed to serious danger.

System protection or wide area protection is used to save the system from a partial or total blackout or brown-out in operational situations when no particular equipment is faulted or operated outside its limitations. This situation could appear after the clearance of a very severe disturbance in a stressed operation situation or after a period of extreme load growth. Since it is a protection system, it will operate in such operational situations when the power system would break down if no protective actions were taken. Such protective actions also comprise the shift of setting groups and parameter values for different protection and control devices, blocking of tap-changers, and switch in of shunt capacitors.

Emergency control is associated with continuous control actions to save the power system, such as boosting the exciter on a synchronous generator or changing the power direction of a high-voltage dc (HVDC) link. Fast valving is another type of emergency control used to counteract transient instability.

Normal control actions are associated with continuous control activities, that can be either discrete, e.g., tap-changer and shunt device, or continuous, such as frequency control. Normal control is preventive, i.e., actions are taken to adjust the power system operational conditions to the present and near future expected situation. Normal control is usually automatic, e.g., tap-changer, reactive shunt device, frequency control and automatic generation control (AGC).

The difference between normal and emergency control is the consequence for the power system if the control action is not performed. If a normal, preventive, control action is not performed, there is an increased risk for the loss of power system stability, i.e., stability will be lost if a severe disturbance occurs. If an emergency, corrective, control action is not performed, the system will go unstable. The response requirements (time and reliability) are normally higher for emergency control actions than for normal control actions. Emergency control functions are almost always automatic, while normal control actions can be either automatic or manual, e.g., in conjunction with alarms. The actions taken in the power system are however quite similar for both normal control and emergency control. Protection, system protection, and emergency control comprise corrective (or curative)

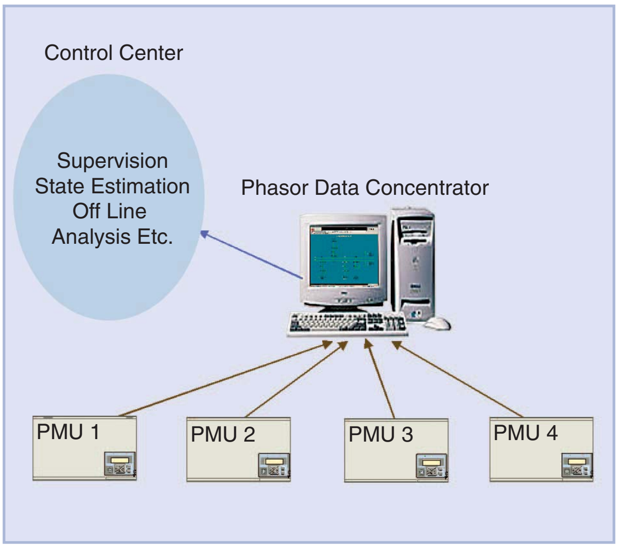


figure 3. PMUs and a PDC in a WAMS design.

measures, i.e., actions are really needed to save the component or the system. Protection could very well be regarded as binary (on/off) emergency control, but by tradition, protection is quite specific.

Voltage control comprises actions like automatic voltage regulators (AVR), tap-changer, and shunt device, automatic or manual control. The control variable is usually the voltage level or reactive power flow. For system protection purposes or "emergency control" also load shedding and AGC can be used.

Primary frequency control is normally performed in the power stations by the governor controls, while secondary frequency control is performed by the AGC change of set-point or start/stop of units by the dispatcher. For emergency control, load shedding as well as actions that reduces the voltage and hence the voltage sensitive part of the load, can be used.

Automatic power flow control is performed by AGC, HVDC-control, unified power flow converters (UPFC), thyristor controlled series capacitors (TCSC), and phase-shift transformers. Load level, network topology, and generation dispatch are the most common parameters that influence the power flow.

Angle control is more accurate if based on PMUs. Without PMUs power flow is an indirect method of measuring and controlling the angle. The actions are similar as for power flow control.

Supervisory controland data acquisition (SCADA) and emergency management system (EMS) functions are tools that assist the power system/grid operator in his effort to optimize the power system operation, with respect to economy, operational security and robustness, as well as human and material safety. Operator actions are normally (at least supposed to be) preventive, i.e., actions taken to adjust the power system operational conditions to the present and near future expected situation. Preventive actions, based on simple criteria, can beneficially be implemented in SCADA/EMS and be performed automatically or be suggested and then released or blocked by the operator. SCADA/EMS systems are normally too slow to capture power system dynamics.

PMU is a device for synchronized measurement of ac voltages and currents, with a common time (angle) reference. The most common time reference is the global positioning system (GPS) signal, which has an accuracy better than 1 μs. In this way, the ac quantities can be measured, converted to phasors (complex numbers represented by their magnitude and phase angle), and time stamped.

Possible Wide Area System Design Architectures

Since the requirements for wide area monitoring and control can vary from one utility company to another, the architecture for such a system must be designed according to what technologies the utility possesses at the given time. Also, to avoid becoming obsolete, the design must be chosen to fit the technology migration path that the utility in question will take. Three major design approaches are discussed below.

"Flat Architecture" with System Protection Terminals

Protection devices or terminals are traditionally used in protecting equipment (lines, transformers, etc.). Modern protection devices have sufficient computing and communications capabilities to perform far beyond the traditional protection functions. When connected together via communication links, these devices can process intelligent algorithms (or "agents") based on data collected locally or shared with other devices.

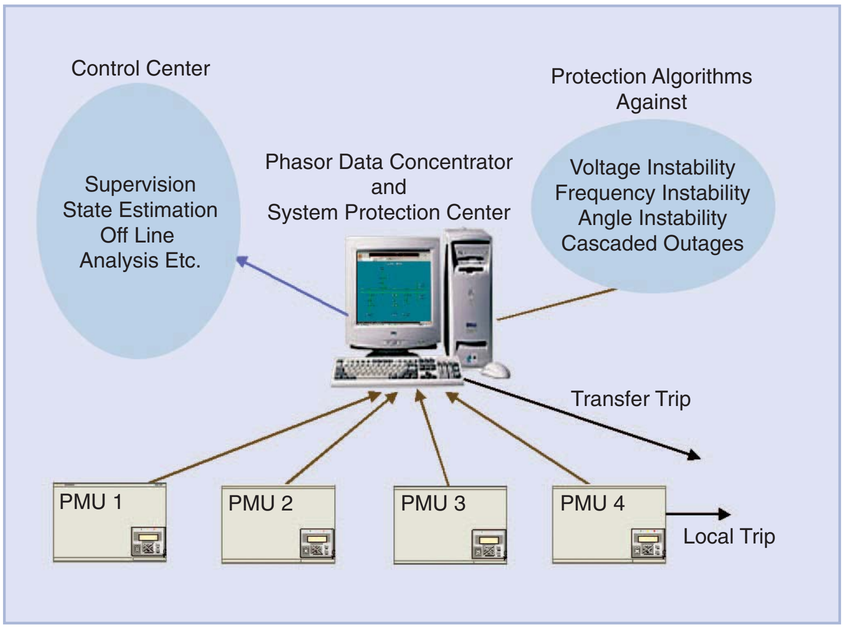


figure 4. Hub-based wide area protection design.

Powerful, reliable, sensitive and robust, wide area protection systems can be designed based on decentralized, specially developed interconnected system protection terminals (SPTs). These terminals are installed in substations, where actions are to be made or measurements are to be taken. Actions are preferable local, i.e., transfer trips should be avoided, to increase security. Relevant power system variable data is transferred through the communication system that ties the terminals together. Different schemes, e.g., against voltage instability and against frequency instability, can be implemented in the same hardware.

Protection systems against voltage instability can use simple binary signals such as "low voltage" or more advanced indicators such as power transfer margins based on the

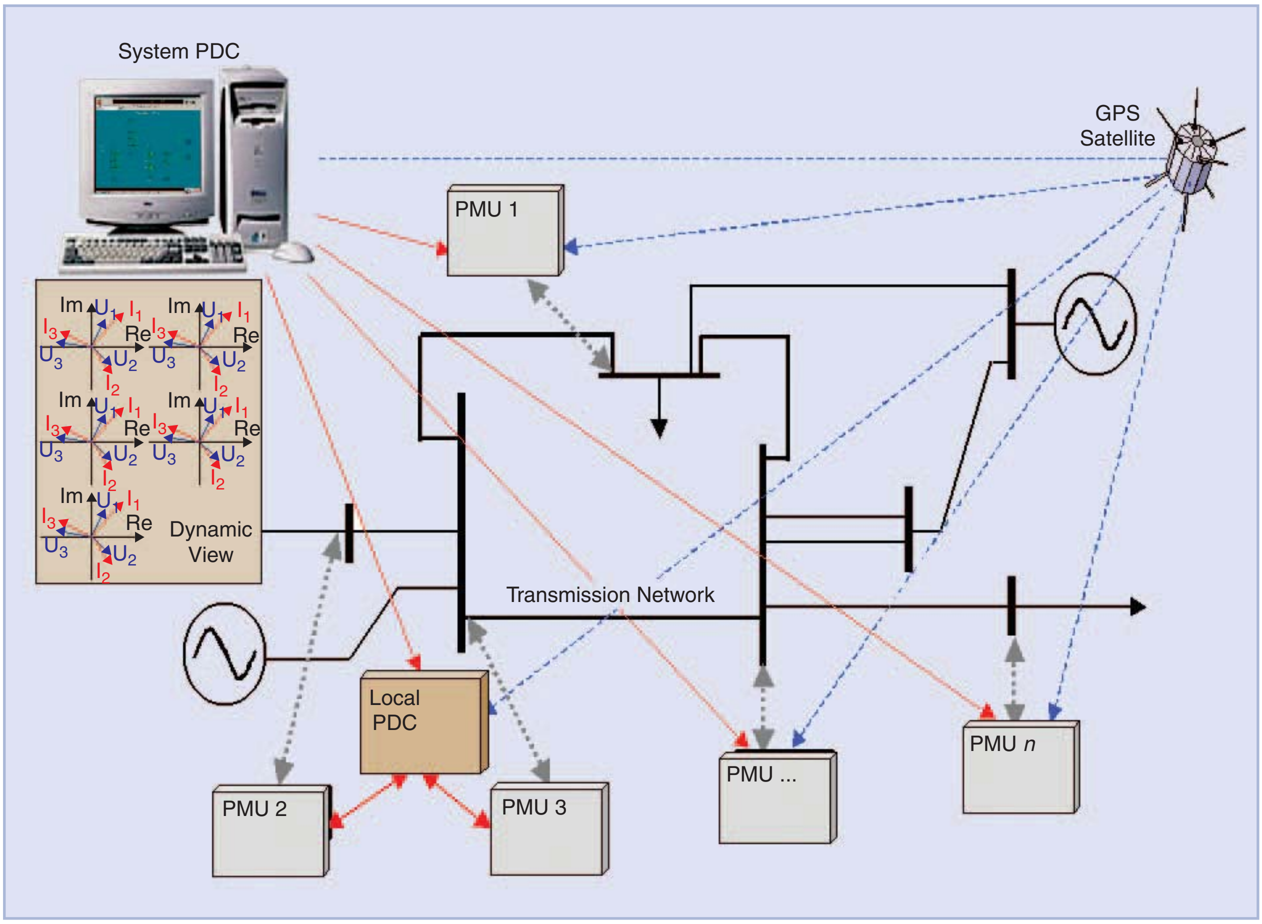


figure 5. Multilayered wide area system architecture.

VIP-algorithm or modal analysis (see Quaintance in "For Futher Reading").

The solution with interconnected system protection terminals for future transmission system applications is illustrated in Figure 1 for protection against voltage instability; similar illustration can be done for angular instability.

Different layers of protection can be used—compare with the different zones of a distance protection. The voltage is for example measured in four 400-kV nodes in a protection system against voltage instability; see Figure 2. In a certain node is a certain action taken if

- ✔ three of the four voltages are low (e.g., <380 kV) or
- ✔ two of the four voltages are very low (e.g., <370 kV) or
- ✔ the local voltage is extremely low (e.g., <360 kV).

Using the communication system, between the terminals, a very sensitive system can be designed. If the communication is partially or totally lost, actions can still be taken based on local criteria. Different load shedding steps, that take the power system response into account, to not overshed, can easily be designed. Löf provides more details about the "flat architecture."

Multilayered PMU Based Architecture

WAMS is the most common application based on PMUs. These systems are most frequent in North America and are emerging all around the world. Their purpose is to improve state estimation, post fault analysis, and operator information. In WAMS applications, a number of PMUs are connected to a phasor data concentrator (PDC), a mass storage accessible from the control center, according to Figure 3.

Starting from a WAMS design, a PDC can be turned into a hub-based system protection center by implementing control and protection functions in the data concentrator; see Figure 4.

A number of local PDCs can be integrated, together with PMUs into a larger system wide solution with a system PDC at the top, located e.g., in the control center; see Figure 5. If emergency control and protection functionality is included in such a wide area system, the bottom layer is made up of PMUs, or PMUs with additional protection functionality (SPT). The next layer up consists of several local PDCs or protection centers, according to Rehtanz.

Enhancements to SCADA/EMS

At one end of the spectrum, enhancements to the existing

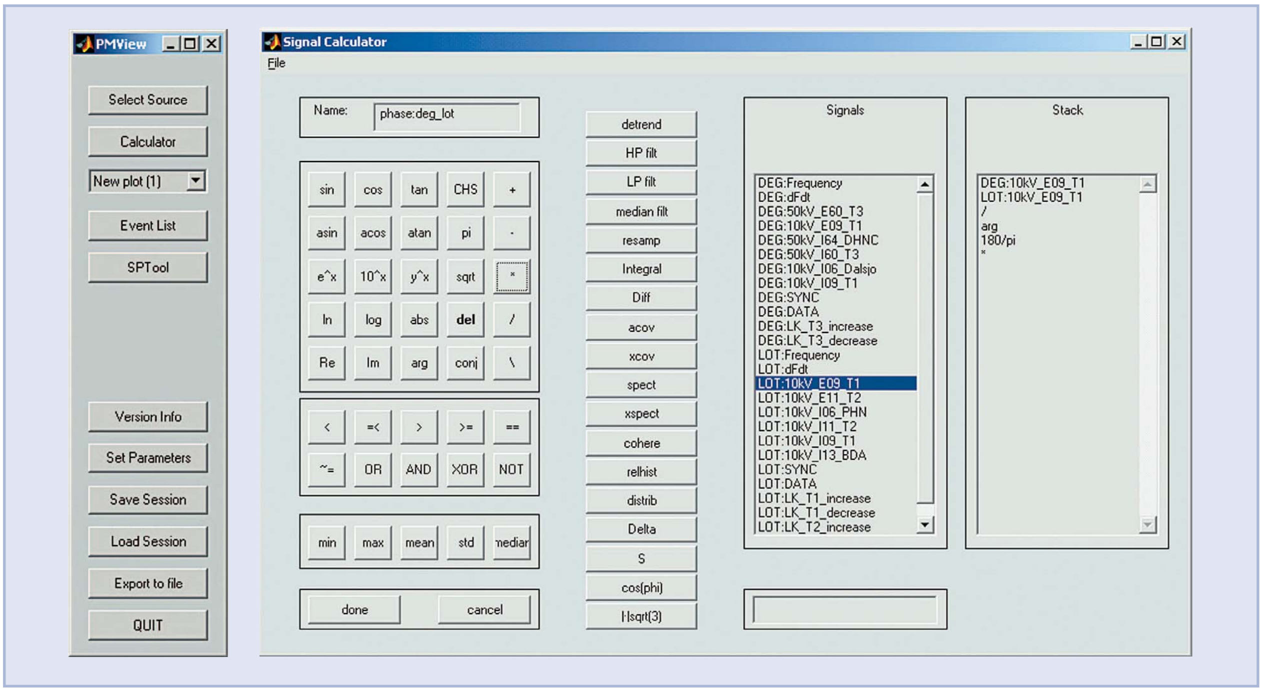


figure 6. Main menu and signal calculator.

EMS/SCADA system can be made. These enhancements are aimed at two key areas: information availability and information interpretation. Simply put, if the operator has all vital information at his fingertips and good analysis facilities, he can operate the grid in an efficient way. For example, with a better analysis tool for voltage instability, the operator can accurately track the power margin across an interface and thus can confidently push the limit of transfer across that interface.

SCADA/EMS system capability has greatly improved during recent years, due to improved communication facilities and highly extended data handling capability. New transducers such as the PMUs can provide time-synchronized measurements from all over the grid. Based on these measurements, improved state estimators can be derived.

Advanced algorithms and calculation programs that assist the operator can also be included in the SCADA system, such as "faster than real time simulations" to calculate power transfer margins based on contingencies.

The possibilities of extending the SCADA/EMS system with new functions tend to be limited. Therefore it might be relevant to provide new SCADA/EMS functions as "standalone" solutions, more or less independent of the ordinary SCADA/EMS system. Such functions could be load shedding, due to lack of generation or due to excessive market price.

Phasor Data Analysis and Handling

This section is a short description of a tentative tool for offline, as well as online, analysis of measurements from PMUs and PDCs. The tool will assemble measurements from several PMUs and PDCs into time-aligned signals. These signals are then processed by the comprehensive functions included in the tool. The program presented here is written in MATLAB but can be compiled into a standalone program.

Overview

The program provides the operations shown below. The main functions are the following:

- ✔ Selection of the input sources. Here the PMUs and the signals from the respective PMU are selected.
- ✔ Calculator. To calculate derived signals the program is equipped with a stack-based calculator that operates on the measured signals. The calculator uses complex arithmetic to facilitate computations. It is also possible to create logical signals, like synthetic trig signals, from measurements. Some more advanced functions like high and low pass filters, spectral analysis, statistics and changing of sampling frequency are also provided.
- ✔ Opening of plot windows. Each window can hold several plots, and each plot can have several signals plotted.
- ✔ Automatic time ordering of events caused by the switching of logical (binary) signals.
- ✔ Interfacing to the signal processing toolbox in MATLAB when running from MATLAB.
- ✔ Version information and automatic downloading of newer version if available and desired.
- ✔ Set preferences such as offset from UTC to local time, time span to study, time axis in seconds or HH:MM:SS and many more options.

- ✔ Saving a session so it easily can be continued later.
- ✔ Loading a saved session.
- ✔ Exporting a session so that the data can be used in another program.

Creation of New Signals

To create derived signals such as power, impedance, phase angle differences or spectrums, the calculator is used. The calculator behaves like a normal stack-based calculator (those familiar with HP calculators will feel comfortable at once). The main difference is that this calculator operates on complex-valued time series rather than scalars.

The example in Figure 6 shows how to create a new signal named "`phase:deg_lot`," whose value is the phase angle difference in degrees between two complex signals. This is just an example on how to make calculations. The phase angle difference will probably be calculated often and hence, there is a predefined function to perform this calculation, given two complex-valued signals. This function is named "Delta" and is found at the fourth button from the bottom. Several other calculations are possible:

- ✔ creation of logical signals based on logical expressions such as $<, \leq, \geq, >, =, \neq$, OR, AND, and NOT
- ✔ creation of some scalar quantities such as max, min, mean value, median value, and standard deviation
- ✔ creation of filtered and resampled signals as well as nontime series quantities such as spectrum, covariance, histograms, and probability distributions.

A Detailed Look at the Calculator

The calculator consists of the following fields going top down and from left to right and omitting the "Done" and "Cancel" buttons.

- ✔ *Name:* The name of the new signal can be left empty. Empty names will be given names calc, calc_1, calc_2, etc.
- ✔ *Standard math operations:* This field contains the standard mathematical operators. They operate on the last or the two last operands in the stack. The functions are those normally found on a calculator with the addition of the operators for complex values, real, imaginary, argument, and conjugate. All operators work on complex data so care must be taken when using, for example, trigonometric functions or logarithms.
- ✔ *Logical operators:* These operators return a time series with zero or one as result depending on if the applied relation is true or false. In addition to the normal logical operators, AND, OR, XOR and NOT it is also possible to check if a time series is for example smaller than a specified value or smaller than another time series. The switching times of a logic signal can then be found through the "Event List" interface in the main panel.
- ✔ *Statistical operators:* In contrast to the previously described operators these operators return a scalar value from a time series. The calculations that can be performed are the calculation of mean and median value, standard deviation, and finding of the smallest and largest value in a time series.
- ✔ *Advanced functions:* These are functions that do not necessarily return a time series, but they have in common that they require additional parameters to produce a result. Parameters can be such things as break point frequencies for high- and low-pass filters. It is also possible to change the sampling frequency of a signal in case signals from different PMUs have different sampling frequency. Another group of functions are those that transform data into representations other than time series. Here we have functions such as spectral and cross-spectral estimates, auto and cross correlation, and empirical probability densities.
- ✔ *Signal list:* This lists the signals available to the calculator. Signals are selected by clicking them. A double click will bring up more information about the selected signal.
- ✔ *Numerical input:* This is the box situated below the signal list. Numerical values and expressions can be entered here. Input can be numbers such as 2.4576 or pure numeric expressions such as exp(i*2*pi/3) which is the complex number $1\angle 120^{\circ}$. Vectors are entered as start:step:stop (only needed for histograms and distributions).
- ✔ *Stack:* This part shows the content of the stack.

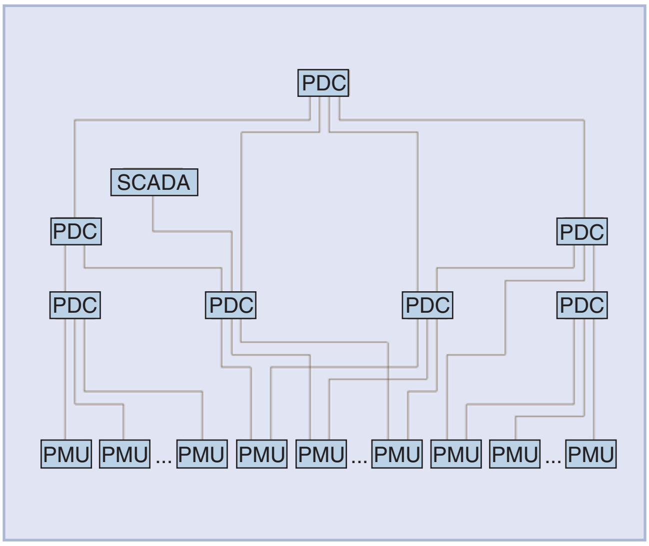


figure 7. Wide area measurement system.

PDCs

It is probably not feasible to enter data streams from more than some 20 to 30 PMUs into one PDC. It is likely that several organizations want to share data from one or several PMUs, especially near interconnections between control areas. There is also a need to filter and decimate the signals in different ways before the data are archived. This leads to the idea of a hierarchy of data concentrators, such as that shown in Figure 7.

A PDC is hence a device (hardware and software) that can receive data streams from PMUs or from other PDCs, calculate new signals, archive data, and send data streams to other PDCs. For phasor data monitoring, tools as described above might be used for online as well as offline analysis.

The PMU can remotely communicate with several clients via TCP/IP and UDP. To ensure that measurements are made and communicated in a consistent manner, the IEEE Standard for Synchrophasors for Power Systems (1344–1995) or PC37.118 is used.

The hardware may or may not be designed to withstand the harsh environment in a substation. Depending on the intended location for the PDC, it may or may not have a fan. The mass storage for archiving data may be a rotating disk or may be some sort of solid-state memory.

Conclusions

We have discussed terminology, phenomena, and solution implementation strategies for wide area system monitoring and control and concluded that different applications will require different solutions. Therefore system design and equipment must be very flexible both in size and complexity.

The use of the PMU has greatly improved the observability of the power system dynamics. Based on PMUs, different types of wide area monitoring, control, and optimization systems can be designed. A great deal of engineering, including power system studies and configuration and parameter settings, is required since every wide area system installation is unique. A cost-effective solution could be based on standard products and standard system designs. An example of a powerful and flexible analysis and monitoring tool for phasors and derived quantities is given and illustrated.

For Further Reading

M. Amin, "Toward self-healing energy infrastructure systems," *IEEE Comput. App. Power*, vol. 14, no. 1, p. 20-28, 2001.

Cigré T.F. 38.02.19, "System protection schemes in power networks," Tech. Brochure, June, 2001.

IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and classification of power system stability," *IEEE Trans. Power Syst.,* to be published.

P. Kundur*, Power System Stability and Control*. New York: McGraw-Hill, chap. 17.

W.H. Quaintance, K. Uhlen, D.E. Julian, J.O. Gjerde, K.T. Vu, and L.K. Vormdal, "Raising energy transfer in corridors constrained by voltage instability—Statnett case," in *Proc. IEEE PES Summer Meeting 2000*, vol. 4, pp. 2021–2026.

P.-A. Löf, "New principles for system protection schemes in electric power networks," in *Proc. Bulk Power System Dynamics and Control V,* Aug. 26–31, 2001, Onomichi, Japan.

C. Rehtanz, "Online stability assessment and wide area protection based on phasor measurements," in *Proc. Bulk Power System Dynamics and Control V,* Onomichi, Japan, Aug. 26–31, 2001.

Biographies

Daniel Karlsson received his M.Sc., Licentiate, and Ph.D. (electrical engineering) degrees from Chalmers University of Technology, Sweden, in 1982, 1985, and 1992, respectively. Between 1985 and 1999, he was an analysis engineer at the Power System Analysis Group within Sydkraft, Sweden. In 1994, he was appointed power system expert and promoted to chief engineer. His work has been in the power system analysis and protection area, and his research has been on voltage stability and collapse phenomena with emphasis on the influence of loads, on-load tap-changers and generator reactive power limitations. In 1999, he joined ABB Automation Technology Products (now ABB Power Technologies) as application specialist. Through the years, he has been active in several Cigré and IEEE working groups. He is a member of Cigré and a Senior Member of the IEEE. He is also an associate professor in electric power systems at Chalmers University of Technology and has supervised a number of M.Sc. and Ph.D. students.

Morten Hemmingsson received his M.Sc. (electrical enginering) from Lund University, Sweden, in 1994. Since then, he has been with the Department of Industrial Electrical Engineering and Automation, Lund University, where he received the Licentiate and Ph.D. degrees in 1999 and 2003, respectively. Between 1995 and 1998, he worked with optimization and control of hybrid electric vehicles. Since 1999 his primary work and research has been in the area of detection of power system events such as powerswings and on on-line monitoring techniques for power system parameters such as damping and oscillation frequencies. He is a Member of the IEEE.

Sture Lindahl graduated with an M.Sc. in electrical engineering from Chalmers University of Technology in 1968 and received a Licentiate of Engineering from Lund University in 1972. He started to work on load-frequency control at Vattenfall, Sweden. In 1977, he moved to Sydkraft, Sweden. In 1981, he became responsible for power system analysis and relay coordination. At that time, he served as member and chair of the working group for system-related issues in Nordel, including load-frequency control. In 1995, he moved to ABB Relays and worked with marketing, customer support and development of protective relays. In 1998, he moved to ABB Generation (now ALSTOM Power). In 2000, he became adjunct professor at Lund University. In 2001, he returned to ABB. In 1998, he became honorary doctor at Chalmers University of Technology. He is a Distinguished Member of CIGRE and a Fellow of the IEEE. p&e

Paper 3: *Trends in intelligent systems, the Web, and e-services in energy*

Full bibliographic reference:

J.M. Akkermans: *Trends in intelligent systems, the Web, and e-services in energy*, in M. Hoppe-Kilpper (Ed.), Proceedings 8th Kasseler Symposium Energie-Systemtechnik, (Keynote 8th Energy and Communication Symposium, Kassel, 13-14 November 2003), pages 7-17, ISET, Kassel, Germany, 2003.

Trends in Intelligent Systems, the Web, and e-Services in Energy

Prof.Dr. J.M. (Hans) Akkermans
Free University Amsterdam VUA, The Netherlands
and EnerSearch AB, Malmö, Sweden

Email: Hans.Akkermans@akmc.nl
World Wide Web: http://www.cs.vu.nl/bi and http://www.enersearch.com

1 Introduction

I briefly review the recent progress made in the area of knowledge-based technologies and distributed intelligence on the Internet and Web. I will particularly discuss two major ongoing developments in distributed intelligence: (1) the next, intelligent WWW generation known as the Semantic Web; and (2) intelligent agents and multi-agents systems as a distributed software architecture particularly suited to new electronic applications in an inherently networked and decentralized environment. These ICT developments will strategically impact the energy industry sector, for example by enabling new electronic energy services. This is illustrated by some recent results from international research projects, market studies and industrial field experiments.

2 WWW's Next Generation: The Semantic Web

An exciting development in current intelligent information processing is the Semantic Web (cf. [Berners-Lee et al., 2001] [Davies et al., 2003]) and the innovative applications it promises to enable. The Semantic Web will provide the next generation of the World Wide Web. The current Web is a very interesting and successful, but also passive and rather unstructured storage place of information resources. This makes it increasingly difficult to quickly find the right information you need, a problem that becomes even more pressing with the scaling up of the Web. The vision of the Semantic Web is to make the Web from a passive information store into a proactive service facility for its users. This is done by equipping it with information management services, based on semantic and knowledge-based methods, that let the Web act - in the eyes of its users - as understanding the contents and meaning (rather than just the syntax) of the many information resources it contains and, moreover, as capable of knowledge processing these resources. In the words of Tim Berners-Lee, credited as the inventor of the Web, and now director of W3C: *"The Semantic Web will globalise knowledge representation, just as the WWW globalised hypertext".* This globalised semantic approach offers concrete research lines how to solve the problem of interoperability between systems and humans in a highly distributed but connected world.

Designing the infrastructure of the Semantic Web poses major technical and scientific challenges. This is already evident if we look at the envisaged technical architecture of the Semantic Web (see Figure 1) that somewhat resembles a delicately layered cake made from a variety of cyberspace ingredients.

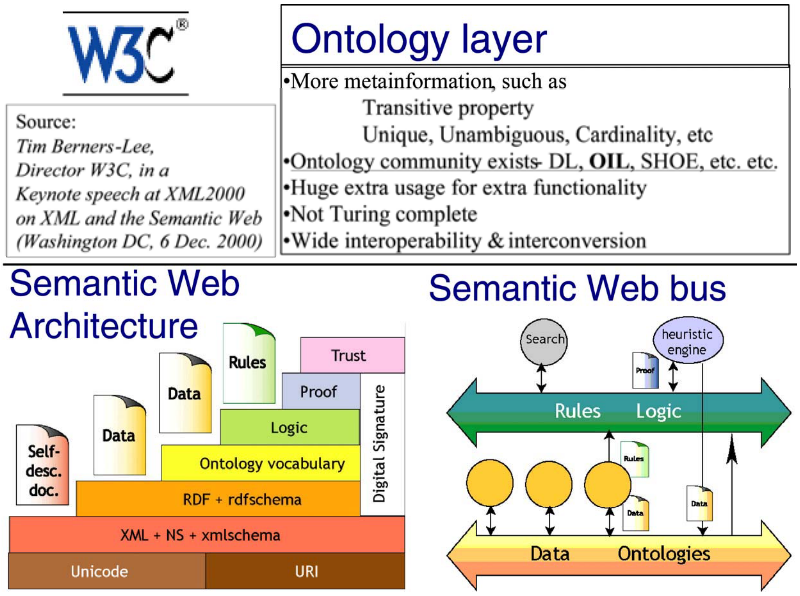


Figure 1. **Ingredients and envisaged technical architecture of the Semantic Web.**

Some of these ingredients are based on combining existing results and experiences that stem from research areas such as intelligent systems, knowledge representation and reasoning, knowledge engineering and management, or ontology and agent technology. Others are still in the process of invention. Recent progress is reported in e.g. [Davies et al., 2003], [Iosif et al., 2003].

Challenging and interesting as this is, it is a necessary but not yet sufficient condition to realize the full potential of the Web. For a comprehensive R&D strategy it is necessary to look at the broader picture (depicted in Figure 2) of the Semantic Web: how it is going to be useful in practical real-world applications, and how it will interact with and be beneficial to its users.

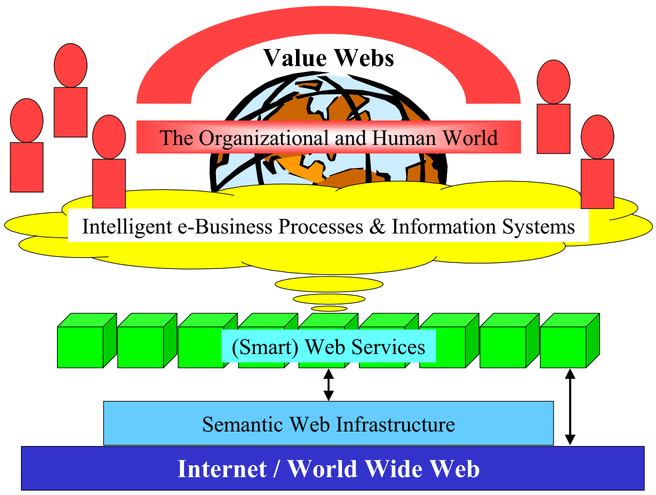


Figure 2. **The broader picture: Semantic Web infrastructure, smart services, e-applications and their human-world context.**

The ongoing worldwide research effort related to the Semantic Web currently shows an emphasis on those technological issues that are indicated in Figure 2 as web infrastructure and, to a lesser extent, smart web services. This is highly important research because generic semantic infrastructure (such as web ontology languages and content libraries) and associated generic smart web services (such as semantic search, semantic browsing, reasoning, knowledge processing and ontology management services) are a *conditio sine qua non* for the Semantic Web.

Nevertheless, it is also important to look already from the start from an *outside-in* perspective. What are the new business, domain, or user/customer applications that are not yet possible today but will be tomorrow as a result of the Semantic Web? Why would businesses, markets or individuals be willing to adopt such innovations?

After all, many great innovations fail or have very long lead times because of significant upfront investments. These are in many cases not just of a financial nature: in addition they require behavioural or -even more problematic- cultural changes from their adopters (whether individuals or organizations). We must recognize that the Semantic

Web is such a great innovation. Consequently, there is no reason to assume that the new wave of intelligent information processing is immune to the age-old established social laws that govern innovation adoption [Rogers, 1995].

3 Distributed intelligence: agents and electronic services in energy

To illustrate some of the pertinent issues I will consider a few specific examples of advanced intelligent information processing that aim the creation and introduction of innovative e-applications for end users (the third level in Figure 2). In addition to the Web becoming smarter (which is denoted by the Semantic Web effort), it will also become more universal in the sense that it will not just connect computers, but essentially any device. This is variously referred to as “ambient intelligence”, “universal connectivity” or “pervasive computing”. Mobile commerce applications are one step in this direction, but basically all equipment, including home appliances such as personal audio and video, telecom and home control systems, and even heaters, coolers or ventilation systems, will become part of the Web. This enables a broad spectrum of e-applications and e-services for end consumers in many different industry areas: home security, e-health, e-entertainment, e-shopping, distance learning, digital media services, and smart buildings that are able to manage themselves. All of these new imagined e-services are technically challenging, but will also require and induce different behaviours and attitudes from the end consumers as well as from the businesses delivering these e-services.

Figure 3. **Smart building field experiment site at ECN, Petten, The Netherlands.**

As a specific example, we take smart buildings. With several colleagues from different countries, we are researching how smart buildings can serve those who live or work in it

[Ygge & Akkermans, 1999], [Gustavsson, 1999], [Kamphuis et al., 2001]. This work has progressed to the point that actual field experiments are carried out (Figure 3), whereby the social aspects are investigated as an integrated part of the research. One of the issues studied is comfort management: how buildings can automatically provide an optimally comfortable climate with at the same time energy use and costs that are as low as possible.

Technically, smart comfort management is based on intelligent agents (so-called *HomeBot* agents, see e.g. [Ygge and Akkermans, 1999], [Gustavson, 1999]) that act as software representatives of individual building users as well as of various types of equipment that play a role in the energy functionality, usage and production in a building (e.g. heaters, sun-blinds, ventilators, photovoltaic cells). These *HomeBot* agents communicate with each other over Internet and various communication media, and negotiate in order to optimise the overall energy efficiency in the building. This optimisation is based on multi-criteria agent negotiations taking place on an electronic marketplace. These take place in the form of a multi-commodity auction, where energy is being bought and sold in different time slots. They are based on the current energy needs, local sensor data, model forecasts (e.g. weather, building physics), and the going real-time power prices. The e-market outcome then determines the needed building control actions in a fully distributed and decentralised way.

The calculation model optimises the total utility, which is a trade-off between cost and comfort, over the coming 24 hours, taking into account both the customer preferences and the actual energy prices. This optimisation is redone every hour, because expected energy prices, outside temperatures, etc. may change, which results in different optimal device settings. Needed forecasts of comfort aspects in a building are based on simple thermodynamic climate models. Energy prices are in general known a certain period (typically 24 hours) in advance. The system reacts on electricity prices, trying to use as little energy as possible when prices are high. In simulations we have concentrated on two dimensions: the economic aspect and the inside climate.

The economic aspect is illustrated by a scenario featuring two archetypes: Erika, a yuppie who wants to make no concessions to her comfort level whatsoever irrespective of cost; and Erik, a poor student who wants to keep comfort levels acceptable when at home, but also needs to economise as much as possible. Some typical results are presented in Figure 4. They do show that significant savings without loss of comfort are possible in smart self-managing buildings.

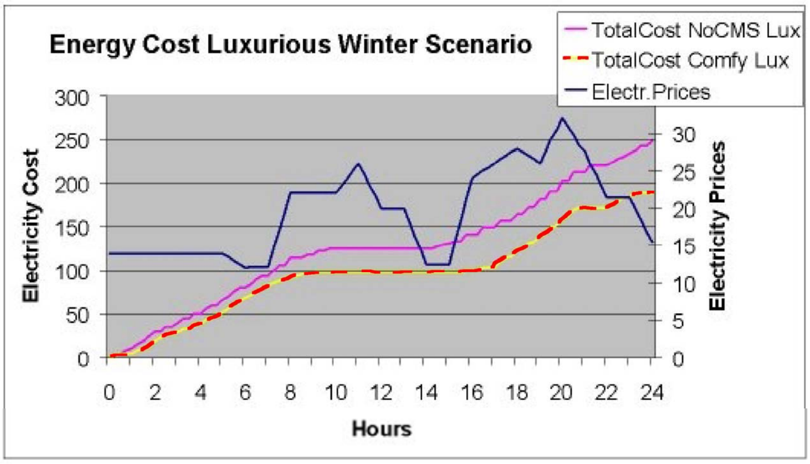


Fig. 4a

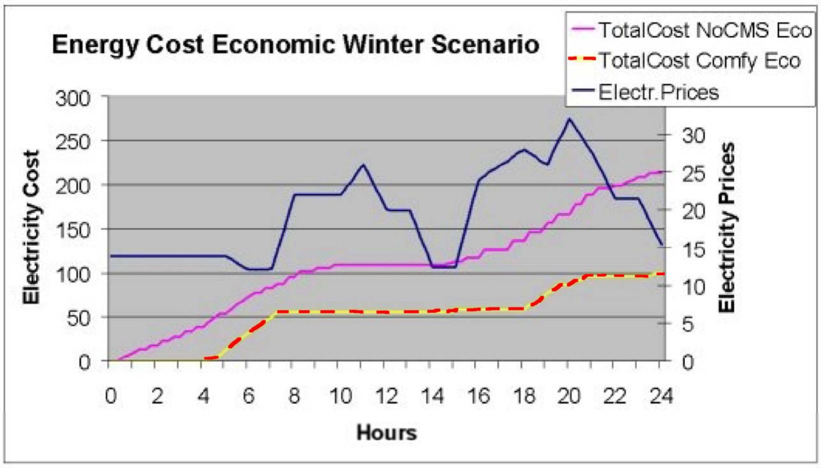


Fig. 4b.

Figure 4. Cumulative costs for a smart building scenario on a Winter day in Holland: savings vary from 20% in the luxurious setting (yuppie Erika, Fig. 4a) to 45% in the economic setting (student Erik, Figure 4b).

There are several general points beyond the specific e-application that are worth noting here in the context of intelligent information processing. First, most current multi-agent applications carry out information and transaction services. This application does that as well but it goes a significant step further: it is an example where agents carry out control tasks through an electronic marketplace that is a fully decentralized and large-scale alternative to common industrial central controllers [Ygge & Akkermans, 1999].

Secondly, technical and social considerations come together in the notion of comfort. In this application, comfort is the specialization of what counts as "*customer satisfaction*", an inherently qualitative and perceptual notion for most customers:

- People will typically be able to say whether or not they "like" the climate in a building, but they will find it extremely hard to make this explicit beyond qualitative statements.
- Comfort is a personal concept: users will generally differ in to what extent a given building climate is perceived as comfortable, and what climate they personally prefer.
- Comfort is a sophisticated multi-dimensional concept, as it causally depends on many interacting factors such as air temperature, radiant temperature, humidity, air velocity, clothing, and a person's metabolism (a measure of the person's activity).
- Delivering comfort in buildings is an economic issue: from marketing studies it is known that the financial costs of energy and equipment needed for heating, cooling, air quality, and climate control are key issues for customers and building managers.

Generally speaking, distributed intelligence techniques will require not only technological research: social and economic studies need to be integrated in a holistic fashion. Agent technology is promising for many more applications than the ones discussed above: the EU-project CRISP is developing agent applications for a variety of novel scenarios in Distributed Energy Resources (DER) including demand-supply matching, decentralized network control and intelligent load shedding. The EU-project BUSMOD investigates new, networked business models for DER.

4 The social challenge: business and market logics

Intelligent information processing will become a societal success only if it is able to deal with three very different logics of value, that are stated in terms of not necessarily compatible considerations of technology, business models, and market adoption (Figure 5).

To start with the market considerations, the recent rise and fall of many e-commerce initiatives is testimony to the importance of correctly understanding the market logics. Extensive customer surveys were done related to the applications discussed in the previous section, with interesting conclusions ([Sweet et al., 2000], [Olsson and Kamphuis, 2001], [Jelsma, 2001]) such as:

- There actually *is* a strong customer interest in a broad variety of new-e-services, with a variability of this interest across different market segments.
- However, price and cost considerations are primary in this sector, with typically a window for incurring extra costs to the customer for new e-services of no more than 5-10%.
- Design logics of modern buildings (cf. the one of Figure 3) can be such that they run counter to the use(r) logics, so that sometimes they prevent their users from doing the right thing, even if both share the same goal of energy efficiency or comfort optimization.

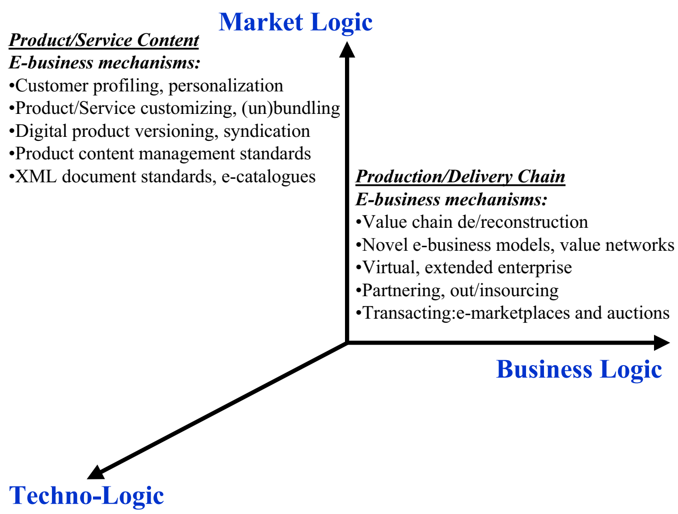


Figure 5. **Three different value logics at play in e-applications [Akkermans, 2001].**

Market logics refer to the demand side. Business logics refer to the supply side. Due to the developments of the World WideWeb, the same (digital) product or service can be created by wholly different value constellations. The degrees of freedom in designing business models have therefore significantly increased. An example of this is depicted in Figure 6. It shows a highly networked business model [Gordijn and Akkermans, 2001; Gordijn, 2002, Gordijn and Akkermans, 2003] relating to the offering of a whole bundle of utility-offered services (as considered in the OBELIX EU project; the BUSMOD project is investigating similar networked business models for distributed power generation and

DER). Clearly, many actors play a role, last but not least the customer, and establishing the business case for all actors is thus an important but non-trivial exercise. For example, it requires a thorough sensitivity analysis with respect to changes in important financial parameters in the business model. Such considerations similarly apply in the discussed smart building services, because many actors come into play also there and there is quite some freedom in designing the value constellation.

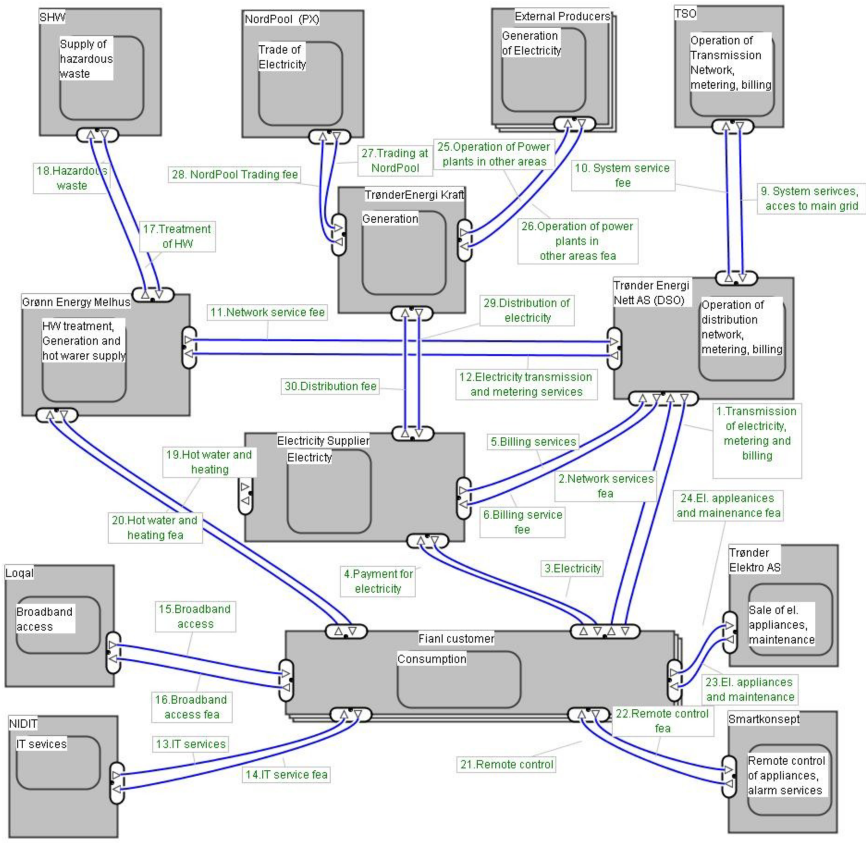


Figure 6. **Networked business model for new service bundles in energy by TrønderEnergi AS, Norway. The model is based on a methodology by the Free University Amsterdam, and developed for this case by SINTEF Energy Research in the EU-project OBELIX.**

Generally, distributed intelligence must ultimately enable the creation of *value webs*. Hence, there is a clear need to develop scientifically grounded business analysis tools that help in understanding and designing the intertwined business-technology aspects of the next wave of intelligent information processing applications.

5 Conclusion

We are on the eve of a new era of intelligent information processing as a truly promising development centred on the Internet, the (Semantic) Web, and their distributed information system applications. In order to realize its full potential, however, we have to take it for what it is: a great innovation. This implies that we simultaneously have to address the technological, social, and business considerations that play a role in innovations and their adoption by the society at large.

Acknowledgements. This work has been partially supported by the European Commission, in the context of the projects OBELIX (project no. EU-IST-2001-33144; http://obelix.e3value.com), BUSMOD (project no. EU-EESD-NNE5-2001-00256; http://busmod.e3value.com), and CRISP (project no. EU-EESD-NNE5-2001-00906; http://www.ecn.nl/crisp).

6 References and further reading

[Akkermans, 2001] J.M. Akkermans: *Intelligent E-Business – From Technology to Value*, IEEE Intelligent Systems, Vol. 16, No. 4 (July-August 2001), pages 8-10. (http://computer.org/intelligent).

[Berners-Lee et al., 2001] T. Berners-Lee, J. Hendler, and O. Lassila: *The Semantic Web*, Scientific American, May 2001.

[Davies et al., 2003] J. Davies, D. Fensel, and F. van Harmelen (Eds.): *Towards The Semantic Web – Ontology-Driven Knowledge Management*, Wiley, Chichester, UK, 2003.

[Gordijn & Akkermans, 2003] J. Gordijn and J.M. Akkermans: *Value-Based Requirements Engineering: Exploring Innovative E-Commerce Ideas*, Requirements Engineering journal, Vol. 8 (2003), pages 114-134 (Also available from the website of Springer-Verlag, 15 May 2003).

[Gordijn, 2002] J. Gordijn: PhD Thesis Free University Amsterdam VUA , June 2002. (See also http://www.cs.vu.nl/~gordijn/).

[Gustavsson, 1999] R. Gustavsson: *Agents with Power*, Communications of the ACM, Vol. 42, No. 3 (March 1999), pages 41-47.

[Iosif et al., 2003] V. Iosif, P. Mika, R. Larsson, and J.M. Akkermans: *Field Experimenting with Semantic Web Tools in a Virtual Organization*, in [Davies et al., 2003], Chapter 13, pp. 219-244.

[Kamphuis et al., 2001] R. Kamphuis, C. Warmer, and J.M. Akkermans*: SMART - Innovative services for smart buildings*. In ISPLC-2001, Proceedings of the 5th International symposium on Power-Line Communications and Its Applications, pp. 231-236. Lund University, Sweden, 2001.

[Jelsma, 2001] J.Jelsma: *The SMART System And Its Test Building: Matching Design Logics*, Netherlands Energy Research Foundation ECN, Report ECN-C-02-008, Petten, The Netherlands, December 2001.

[Olsson & Kamphuis, 2001] M. Olsson and R. Kamphuis: *Market Survey of Last-Mile Communication Services Using PLC*, PALAS EU-IST-1999-11379 Project Deliverable D9, Netherlands Energy Research Foundation ECN, Unit DEGO, Petten, NL, June 2001.

[Rogers, 1995] E.M. Rogers: *Diffusion of Innovations*, 4th Ed., The Free Press, New York, 1995.

[Sweet et al., 2000] P.S. Sweet, M. Olsson, and J.M. Akkermans: *PLC Service Business Model Development and Market Survey Instrument*, PALAS EU-IST-1999-11379 Project Powerline as an Alternative Local AccesS, Deliverable D7, EnerSearch, Malmö, Sweden, December 2000. (Available from http://palas.regiocom.net and http://www.enersearch.se).

[Ygge & Akkermans, 1999] F. Ygge and J.M. Akkermans: *Decentralized Markets versus Central Control - A Comparative Study*, Journal of Artificial Intelligence Research Vol. 11 (1999), pages 301-333 (http://www.jair.org). (Related work, see: http://www.enersearch.com).

Paper 4: *System Protection Schemes Revisited – Experiences from Recent Power System Blackouts*

Full bibliographic reference:

M. Kockott, D. Karlsson, and S. Lindahl: *System Protection Schemes Revisited – Experiences from Recent Power System Blackouts*, in Proceedings Fifth CIGRE Southern Africa Regional Conference, 24-27 October 2005, Somerset West, Western Cape, South Africa. (See also http://www.cigre.org/publications).

SYSTEM PROTECTION SCHEMES REVISITED - EXPERIENCES FROM RECENT POWER SYSTEM BLACKOUTS

Mike Kockott Daniel Karlsson Sture Lindahl

Mike.Kockott@se.abb.com

ABB Power Technology, Substation Automation, SE-721 59 VÄSTERÅS, **SWEDEN**

SUMMARY

There are two types of protection in power systems, viz. equipment protection and system protection schemes. Equipment protection is designed to detect faults in power system components and also have the task to detect if the component is subjected to abnormal operating conditions such as: overspeed, overexcitation and overload, that may cause damage. System protection schemes (SPS) are also called emergency control systems, remedial action schemes or special protection systems. They are designed to mitigate the consequences of severe contingencies and to prevent, if possible, total or partial blackout of the power system. Many utilities have installed SPS's for this purpose. Underfrequency load shedding is one such SPS that has been in use since the 1940's. The paper lists three classical types of SPS and indicates the effectiveness of each to mitigate the consequences of severe contingencies. Five severe blackouts occurred during the autumn of 2003 – North America (2003-08-14), London (2003-08-28), Scandinavia (2003-09-23), Italy (2003-09-28), and Chile (2003-11-07). Experience obtained from blackouts has allowed us to draw these conclusions that are related to the reliability of power supply systems. The conclusions cover the effectiveness and recommendations regarding equipment protection and classical system protection schemes, as well as the advantages to be gained from the implementation of potential wide area protection systems based on data acquisition from phasor measurement units.

EARLIER BLACKOUTS

A remote backup relay operated because of high load current and caused a severe blackout in North America in 1965 [13] and [17]. The operation caused the disconnection of one of the five 230-kV lines from Beck power plant to Toronto. The flow of power was thus shifted to the remaining four lines going north from the Beck power plant. Each of the lines was then loaded beyond the level at which its protective relay was set to operate. They tripped out successively in a similar manner in a total of 2.5 seconds. The blackout affected some 30 million people in Canada and USA, including New York City and lasted 13 hours.

In 1977, an intense thunderstorm accompanied by heavy winds and rain caused a blackout in USA that affected some 3 million people and lasted 22 hours [14] and [19]. Lightning struck the towers on a section of the right-of-way between two substations. Less than 20 minutes later, other towers were struck. These two lightning strokes initiated a chain of events that led to the shutdown of the power supply for the city of New York.

A failure of a disconnector in a 400-kV substation caused a voltage collapse in Sweden in 1983 [5] and [18]. As a result, two out of seven 400-kV lines from the north of Sweden were lost. A 220-kV line was tripped due to thermal overload about 8 seconds after the initial earth fault. About 50 seconds after the initial fault, a third 400-kV line was tripped by its distance protection. The remaining four 400-kV lines became heavily overloaded and a cascading tripping of these lines took place. The blackout affected 4.5 million people and lasted 5.5 hours.

SYSTEM PROTECTION SCHEMES

The most common system protection schemes are: (1) underfrequency load shedding, (2) generator tripping, and (3) undervoltage load shedding.

Underfrequency load shedding has been in use since the 1940's, [15]. After the 1965 blackout in North America, many electric power utilities installed underfrequency load shedding relays. Sustained outages of several power transmission lines do not cause significant frequency drop in large power systems. Recent blackouts have proven that underfrequency load shedding systems cannot cope with severe transmission system faults.

Generator tripping and braking resistors are used to prevent transient instability in power systems [2], [3], [4], [7], [8] and [9]. Classical transient instability appears not to have caused any of the recent blackouts.

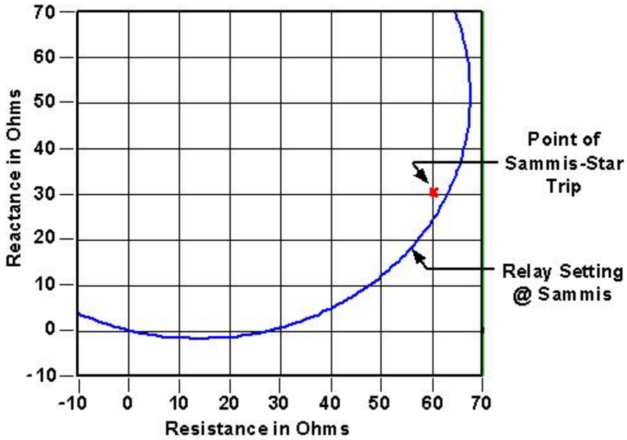
Some power utilities have installed undervoltage load shedding relays [10], [11] and [12]. Undervoltage load shedding has a potential to limit the consequences of multiple transmission line outages. There are, however, numerous scientific papers that advocate more advanced protection systems against voltage collapse. It is often claimed that undervoltage load shedding relays are difficult to set. This may have deterred utilities from installing undervoltage load shedding relays.

EXPERIENCES FROM RECENT BLACKOUTS

The autumn of 2003 saw five power system blackouts in: North America (2003-08-14), London (2003-08-28), Scandinavia (2003-09-23), Italy (2003-09-28), and Chile (2003-11-07). This section will summarize experience from three of the blackouts.

North America 2003-08-14

The power system in North America experienced a blackout on 2003-08-14 [16]. The power outage affected about 50 million people and the disconnected load was about 61,800 MW. The blackout began at 16:05 Eastern Daylight Time (EDT), and power was not restored for two days in some parts of the United States. Parts of Ontario suffered rolling blackouts for more than a week before full power was restored. Three 345-kV lines failed in a sequence that started one hour before the blackout. Each failure was the result of a contact between a line and a tree. As each line failed, its outage increased the loading on the remaining lines. As each of the transmission lines failed, and power flows shifted to other transmission paths, voltages in the rest of the system degraded further. The fourth 345-kV line was tripped from Zone-3 of the distance relay as shown in Figure 1, [16].



Once more Zone-3 of a distance relay is directly involved in the sequence of events that resulted in a major blackout.

Figure 1: R/X-diagram for the distance protection

Scandinavia 2003-09-23

On 2003-09-23, the Nordel power system experienced the most severe disturbance in 20 years. The blackout affected the southern part of Sweden and the eastern part of Denmark, including its capital city of Copenhagen. The cause was a close coincidence of severe faults leading to a burden on the system far beyond the contingencies regarded in normal system design and operating security standards.

Prior to the disturbance, operating conditions were stable and well within the constraints laid out in the operational planning and grid security assessment. The demand in Sweden was around 15,000 MW, which was quite moderate due to the unusually warm weather for the season. The nuclear generation in the affected area was limited due to on-going annual overhaul programs and delayed restarts for some units due to nuclear safety requirements. The generation in Zealand was scheduled according to the spot market trade on NordPool to an export of 400 MW to Sweden. Two 400-kV lines in the area were out of service due to scheduled maintenance work. Likewise, the HVDC links to Poland and Germany were taken out of operation due to the annual inspection and some minor works.

At 12:30, unit 3 in Oskarshamn Nuclear Power Plant started to pull back by manual control from its initial 1,235 MW generation to around 800 MW due to internal problems. The reactor scrammed to a full shutdown and stop after around 10 seconds. The system could handle this outage without any immediate serious consequences.

At 12:35, a double busbar fault occurred in a 400-kV substation on the western coast of Sweden. Two 900-MW units in the nuclear power station of Ringhals are normally feeding its output to this substation over two radial lines, connected to separate busbars. The busbars are connected to each other through certain bays, equipped with circuit breakers that are designed to sectionalise and split the substation in order to contain a fault on one busbar and leave the other intact with its connected lines in service. A fault on one busbar should therefore disconnect only one of the two nuclear units.

During some 90 seconds after the busbar fault the oscillations faded out and the system seemed to stabilize. Meanwhile the demand in the area recovered gradually from the initial reduction following the voltage drop by action of the numerous feeder transformer tap-changers. This lowered the voltage further on the 400-kV grid down to critical levels. Finally the situation developed into a voltage collapse in a section of the grid southwest of the area around the capital city of Stockholm. Within seconds following the voltage collapse, circuit breakers in the entire southern grid were tripped from distance protections and zero-voltage automatic controls. The interconnection to Zealand was disconnected as well. This system was heavily affected by the transient conditions on the Swedish grid and it did not manage to island itself to a stable situation before it broke down completely.

Figure 1 shows the voltage on the 400-kV busbar where the nuclear unit that tripped had been connected. It took about 90 seconds from the double busbar fault until the voltage collapsed. Figure 3 shows the position for a 400/130-kV on-load tap changer during the blackout. It shows the typical pattern of a voltage collapse with declining 400-kV voltage and a sequence of tap changer movements to maintain the voltage level on the 130-kV network.

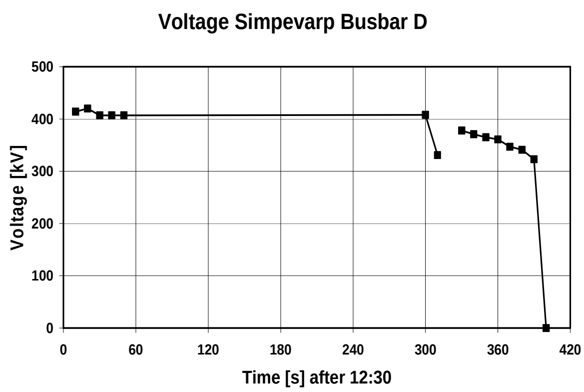


Figure 1: EHV voltage recordings

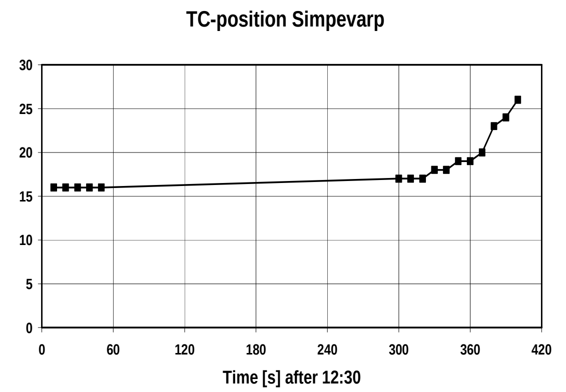


Figure 2: Tap changer recordings

Three phasor measuring units (PMUs) were temporarily installed on the island of Öland close to the spot where the nuclear unit that tripped first was connected. The PMUs were connected to 50-kV and 10-kV busbars in three substations.

Figure 3 shows the recorded voltages in the three substations. It is possible to see the power oscillation in connection with the double busbar fault and the loss of the other nuclear units. The electromechanical oscillation was damped out quite well. The slow voltage collapse started. It is also possible to see the rapid voltage variation when eastern part of Denmark lost synchronism with the reset of the Nordel-system.

Figure 5 shows that the system frequency increased at the end of the slow voltage collapse. The depressed voltages in the southern part caused a load reduction because of the voltage dependence of the load. The load reduction was so big that it influenced the total power balance in the synchronous Nordel-system and the system frequency started to increase. It is obvious that such an increase of the system frequency makes it more difficult for the underfrequency load shedding system to operate and relieve the stressed system. The first step of the underfrequency load-shedding relay has a setting of 48.8 Hz. We note that the phase shift caused by tripping circuit breakers on the 400- and the 130-kV network can be observed as a spike in the frequency recorded from the rate of change of the phase angle. Note that the frequency recordings from two different 50-kV substations coincide.

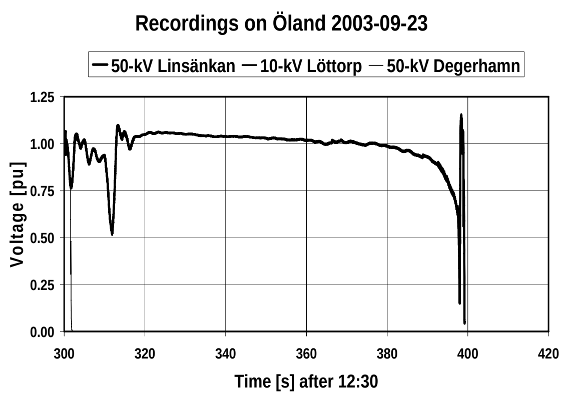


Figure 3: MV voltage recordings

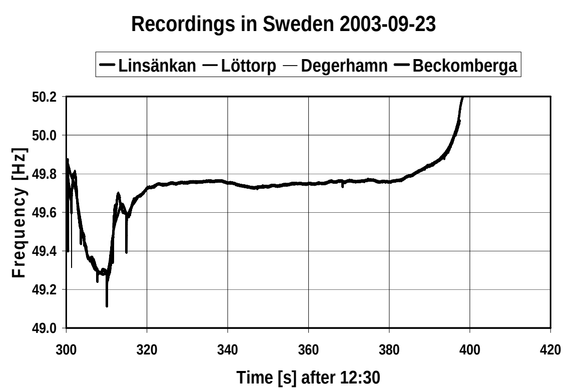


Figure 4: Frequency recordings

The blackout in southern Sweden and eastern Denmark 2003 demonstrated that the system operator sometimes tries to energise too big portions of the power system. Such attempt may fail and retard the voltage restoration. Agneholm [1] has described the automatic equipment for zero voltage tripping, which is the first stage in the power system restoration in Sweden. The automatic equipment is a distributed master reset that makes it possible to start the restoration immediately from a well-defined switching state. Each 220- and 400-kV circuit breaker has automatic equipment for zero voltage tripping. Zero-voltage equipment trips its circuit breaker when the voltage has been lower than 30% of the nominal voltage for more than 7 seconds [6]. Generators, motors and shunt capacitor may also use automatic switching equipment for zero voltage tripping.

Italy 2003-09-28

The sequence of events was triggered by a trip of the Swiss 380-kV line Mettlen-Lavorgo (also called the "Lukmanier" line) at 03:01 caused by a tree flashover. Several attempts to automatically re-close the line were unsuccessful. A manual attempt at 03:08 failed as well. Meanwhile, other lines had taken over the load of the tripped line, as is always the case in similar situations. Due to its proximity, the other Swiss 380-kV line Sils-Soazza (also called the "San Bernardino" line) was overloaded. The allowable time period for this overload was about 15 minutes according to calculations by the experts. At 03:11, a phone conversation took place between the Swiss co-ordination centre of ETRANS in Laufenburg and the Rome control centre of GRTN, the Italian transmission system operator. The purpose of the call was to request from GRTN countermeasures within the Italian system, in order to help relieving the overloads in Switzerland and bring the system back to a safe state. In essence, the request was to reduce Italian imports by 300 MW, because Italy imported at this time up to 300 MW more than the agreed schedule. The reduction of the Italian import by about 300 MW was in effect 10 minutes after the phone call, at 03:21, and returned Italy close to the agreed schedule. This import reduction, together with some internal countermeasures taken within the Swiss system, was insufficient to relieve the overloads. At 03:25, the line Sils-Soazza also tripped after a tree flashover. The sag of the line conductors, due to overheating, probably caused this flashover.

Having lost two important lines, the then created overloads on the remaining lines in the area became intolerable. By an almost simultaneous and automatic trip of the remaining interconnectors towards Italy, the Italian system was isolated from the European network about 12 seconds after the loss of the line Sils-Soazza. During these 12 seconds of very high overloads, instability phenomena had started in the affected area of the system. The result was a very low system voltage in northern Italy and the trip of several generation plants in Italy.

Countermeasures were implemented within Italy in order to face a disconnection of the country and sudden loss of the import, for example automatic shedding of parts of the load. These measures were automatically activated, but, due to the loss of generation plants, it was impossible for the Italian system to operate separately from the UCTE network. About 2 minutes and 30 seconds after the disconnection of the country, the blackout was an unavoidable fact. The frequency decay is shown in Figure 6. Note that many pump storage units were in service. Disconnection of these pump storage units, when the second 380-kV line from Switzerland tripped, could probably have made the task for the underfrequency load shedding system a lot easier. This indicates the potential for a more advanced system protection scheme than underfrequency load shedding.

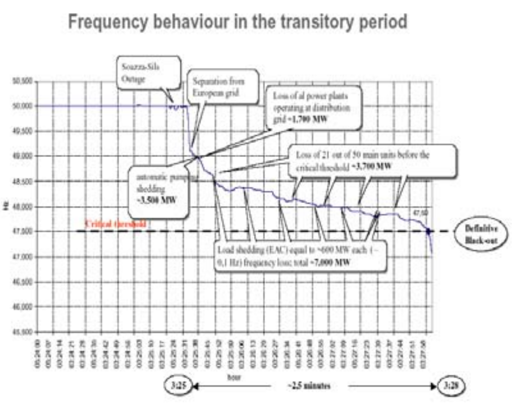


Figure 5: Frequency recordings

PHASOR MEASUREMENT BASED WIDE AREA PROTECTION

Wide Area Measurement Systems (WAMS) is the most common application based on phasor measurement units. These systems are most frequent in North America and are emerging all around the world. The main purpose is to improve state estimation, post fault analysis, and operator information. In WAMS applications a number of PMUs (Phasor Measurement Units) are connected to a phasor data concentrator (PDC), which basically is a mass storage, accessible from the control centre, according to Figure 7. Starting from a WAMS design, a phasor data concentrator can be turned into a hub-based System Protection Centre, by implementing control and protection functions in the data concentrator, Figure 8.

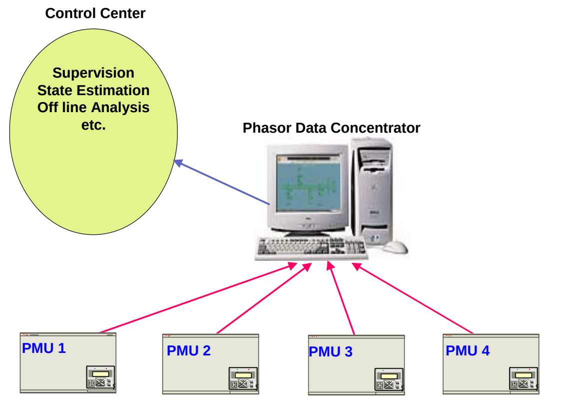


Figure 7. PMUs and a PDC in a WAMS design.

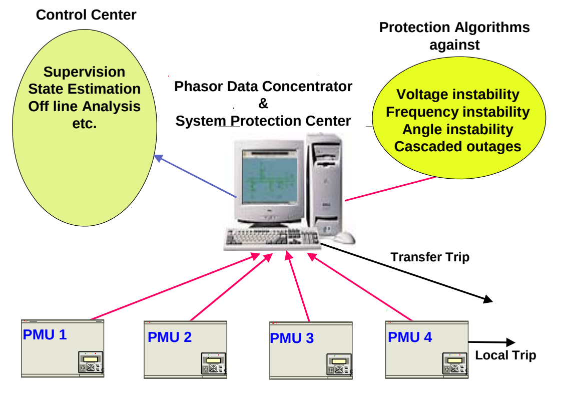


Figure 8. Hub based WAMS design.

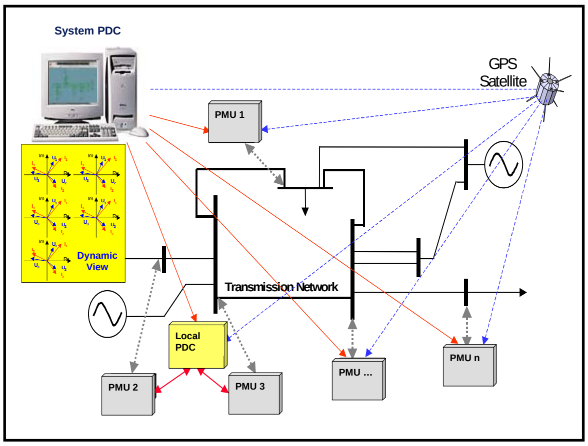


Figure 9. Multilayered wide area system architecture.

A number of Local PDCs can be integrated, together with PMUs into a larger system wide solution with a System PDC at the top, located e.g. in the control centre, see Figure 9. If emergency control and protection functionality is included in such a wide area system, the bottom layer is made up of PMUs, or PMUs with additional protection functionality. The next layer up consists of several local PDCs or Protection Centers [20].

CONCLUSIONS

The earlier and recent blackouts allow us to draw some conclusions related to the reliability of power supply systems and system protection schemes.

Equipment Protection

The most urgent measure is to get rid of Zone-3 of distance relays on the transmission systems. Nowadays, major transmission systems are equipped with duplicated line protection, busbar protection and breaker failure protection. Such a fault clearance system can withstand the single failure criterion with minimal disconnection of HV equipment and have a back-up fault clearance time of 250 milliseconds or less. Zone-3 in distance relays should not be used as overload protection. The removal of Zone-3 may create a need for a better thermal overload protection to fully utilise the temporary overload capability of the conductors.

Underfrequency Load Shedding

Underfrequency load shedding systems are required in most power systems to handle loss of generating units. Operational experience shows that underfrequency load shedding may not handle loss of transmission capacity.

Undervoltage Load Shedding

Undervoltage load shedding has the potential to handle loss of several power lines at normal frequency. Undervoltage load shedding may form a last ditch of defence. Many researchers have argued that undervoltage load shedding relays may be difficult to set and that more sophisticated relays are needed.

System Protection Schemes

System protection schemes have the potential to activate appropriate actions. Such schemes may limit disconnection of customers and may help in anticipated situations.

REFERENCES

[1] Agneholm, E.: "The Restoration Process following a major Breakdown in a Power System", TechnLic Thesis, Technical Report No. 230L, Department of Electric Power Engineering, School of Electrical and Computer Engineering, Chalmers University of Technology, Göteborg, 1996.

[2] Coetzee, G.J. & Wittwer, F.: "Development of a transient stability protection system for Eskom's Matimba power station", Developments in Power System Protection, March 25-27, IEE Conference Publication No. 434, pp. 36-39, 1997.

[3] Fouad, A.A.; Ghafurian, A.; Nodehi, K. & Mansour, Y.: "Calculation of Generation-shedding Requirements of the BC Hydro System Using Transient Energy Functions", IEEE Trans. on Power Systems, vol. PWRS-1, no. 2, pp. 17-24, May, 1986.

[4] Grobovoy, A.A.: "Russian Far East Interconnected Power System Emergency Stability Control", IEEE Power Engineering Society Summer Meeting, 2001, vol. 2, pp. 824-829, 2001.

[5] Larsson, S. & Kearsley, R.: "The Blackout in the Swedish Power Supply System, December 1983", Paper presented at the 5th CEPSI Conference, Manila, November 1984.

[6] Lohage, L.; Hermansson, H. & Almgren, B.: "Automatic Switching of Circuit-Breakers", Paper 2B-8 presented at the CIGRE-symposium in Bournemouth, June 1989.

[7] Ohura, Y.; Matsuzawa, K.; Ohtsuka, H.; Nagai, N.; Gouda, T. Oshida, H.; Takeda, S. & Nishida, S.: "Development of a Generator Tripping System for Transient Stability Augmentation Based on the Energy Function Method", IEEE Transactions on Power Delivery, vol. PWRD-1, no. 3, pp. 68-77, August 1986.

[8] Peelo, D.F.; Hein, D.W. & Peretti, F.: "Application of a 138 kV 200 MW braking resistor", Power Engineering Journal, vol. 8, no. 4, pp. 188-192, 1994.

[9] Shelton, M.L.; Winkelman, P.F.; Mittelstadt, W.A. & Bellerby, W.J.: "Bonneville Power Administration's 1400 MW Braking Resistor", IEEE Transactions on Power Apparatus and Systems, vol. PAS-94, no. 2, pp. 602-611, March/April 1975.

[10] Taylor, C.W.: "Concepts of Undervoltage Load Shedding for Voltage Stability", IEEE Transactions on Power Delivery, vol. 7, no. 2, pp. 480-488, April 1992.

[11] Taylor, C.W.: "Power System Voltage Stability", McGraw-Hill, 1993.

[12] Taylor, C.W.; Comegys, G.L.; Nassief, F.R.; Elwood, D.M. & Kundur, P.: "Simulation and implementation of undervoltage load shedding for Pacific Northwest voltage stability", CIGRE, paper 38-103, 1994.

[13] Vassell, G.S.: "Northeast Blackout of 1965", IEEE Power Engineering Review, pp. 4-8, January 1991.

[14] Wilson, G.L. & Zarakas, P.: "Anatomy of a Blackout: How's and Why's of the series of events that led to the shutdown of New York's power in July 1977", IEEE Spectrum, vol. 15, no. 2, pp 39-46, February 1978.

[15] "Automatic Load Shedding", AIEE Committee Report, AIEE Trans., vol. 73, pp. 1143-1146, December 1955.

[16] "Causes of the August 14th Blackout", Interim Report from the U.S.-Canada Power System Outage Task Force

[17] "Northeast Power Failure, November 9 and 10, 1965: A report to the President", Federal Power Commission, U.S Government Printing Office, Washington, December 6, 1965.

[18] "The Blackout in Sweden 1983-12-17", Vattenfall, 1984-02-07.

[19] "The Con-Ed power failure of July 13-14, 1977", Federal Energy Regulatory Commission, U.S. Department of Energy, Final Staff Report, June 1978.

[20] Löf, P.-A., "New Principles for System Protection Schemes in Electric Power Networks", Bulk Power System Dynamics and Control V, August 26-31, 2001, Onomichi, Japan.

SUMMARY OF AUTHORS' BIOGRAPHY

Sture Lindahl was born in Råneå, Sweden. He graduated with an MSc in Electrical Engineering from Chalmers University of Technology in 1968 and got a Licentiate of Engineering from Lund University in 1972. He started to work on load-frequency control at Vattenfall, Sweden. In 1977, he moved to Sydkraft, Sweden. In 1981, he became responsible for power system analysis and relay co-ordination. At that time, he served as member and chairman of the working group for system-related issues in Nordel, including load-frequency control. In 1995, he moved to ABB Relays and worked with marketing, customer support and development of protective relays. In 1998, he moved to ABB Generation (now ALSTOM Power) and participated in the development of Powerformer™, the new high-voltage generator that can be connected directly to the transmission network. In 2000, he became adjunct professor (part-time) at Lund University. In 2001, he returned to ABB where he was responsible for application research in the area of protective relays until he left for Gothia Power 2005. In 1998, he became Honorary Doctor at Chalmers University of Technology. Sture Lindahl is a Distinguished Member of CIGRE and a Fellow of IEEE.

Daniel Karlsson received his Ph. D in Electrical Engineering from Chalmers University in Sweden 1992. Between 1985 and April 1999 he worked as an analysis engineer at the Power System Analysis Group within the Operation Department of the Sydkraft utility. From 1994 until he left Sydkraft in 1999 he was appointed Power System Expert and promoted Chief Engineer. His work has been in the protection and power system analysis area and the research has been on voltage stability and collapse phenomena with emphasis on the influence of loads, on-load tap-changers and generator reactive power limitations. His work has comprised theoretical investigations at academic level, as well as extensive field measurements in power systems. Most recently Dr. Karlsson hold a position as Application Senior Specialist at ABB Automation Technology Products and now he is with Gothia Power. Through the years he has been active in several Cigré and IEEE working groups. Dr. Karlsson is a member of Cigré and a senior member of IEEE. He has also supervised a number of diploma-workers and Ph. D students at Swedish universities.

Mike Kockott was born in East London, South Africa. He graduated with a BSc in Electrical Engineering with honours from the University of Cape Town in 1980. After leaving university he entered into the SA Navy for his two-year period of National Service. After completion of his National Service, he joined Eskom where he worked from the beginning of 1983 until November 1999. His career began at System Operations where he calculated protection settings for transmission system equipment and performed post-fault investigations. He left System Operations as a Senior Engineer and joined the protection design department. At one time he held the position of Design Manager for all feeder related protection schemes. He later moved on to become a Senior Consultant. In 1996 he was appointed as the South African member to Cigré Study Committee 34. On leaving Eskom, he commenced employment with ABB in Sweden in January 2000. He currently holds the position of Protection Application Senior Specialist.

Paper 5: *Intelligent Load Shedding to Counteract Power System Instability*

Full bibliographic reference:

D. Andersson, P. Elmersson, Å. Juntti, P. Carlsson, Z. Gajić, D. Karlsson, and S. Lindahl: *Intelligent Load Shedding to Counteract Power System Instability*, in Proceedings CIGRE Conference, Paris, France, 29 August – 3 September 2004, paper No. 207-04. (See also http://www.cigre.org/publications).

277-04
Intelligent Load Shedding to Counteract Power System Instability

Dan Andersson, Peter Elmersson & Åke Juntti
Sydkraft Elnät, Sweden

Per Carlsson
Information Technology, Uppsala University, Sweden

Zoran Gajić*, Daniel Karlsson & Sture Lindahl
ABB, Sweden,

This paper addresses indicators of imminent power system instability; advanced methods to smoothly reduce load - with and without communication, including some dynamic price based mechanisms; dynamic load response due to change in supply voltage or reactive power support; power system response due to change in load; and impact of dispersed generation in power systems in transition towards an instability. The results in the paper are based both on theoretical studies and field measurements. The main part of the paper is based on recordings from the 50 kV Öland system during the abnormal power system conditions related to the Swedish blackout 2003-09-23.

Keywords: Load shedding – Power System – Stability – Dynamic price - Interaction

1. Background and Introduction

Load shedding as the last resort to avoid a major power system breakdown has been utilized for a long time, mainly triggered by underfrequency or undervoltage relays and actuated by distribution system circuit breakers. Deregulation, dispersed generation, load growth and the ever increasing dependence on reliable electricity supply of modern society have forced the need for more “intelligent load shedding”, as a means to preserve system integrity and provide acceptable system performance. The aim is to provide smooth load relief, in situations where the power system otherwise would go unstable. Different types of “intelligent load shedding” have been discussed in literature for a rather long time [1-4].

Identifying methods to fast and reliably detect a power system operational transition towards an instability is the first part of the “intelligent load shedding” task, while identifying methods to activate “intelligent load shedding”, is the second one. The activation part also comprises methods to identify the amount and the location of the required load shedding. To counteract imbalance between load demand and generation, underfrequency controlled load shedding, has been applied by almost every utility and grid operator, for a very long time. Methods to counteract loss of transmission capacity, and imminent voltage instability have, however, not been that common [5-7]. Lack of systems to detect imminent voltage instability has significantly contributed to the severity of the recent large disturbances [8]. These disturbances clearly show that voltage level, and reactive power output from generators connected to the transmission grid, are fairly good indicators of transmission system capacity compared to the demand, and can suitably serve as triggers to activate load shedding [9]. To improve from today’s circuit-breaker controlled load shedding, to a more “intelligent” method, aiming at providing the necessary load relief to the power system at the “lowest total cost”, different methods can be used, such as:

- Direct order to individual load objects to reduce power or to switch off.
- Use of distribution system on-load tap-changer (OLTC) control, to gain time for other actions, and at least make sure that the tap-changer controllers not make the situation worse.

*ABB Automation, ATCE/SA/A, SE-721 59 Västerås, Sweden; E-mail: zoran.gajic@se.abb.com

- Using price levels, with different levels of “negotiations” to achieve a load relief.
- Boosting dispersed generation to increase active and reactive power supply to, at least temporarily, reduce the demand on the transmission grid.

To achieve “intelligent load shedding” as described above it is important to keep track on load available to shed, to find an “optimal” amount of load to shed, to find an ”optimal” location of load to shed. It is also important to identify methods to estimate the power system response to a load relief, and finally, to evaluate how to utilize price and market instruments for direct or indirect load control and load relief. Price and market instruments are, however, very much dependent on communication capability. The area of “intelligent load shedding” covers theoretical work based on customer categories, load pattern and computer simulations, as well as field measurements, especially in radially fed distribution systems. The measurements in this report are performed with phasor measurement technology to capture also the dynamic properties of large wind power farms in a fairly weak system.

2. Smooth Load Relief

Smooth load relief as a part of a power system instability counteracting scheme, is the natural consequence of the ever increasing demands on transmission system loadability, higher demands on power system reliability and the technical possibilities to really achieve “intelligent load shedding”.

2.1 Remote Load Object Switching

A first step to make load shedding more intelligent would be to address individual load objects with low short-term priority, a typical example is to shut down hot water heaters, space heaters and air-conditioners in residential areas. Such a system requires in its most simple form a broadcasting network to address the different devices. A more advanced scheme comprises a two-way communication network, where each load reports its present status of interruptable load amount, and price tag or price ladder. A continuously updated activation table is then kept at the load shedding control center, and when activated a specified amount of connected load is shed in the order of priority, which means in some respect lowest cost.

2.2 Supply Voltage Control

The major disturbances throughout the world in 2003 have clearly illustrated the need for different modes of voltage control, since the requirements during normal operation conditions and abnormal conditions, sliding towards instability, are very different. In the following, focus will be on possibilities to improve tap-changer control in order to perform properly also for disturbed conditions. Figure 1 shows the tap-changer position for a power transformer, from the transmission level to the subtransmission level in southern Sweden, immediately prior to the system separation, September 23. The tap-changer is designed only to keep the voltage at the low voltage side within certain limits, around the set point. When the transmission side voltage decreases, the tap-changer operates to fulfill its task. As a consequence, the tap position increases nine steps within 80 seconds, keeping up the downstream voltage – and thereby the load – drawing more power from the already weakened transmission system. There are reasons to believe that this tap-changer could have been more “intelligent”, which will be further discussed in the following.

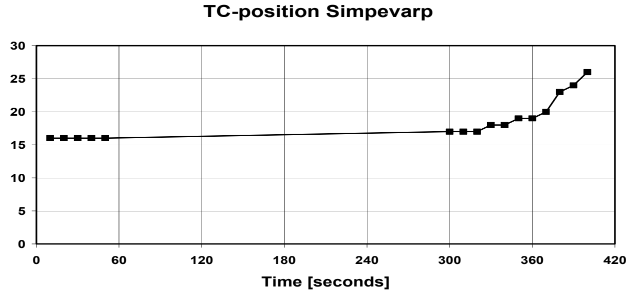


Figure 1. Transformer tap-changer position immediately prior to the system separation.

The main purpose of the on-load tap-changer is to keep low voltage (LV) side busbar voltage within a preset dead band. Thus, its main function is to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an OLTC shall react and change position in accordance with LV side load variations. However, the OLTC will as well react on abnormal voltage variation on the high voltage (HV, in distribution systems the supply) side of the power transformer. Often such reaction is not desirable because it just further increases total load on the HV system (i.e. transmission system). Especially, such behavior shall be prevented during critical operation states of the transmission system, such as a slow power system voltage decrease.

All currently commercially available automatic voltage regulators (AVRs), just measure the LV side voltage of the power transformer in order to make decisions about OLTC position. Such a principle has a major drawback that typically speeds up a power system voltage collapse. However, some modern intelligent electronic devices (IEDs) used for such automatic control do have the capability to measure power system voltage on both sides of the power transformer, as shown in Figure 2.

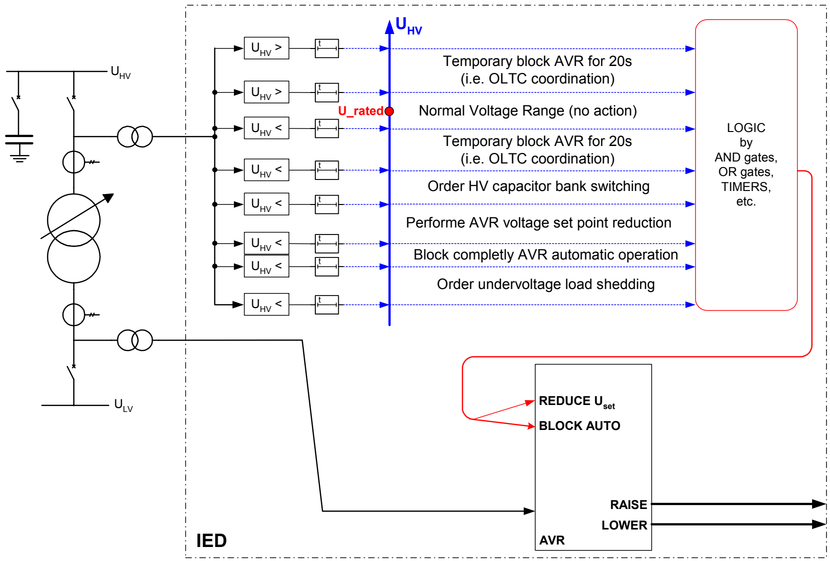


Figure 2. Proposal for an improved automatic on-load tap-changer control scheme.

Voltage transformers are typically available on the HV side of the power transformer due to other reasons. By using a number of over- and undervoltage triggers it is then possible to monitor HV side voltage magnitude and consequently influence the operation of the AVR or other equipment in the substation. For the best scheme security it is desirable to measure all three phase-to-earth voltages from the HV side, in order to take necessary action only when all three voltages are above or below the pre-set level. Therefore, operation of the AVR will be influenced by the measured voltage level on the HV side of the power transformer. The following are typical actions, which can be taken:

- Temporary AVR block (e.g. for 20 s).
- Temporary AVR voltage set point change (typically reduction).
- Complete AVR block.
- HV shunt capacitor (reactor) switching.
- Undervoltage load shedding.

Such a scheme can be tailor made in strict requirements of every power system operator and characteristics of the individual power system. In addition to excellent performance for HV side voltage variations it can as well be used to improve time coordination of the OLTCs connected in series as well as to minimize the number of necessary tap-changer operations [10].

3. Load and Supply Interaction – Field Test from the Island of Öland

The test area, the island of Öland, is radially fed from the mainland 130 kV subtransmission network. A fault on the 130 kV system will, after the fault clearance process is completed, reduce the source impedance of the feeding network. From such a disturbance the change in supply voltage can be compared to the change in supplied power at the feeding point of the radial system. The change in voltage, that reflects the strength/weakness of the system, is important to be able to estimate suitable trigger levels for undervoltage based remedial actions against instability. The relation between voltage and power provides valuable information for reliable load model design, for voltage stability studies. A fault on the 50 kV radial distribution network on Öland causes a line trip and a power reduction corresponding to the line load. The voltage response to such a load relief (when the fault is cleared, but before the reconnection of the line) is related to the source impedance of the feeding network and the amount of disconnected load. The size of the source impedance turns out to be a very important variable, to be able to estimate the required amount of load to shed in order to achieve a certain effect, such as voltage recovery. Methods to estimate the source impedance on-line, during disturbed conditions, are described in [11].

3.1 Load Response due to Change in Supply

This section illustrates the load response due to changes in the source impedance, based on recordings from the test period. A typical example is load variation due to 130 kV line fault on Swedish mainland. One such incident was a line-to-line-to-earth fault, 2003-04-12. The line was tripped and the Öland supply source impedance was temporarily increased. After approximately one second the line was successfully reclosed and the Öland supply source impedance was restored to the pre-fault value. The total Öland active and reactive power consumption variations during this incident are shown in Figure 3.

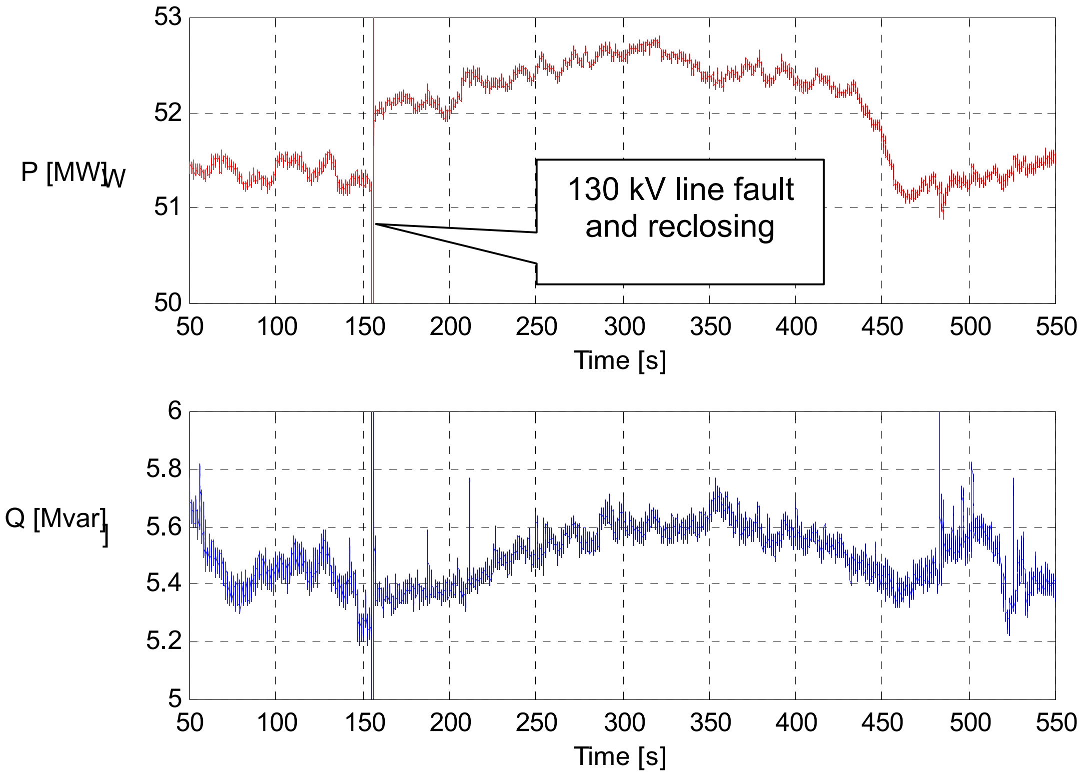


Figure 3. Öland total load variation due to a 130 kV mainland line fault.

It is shown in the figure that it takes around 5 minutes before the active power settles down to approximately the same value it had just before the fault. Therefore the load can be quite dependent on voltage variations caused by source impedance changes. This shall be kept in mind when load shedding schemes are designed.

3.2 System Response due to Change in Load

This section illustrates the system response due to changes in the load, based on recordings from the test period. A typical example is load variation due to 50 kV line fault on Öland. One such incident happened on 2003-05-26. The line was tripped and one part of the total Öland load was dropped-off. The positive sequence supply voltage dropped to about 60% of its rated value during the fault. After approximately 30 s the line is successfully reclosed and the load is re-connected. Load variations during this incident are shown in Figure 4. From the figure it is obvious that active power settles down to approximately the same value as it had just before the fault after some 40 s after the reclosing.

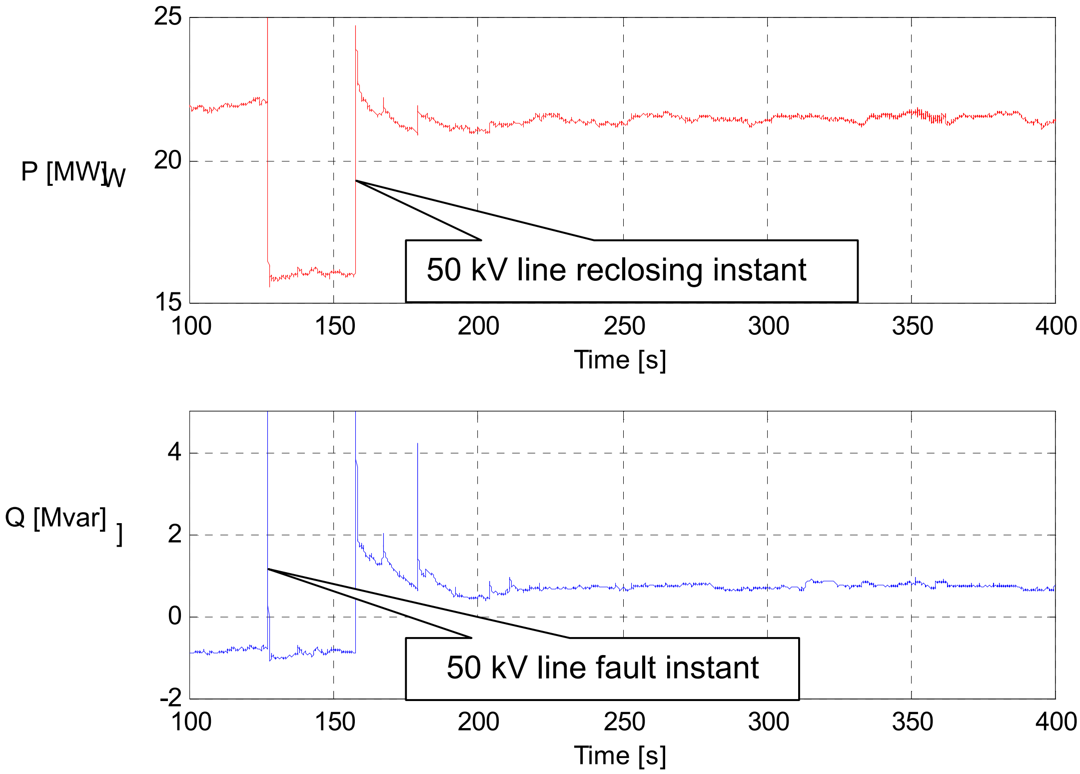


Figure 4. Öland total load variation due to 50 kV line fault.

Another very interesting example of interaction between load and supply is taken from the final seconds preceding the system separation due to the voltage collapse, 2003-09-23. The blackout was a typical voltage collapse due to loss of three big generators (in total 3000 MW) and a double busbar fault, causing the loss of a number of major transmission lines. As shown in Figure 5 during the final stage of the collapse, power system frequency went upwards and therefore definitely prevented the underfrequency load shedding scheme from operation. The frequency increase can be explained as load active power drop due to very low voltage levels in this part of the country. This incident very clearly shows that the short time load is very much dependent on the supply voltage magnitude. Thus it should be interesting to use combined information about frequency and voltage variations during power system abnormal situations in order to make more intelligent decisions about load shedding. As seen from Figure 5, such an approach might be much more effective in the final stage of the voltage collapse. Another interaction between power supply system and load is visible during power system restoration after the Swedish blackout. The example shown in Figure 6 is active power and voltage variations in a 10 kV substation in the Northern part of Öland (quite remote part of the Swedish mainland system) during the restoration. Large voltage fluctuations are due to many unsuccessful switching attempts of a shunt reactor in mainland Sweden. Obviously, it is very important for the system operator to be able to take automatic control of shunt compensating devices out of service, due to abnormally weak power system condition [12]. Otherwise influence of just one shunt device can be quite high and it can be immediately tripped by the automatic voltage control scheme. For the power system operator it is of outmost importance to be able to override such automatic control during the restoration.

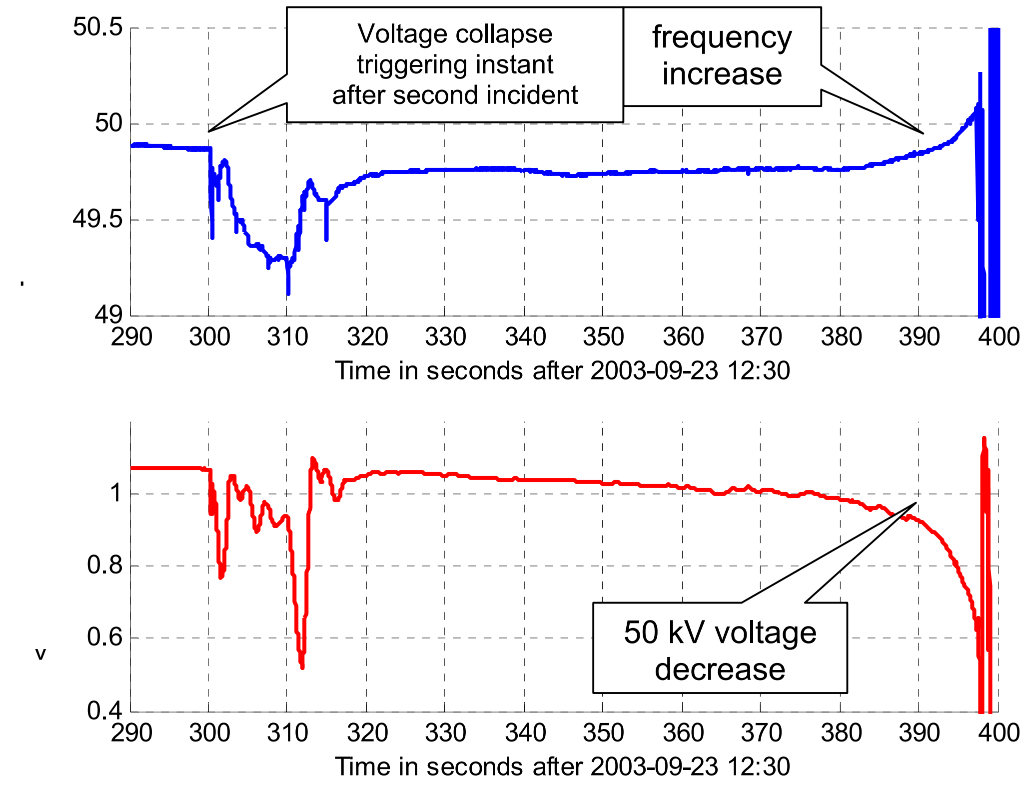


Figure 5. Frequency and voltage during the Swedish blackout.

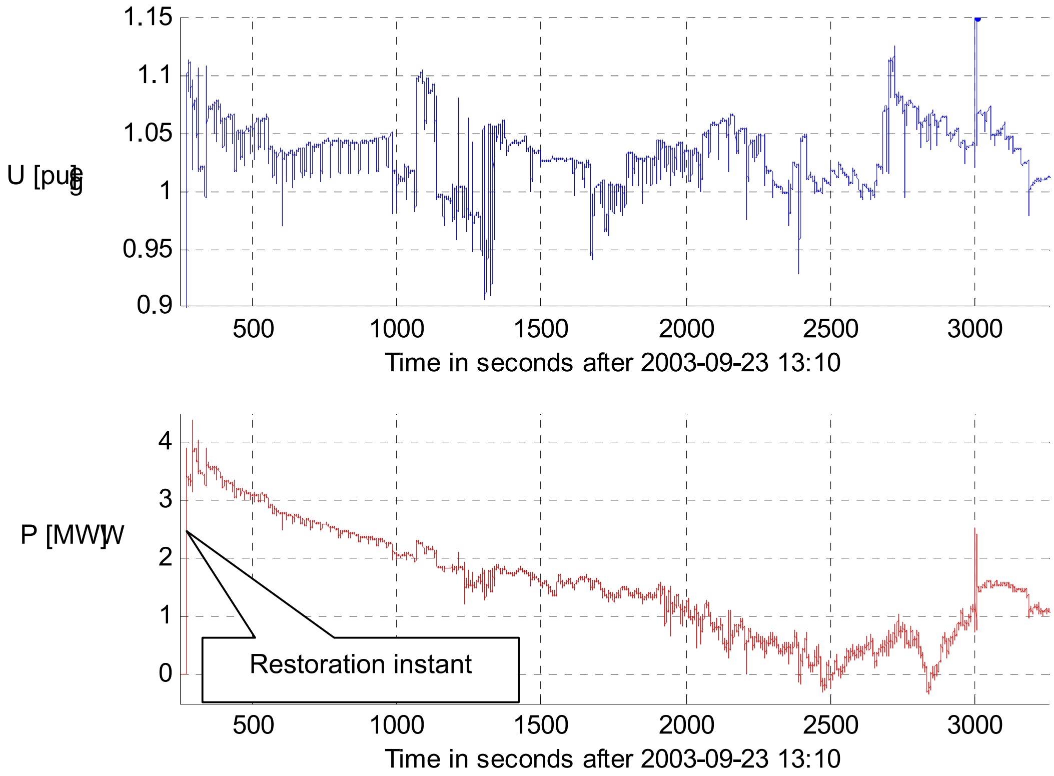


Figure 6. Distribution level voltage and active power during the restoration, after the blackout.

4. Impact of Dispersed Generation on Power System Stability

Generally, dispersed generation helps to supply the load when the transmission system capacity is reduced. However, there is a severe risk that the dispersed generation trips for nearby line faults. It was experienced during the test period that a 4 MW input from a wind power farm was lost due to a line fault about 50 km away. The ability of the dispersed generation to contribute to the voltage control in the area is also of great importance, and varies very much with respect to the design, from simple asynchronous generators to more sophisticated solutions, based on permanent magnetic rotors and power electronics. It has also to be kept in mind that during low network voltage conditions, the reactive power support from shunt capacitors is significantly reduced. So, in conclusion, dispersed generation can have a positive impact on the power system stability, but the design and control systems have to be carefully chosen.

An interesting example of dispersed generation behavior during abnormal conditions, is the trip of the entire *Utgrunden*, a 10 MW off-shore wind power farm in the Southern part of Öland, at the second incident (double busbar fault) of the Swedish blackout at 12:35, as shown in Figure 7. Thus, the wind power farm was not available to help the weakened power system at the final stage of the voltage collapse. This wind power farm was resynchronized to the system around 16:05 as shown in Figure 7, then it took more than one hour before it was loaded to its full capacity. It was fully loaded for approximately one hour and then the load was reduced. Finally just before 19:00 it was tripped again. Therefore this wind power farm was not available in the first hours of the restoration, but after that, when distribution load was started to be connected back into service, it was utilized by its full capacity for about an hour. Finally it was tripped again for longer period. The obvious lesson learned here is that the control and protection relay settings for such wind power farm shall be done carefully in order to utilize the wind power farm capacity to support the transmission system in stressed situations.

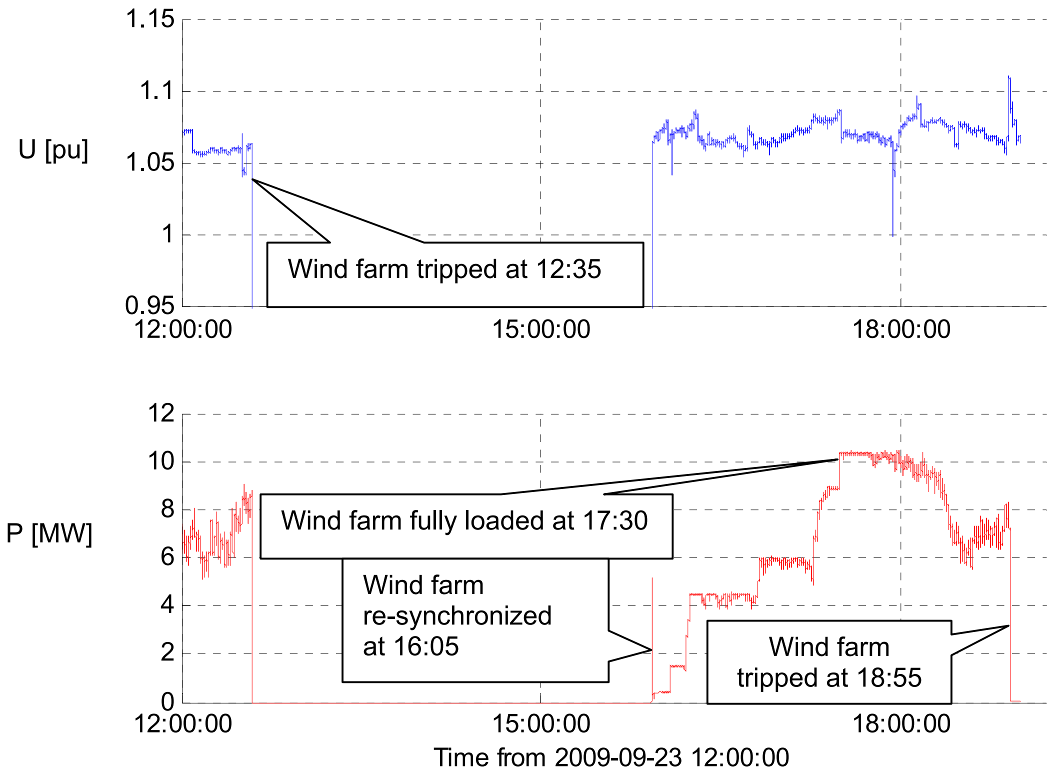


Figure 7. The 10 MW wind power farm behavior on 2003-09-23 during Swedish power system blackout and restoration.

5. Conclusions

This paper focuses on interaction between load and supply in power systems. Knowledge about this interaction is crucial to develop load shedding schemes, that better reflect society requirements than most existing schemes. Three phasor measurements devices have been used to collect data from faults and disturbances during the summer of 2003, in a radially fed area with a considerable amount of wind power generation. The Swedish blackout, September 2003, provided highly valuable information on load response to combined loss of generation and loss of transmission capacity. Also power system requirements for a smooth restoration process were clearly illustrated. Methods to design "intelligent load shedding" schemes are also described and discussed in general terms.

6. Acknowledgement

The paper is based on work performed within the CRISP: distributed intelligence in CRitical Infrastructures for Sustainable Power, financially supported by the European Commission, contract nr. ENK5-CT-2002-00673: CRISP, which is gratefully acknowledged.

7. References

[1] **Intelligent load shedding schemes for industrial customers with cogeneration facilities,** *Maiorano, A.; Sbrizzai, R.; Torelli, F.; Trovato, M.;* Power Engineering Society 1999 Winter Meeting, IEEE, Volume: 2, 31 Jan-4 Feb 1999; Page(s): 925 –930.

[2] **Using artificial neural networks for load shedding to alleviate overloaded lines,** *Novosel, D.; King, R.L.;* IEEE Transactions on Power Delivery, Volume: 9 Issue: 1, Jan. 1994; Page(s): 425 –433.

[3] **Application of df/dt in power system protection and its implementation in microcontroller based intelligent load shedding relay,** *Shih, L.J.; Lee, W.J.; Gu, J.C.; Moon, Y.H.;* Industrial and Commercial Power Systems Technical Conference, 1991. Conference Record. Papers presented at the 1991 Annual Meeting, 6-9 May 1991; Page(s): 11 –17.

[4] **A microcomputer-based intelligent load shedding relay,** *Lee, W.-J.; Gu, J.-C.;* IEEE Transactions on Power Delivery, Volume: 4 Issue: 4 , Oct. 1989; Page(s): 2018 –2024.

[5] **System Protection Schemes in Power Networks,** CIGRE Technical Report no. 187, June 2001.

[6] **Power System Voltage Stability,** C.W. Taylor, 1994, ISBN No: 0-07-063184-0.

[7] **Undervoltage Load Shedding Guidelines,** Western Electricity Coordinating Council, July 1999

[8] http://www.nerc.com/
http://www.svk.se/docs/aktuellt/Avbrott030923/Disturbance_Sweden_DenmarkSept23.pdf
www.ucte.org/news/e_default.asp#27102003

[9] **Special Protection Scheme against Voltage Collapse in the South Part of the Swedish Grid**, 1996 CIGRE Conference in Paris, *Ingelsson, Karlsson, Lindström, Runvik and Sjödin*.

[10] **Coordinated Voltage Control in Electrical Power Systems,** Mats Larsson, Dissertation, Lund University, Sweden, December 2000.

[11] **Voltage Instability Predictor (VIP) and its Applications,** *Khoi Vu*, et al., 13th PSCC, Trondheim, Norway, June, 1999.

[12] **Protection Strategies to Mitigate Major Power System Breakdowns**, Mattias Jonsson, Dissertation, Chalmers University, Sweden, June 2003.

Paper 6: *On the use of distributed generation to increase EPS robustness*

Full bibliographic reference:

M. Fontela, B. Enacheanu, C. Andrieu, S. Bacha, N. Hadjsaid, and Y. Besanger: *On the use of distributed generation to increase EPS robustness*, IEEE General Meeting 2005, June 2005, San Francisco, USA.

On the use of Distributed Generation to increase EPS robustness

M.Fontela , B.Enacheanu, C.Andrieu, S.Bacha, N. Hadjsaid, *Senior Member IEEE* and, Y.Besanger, *Member IEEE*

***Abstract*— The article discusses the behavior of the Distributed Generation (DG) in order to increase the EPS (Electric Power System) robustness. Special attention is paid to the DG influence during emergency states such as the propagation of cascading failures or other major events. In one hand, a high amount of DG can improve the system response to these disturbances but, on other hand, a massive DG insertion could endanger the system operation. The article proposes a methodology to define the robustness and risk of a system operating point through the evaluation of a robustness index. Furthermore, EPS robustness could be enhanced by new emergency strategies such as intentional islanding operation. This would require new ICT components (Information and Communication Technologies) in order to share and analyze the information and then, elaborate decisions to avoid total blackouts.**

***Index Terms*— Distributed Generation, Robustness, Index, Blackouts, Major events, Intentional Islanding, ICT components.**

I. Introduction

DURING the last years, some important blackouts and cascading failures (USA, Italy, Sweden & Denmark, Algeria…) have appeared in the world affecting the normal life of countries and causing important economic costs. The causes of these blackouts are different depending on the nature of the failure, but, in general, a blackout is the result of a combination of events from some first disturbances and finishing by a voltage collapse, lines tripping, a frequency deviation or a loss of synchronism in the system [1].

The decentralization of the energy production in the system could help operators to counteract these blackouts. The flows of energy in the transmission sub-system are reduced by the DG insertion and the save of the system in autonomous sub-systems in case of very critical state of the whole system is favored. Thus, a high amount of DG could improve the EPS robustness.

However, the system robustness can be decreased if the DG becomes excessive, because the DG dynamic performance and system controllability. So, an appropriate amount of DG insertion should be defined through an evaluation of the system operating point with different robustness indices.

This paper deals with the influence of DG in the EPS operation and the definition of a robustness index in order to define an appropriate DG insertion. The main conclusions of the article are illustrated with EUROSTAG simulations based on a European-adapted 39buses network (adaptation of the IEEE New England 39 buses to European data).

The works included in the article are integrated in the CRISP[1] project.

II. Plans for DG installation

The international agreements to reduce the Greenhouse gazes emissions and new rules such as European directives to increase the renewable energy sources have promoted the creation of national plans to install new DG resources, e.g. The EU (European Union) goal is a 22% production from RES in 2010 [2].Thus, this general tendency and goal in EU are followed. Countries such as Denmark or Germany are promoting the wind energy installation. Germany is planning to increase its wind capacity from around 13 GW wind capacity installed mid of 2003 to an expectation near to 30 GW in 2010. The Danish Government is planning to install 4GW off-shore and 1.5GW on-shore before the year 2030 [3], [4].

III. DG influence during major events

The following section comments the influence of DG during disturbances. DG can have in some cases a critical influence in the sequence of events before a blackout. This DG influence was studied in a test case. This test case was chosen by the authors in order to analyze a common European case.

[1] ***CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power.*** Project funded by the European Community under the Fifth RTD Framework Programme (2002-2005). Project Co-ordinator: ECN. Partners: ABB, BTH, IDEA, ECN, ENECO, EnerSearch and Sydkraft. Contract No. ENK5-CT-2002-00673.

This work was supported by Inventer la Distribution Electrique de l'Avenir (IDEA), joint research laboratory between EDF (French provider of Electricity), Schneider Electric S.A. and INPGrenoble.

M. Fontela, B.Enacheanu, S.Bacha, N. Hadjsaid and Y.Besanger are with IDEA and the Laboratoire d'Electrotechnique de Grenoble, Institut National Polytechnique de Grenoble, Saint Martin d'Hères, 38402 France (e-mail: fontela@leg.ensieg.inpg.fr - enacheanub@leg.ensieg.inpg.fr bacha@leg.ensieg.inpg.fr – hadjsaid@leg.ensieg.inpg.fr – besanger @leg.ensieg.inpg.fr)

C.Andrieu is with Schneider Electric and IDEA. Institut National Polytechnique de Grenoble, Saint Martin d'Hères, 38402 France (e-mail: andrieu@leg.ensieg.inpg.fr)

A. *Test case*

The study of the DG influence when faced to major contingences was carried out using a study case: the IDEA_CRISP_39buses network that is an adaptation of the IEEE New England 39 buses system. The architecture of this IEEE network is mostly kept. However, the parameters of its different elements were adapted to normal European data. So, the transmission system is considered at 400 kV and the generators (Gen 1 to Gen10) produce the energy at 20 kV. The installed power is 9085 MVA and it is shared in three different types of generators: 4 thermal units of 1000 MVA each one (GEN4, GEN6, GEN8 and GEN9), 3 nuclear units of 1080 MVA each one (GEN1, GEN2 and GEN3) and 3 hydro units of 615 MVA each one (GEN5, GEN7 and GEN10). The total consumption is 6141.6 MW/ 1470.9 MVAr split in 18 loads. The load model associated with the consumption is the impedance model (a square variation with the voltage). The generators regulations are of two types: a voltage regulation and a frequency regulation. The voltage regulator is the IEEE voltage regulator type A [5]. The frequency regulator is a torque regulation with a speed droop of 4% [6].

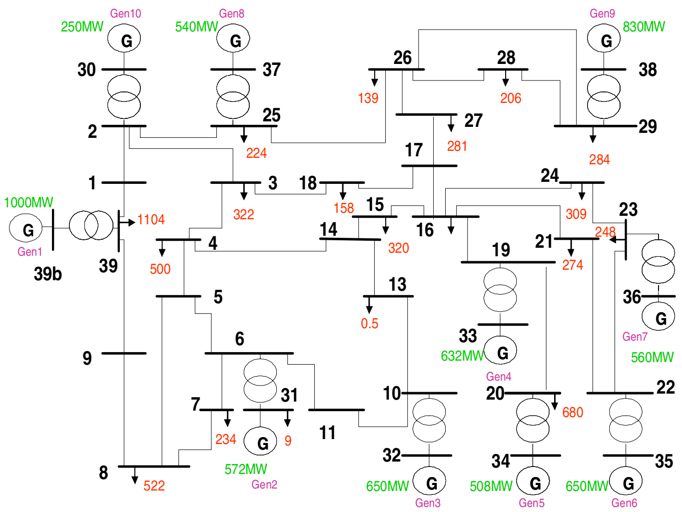


Fig. 1. Study case architecture without DG insertion (green: generators active power in MW; red: load consumed active power in MW)

The study case includes, as well, a 63 kV sub-transmission loop and 2 real French 20 kV distribution networks (STN) and several distributed resources (DR) by means of equivalent synchronous machines injecting 100 MW in the transmission system to build different DG insertion cases: 10%, 20%, 30%,40%, 50% and 60%.

In the two real French distribution networks (loads of 23 MW-13.2MVar and 25MW-12MVar), several asynchronous (5, in total 4.6MVA) and synchronous (13, in total 83.83 MVA) generators are placed and dispatched injecting 7.65 MW and 2.04 MW, respectively, in the sub-transmission loop. A load shedding is disposed consisting in 4 steps and disconnecting the 15% of the load at 49, 48.5, 48 and 47.5 Hz.

Different scenarios of DG dynamic behavior were simulated with different amount of DG insertion in the system:

- Instantaneous DG disconnection protection
- DG without problems of disconnection protection
- DG with intermittence
- DG participation to the voltage control
- DG participation to the frequency control

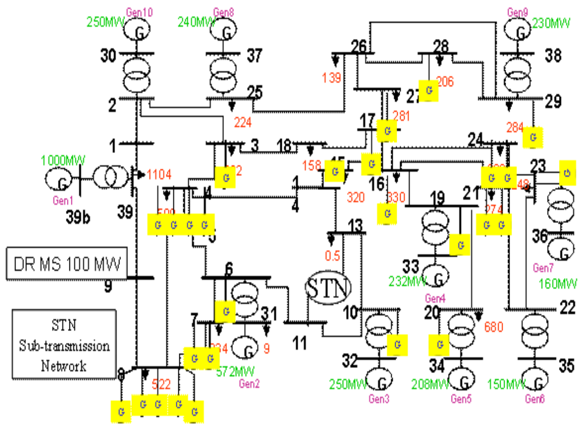


Fig. 2. Study case architecture with DG insertion (green:generators active power in MW; red: loads consumed active power in MW;)

B. *Major events*

DG can have an influence in the whole system during relevant major events; these influences are summarized in the next paragraph:

- Short-circuits: there is a negative influence of DG in the dynamic response of the system because the setting points of the disconnection protection. Normal values for the setting points of this protection in Europe are 0.85 Un and 49.5/47.5 Hz instantaneous or with a delay. A big disconnection of DG after a failure can lead the system to a total blackout [7].
- Frequency deviation: large excursions of frequency during some time can disconnect also DG units and be critical for the system. One main example of this fact could be seen during the Italian blackout [8]. However, DG could support the system in case of frequency deviation by means of its participation in the reserves (primary, secondary and/or tertiary) and avoiding the problems of the disconnection protection.
- Lines tripping: a high amount of DG insertion can reduce the flows of energy in the transmission lines and limit the energy dependency from other countries. Thus, the losses of international interconnections and main transmission lines constitute less important events for the survivability of the system. The overloads caused by the first lines tripping can not be followed by more overloads in other lines of the system and so, the cascading line tripping could be not started. In figure 3, it is shown, the variation of power flow in the transmission lines with 50 % DG insertion. The positive power variation represents a reduction in the power transit in the transmission lines.

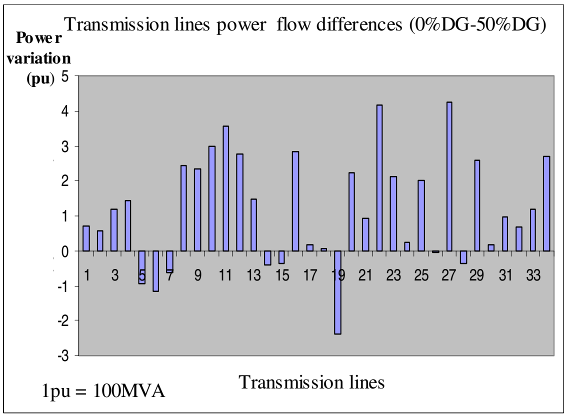


Fig. 3. Power flow reduction in transmission system with 50% DG insertion

- Voltage collapse: the voltage collapse is a complicated phenomenon. It consists on a voltage reduction in some part of the system down to a critical voltage that leads the system to a blackout because a progressive voltage reduction and the disconnection of elements. It is sometimes explained by the absence of reactive sources in the system. At this point, DG could contribute to local voltage managements [9] at distribution and sub-transmission systems reducing the reactive power consumption from the transmission system.
- Loss of synchronism: DG insertion in the form of synchronous machines can affect the transient and dynamic stability. The influence of DG depends on the configuration of the system (location and operating points of the generators). The Critical Clearing Times (CCT) can be reduced by the DG insertion.

IV. Robustness Index

A. *Robustness definition*

The robustness represents, in general, the suitable operation of the EPS. Therefore, it can be defined as the capacity of a system to be stable, in an operating point, faced to small and major disturbances.

B. *Robustness index and evaluation methodology*

The robustness is evaluated taken into account a methodology consisting on the evaluation of several indices which form a main robustness index (RI). This evaluation is carried out testing the system dispatching (operating point) to the appearance of different contingencies (load evolutions, loss of lines, loss of generators, short-circuits, (n-1),…,(n-k) combination of disturbances) which cover the main small and major events. The result of this methodology is the evaluation of our system, if the system is not satisfactory the robustness indices will indicate the operator some valuable information such as: the level of risk (seconds or minutes expected before a blackout if some of contingencies occurs) or the limits and deficiencies in the system.

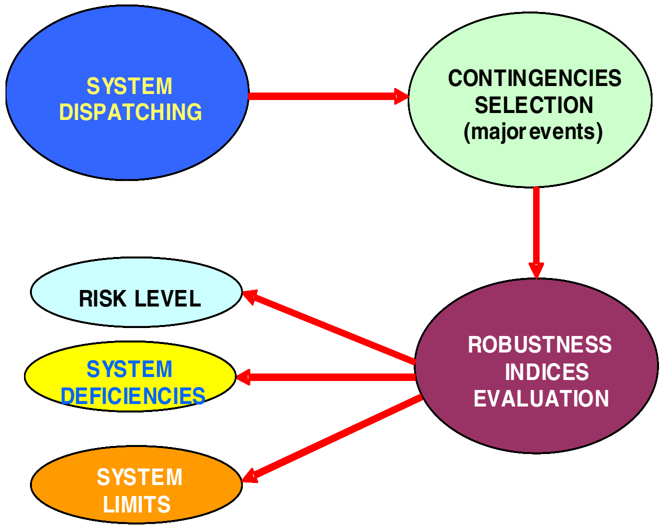


Fig. 4. Robustness evaluation methodology

The robustness index (RI) is composed of six terms or indices as it is shown in the equation (1):

$$(\mathbf{RI}) = \max\{(\mathbf{SSS});(\mathbf{SPIR});(\mathbf{VCI});(\mathbf{FD});(\mathbf{LS});(\mathbf{RTM})\} \qquad \mathbf{(1)}$$

Where:

- SSS (small-signal stability) is a view of the small-signal stability of the system.
- SPIR (static performance indices robustness) is a static view of the system (overloads); it takes into account the flows in lines, reactive power of generators and ensures that the voltage levels are in the normalized limits. Both, SSS and SPIR terms gives a static view of the system, they should be evaluated before and after a selection of contingencies that the operators consider relevant or probable for the system operation.
- VCI (voltage collapse indicator) gives an idea to the proximity to the voltage collapse if the voltages in the system exceed defined thresholds. The voltage collapse is a complex phenomena and the critical voltage point, from the voltage collapse is initiated, depends on the load and the type of the system; traditionally the different studies about the voltage takes into account static situations of the system and evaluates different mathematical methods from the EPS equations [10].
- FD (frequency deviation) term gives an evaluation of the system response in terms of frequency. This is why the FD term includes the primary reserve, load shedding over 48.5 Hz and amount of DG disconnection protection with instantaneous disconnection or very fast disconnection.
- LS (Loss of synchronism) contains the behavior of the system after a contingency in terms of stability.
- RTM (Real Time Margins): it evaluates the margins of real time (up and down available power reserves).

The robustness indices enable us to compare different dispatching situations and so the cases, with and without DG. They can be used, as well, to verify the increase of robustness that could be found with the DG when faced to some major events. The RI index can take a discrete interval of values as it is shown in equation (2):

$$(\mathbf{RI}) = \begin{cases} \mathbf{3 \Rightarrow Serious\quad danger} \\ \mathbf{2 \Rightarrow 0perator\quad control\quad actions\quad required} \\ \mathbf{1 \Rightarrow Alert\quad operator\quad sup\,ervision} \\ \mathbf{0 \Rightarrow Normal\quad operation} \end{cases} \qquad (2)$$

These values are representative of different risk levels if the worst contingence occurs:

- If RI is equal to 3, the risk level is the higher one and the time in which the system could shut down is reduced, in the range of some seconds.
- If RI is equal to 2, the risk level can not be neglected and e.g. cascading failure could happen if the line overloads are not solved by the operator. The expected available time for operator action is around one minute to 10 minutes.
- If RI is equal to 1, the system is in alert because some lines could be lightly overloaded and the maximal time to solve the overloads is around 15 to 20 minutes. On other hand, the voltage profile could be optimized in order to not exceed a first alert value (390kV). The possibility of voltage collapse should be evaluated immediately because the voltage collapse can appear from some minutes to 10 minutes; the operator should compute and visualize the critical voltage at the buses and particularly at the lower voltage buses.
- If RI is equal to 0, the system is in stable operation, all the parameters are in the expected intervals and no special critical state is probable (according to the contingencies selection) under these conditions.

The different terms which form the RI index are described in detail in the following paragraphs:

- The term SSS must be evaluated from the state-space matrix of the system, the small-signal stability is guaranteed if all the eigenvalues have a negative real component. If this real component is equal to zero, neither the stability nor the instability can be confirmed and so, this state could constitute an alert state by the incertitude of the system behavior. Finally, if some real component of the eigenvalues is positive the system is instable to small-signals and so it is unstable to major events. The formulation of this index is expressed as follows:

$$(\mathbf{SSS}) = \begin{cases} \mathbf{3} & \mathbf{if} \quad \mathbf{Re(Eigenvalues) > 0} \\ \mathbf{1} & \mathbf{if} \quad \mathbf{Re(Eigenvalues) = 0} \\ \mathbf{0} & \mathbf{if} \quad \mathbf{Re(Eigenvalues) < 0} \end{cases} \qquad (3)$$

- The SPIR term must be evaluated to evaluate the capacity of the system when faced to overloads caused by the loss of elements in the system (mainly loss of lines). The SPIR term is composed of several indices which evaluate the technical limits of the system: power in lines, current in the lines, reactive power limits in generators and voltage in the normal interval.

$$(\mathbf{SPIR}) = \mathbf{max}\{(\mathbf{PII}); (\mathbf{PIV}); (\mathbf{PIP}); (\mathbf{QLI})\} \qquad (4)$$

The PII [11] term evaluates the distance to the lines overload in terms of current on the lines, the severity of the overload defined different levels on danger depending the available time for operator's action to solve the overload.

$$\mathbf{PII_1} = \left[\frac{(|\mathbf{I}|)}{\mathbf{Im\,ax}} * \mathbf{100} \right] \qquad (5)$$

Thus, the values of the PII term depend on the value of PII_1 identifying the severity of the situation or risk level for the system with the available time to solve the overload (big overloads imply the tripping of the lines in a short period of time).

$$\mathbf{PII} = \begin{cases} \mathbf{3} & \mathbf{if} \quad \mathbf{PII_1 > 170} \\ \mathbf{2} & \mathbf{if} \quad \mathbf{130 < PII_1 < 170} \\ \mathbf{1} & \mathbf{if} \quad \mathbf{110 < PII_1 < 130} \\ \mathbf{0} & \mathbf{if} \quad \mathbf{PII_1 < 110} \end{cases} \qquad (6)$$

The PIP illustrates the distance to a defined maximal active power on the lines.

$$\mathbf{PIP_1} = \left[\frac{(|\mathbf{P}|)}{\mathbf{P\,max}} * \mathbf{100} \right] \qquad (7)$$

$$\mathbf{PIP} = \begin{cases} \mathbf{3} & \mathbf{if} \quad \mathbf{PIP_1 > 170} \\ \mathbf{2} & \mathbf{if} \quad \mathbf{130 < PIP_1 < 170} \\ \mathbf{1} & \mathbf{if} \quad \mathbf{110 < PIP_1 < 130} \\ \mathbf{0} & \mathbf{if} \quad \mathbf{PIP_1 < 110} \end{cases} \qquad (8)$$

The PIV evaluates the distance of the voltage profile to the the normal voltage limits through the evaluation of the index PIV_1.

$$\mathbf{PIV_1} = \frac{(|\mathbf{V - 1}|)}{\mathbf{\Delta V}} \qquad (9)$$

with ΔV= 0.05pu (corresponding to the interval between 380kV-420kV, normal range for transmission lines in the French law).

$$\mathbf{PIV} = \begin{cases} \mathbf{3} & \mathbf{if} \quad \mathbf{PIV_1 > 1} \\ \mathbf{0} & \mathbf{if} \quad \mathbf{PIV_1 < 1} \end{cases} \qquad (10)$$

The QLI (reactive power generator limits) must be evaluated for all generators, and it evaluates the reactive power capacity of the generators, when the indicator QLI_1 (equation (11)) is equal to 1, the generator can not supply more reactive power than it is supplying at that moment.

$$\mathbf{QLI} = \begin{cases} \mathbf{2} & \mathbf{if} \quad \mathbf{QLI_1 = 1} \\ \mathbf{0} & \mathbf{if} \quad \mathbf{QLI_1 < 1} \end{cases} \qquad (11)$$

where:

$$\mathbf{QLI_1} = \left|\frac{(\mathbf{Qg})}{\mathbf{Qg\,lim\,it}}\right| \qquad (12)$$

The alert of QLI index is not necessary a serious danger for the system but, it could evolve into problems for the operator because a deficiency of reactive power could appear in local zones where the reactive power is not produced.

- The VCI compares the voltage levels at the different buses in the system with a threshold different. This threshold (TH_1) would represent an alert to the system operator in order to predict the voltage collapse. The problem about the efficiency of the threshold is that the critical voltage depends on the type of load and elements in the system, so the efficiency of the proposed VCI is limited. The thresholds (critical voltage point) should be evaluated at each operation point; this requires a lot of computation for each situation. However, the authors introduce this VCI to give to the operator an alert in order to supervise the system and try to avoid the voltage collapse phenomena.

$$(\mathbf{VCI}) = \begin{cases} \mathbf{3} & \mathbf{if} \quad \mathbf{Vbuses < TH_2} \\ \mathbf{1} & \mathbf{if} \quad \mathbf{Vbuses < TH_1} \\ \mathbf{0} & \mathbf{in} \quad \mathbf{other} \quad \mathbf{case} \end{cases} \qquad (13)$$

The threshold (TH_1) is established in the 2.5% of distance to the normal minimal limit in normal operation (390 kV); the threshold TH_2 is established at 10%-360 kV as a serious indicator of voltage collapse.

- The FD term evaluates the dynamic responses of the system in terms of active power balance. Its value depends on the evaluation of the FD_1 , equation (14):

$$(\mathbf{FD_1}) = \frac{[(\mathbf{PR}) + (\mathbf{IL})]}{[\mathbf{ALEA} + (\mathbf{DG_1}) + (\mathbf{DG_2})]} \qquad (14)$$

where PR is the primary reserve (MW), IL is the amount of interruptible loads or load shedding (MW) planned up to 48.5 Hz, DG_1 (MW) is the DG with instantaneous or very quick (100ms) disconnection protection, DG_2 (MW) is the DG with temporized disconnection protection at 49.5 Hz and ALEA is the maximal load variation or generation loss forecast by the operator (the generators included in ALEA should not be included in DG_1 and DG_2). The $alea_1$ is the load variation, short-circuit or event that provokes that the system arrives to the setting points of the disconnection protection before 49 Hz and 0.85 Un. DG influence in the system is given through FD index, notably in terms of disconnection protection and lack of sources.

$$(\mathbf{FD}) = \begin{cases} \mathbf{0} \quad \mathbf{if} \quad \mathbf{alea < alea_1)} \\ \mathbf{3} \quad \mathbf{if} \quad \mathbf{(alea > alea_1) and (FD_1 < 1)} \\ \mathbf{0} \quad \mathbf{if} \quad \mathbf{(alea > alea_1) and (FD_1 > 1)} \end{cases} \qquad (15)$$

FD_1 gives a good view of the system and quantifies the risk of the system in case of an excessive DG insertion. Thus, it should be compared to primary reserve and first load sheddings, which are the supporting of the system in case of emergency.

- The LS is an indicator to show if the synchronism is lost system after the selected contingency.

$$(\mathbf{LS}) = \begin{cases} \mathbf{3} \quad \mathbf{if} \quad \mathbf{lost} \quad \mathbf{of} \quad \mathbf{synchronism} \\ \mathbf{0} \quad \mathbf{if} \quad \mathbf{system} \quad \mathbf{is} \quad \mathbf{not} \quad \mathbf{lost} \end{cases} \qquad (16)$$

- RTM is an indicator of the control margins in the system. These margins should ensure a suitable real-time operation. If appropriate margins are not found in the system, this could be endangered by power evolutions and events.

$$(\mathbf{RTM}) = \begin{cases} \mathbf{2} \quad \mathbf{if} \quad \mathbf{RTM_1 < 1} \\ \mathbf{0} \quad \mathbf{if} \quad \mathbf{RTM_1 > 1} \end{cases} \qquad (17)$$

where:

$$(\mathbf{RTM_1}) = \frac{\mathbf{Real \quad Time \quad Reserves}}{\mathbf{Expected \quad reserves}} \qquad (18)$$

The index indicates a 2 if the system does not count with enough reserves, this warns the operator about a situation which can become critical in case of high rise of the demand. The operator could mobilize new generators (tertiary reserves) or proposed some loads to be disconnected to contribute to the grid healthy and operation [12].

V. RESULTS: APPROPRIATE AMOUNT OF DG INSERTION

Different scenarios of DG behavior were simulated with different amount of DG insertion in the system in order to apply the mentioned methodology and index and define an appropriate amount of DG insertion in the chosen test case. The different studied scenarios were the following ones [13]:

- Scenario 1: Instantaneous disconnection protection.
- Scenario 2: DG without problems of disconnection protection.
- Scenario 3: Intermittence insertion.
- Scenario 4: DG participation to the ancillary services.

A. Scenario 1: Instantaneous disconnection protection

The appearance of a short-circuit at the transmission level is an event which can provoke the propagation of a voltage deep and frequency deviations in the system and so, the disconnection of generators[14]. DG should be limited in order to not shed loads after a fault in a transmission line. One should take into account that load shedding is an emergency tool and if the load shedding is used (at 49 Hz) by a first short-circuit; the system could remain in a bad operating point to face latter events.

Therefore, in this case a slightly lower level than the primary reserve is the appropriate amount of DG insertion (instantaneous disconnection protection). In this way, the FD value is equal to 0 (and so, RI =0) and load shedding is not activated to save the system after a short-circuit in the transmission system.

B. Scenario 2: DG without problems of disconnection protection

The appropriate DG insertion is fixed by the resources of the system (active and reactive power) and the dynamic behavior of the system when faced to the chosen contingencies (transient stability and none loss of synchronism). The high degree DG insertion makes that some centralized generators could be closed or stopped. So, the operators should be able to guarantee reserves and a good voltage plan with the existent generators. The maximal amount of DG insertion is placed here around 50% of the total production (FD and RI equal to 3 for the lack of all DG, but the system is saved by 3 load shedding steps, operators can accept the situation considering "improbable" to loose all DG at the same time). Otherwise, according to FD, the maximal DG insertion would be (PR+IL).

For higher amount of DG insertion such as 60%, stability problems were found in the system.

C. Scenario 3: Intermittence insertion

The study of the intermittence effects on the EPS was carried out with the insertion of asynchronous generators in the test case (with a 10% of DG by means of the power equivalents and the two real French networks). The asynchronous generators have a wind distribution which depends on the installation point of the windmill because the different wind speeds in each position. Several cases were analyzed, creating windmill farms which were placed into two different voltage levels: sub-transmission system (the green circle crown, composed by 9 asynchronous machines, 15.3 MVA) and the transmission system (the blue circle crown, composed by 10 asynchronous machines each one, 17 MVA).

The results of the simulations have enabled to conclude that the effects of the intermittence are mainly a local voltage variation depending on the wind speed and so depending on the reactive and active power production. The voltage variation is propagated from the sub-transmission system (distribution system in case of DG intermittence insertion at this level) to the transmission system.

The voltage variations at the transmission systems are the result of the combination of all the different local variations and the action of primary voltage and frequency regulations. The primary reserve could be used after high active power variations caused by the intermittence and so the system will be placed in a critical situation if something happens during the restoration of the reserves (secondary control). Two main problems are introduced by the intermittence:

- Ensuring the schedule plan of production; imbalances cause new costs which are the result of the market mechanisms.
- Uncertainty in the position and time of the power injections.

In this scenario 3, the appropriate DG insertion is fixed by the resources of the system (active and reactive power reserves). TSO should be able to control the system in real time and adapt the system to the real-time events. As it was commented in the scenario 1 and 2, about the DG protection setting points, most of wind power can be disconnected from the network in case of a system disturbance near their location, the propagation of a voltage deep through the transmission system or high wind speeds. This could lead the system to a huge lack of generators in a domino effect and a final global blackout (FD would be 3 if the expected error in DG variation is very big and SPIR would take into account the overloads after the generation variation).

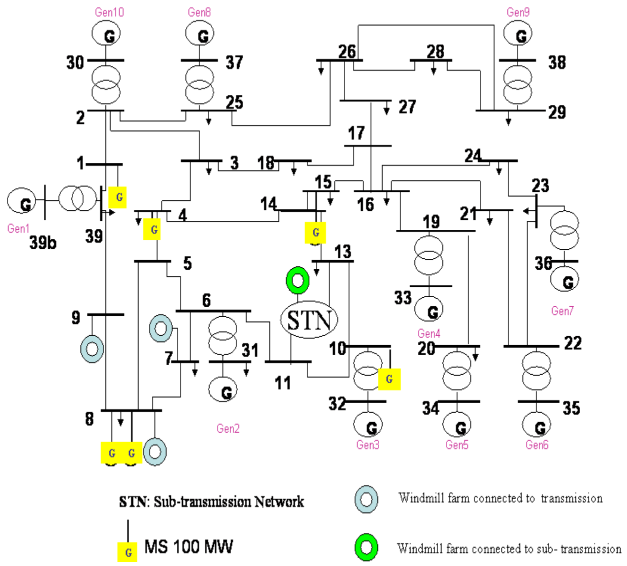


Fig. 5. Windmills farm insertion in the study case.

The lack of intermittence sources is a problem that can be compared to the scenario 1 with the lack of generators by the disconnection protection. The system stands the lack of generators without load shedding at a level slightly lower than the primary reserve.

D. Scenario 4: DG participation to the ancillary services

One possible scenario which can appear in the next years is the participation of the DG to the ancillary services (frequency and voltage control).

1) DG participation to the voltage control

The main problem of the changes in the voltage regulators are the whole network stability. The wrong tuning of the DG voltage regulations could lead the system to an unstable situation in which the system can not stand the disturbances and the system loss or undesirable oscillations (around 1 to 2 Hz frequency) can appear as it is shown in figure 6.

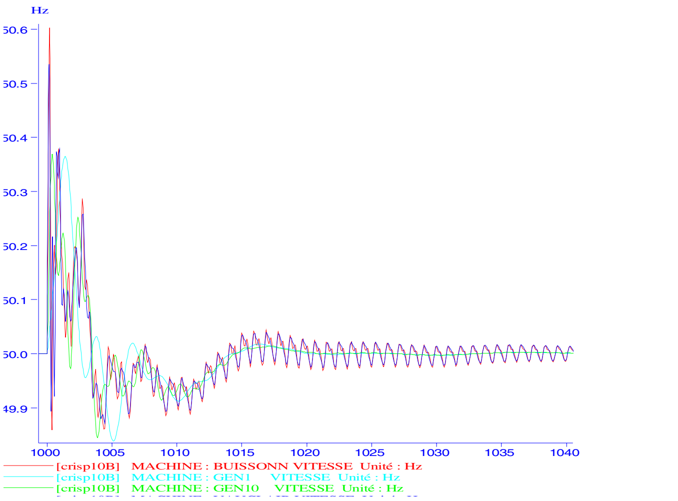


Fig. 6. Oscillations after a 3-phases-200 ms short-circuit in a system with wrong tuning of DG voltage regulations (small-signal stability verified and transient stability, computed CCT= 0.494 s for the simulated short-circuit)

2) DG participation to the frequency control

The new point, that this paper wants to emphasize, is the participation of the DG to the primary reserve in a situation in which the system do not dispose enough resources. The increase of reserves in the system influences the transient response of the system. The frequency deep after an event, e.g. a load variation is lower and that would create a better dynamic behavior from the frequency point of view. However, special attention should be paid to the transient and dynamic stability of the system in order to guarantee that the insertion of speed regulators for the DG do not lead to stability problems. That was not always the case in the developed simulations. The conclusions of the simulations carried out are the next ones:

- The participation to the primary reserve implies improvements in the system robustness because the better behavior of the system when face to some events such as loss of international interconnection, loss of generators and load variation. The security of the system in terms of generation adequacy is enhanced by the increase of the primary reserve.
- Possibility of oscillations between the different generators caused by the different dynamic performances, specially when face to a short-circuit. The small generators have a faster reaction (lower inertia constant) than the big generators (bigger inertia constant).

VI. DG AS A TOOL TO STOP BLACKOUTS

DG could be considered also as a tool to save the system in emergency operations. The system can be saved through critical states such as local intentional islanding operation at transmission, sub-transmission and/or distribution levels [15].

These new critical states would require the development and installation of a distributed intelligence (in main substations) to enable the control of the sub-systems and their participation on the system restoration. Some main ICT (Information and Communication Technologies) components [16] can be identified: a main tool (IODI, Islanding Operation Distributed Intelligence) to advise the operator the creation of islands and different controls (frequency, voltage, protection and configuration) which would control the basic elements (generators, loads, protections or switches).

The split of the system in parts prevents the solidarity between the different areas and so, the sub-systems represent less robust systems. Furthermore, the present protection schemes are not adapted to this type of operation and a single failure could shut down the sub-system. So, intentional islanding operation constitutes a very critical state before the total blackout. On the other hand, it could be a useful tool to ensure the continuity of supply.

The islands creation should be based on measures on the system state (voltage, frequency and derivative of frequency) and the verification of the robustness index which guarantee the new island healthy. In figure 7, they are shown the different required controls and information (from essential elements) in order to maintain the island and control the local restoration (islands connection, black-start of generators, interruptible loads…).

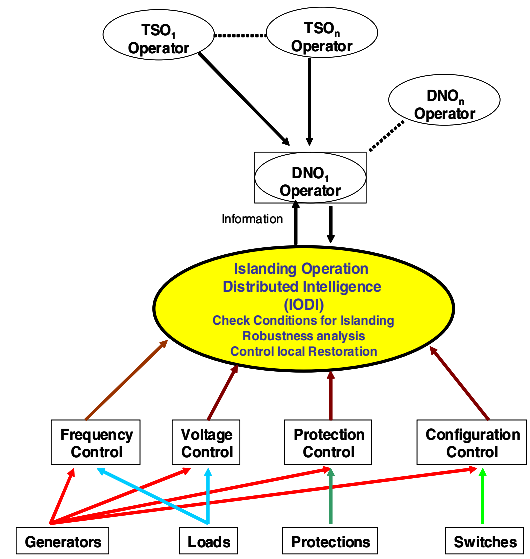


Fig.7. Islanding operation distributed intelligence (IODI)

VII. CONCLUSION

The article has commented the DG behavior during major events such as short-circuits, frequency deviation, line tripping or voltage collapse. The paper proposed a methodology to study the robustness of the EPS. This methodology consists on the evaluation of a robustness index in case of appearance of selected contingencies. The methodology was applied to a test case in order to survey the influence of DG during disturbances and to fix criteria to limit the DG insertion in the EPS.

These limits were established taking into account different scenarios of DG dynamic behavior. In general terms, the DG disconnection protection and the intermittence are sources of potential problems for the whole system, so, reduced amount of DG penetration seems to be more appropriated for a low risk level operation. On other hand, new control strategies such as the DG participation to the ancillary services or the intentional islanding could constitute future tools to increase the system robustness, notably to counteract total blackouts.

VIII. REFERENCES

[1] Techniques de l'Ingénieur D4807, "Plan de defense des réseaux contre les incidents majeurs".

[2] EU Directive 2001/77/EC on the promotion of the electricity produced from renewable energy source in the internal electricity market. [Online]. Available: http://europa.eu.int/comm/energy/res/legislation/electricity_en.htm

[3] ETSO report, "Report on Renewable Energy Sources (RES) ", Brussels, December 2003. [Online]. Available: http://www.etso-net.org/activities/Renewables/e_default.asp

[4] Rapport final de la Commission Ampere, October 2000. [Online]. Available:http://mineco.fgov.be/energy/ampere_commission/ampere_commission_fr.htm

[5] Paul.M.Anderson and A.A.Fouad, *Power System Control and Stability.* The Iowa State University Press, 1977.

[6] Prabha Kundur, *Power System Stability and Control* New York, Mc Graw-Hill, 1994, ISBN 0-07-035958-X

[7] Rodriguez, J.M.; Fernandez, J.L.; Beato, D.; Iturbe, R.; Usaola, J.; Ledesma, P.; Wilhelmi, J.R; "Incidence on Power System Dynamics of High Penetration of Fixed Speed and doubly Fed Wind Energy Systems: Study of the Spanish Case". *IEEE Transactions on Power Systems*, Vol.17, No.4, pp 1089-1095, November 2002.

[8] UCTE report, "Final Report on the Investigation Committee on the 28 September 2003 Blackout in Italy". April 2004. [Online]. Available:http://www.ucte.org/pdf/News/20040427_UCTE_IC_Final_report.pdf

[9] Caire, R.; Retiere, N.; Morin, E.; Fontela, M.; Hadjsaid, N.; "Voltage Management of Distribution Generation in Distribution Networks", in *IEEE Power Engineering Society General Meeting*, Vol. 1, pp 282-287, July 2003.

[10] Tran Quoc Tan, "Analyses et Outils pour la proposition des parades contre les risques d'instabilité de tension dans les grands réseaux de transport et interconnexion". Ph.D.dissertation, Laboratoire d'electrotechnique de Grenoble (LEG), INPGrenoble, 1993.

[11] Benahmed, «Analyse de sécurité des réseaux électriques THT par la méthode des Indices de Performances ». Ph.D.dissertation, Laboratoire d'electrotechnique de Grenoble (LEG), INPGrenoble, 1991.

[12] The California ISO, "Load Voluntary Reduction Program". [Online]. Available: http://www.caiso.com/

[13] M.Fontela, C.Andrieu, S.Bacha and N.Hadjsaid, "Distributed Generation as a means to increase system robustness", Deliverable D1.3 of ENK5-CT-2002-00673 CRISP-Project.

[14] M.Fontela, Ha Pham-Thi-Thu, C.Andrieu, S.Bacha , N. Hadjsaid and Y.Besanger. "Limits of DG insertion in Electric Power Systems". CRIS Conference, Securing Critical Infrastructures 2004.

[15] Ahmed, S.S.; Sarker, N.C.; Khairuddin, A.B.; Ghani, M.R.B.A.; Ahmad, H.; "A scheme for controlled islanding to prevent subsequent blackout". *IEEE Transactions on Power Systems*, Vol.18, Issue: 1, pp: 136-143, Feb. 2003.

[16] B.Tornqvist, M.Fontela, Per Mellstrand, R.Gustavsson, C.Andrieu, S,Bacha, N. Hadjsaid and Y.Besanger. "Overview of ICT components and its application in Electric Power Systems". CRIS Conference, Securing Critical Infrastructures 2004

IX. BIOGRAPHIES

Miguel Fontela received his DEA from INPGrenoble in 2002. He was working in Power Electronic field, in France at the Laboratoire d'Electrotechnique de Grenoble (LEG). He is now working toward a PhD degree. His research is centered on the impacts and production control of dispersed generation on transmission system.

Bogdan Enacheanu received his DEA from INPGrenoble in 2004. He is now preparing a PhD degree. His research interest is located on new architectures of distribution networks.

Christophe Andrieu received his Engineering Diploma and his DEA in electrical Engineering from INPG in 1991, and Doctorat de l'INPG degrees from the Institut National Polytechnique de Grenoble (INPG) in 1995. He joined the Research and Development Center of Schneider Electric SA in 1995.

He works on electrical power system analysis and becomes involved in distributed resources connection and exploitation. He works with IDEA as a Researcher and as a Project Manager on Dispersed Generation.

Seddik Bacha received his Engineer and Magister from Ecole Nationale Polytechnique of Algiers respectively in 1982 and 1990. He joined the Laboratoire d'Electrotechnique de Grenoble (LEG) and received his Doctorat and HDR respectively in 1993 and 1998. He is presently manager of Power System Group of LEG and Professor at the University Joseph Fourier of Grenoble.

His main fields of interest are power electronics system, modeling and control, Power Quality, Renewable Energy Integration.

Nouredine Hadjsaid received his Diplôme d'Etudes Approfondies (DEA) and Doctorat de l'INPG degrees from the Institut National Polytechnique de Grenoble (INPG) in 1988 and 1992. From 1988 to 1993, he served as a research and teaching assistant at the Ecole Nationale Supérieure d'Ingénieurs Electriciens de Grenoble (ENSIEG) and at the Laboratory d'Electrotechnique de Grenoble (LEG).

He is presently professor at INPG-ENSIEG-LEG and Manager at IDEA. His research interests are power system operation and security.

Paper 7: *A new restoration process following a blackout in a power system with large scale of dispersed generation*

Full bibliographic reference:

Ha Pham, Y. Besanger, C. Andrieu, N. Hadjsaid, M. Fontela, and B. Enacheanu: *A new restoration process following a blackout in a power system with large scale of dispersed generation*, IEEE PES T&D Conference 2005, October 2005, New Orleans, USA.

A new restoration process in power systems with large scale of dispersed generation

T.T.Ha Pham, Y. Bésanger *Member IEEE,* C.Andrieu, N. Hadjsaid *Senior Member IEEE*, M.Fontela, B.Enacheanu

***Abstract* - This paper presents a new effective restoration procedure designed for the Electrical Power System (EPS) with large scale of dispersed generation (DG) penetration. The "deep build - together" strategy is proposed to simultaneously consider this rebuilding by transmission and distribution networks, thereby, to serve the maximum of customers in a minimum of time. The restoration problem has to be now formulated as a multilevel, multi-objective optimization problem with constraints. The proposed method is designed with consideration to the network in the coming year which requires the introduction of new Information and Communication Technologies (ICTs) components.**

Some simulations, using Eurostag software and a part of an IEEE New England 39 buses power system including a French type distribution network, with different cases (with a large scale of DG contributing or not in restoration process), will be shown to illustrate the DG ability in restoration process. The benefits of employing DG are also quantified.

***Index Terms* - Dispersed generation, black-out, intentional islanding, restoration process, power system simulation, decision tree, dynamical programming.**

I. Introduction

The arrival with maturity of dispersed generation (DG) technologies over the last decade allows an appropriate amount of local DG insertion. In fact, a high DG penetration rate in the power system has different impacts. On the one hand, it could have positive influences in normal operation by the means of sources to satisfy the thermal constraints of feeders, to balance the voltage profile in the distribution networks, to reduce power losses and to help for "peak load shaving". On the other hand, the behaviors of DGs during a disturbance represent a critical point. Special attention is paid in major region-wide accident (i.e. partial or total blackout), because today the DGs can not stay online in case of failure by its disconnection protection. As a consequence, a high rate of DG insertion can make the power system more vulnerable. Therefore, the control of DGs in particular and the whole power system in general (in critical situations) faces now to new challenges. Under these circumstances, a new effective restoration procedure designed for the EPS with large scale of DG penetration is required for further benefits of using DG in the system.

The almost common restoration plan in use today is made for bulk transmission systems [1], [2], [3], [4] and [9]. Two major strategies to restore a power system following a blackout are known: the **build-up** and **build-down** strategies [1], [2]. The first one is to re-energize the bulk power network before synchronizing most generators. While the second one is to restore islands that will then be mutually interconnected. A mixed solution called **build-together** is also used on transmission system.

In this paper, we propose a restoration process simultaneously in transmission and distribution network with the aid of DG: a **“deep build -together”** strategy. This strategy is to re-energize by islanding in transmission network while distribution network cells are being formed and expanded based on the availability of DG black-start and power unit's capacity without support by main EPS. The priority tasks in transmission level are: to black-start successfully at least one unit; to restart up the non black-start capacity units in order to take more units in operation and then, to pick up the load in adequation with the decrease of load demand that is recovered by the DG support as soon as possible. At the distribution level, instead of staying in black till the EPS would be restored and available (normally during for several hours), DG could facilitate the apparition of a lot of autonomous areas or cells using DG black-start capacity, providing the local service continuity and energizing the grid as large as possible by switching operation. This concept is called "intentional islanding" multilevel. As a result, the volume of load restored during the restoration process is more important at any time and the collapsed time of many customers is shorter.

Since the main information and communication control system is now applied in the transmission level (SCADA, EMS), in the future, the introduction of new Information and Communication Technology (ICT) components in the specific points of distribution networks is also required.

II. Specific definitions

A network cell in the distribution system is a conceptual object corresponding to the elements which can be isolated from the main grid by opening switches, and operated in intentional islanding mode. A network cell is represented by data that can describe certain elements such as buses, lines, generators, loads, transformers, etc…

A subsystem is defined as a group of network cells or subsystems of lower level in the hierarchical structure.

Sectionalizing switch is the switch in the feeder which is equipped with the necessary ICT components for measure and remote control.

T.T. Ha Pham is PhD student at the Power Engineering Laboratory of Grenoble, France (e-mail: Ha.pham-Thi-Thu@leg.ensieg.inpg.fr).

Y.Bésanger is Associate Professor at the Laboratoire d'Electrotechnique de Grenoble France. (e-mail: besanger@leg.ensieg.inpg.fr)

GIE IDEA, 946, rue de la houille blanche, 38402 Saint Martin d’Hères Cedex, France

Laboratoire d'Electrotechnique de Grenoble, UMR 5529 INPG/UJF CNRS, ENSIEG BP 46, 38402 Saint Martin d’Hères Cedex, France
This work has been achieved in the framework of CRISP EU project.

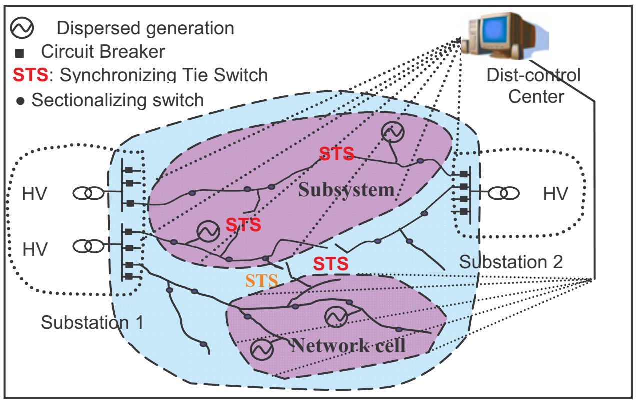


Fig.1. Specific definition representation

Synchronizing tie switch (STS) is a normally open switch between two feeders which is equipped with ICT components of detection and measurements for the synchronization of the network cells in distribution network. The description of these definitions is shown in Fig.1.

III. Problem Formulation

The system restoration process based on the methodology mentioned above should be formulated mathematically as a system restoration multilevel, multi-objective optimization problem.

A. *Transmission network level*

In the transmission network, the restoration duration depends essentially on the availability of prime movers (types and sizes), different physical characteristics and requirements of generating units. The objective functions in transmission network restoration process are:

Maximizing restored load in the system:

$$\text{Maximize } \sum_i \int_T \left(P_{iT} - P_{iD}\right) \cdot dt \qquad (1)$$

Minimizing restoration process duration:

$$\text{Minimize } T = \sum t_i \qquad (2)$$

where: P_{iT}: load restored by the main EPS
P_{iD}: load restored by distribution network cells
t_i : the time according to each activity,
T : the restoration process duration.

Comment: The switching operation time to energize transformers, lines, and load picked up is much less important than the time to make generation available. Thus, in this estimates, the load can be picked up as soon as generation becomes available.

Constraints:

- Generating constraints:
  - Active power output limit:

$$P_{Gi} \le P_{Gi\,nom} \qquad (3)$$

  - Reactive power over/under excitation limits:

$$Q_{Gi\,\min} \le Q_{Gi} \le Q_{Gi\,\max} \qquad (4)$$

  - Primary reserve active power limits:

$$RP_{Gi} > 0 \qquad (5)$$

  - Critical intervals for different types of boilers.

- Line constraints:
  - Line thermal limit:

$$I_i \le I_{\max} \qquad (6)$$

  - Voltage transient limits,
  - Line stability limits [5]:

$$L_{\max} = \frac{A_n}{V_n^2} \cdot \frac{1}{2\pi f C_c \cdot \left(X_d + X_t\right)} \qquad (7)$$

where: A_n rated power of equivalent power plant
V_n operating nominal voltage
C_c cross capacity of line pi-model
X_d, X_t direct axis synchronous machine reactance, and transformer reactance respectively.

B. *Distribution network*

In the distribution network, the problem consists of determining a control strategy as soon as possible after the blackout (comprising a series of switching operations), in order to form the "network cells" in islanding operating mode based on DG unit capacity. We will consider a hybrid restoration/reconfiguration problem in which decision variables are the switch or circuit breaker status.

The major differences of restoration constraints between transmission level and distribution level are:

- The volume of load is pre-existent whenever a switching operation in the distribution level while DG capacity is limited,
- The dynamic of DG is limited by the primary reserve and frequency control capacity of the speed regulator.

The problem can be divided into three subroutines:

(B1) Network cell forming based on black-start capacity of DG unit(s).

Consider a feeder under a substation which disposed at least one DG unit with black-start capacity P_{DG}. Let K = {K_1, K_2... K_N} represent the set of sectionalizing switches; P_F = {P_{F1}, P_{F2}... P_{FN}} and P_{loss} = {P_{loss1}, P_{loss2}... P_{lossN}} represent the load restored and network power loss respectively whenever the sectionalizing switch closed.

Let U= {U_1, U_2…U_M} represents the set of node voltage in the forming network cell (M). The mathematical formulation of the problem is shown below:

Objective function:

$$\text{Maximize } \sum_i \int_T P_{Fi} \cdot dt \qquad (8)$$

Constraints:

- At any switching operating K_i, the picked up load should not exceed the active primary reserve of DG black-start unit RP_{DG}:

$$\left(P_{Fi} + P_{Loss\,i}\right) \le RP_{DG} \qquad (9)$$

- The total load to be restored should not exceed the black-start capacity of DG unit P_{DG}.

$$\sum_i \left(P_{Fi} + P_{Lossi}\right) \le P_{DG} \qquad (10)$$

- After any switching operating K_i, the voltages at all the nodes in network cell should be within tolerable limits:

$$U_{\min} \le U_i \le U_{\max}\ , \forall i \in M \qquad (11)$$

The optimal solution:

By the end of this subroutine, apart from the best solution in term of maximum of restored load, a great other number of possible solutions should be found corresponding to different topologies with different restored load rates. Taking into account also the network cell expansion possibilities, it is necessary that the formed network cell has the links to some synchronizing tie switches in order to connect it with the others. Because the more the network cells are expanded, the more they have possibilities to reach to the other DG capacity, and other loads. Consequently, the optimal solution in this stage is the network cell with maximal total load restored and having one or several synchronizing tie switch access.

(B2) Network cell expansion

The network expansion process in the distribution system is recognized by rebuilding the subsystem hierarchies. Whenever the numerous network cells (NZ) are formed, represented by the set $Z = \{Z_1, Z_2 \dots Z_{NZ}\}$, the existing synchronizing tie switches between the network cells under a substation represented by $STS = \{STS_1, STS_2 \dots STS_X\}$ are determined by the "forming network cell" subroutine, it is possible that some of formed network cells have access to the same synchronizing tie switch, i.e. having a common electrical liaison. In this case, they could be able to be synchronized each other into a subsystem if the constraints mentioned below are respected:

- In each network needed to be synchronized, the primary reserve availability in the DG black-start unit must be enabling and the frequency must be within the secure band of ± 1Hz.

$$RP_{Z\,i} > 0 \;\; for \;\; Z_i \in Z \qquad (12)$$

$$49\,Hz \le f \le 51\,Hz \;\; \text{(for } f_{ref} = 50\text{Hz)} \qquad (13)$$

- At the specific interconnection point k^{th} (synchronizing tie switch), the difference between the measurable frequencies in the network cell i^{th} and j^{th}, the node voltage and rephrasing angle at both ends of the interconnection line must be within authorized limits:

$$\left| f_{ik} - f_{jk} \right| \le \Delta f_{authorized} \qquad (14)$$

$$\left| U_{ik} - U_{jk} \right| \le \Delta U_{authorized} \qquad (15)$$

$$\left| \varphi_{ik} - \varphi_{jk} \right| \le \Delta \varphi_{authorized} \qquad (16)$$

The synchronizing network cells contribute many advantages to the whole subsystem. Since the availability of DG black-start unit capacity is not homogeneous electrically and geographically, there will be some networks cells profusely of energy but others will not. The interconnection, thereby, permit the "strong" one to be very helpful for the "stressed" other.

(B3) Subsystem stabilization

The solution obtained by the two subroutines given above allows forming one or several subsystem(s) under a substation. There should be cases where a certain percentage of loads were not restored while the DG unit capacity would not be all solicited. Thus it is necessary to stabilize and increase the restored load volume if possible. The problem returns to a maximum restored load optimization with constraints problem in upper level.

Objective function:

$$\text{Maximize} \sum_{i} \int_{T} P_{S\,i} \cdot dt \qquad (17)$$

where: S represents all the loads connected under the substation.

Constraints are similar to (9), (10) and (11) as given in the first subroutine applied in each subsystem's load, and substation network's topology.

IV. Proposed General Procedure

The violent disturbances in the system before the system collapse lead to assume that all of DGs were disconnected from the grid by security reasons. In preparing the system for restoration service, all the sectionalizing switches needed to be opened.

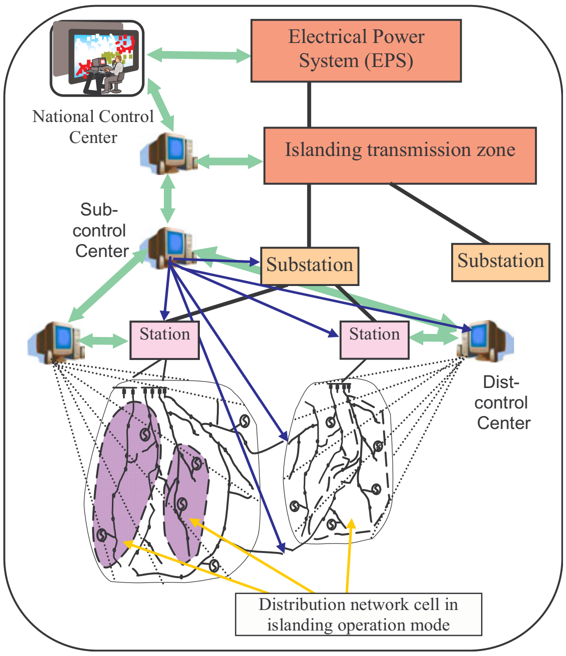


Fig.2. Restoration system process control

The generalized procedure for restoration in power system with large scale of dispersed generation based on the theory and problem formulation discussed earlier is composed of two main streams: **Downward stream** and **Upward stream** as given below. The principle is described in the Fig. 2.

Downward stream:

- Stage 1: System's operators identify system status including the circuit breakers, connection possibilities, black-start unit capacity, location of critical load…etc.
- Stage 2: After starting at least one black-start unit, emergency energy from black-start units have to be sent to the large thermal power plants within critical minimum interval and then to the non critical minimum interval units.

In this stage, if the distributed resources are locally available, it can be also used to supply the thermal unit's equipments, enabling them to hot restart.

▪ Stage 3: The more units are taken in operation, the more quickly the subsystem and its load will be energized. Loads at various level voltages are then reconnected.

It is clear that the time needed from black-starting a unit to energizing the subsystem (several hours, depending on the restart back capacity of the large thermal units) is much longer than network cell forming in the distribution system. So, in this stage, almost of possible network cells and sub-systems in distribution grid are already done. The load demand to the upper level should then be decreased. It is regarded as a "fictive load shedding" from operators' point of view. Influence of this phenomenon could be positive and negative depending on the load location. It will be positive when the concerned load is not critical to stabilize the system and negative where it is. So, in the restoration process, the operators have to be informed online about the load restored status by the upward stream process in order to take the correct decisions.

Upward stream:

The network cells and subsystem in distribution level are formed under the control of an intelligent agent at the substation.

▪ *Network cell forming based on black-start capacity of DG unit(s).*

The decision problem of the optimization network cell forming based on black-start capacity of DG unit(s) in a feeder under constraints that we face involves deciding on switch/breaker status (open or closed). In order to find the optimal solution of physical network cell, we propose to solve this problem a by Branch and Bound (B&B) method in dynamical programming. The search method allows us to cross through the space of possible system states, whereas domain specific knowledge of network topology is essential for limiting the size of the decision tree.

The B&B method: Consider the set of sectionalizing switches in order, and for each one, decide to close or not. Whether the k^{th} switch is denoted, we have two possibilities: the k^{th} switch will be closed if the constraints (9), (10) are satisfied; and it will remain to be opened if not.

The effectiveness of the method depends on the choice of the searching strategy control: breadth-first or depth-first. In the context of this problem, the best choice was depth-first because it permit to simulate the operator procedure as a part of the searching process.

Comment: In this state, in order to reduce the calculation duration, the losses in the network of each switching operation is considered approximately to a certain percentage of each bloc of loads restored. This estimate can be found in the operation in normal state condition. The consideration in details will be done by the load flow calculation after the solutions have been found.

Whenever we have the set of solutions (the possible physical network cells) obtained by the B&B method classed in term of load restored maximization order, we have to verify the feasibility of each solution by the load flow interactive calculation in order to consider the electrical constraints (11) for each switching operation.

For some cases we should choose between different solutions:

- The restored load is maximized but there is no possibility to expand to other cells

- The restored load is less than the previous solution but the cell has the links to some synchronizing tie switches.

If so, the second one is more preferred because it allows the network cells to be expanded in the next step.

▪ *Network cell expansion - Substation stabilization*

The network expansion process in the distribution system is done at the synchronizing tie switches. If two network cells have access to the same STS and the conditions (14), (15), (16) are satisfied, they can be joined together to get a new subsystem.

Then, we apply the B&B method to solve and verify the global optimization subsystem forming for the concerned substation.

▪ *Upward stream stop conditions*

Since the distributed generation capacity is limited and it plays the role of secures, so the upward stream should be stopped at any moment whenever: (1) the load is critical, necessary to stabilize the transmission network; (2) islanding transmission zone could energize successfully the substation; (3) the distribution islanding under the substation is formed, stabilized and it can not expand more.

V. Study Case

To demonstrate the effectiveness of the proposed solution in integrated power system's point of view, let's consider a part of the IEEE New England 39 buses power system including a French type distribution network. The Eurostag software in batch mode controlled by Matlab programming is used to solve the problem. Two study cases are taken to simulate the service restoration:

Case 1 (Base case): 20% DG penetration which do not contribute for restoration process.

Let's consider a part of the IEEE New England 39 bus bulk power system (Fig.3) in which 2 hydro-black-start units of 615 MW (Gen5 and Gen7), 2 thermal units of 1000 MW. The total load is about 2159MW and 395,7MVAr.

Assume that the time to start back the large thermal unit in this case is about 2 hours (including the time for energizing ancillary systems, etc.). The time for switching is about 2 to 5 minutes (including risks of failure).

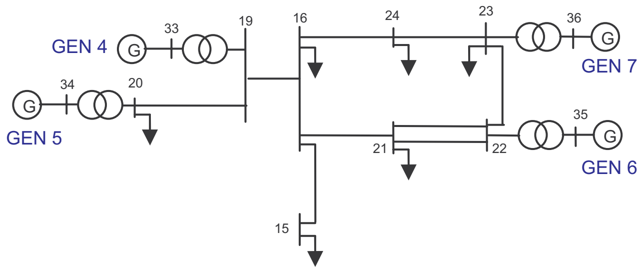


Fig.3. A part of IEEE New England 39 bus power system

The result of the optimal restoration action sequence is recapitulated in the table 1.

TABLE 1. RESTORATION ACTION SEQUENCE

	Actions		Time (h)
#1	Black-start GEN7	Black-start GEN5	0.00
#2	Energize B23-B22	Energize B19-20	0.05
#3	Start GEN6	Start GEN4	2.05
#4	Energize B22-B21, pick up load B21		2.30
#5	Energize B21-B16, pick up load B16		3.00
#6	Energize B16-B24, pick up load B24		3.30
#7	Synchronize 2 subsystem (B19-B16)		3.40
#8	Pick up load B15		4.10

In this procedure, the estimated restoration duration is about 4 hours. The critical event is to restart the non black-start units. If after black-out, the thermal units can operated in islanding mode with their auxiliaries, they can be hot restarted and taken into system operation in about 30 minutes. However, if fail takes a long time, the thermal units should be scheduled for a cold restart which required an elapsed time of 3 to 24 hours.

Case 2: 20% DG penetration which contribute for restoration process.

Upward stream:

The upward stream is carried out in the distribution substations. Let's consider the one including the 300 buses French type distribution network of 20kV.

- Network cell forming:

The figure Fig.4 gives an example of three feeders D5, D6 and D9 under the concerned substation. The feeder D8 is not mentioned here to simplify the figure size but it is taken in calculation in the table 2. The load connected to these feeders is about 11.23 MW and 6.1MVAr. There is 7 asynchronous DG of 0.4 MW and 2 DG black-start unit of 1.2 MW and 3 MW. The primary reserve which is defined in the speed regulator of DG black-start unit is about 20% of nominal power rate. The feeder D6 has 3 accesses to synchronizing tie switches: STS1 (with D9), STS2 (with D5) and STS3 (with D10). The feeder D9 has an access to STS2. The feeder D5 has an access to STS1 with D6. Assuming also that the time for a switching operation is about 1 minute and the time for restarting an asynchronous generator is about 5 minutes.

The optimal topology solution obtained for network cell forming under these feeders is shown in the figure Fig.4.

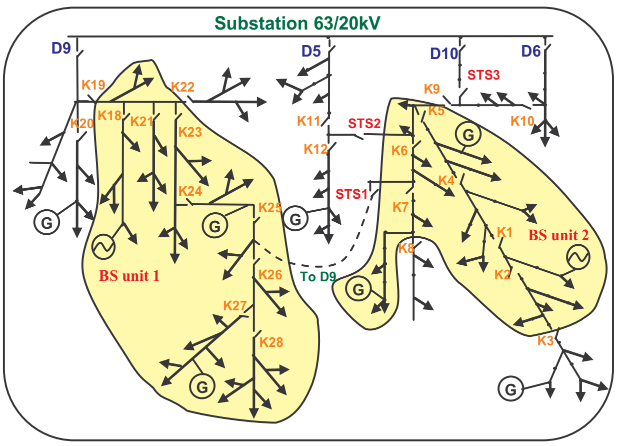


Fig.4. Optimal solution for network cell forming

The profile of voltage in these network cells which is verified by an interactive load flow calculation shows normal conditions.

These network cells are successfully formed and the constraints are all satisfied.

The same process is applied to the whole substation. We obtained 4 optimal network cells which are described in table 2 below:

TABLE 2. NETWORK CELLS IN THE DISTRIBUTION GRID TEST

Cell	feeder	DG - BS capacity MW	No BS capacity MW	Optimal switching sequence	restored load MW	No restored load MW	Access to STS
	D5	0	0.3			0.65	STS2
# 1	D6	1.5	3 x 0.3	K2- K1-K4-K5-K6-K7	1.662	3.648	STS1, STS2
-	D7	0	0.3	-	-	1.10	no
# 2	D81	1.2	4 x 0.3	K13-K14-K15	1.4		K16 – K17
# 3	D82	1.2	0	-	0.94		K16 – K17
# 4	D9	3	4 x 0.3	K18-K21-K22-K23-K24-K25-K26-K27-K28	3.271	1.99	STS1
-	D10	0	0	-	-	0	STS3
	Total	**6.9**	**3.6**		**7.273**	**7.388**	

DG – BS capacity: DG black start capacity

As we can see in the table 2, with participation of DG units, after the network cells formed, 7.273 MW load are restored, equivalent to 49% total of load under the substation.

- Network cell expansion – substation stabilization:

We can also see that the formed network cell can be expanded by synchronizing D6 to D9 at STS1, D81 to D82 at K16 and K17.

In this stage, load is not all restored yet while some DG capacity rest available. The optimal sequence to expansion the subsystem obtained is K11, K12 in D5 and K20 in D9. Then the supplementary supplied load is about 1.113 MW. The benefit of using DG during the restoration process in this example is finally represented in Fig.5 in term of total MWh restored. Also, the time for distribution islanding forming and expansion is about 1640 seconds (about 30 minutes). At the end, the total restored load is about 8.4 MW equivalents to 57.3% of substation load.

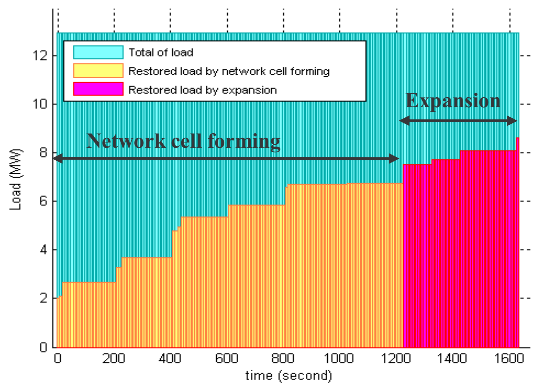


Fig.5. The restoration process in distribution system

Downward stream:

Assuming that the load connected in B24, B15 and B23 of the transmission network is partially supplied by distributed resources. The restoration process of the integrated system for case 1 and case 2 is shown in the Fig.6.

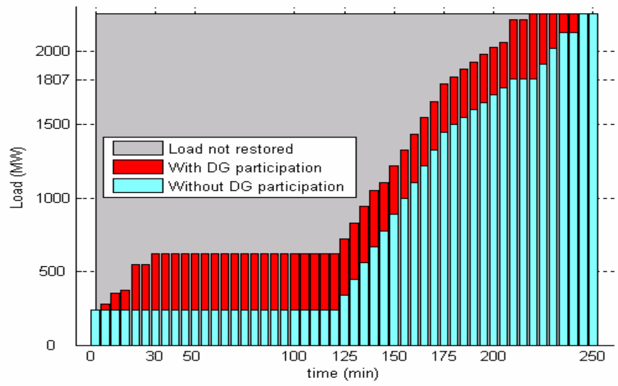


Fig.6 The restoration process

The interesting results given by this figure are the benefits from client's point of view in term of MWh restored load and reduction of collapsed time. With participation of DG, 623.8MW (27.6% of total load) are carried up within 30 minutes instead of about 125 minutes in case of no DG participation. 1827.2 MW of load (80.9% of total load) is picked up in about 175 minute in case with DG participation instead of about 225 minutes in case without DG participation. The restoration process for the whole system (100% of total load) in case of DG participation is about 20 minutes shorter than without DG participation.

VI. Conclusion

This paper proposes a new restoration process for the EPS with large scale of DG. It serve as a system dispatcher's aid after a blackout. The proposed procedure has been designed to provide flexible topologies of system networks in order to take account the unpredicted events in restoration process. The major advantages of this work are:

- Proposition of a **deep build together** strategy for considering simultaneously the expanding of restoration scheme both in the transmission and distribution level.
- Proposition of an approach for forming the network cells in the distribution grid. This approach is based on the Branch and Bound method which determines the switching operation sequence to maximize the MWh load restored with a limited DG black-start unit capacity. The possibilities to expand the restored distribution grid are also considered.
- Quantification of the benefit of using DG in the restoration process.

The benefit of using DG in restoration service obtained in this study will be a good appreciation for the high rate of DG insertion in the power system of tomorrow.

Further work will attempt to extend the proposed procedure considering the new network architectures of tomorrow: "flexible distribution network" with high rate of DG penetration.

References

[1] M.M. Adibi, L.H.Fink "Power System Restoration planning" *IEEE Transaction on Power Systems* Vol.9, N°1, pp. 22-28, February 1994

[2] L.H. Fink, K.L. Liou, C.C. Liu "From Generic Restoration Actions to Specific Restoration Strategies" *IEEE Transaction on Power Systems*, Vol. 11, N°2, pp. 745-751, May 1995.

[3] C.C.Liu, K.L.Liou, R.F.Chu, A.T.Holen "Generation Capacity Dispatch for Bulk Power System Restoration. A Knowledge-Based". *IEEE Transaction on Power Systems*, Vol.8, N°.1 pp 316-323, Feburary 1993

[4] E. Agneholm "The Restoration Process following a major Breakdown in a Power System". Technical Report N°230L 1996.

[5] S.Corsi, M.Pozzi, "A Multivariable New Control Solution for Increased Long Lines Voltage Restoration Stability During Black Startup", IEEE Transaction on Power Systems, Vol.18, N°.3, August 2003.

[6] A.L. Morelato, A. Monticelli, "Heuristic search approach to distribution system restoration". *IEEE Transaction on Power Systems* Vol.14, N°.2, May 1999.

[7] M.M.Adibi, D.P. Milanicz, "Estimation restoration duration". *IEEE Transaction on Power Systems*, Vol.14, N°4, pp. 1493-1498, August 1999.

[8] P.Kundur, 1994, "Power System Stability and Control" New York, Mc Graw-Hill, ISBN 0-07-035958-X

[9] A.Ketabi, "New Approaches for Bulk Power System Restoration", Thesis of INPG - Intitut National Polytechnique de Grenoble, 2001.

[10] M.Fontela, T.T.Ha Pham, C.Andrieu, S. Bacha, N.Hadjsaid, Y.Besanger "Limits of DG insersion in electrical power system". Securing Critical Infrastructures – 2nd Conference on Critical Infrastructures, Grenoble October 2004

[11] B.Enacheanu, M.Fontela, C.Andrieu, T.T.Ha Pham, Y.Besanger, A. Martin, " New control strategies to prevent blackouts: islanding operation in distribution networks". CIRED 18th International Conference on Electricity Distribution, Turin, June 2005.

T.T. Ha Pham received her DEA from INPGrenoble in 2003. She was working in the reliability of electrical power network. She is now working toward a PhD degree in collaboration between IDEA, Laboratoire d'Electrotechnique de Grenoble (LEG) in France and Hanoi University of Technologies of Vietnam. Her research areas include the impacts and control of dispersed generation insertion in power system restoration.

Yvon Bésanger received his Ph.D. in Electrical Engineering from the INPGrenoble in 1996. He is currently Associate Professor at the National Superior Electrical Engineering School of Grenoble (ENSIEG) and the Power Engineering Laboratory of Grenoble (LEG). His research interests are distribution networks operation and reliability, FACTS devices and power system dynamic stability

Nouredine Hadjsaid received his DEA and Doctorat de l'INPG degrees from the INPGrenoble in 1988 and 1992. From 1988 to 1993, he served as a research and teaching assistant at the Associate Professor at the National Superior Electrical Engineering School of Grenoble (ENSIEG) and the Power Engineering Laboratory of Grenoble (LEG). He is presently professor at INPG-ENSIEG-LEG and Manager at IDEA. His research interests are power system operation and security.

Christophe Andrieu received his Engineering Diploma and his DEA, and Doctorat de l'INPGrenoble degrees from INPGrenoble in 1995. He joined the Research and Development Center of Schneider Electric SA in 1995. He works on electrical power system analysis and becomes involved in distributed resources connection and exploitation. He works with IDEA as a Researcher and as a Project Manager on Dispersed Generation.

Miguel Fontela received his DEA from INPGrenoble in 2002. He was working in Power Electronic field, in France at the Laboratoire d'Electrotechnique de Grenoble (LEG). He is now working toward a PhD degree. His research is centered on the impacts and production control of dispersed generation on transmission system.

Bogdan Enacheanu received his DEA from INPGrenoble in 2004. He is now preparing a PhD degree. His research interest is located on new architectures of distribution networks.

Paper 8: *Integration of new ICTs for EPS in the scope of utilities services*

Full bibliographic reference:

M. Fontela, P. Mellstrand, B. Stahl, C. Andrieu, R. Gustavsson, B. Enacheanu, and A. Martin: *Integration of new ICTs for EPS in the scope of utilities services*, CIRED 2005 conference, June 2005, Turin, Italy, Paper 373.

INTEGRATION OF NEW ICTS FOR EPS IN THE SCOPE OF UTILITIES SERVICES

Miguel FONTELA*, Per MELLSTRAND[+], Björn STAHL[+], Christophe ANDRIEU[++], Rune GUSTAVSSON[+], Bogdan ENACHEANU[++], Alexandre MARTIN[++]
* IDEA & Laboratoire d`Electrotechnique de Grenoble - France
[+] Blekinge Institute of Technology - Sweden
[++] IDEA & Schneider Electric - France
France & Sweden
fontela@leg.ensieg.inpg.fr, andrieu@leg.ensieg.inpg.fr, pme@bth.se

INTRODUCTION

New era of information and communication technologies (ICT) is changing traditional works and solving challenges for human activities. Progress and advances in different fields are being carried out in order to improve the quality of operations and perform automations.

EPS (Electric Power Systems) are not an exception for these advances. Thus, information and communication technologies introduce new ways to develop EPS tasks. However, this is only possible if the EPS special requirements on ICT are met (notably in terms of reliability and timing constraints).

The paper proposes a definition for ICT, and then current practices and standards of EPS are briefly cited. The paper analyses the use of the new ICT components in a fault localization and isolation task. The required ICT components are described and a demonstrator is presented. This demonstrator was used in the laboratory experiences in order to evaluate the timing necessary to implement the fault localization ICT under TCP/IP communication protocol.

The works included in the article are integrated in the CRISP[1] project and in the EURODOC program (PhD mobility) of the French Rhone-Alpes Region.

ICT DEFINITION

Information and Communication Technology can be defined as follows:

The technology involved acquiring, storing, processing and distributing information by electronics means (including radio, television, telephone, and computers).

Three processes are involved inside the ICT definition: information acquisition, communication of the information between different entities and information computerization (it includes information analysis, storing and visualization).

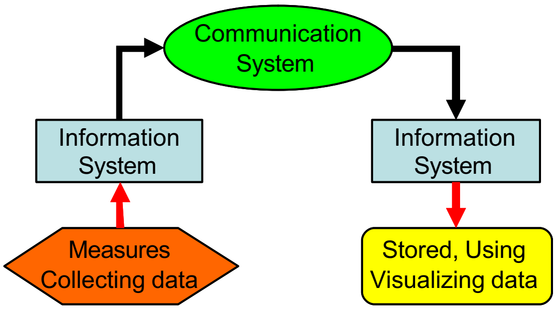


Figure. 1.-Information vs Communication vs Computerization

Communication is the fact of transmitting information between two or more points/agents of the system. The information and communication processes are related very closely. The information system is responsible of obtaining or measuring the parameters/variables that the systems need to control for a normal operation. So, at this step the information exists and can be transmitted from this point of measure to other points of the system for further utilization.

The communication system is responsible of this transmission and different communication media are used to transfer the information. The information transformed into different signals (analog or digital) is transmitted by the communication media to different centers where these signals are converted into other formats (data formats exploitable by the centers) and finally the communication process is finished when these data (information) are stored.

The computerization consists in the use of the information or data in order to analyze the system or to establish a help for taking conclusions and so elaborating decisions. The computerization can be carried out there where there is the information (with or without communication between two entities because a same entity can obtain the information and computerize it). This computerization system includes the coordination between different agents and actors and refers mainly to the different computer tools and operating systems that can be applied in a computer, PLC or Control unit.

[1] ***CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power.*** Project funded by the European Community under the Fifth RTD Framework Programme (2002-2005). Project Co-ordinator: ECN. Partners: ABB, BTH, IDEA, ECN, ENECO, EnerSearch and Sydkraft. Contract No. ENK5-CT-2002-00673.

Current practices in EPS. The use of communication media in SCADA (Supervisory Control and Data Acquisition) systems or EMS (Energy Management Systems) for EPS depends on different factors such as the nature of the media, possibility of interference or electromagnetic distortion, investment cost for installation or the requirement of special licenses.

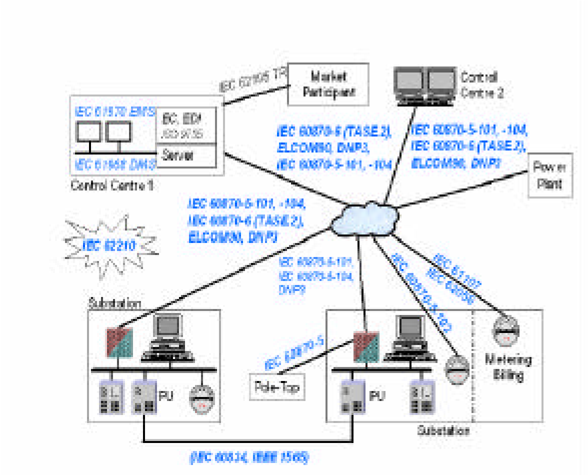


Figure. 2.- Some Standards of Electric Power System Communication

The International Standard Associations like IEC or IEEE have been working to establish standards and recommended practice for the communication between different agents and for different tasks in EPS (market, substation automation, communications inside SCADA…) [1]. In figure 2, some standards of EPS communications are cited.

The main component of the EPS communication system is the SCADA system. Basically, it is the architecture to acquire, store and process the parameters needed to control the system. The SCADA of TSOs or utilities is normally composed of several types of communication systems such as [2]:

- Fixed networks including public switched telephone and data networks
- Wireless networks including cellular telephones and wireless ATM (Asynchronous Transfer Mode), radio systems, microwave (radio signals operating on the 150 MHz to 20 GHz frequency range)
- Power line carrier is the most commonly used communication media for protection function. However, this medium does not offer a reliable solution for wide area data transmission. Communication with remote sites can not be maintained during a disturbance.
- Computer networks including various dedicated LANs, WANs, and the Internet.
- The satellite network is another segment of the communications system that can provide important services which are difficult to carry out with normal communication techniques. These services include detailed earth imaging, remote monitoring of dispersed localizations and time synchronization using signal from GPS (Global Positioning System).

The delays or latencies and data rate of such communication media differ from a system to another. In table 1, a comparison is carried out in the case of wide area measurement networks [3]:

TABLE 1-Communication delays of some communication in wide area measurement networks

Communication link	Associated delay-one way (milliseconds)
Fiber-optic cables	100-150
Digital microwave links	100-150
Power line (PLC)	150-350
Telephone lines	200-300
Satellite link	500-700

The different data rate of the currently media used in the power system are compared in Table 2 [4], [5], [6]:

TABLE 2- Communication data rate for different communication media.

Communication link	Associated data rate
Fiber-optic cables	1 Gbits/s
Radio frequency	9.6 kbits/s
Power line (PLC)	2 Mbits/s

Future applications on ICT components to develop traditional and new functions in EPS can be carried out with Internet or with Virtual Private Networks (VPN). Internet presents the advantages in terms of availability through telephone lines; but, the security questions are not cleared and as EPS is a critical infrastructure for societies, the use of Internet for EPS should be limited for non-critical issues. Thus, the option of VPN seems to be more adequate.

This VPN could be physically established through IP networks. The utility IP network could be used to unify the different activities inside the SCADA (communication between SCADA components, measurements…). An example of this case is shown in figure 3.

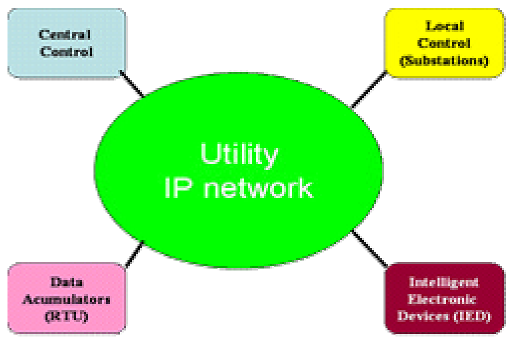


Figure. 3.- IP network for an utility SCADA system.

One practical example of these VPN uses is used by REE (Red Eléctrica Española), Spanish Transmission System Operator, in order to establish a strategy to interrupt loads if needed in the control of the transmission system [7].
This article proposes the use of an TCP/IP network for a fault

localization speed-up with a new localization algorithm [8]. The applicability of such algorithm in real practice is closely related to the total timing processing (including the three ICT components: information acquisition, communication and computerization).

PROPOSED ICT DESCRIPTION: DEMOSTRATOR

As it was mentioned, the paper presents a practical implementation of a distributed intelligence. In this case, the distributed intelligence is a help tool to fault diagnostic (HTFD). This HTFD contains the fault localization algorithm and needs to evaluate different information (from EPS devices such as fault passage indicator (FPI), switch (SW) and fault recorder (FR)) to indicate to the operator the probable fault placement in the network. After these indications, the operator could isolate the faulted section in a reduced time delay and continue to supply so many customers as possible [9].

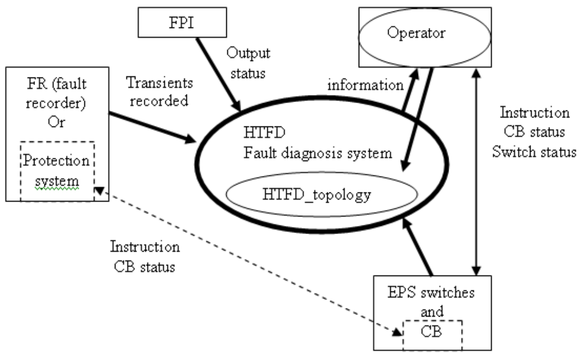


Figure. 4.- Context diagram for the Fault Diagnosis system

The tool proposed represents an additional function to the existing protection system. The main existing information systems are taken into account in the proposed tool, the required information exchanges as described in the figure 4. The Fault Diagnosis ICT System has four main sources of information:

- Fault Passage Indicator: The FPIs are distributed in general at key points of the distribution EPS, on the main feeder and derivations, being associated in general with the boundaries of elementary areas. The FPI sends state information to the Fault Diagnosis System through the FPI_ICT component.

- Fault Recorder or the protection system: The voltage and the current are measured in magnitude and in phase at a given point of the network in case of fault, the sending-end of a feeder in general. Then, FR sends electrical variable information to the Fault Diagnosis System. This information may involve a heavy file (transients), while the real information needed by the localization tool is small. Indeed, a solution with a local analysis and data reduction is proposed. The FR_ICT_component is developed to treat the transient measurements and send only the essential data to the main tool.

- The EPS Switch: EPS Switches allow reconfiguration of the power network by opening or closing a flow point. They may or they may not be associated with an FPI, depending on the planning and exploitation choices of the operator. Each switch change in the network has to be taken into account properly in the topology description inside the Fault Diagnosis System: the reconfiguration has a great influence in the fault localization evaluation. The EPS Switch communicates its state to the Fault Diagnosis System and receives orders from the operator to modify its state. The EPS_ICT_component is developed as part of the system to carry out these functions.

- The Operator: The main role of the operator is to make decisions when different actions are needed and may endanger the EPS proper running. The HTFD tool communicates information and proposes decisions to the operator. Then, the operator sends orders to CB and EPS switches with existing control system.

The Fault Passage Indicator and the EPS Switch all are connected and distributed into the power grid. The Fault Recorder is linked to the protection system, collecting transients measured by the protection devices distributed at each sending-end feeder. Their localization is given by the operator in the network topology included in the HTFD tool.

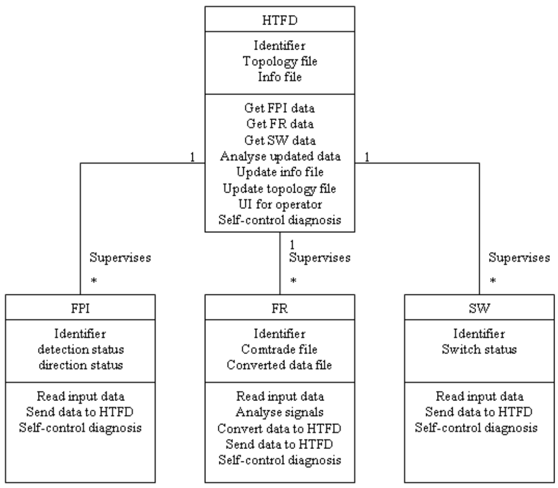


Figure 5.- Class diagram for the ICT main components in the Fault Diagnosis System

In figure 5, the network components (FPI, FR and SW) are represented by objects / classes within the Fault Diagnosis System. The network components will then have their ICT counterparts as distributed subsystems within the Fault Diagnosis System (figure 4). The network component objects will have their 'controlling' part, including intermediate calculations, deployed on the ICT component and an information part on the HTFD subsystem.*

The operator role is not specified in the diagram, but is represented by the UI 'attribute' of the HTFD class. The UI (User Interface) takes care of representing the right information to the operator and receiving information from the operator. The operator sends the instructions to the EPS switches by an existing control system. The HTFD needs to know the state of the switches in order to update the network configuration. The network topology is important in this application and some data required are specific to the fault localization. But some other data are common with other possible applications to be developed in the future: local demand supply matching (local market may introduce temporary changes in the local power system configuration), power quality studies (voltage profile, harmonics).

The different ICT components were integrated in a demonstrator (see figure 6) in order to test their performances with TCP/IP network.

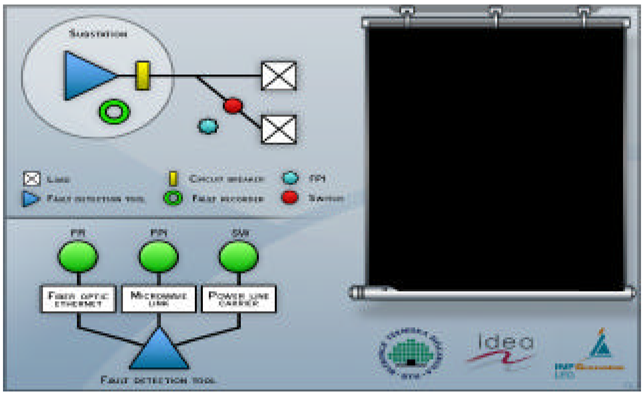


Figure 6.- Demostrator interface for the test of the system under TCP/IP network

In a very simple case, the demonstrator consists of a number of PCs, some acting as nodes and other as communication links (communication links between the information points (FPI, FR and SW) and the main tool (HTFD)), all running the FreeBSD operating system. The different communication properties, such as throughput and latency, were simulated on the computers acting as links by using the dummynet [10] feature in FreeBSD in conjunction with bridging.

The visualization and control tool was implemented in the C programming language and executed on a node-type computer in the network. The user interface is shown in figure 6.

RESULTS

Two time frames were evaluated for the communication sequences: time for transmitting data files and time for communication streams. Actually the total communication time is larger than the time needed for file transmission: the transmitted files are usable before the last messages of acknowledgement between the PCs. If the same device has several messages to send in a short delay, the PCs remain connected and the messages are sent successively when FP flag (end of last message) is passed.

A typical value is the stream rate in Kbit/s, given in our demonstrator a typical latency (TL) for a simple way. A simple file sent takes nearly 5*TL for the total communication sequences (from synchronization to disconnection), and the useful transmission of a short file takes nearly 3*TL.

TABLE 3- Measured latency for a simple way and various stream rate (specific bridge)

Data rate (Kbit/s)	TL (ms)
1000	8
565	11
140	10
40	18
12	50
10	57
9.6	66

In the demonstrator, if no bridge is used, the TL found is 0.2ms; Launching a call to establish the communication or printing a reference date in a file takes nearly 4ms each, this time being added as a first step of connection requirement.

The following figure gives the case of an order emitted from the tool (HTFD device) to a switch (SW device) with a direct link between them at 10Mbit/s.

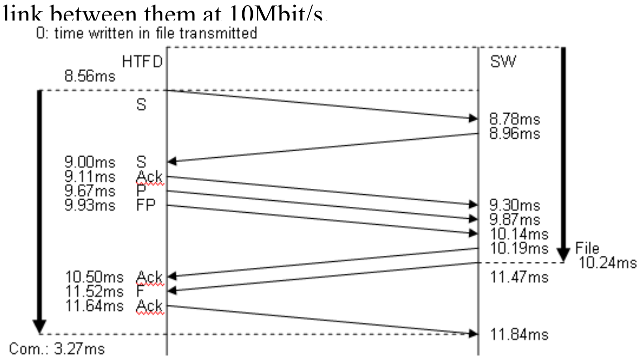


Figure 7.- Exchanges messages to send data from HTFD to the SW with 10 Mbit/s link

The following figure gives the same case with a bridge set to 9.6Kbit/s

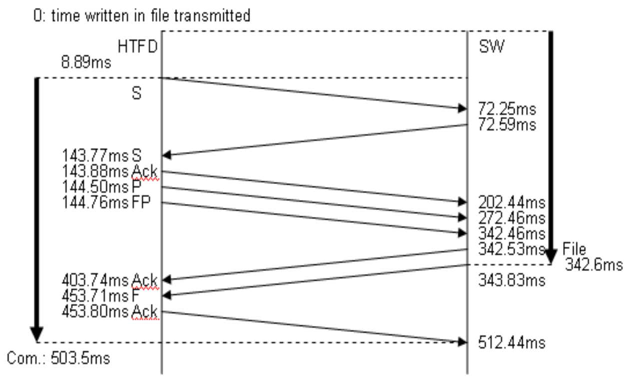


Figure.8.- Exchanges messages to send data from HTFD to the SW with 9.6 Kbit/s link

The purpose was to evaluate the total time required for the localization. As indicated the latency for real message transmission can be higher or lower depending on the stream rate capacity and CPU capacity. In the developed tests, the IP performances seem acceptable for its application in real practice.

CONCLUSION

The paper has presented a view of new ICT components to be introduced in the EPS operation. The applicability of new ICT depends both in the computerization timing of new algorithms and also in the communication and information system delay.

TCP/IP communication protocol is a wide-spread standard which could be valuable in order to implement the communication between different distributed intelligence in EPS. Here, the IP network was tested for a fault diagnostics use, but other uses could be thought for the future (e.g. Virtual power plants or islanding operation).

One critical parameter in EPS is the ICT systems security and quality of performance. At this point, IP networks depend on messages collision, loss of messages, congestion in the network and external intrusions. Special attention should be paid to these problems for correct operation and one can think about priorities associated to the information in a layered router strategy (different pre-defined IP routes for different information priority).

REFERENCES

[1] CIGRE B5.11, 2003. "The automation of new and existing substations: why and how".

[2] Donald.G. Fink and H.Wayne Beaty, 2000. *Standard Handbook for Electrical Engineers*. Section 10, Supervisory Control and Data Acquisition, pp-10-147 to 10-168. Ed.Mc-Graw Hill.

[3] Biju Naduvathuparambil et al, 2002. "Communication Delays in Wide Area Measurement Systems", *Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory*, Pages: 118 – 122.

[4] Bin Qiu, 2002. "Next Generation Information Communication Infrastructure and Case Studies for Future Power Systems" Ph.D dissertation Virginia Tech.

[5] M.Fontela, C.Andrieu, S.Bacha,N.Hadjsaid, Yvon Besanger, Rune Gustavsson, Bjorn Tornqvist and Per Mellstrand, 2004. "State of art of ICT components and its uses in Electric Power Systems (EPS)". Internal report of ENK5-CT-2002-00673 CRISP-Project.

[6] CIGRE Joint Working Group 34/35.11, 2001. "Protection using telecommunications".

[7] REE, Sistema de Comunicacion, Ejecucion y Control de la Interrumpibilidad (SCECI), 2004. "Protocolo de Comunicaciones entre los sistemas de Gestion del Operador del Sistema y Equipos de Control de Consumidores Interrumpibles y Empresas Distribuidoras". Draft 6.1, 26. [Available on line in Spanish]: http://www.ree.es/cap03/pdf/Protocolo_Comunicaciones_SCECI_rev6.1.pdf

[8] C.Andrieu, B.Raison, D.Penkov, M.Fontela, S.Bacha and N.Hadjsaid, 2003. "Fault detection, analysis and diagnostics in high-DG distribution systems", Deliverable D1.4 of ENK5-CT-2002-00673 CRISP-Project.

[9] C.Andrieu, B.Raison, and M.Fontela, 2003. "Simulation tool for fault detection and diagnostics in high-DG power networks", Deliverable D2.3 of ENK5-CT-2002-00673 CRISP-Project

[10] L.Rizzo, 1997. "Dummynet: A simple approach to the evaluation of network protocols", *ACM Computer Communication Review*.

Paper 9: *Limiting the DG insertion: a deterministic criterion*

Full bibliographic reference:

M. Fontela, C. Andrieu, S. Bacha, N. Hadjsaid, and Y. Besanger: *Limiting the DG insertion: a deterministic criterion*, CIRED 2005 conference, June 2005, Turin, Italy, Paper 371

LIMITING THE DG INSERTION: A DETERMINISTIC CRITERION

Miguel FONTELA*, Christophe ANDRIEU +, Seddik BACHA*, Nouredine HADJSAID* and Yvon BESANGER*
*** IDEA & Laboratoire d`Electrotechnique de Grenoble - France**
+ IDEA & Schneider Electric - France
fontela@leg.ensieg.inpg.fr

INTRODUCTION

The dependence of present societies on the electricity supply does that the electric power system (EPS) is one of the critical points in the normal life and defence of a country. The absence of electricity provokes problems for daily life and so, EPS constitutes a critical infrastructure for societies .

The international agreements to reduce the Greenhouse gazes emissions and new rules such as European directives to increase the renewable energy sources have promoted the creation of national plans to install new DG resources. These new plans fix a tendency to integrate a high quantity of new DG sources. The special dynamic performances of DG make that new considerations and criteria should be taken into account in the EPS control and planning in order to guarantee a suitable operation and, therefore, the system's robustness.

The article gives an overview of the different impacts and the influence of DG in the EPS operation. The amount of DG insertion in the EPS should be limited to prevent catastrophic consequences in real-time operation. Thus, a deterministic criterion is proposed to be taken into account in the study of the system robustness. The main conclusions of the article are illustrated with EUROSTAG simulations based on a European-adapted 39buses network (adaptation of the IEEE New England 39 buses to European data).

The works included in the article are integrated in the CRISP[1] project.

1 ***CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power.*** Project funded by the European Community under the Fifth RTD Framework Programme (2002-2005). Project Co-ordinator: ECN. Partners: ABB, BTH, IDEA, ECN, ENECO, EnerSearch and Sydkraft. Contract No. ENK5-CT-2002-00673.

This work was supported by Inventer la Distribution Electrique de l'Avenir (IDEA), joint research laboratory between EDF (French provider of Electricity), Schneider Electric S.A. and INPGrenoble.

M. Fontela; S.Bacha, N. Hadjsaid and Y.Besanger are with IDEA and the Laboratoire d'Electrotechnique de Grenoble, Institut National Polytechnique de Grenoble, Saint Martin d'Hères, 38402 France (e-mail: fontela@leg.ensieg.inpg.fr - bacha@leg.ensieg.inpg.fr - hadjsaid@leg.ensieg.inpg.fr besanger@leg.ensieg.inpg.fr)
C.Andrieu is with Schneider Electric and IDEA. Institut National Polytechnique de Grenoble, Saint Martin d'Hères, 38402 France (e-mail: andrieu@leg.ensieg.inpg.fr)

DG INSERTION IN EPS

The generation of energy is normally carried out in the transmission system by means of huge power plants (1000-1300 MW) based on thermal, nuclear or hydro energy. But, this is not the unique power injection in the electric networks. There are other generation injections, called DG, e.g. CHP (Combined Heat and Power) generators and small local independent producers at the sub-transmission system, or the small dispersed generators at the distribution system.

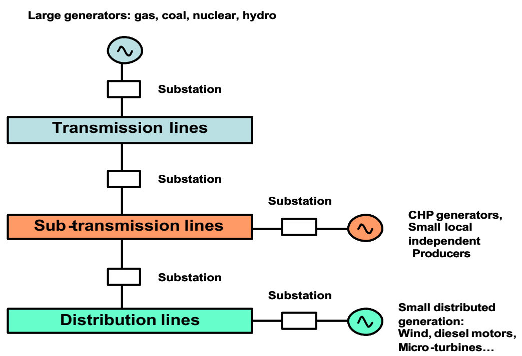


Figure.1.-DG insertion in Electric Power Systems

The voltage level for the DG connection (sub-transmission or distribution) depends essentially on rated power of generators and the local network characteristics. The liberalisation of the energy market has favoured the apparition of these new DG producers.

DG units are based on conventional and non-conventional energies. The conventional DG corresponds to micro-turbine, CHP, fuel cells, Diesels or storage among others. The non-conventional energies refer to the renewable sources such as wind energy, hydro or PV. Renewable sources are widely seen as a relevant tool to comply the obligations coming from the Kyoto protocol. The estimation of new DG based on RES (Renewable Energy Source) is shown in figure 2 by ETSO (European Transmission System Operators) data [1] for the percentage of the total capacity which is based on renewable energies. In this figure 2, it is also shown the tendency to new DG installations. Hydro power is the renewable energy source that contributes with the biggest share to the renewable generation in Europe.

However, the present plans to install DG-RES are concentrated in the off-shore and on-shore wind power potential. The exploitation of the wind energy is now expected to be the main driver for reaching the targeted RES development in the future.

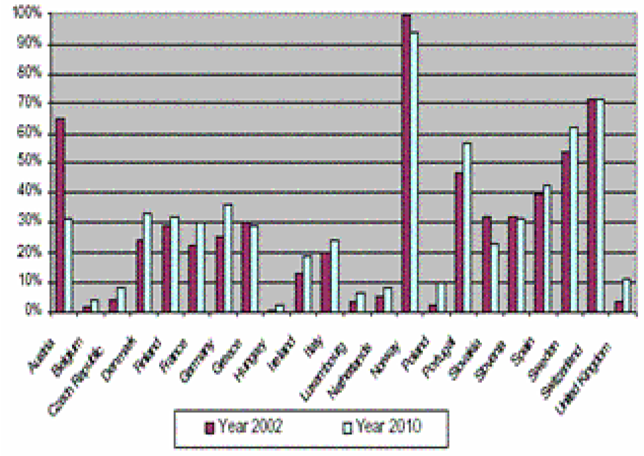


Figure.2.-ETSO data about the DG-RES capacity

DG can cause some impacts on the EPS. These impacts could be classified in two different groups: impacts on the distribution system and impacts on the transmission system. The main impacts that DG could cause on the distribution system are the next ones [2], [3]:

- Impacts on the energy direction: traditionally the EPS was designed for a top-down energy flow but the DG implies a bottom-up energy flow. Thus, it is possible that the energy is injected into the sub-transmission and transmission systems
- Impacts on the protections (setting points, selectivity and bad operation of protection).
- Impacts on voltage profile.
- Impacts on stability.
- Impacts on power quality (harmonics, sags, surges and deeps).
- Impacts on the planning, exploitation and observability of distribution networks: the distribution networks were not designed to insert the DG in a high amount. So, it is probable that some changes will take place in its exploitation and observability [4], [5]. The DG should be controlled by the utilities and DSO (Distribution System Operators); it will mean an increase of SCADA data. It is also possible that the traditional radial architecture will be changed into a meshed one.
- Economic impact on the energy markets: associations and agreements of DG producers to propose bids in energy markets (day ahead, balancing or ancillary services markets).

On the other hand, the main problems that a large amount of DG insertion could cause to the transmission system deal with prevision of reserves, operation in real-time and emergency strategies. The main impacts of a high amount of DG on the transmission system can be summarized as follows:

- Risk of congestion in specific areas.
- Intermittence problems [6]: uncertainty in the power injection (location and amount).
- Change of real-time exploitation margins.
- Change of the real-time exploitation strategies (DG as a base power because ecologic-friendly energy).
- Apparition of unexpected reactive power flows in the transmission system (flows in the lines down to the natural power).
- Closure of centralised power plants because economic and polluting reasons.
- Lack of DG sources caused by unforecasted weather conditions or by technical reasons (disconnection protection).

DETERMINISTIC CRITERION

The EPS are interconnected in order to increase the support between national systems and so, ensure a better quality of supply to the customers. TSO (transmission system operators) take some security criteria (e.g. (n-1) criterion) in order to guarantee a suitable system's robustness. Some examples of adequacy criteria are the following ones [7], [8]:

- Probabilistic
  -LOLF (loss of load frequency) (unit: failures/year)
  -LOLP (loss of load probability): a loss of load will occur when the system load exceeds the generating capacity in service. The overall probability that the load demand will not be met is called the loss of load probability or LOLP (unit: dimensionless)
  -LOEP (loss of energy probability) or LOEE (loss of energy expectation): the loss of energy method is a variation of the loss of load method. Here the measure of interest is the expected non-served energy split by the total energy demand over a period of time.
  -EUE (Expected Unserved Energy).

- Deterministic (working rules coming from experience):
  -Percentage reserve: it consists on defining a reserve for each system, representative ranges are 10-30% of peak demand in installed capacity and 2-10%in operation. This criterion compares the adequacy of reserve requirements in totally different systems on the sole basis of their peak load.
  -Another widely used criterion calls for a reserve equivalent to the capacity of the largest unit on the system plus a fixed percentage of the dispatched capacity.

The article proposes a new deterministic criterion that should be taken into account in the control of the system it consists on the consideration of the DG amount insertion compared to the system action in case of emergency. The system should stand high variations on the DG production: these DG variations of injected power could represent, in some cases and in future perspectives, a bigger power than the biggest

unit in national systems (and so, questioning actual common generation adequacy working rules). They could be caused by weather conditions (e.g. windmills disconnections or errors in forecasted energy) or by (Initial event – DG tripping) caused by the operation of the DG disconnection protection. As systems are interconnected and synchronised, these variations are not reduced to national power plants and the combined apparition of such events could lead the system to resulting blackouts.
An index, that defines the criterion, can be introduced; it is the frequency deviation (FD) index, which evaluates the dynamic responses of the system in terms of active power balance (see equation (1)).

$$(FD) = \frac{[(PR)+(IL)]}{[ALEA + (DG_1) + (DG_2)]} \qquad (1)$$

where PR is the primary reserve (MW), IL is the amount of interruptible loads or load shedding (MW) planned up to 48.5 Hz, DG_1 (MW) is the DG with instantaneous or very quick (100ms) disconnection protection, DG_2 (MW) is the DG with temporized disconnection protection at 49.5 Hz and ALEA is the maximal load variation or generation loss forecast by the operator (the generators included in ALEA should not be included in DG_1 and DG_2). ALEA can be also a short-circuit or event that provokes that the system arrives to the setting points of the disconnection protection before 49 Hz and 0.85 Un. DG influence in the system is given through FD index, notably in terms of disconnection protection and lack of sources.

FD gives a good view of the system and quantifies the risk of the system in case of an excessive DG insertion. If FD < 1, the operator should place an alert because the DG insertion could endanger the whole system in case of major contingences. On other hand, if FD > 1, the system is stable in case of appearance of contingences (ALEA). Thus, the events consequences on frequency are compared to primary reserve and first load sheddings, which are supporting tools of the system in case of emergency (to study the whole system robustness and take into account static and dynamic system indices, special indices can be used [9])

The problems of the disconnection protection could be seen during the last blackout in Italy [10]. Future changes in the legislation are in progress to adequate the protection and improve the DG reaction in case of disturbances [11].

On other hand, DG variations are expected to increase tertiary reserves in order to integrate light and medium DG variations, but if the deterministic criterion (high variation) is taken into account primary and secondary reserves should be increased in order to stand unexpected events (including the DG variations).

STUDY CASE

The study of the deterministic criterion was carried out using a study case: the IDEA_CRISP_39buses network (see figure 3) that is an adaptation of the IEEE New England 39 buses system. The architecture of this IEEE network is mostly kept. However, the parameters of its different elements were adapted to normal European data. So, the transmission system is considered at 400 kV and the generators (Gen 1 to Gen10) produce the energy at 20 kV. The installed power is 9085 MVA and it is shared in three different types of generators: 4 thermal units of 1000 MVA each one (GEN4, GEN6, GEN8 and GEN9), 3 nuclear units of 1080 MVA each one (GEN1, GEN2 and GEN3) and 3 hydro units of 615 MVA each one (GEN5, GEN7 and GEN10). The total consumption is 6141.6 MW/ 1470.9 MVAr split in 18 loads. The load model associated with the consumption is the impedance model (a quadratic variation with the voltage). The generators regulations are of two types: a voltage regulation and a frequency regulation. The voltage regulator is the IEEE voltage regulator type A [12]. The frequency regulator is a torque regulation with a speed droop of 4% [13].

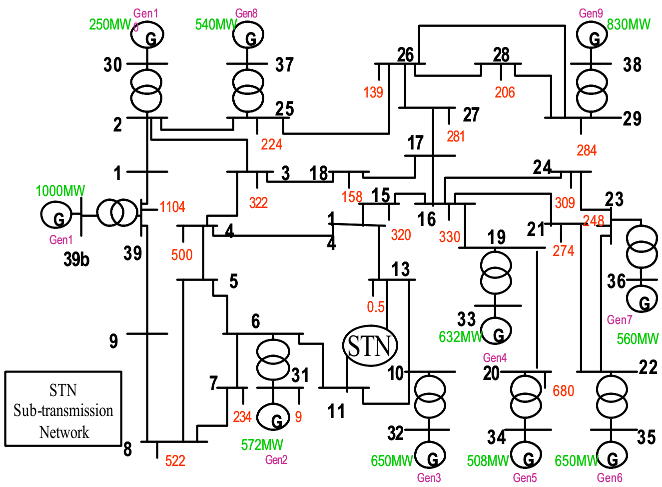


Figure. 3.-Study case architecture without DG insertion (green: generators active power in MW; red: load consumed active power in MW)

The study case includes, as well, a 63 kV sub-transmission loop and 2 real French 20 kV distribution networks (STN) and several distributed resources (DR) by means of equivalent synchronous machines injecting 100 MW in the transmission system to build different DG insertion cases: 10%, 20%, 30%,40%, 50% and 60%.

RESULTS FROM SIMULATIONS

Different scenarios of DG behavior were simulated with different amount of DG insertion in the system in order to apply the index and define an appropriate amount of DG insertion in the chosen test case. Some of the different studied scenarios were the following ones [14]:

- Scenario 1: Instantaneous disconnection protection.
- Scenario 2: DG without problems of disconnection protection.

Scenario 1: Instantaneous disconnection protection

The appearance of a short-circuit at the transmission level is an event which can provoke the propagation of a voltage deep and frequency deviations in the system and so, the disconnection of generators. DG should be limited in order not to shed loads after a fault in a transmission line. One should take into account that load shedding is an emergency tool and if the load shedding is used (at 49 Hz) by a first short-circuit; the system could remain in a bad operating point to face latter events.

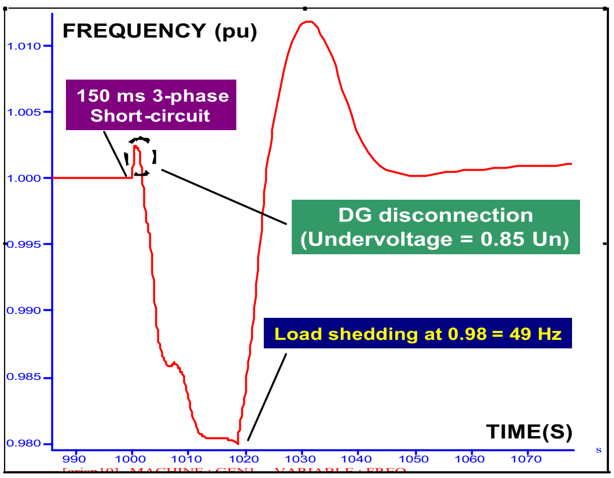


Figure. 4.-Dynamic reaction of the study case (with 10%DG instantaneous protection) faced to a 150 ms 3-phases short-circuit

Therefore, in this case, a slightly lower level than the primary reserve, it is the appropriate amount of DG insertion (instantaneous dis connection protection) regarding adequacy (ability of the system to supply the aggregated demand).

Scenario 2: DG without problems of disconnection protection

In this scenario 2, DG is considered without problems of disconnection protection, what it means that DG has a dynamic behavior equivalent to centralized power plants in the disconnection protection. This assumption will allow us to analyze the system action when faced to problems derived from the loss of generation. This loss of sources could appear e.g. with a high wind turbines insertion when wind is strong enough that causes the turbines cut-out disconnection.
The appropriate DG insertion is fixed by the resources of the system (active and reactive power) and the dynamic behavior of the system when faced to the chosen contingencies (transient stability and no loss of synchronism). The high degree DG insertion makes that some centralized generators could be closed or stopped. So, the operators should be able to guarantee reserves and a good voltage plan with the existent generators. The maximal amount of DG insertion is placed here around 50% of the total production. For higher amount of DG insertion such as 60%, stability problems were found in the system.

TABLE 1- Results in the 50%DG insertion without disconnection protection problems

Events	System saved by	PR (MW)	IL = LS (49 Hz) (MW)	FD (for ALEA = Event)
Loss of DG < PR	PR	731	928.35	> 2.27
Loss of DG = PR	PR	731	928.35	2.27
Loss of 10%DG (600 MW)	PR + LS (49.5 Hz)	731	928.35	2.76
Loss of 20%DG (1200 MW)	PR + LS (49.5 Hz)	731	928.35	1.38
Loss of 30%DG (1800 MW)	PR + LS (49.5 Hz) + LS (49 Hz)	731	928.35	0.92
Loss of 40%DG (2400 MW)	PR + LS (49.5 Hz) + LS (49 Hz)	731	928.35	0.69
Loss of 50%DG (3000 MW)	PR + LS (49.5 Hz) + LS (49 Hz)+ LS (48.5 Hz)	731	928.35	0.55

The limit, in this case, is the system's security (ability of the system to stand disturbances and ensure a good real-time control). The system should be able to share the reserves between the existent generators and stand the lack of a big part of DG sources (errors in forecast, disconnection by wind gusts, weather forecast of strong winds and apparition of storms). An appropriate amount of DG insertion from this deterministic criterion point of view is the one which gives a FD value around 1 and therefore, they do not give rise to important load shedding in case of this DG loss.

CONCLUSIONS

The article has presented a view about the DG insertion, its possible impacts and influences. The special dynamics of DG sources (disconnection protection, intermittence problems) make them especially negative if some disturbances appear.

In order to limit the DG insertion and the negative influence of DG during EPS operation, the paper has proposed a deterministic criterion to analyse the system operation. This criterion is based on a comparison of DG insertion with the very quick emergency strategy (primary reserve and first load shedding step). The criterion is introduced through an index (FD). It was applied in a study case and several contingencies were analysed with different DG behaviour. As conclusion, DG insertion with special dynamics, in disconnection protection or with problems derived from the intermittence, should be limited or changes in the emergency strategy should be considered in order to avoid negative effects on the system. Obligations that TSOs impose to DG producers should be enlarged in the future years in order to adequate the DG behaviour in emergencies.

One economical paradox could appear in the next years after the market deregulation: EPS could need additional reserves for secure and adequate operation with high amounts of DG insertion. Thus, one can see how, in the worldwide, the possibility of load shedding is proposed to customers with economic incentives [15].

The increase of primary reserves would limit the benefits of some actors to integrate other actors, because primary reserve is an obligation and not a service for generators up to a defined level [16]; so, compensations (for extra primary reserve and load shedding capability) could be reviewed in a free concurrency market to those actors that stand the system and TSOs to manage the actor's integration.

REFERENCES

[1] ETSO report ; 2003. "Report on Renewable Energy Sources (RES)", Brussels.

[2] J.F.Canard, 2000. "Impact de la génération d'Energie Dispersée dans les réseaux de distribution". Ph.D.dissertation, Laboratoire d'electrotechnique de Grenoble (LEG), INPGrenoble.

[3] R.Caire, 2004. "Gestion et Strategies de conduite de la Production Decentralisee". Ph.D.dissertation, Laboratoire d'electrotechnique de Grenoble (LEG).

[4] P.Bongrain, J.L.Fraise, 2001. "Connection of Edf's remote control system to Dispersed Generation Units". *CIRED. 16th International Conference and Exhibition on Electricity Distribution*.

[5] Brent Brobak et al, 2002. "Real Time Data Acquisition from Wind Farms in Power System". *IEEE Power Engineering Society Summer Meeting. Volume: 1 , pages:512 vol.1.*

[6] Rapport UCTE, 2004. "UCTE Position Paper on Integrating wind power in the European power systems - prerequisites for successful and organic growth".

[7] Yuri Makarov et al, 2003. "On risk-based Indices for Transmission Systems", *IEEE Power Engineering Society General Meeting*. Pages: 678. Vol. 2.

[8] Jose Fernando Prada, 1999. "The Value of Reliability in Power Systems –Pricing Operating Reserves", Massachusetts Institute of Technology.

[9] M.Fontela, C.Andrieu, S.Bacha, N.Hadjsaid and Y.Besanger, 2004. "Distributed Generation as a means to increase system robustness", Deliverable D1.3 of ENK5-CT-2002-00673 CRISP-Project.

[10] UCTE report, 2004. "Final Report on the Investigation Committee on the 28 September 2003 Blackout in Italy". [Online]. Available: http://www.ucte.org/pdf/News/20040427_UCTE_IC_Final_report.pdf

[11] Journée d'étude SEE (Société de l'Electricité, de l'Electronique et des Technologies de l'Information et de la Communication), 7 December 2004. "Production décentralisée et eolien : états et perspectives".

[12] Paul.M.Anderson and A.A.Fouad, 1977. *Power System Control and Stability.* The Iowa State University Press.

[13] Prabha Kundur, 1994. *Power System Stability and Control* New York, Mc Graw-Hill.

[14] M.Fontela, Ha Pham-Thi-Thu, C.Andrieu, S.Bacha , N. Hadjsaid and Y.Besanger, 2004. "Limits of DG insertion in Electric Power Systems". *CRIS Conference, Securing Critical Infrastructures.*

[15] The California ISO, "Load Voluntary Reduction Program". [Online], Available: http://www.caiso.com/

[16] BOE num.197, Ministerio de Industria y Energia,. (Spanish Energy and Industry department), 18 August 1998. [Online], Available: http://www.cne.es/

Paper 10: *New control strategies to prevent blackouts: intentional islanding operation in distribution networks*

Full bibliographic reference:

B. Enacheanu, M. Fontela, C. Andrieu, P. Ha, A. Martin, and Y. Besanger: *New control strategies to prevent blackouts: intentional islanding operation in distribution networks*, CIRED 2005 conference, June 05, Turin, Italy, Paper 372

NEW CONTROL STRATEGIES TO PREVENT BLACKOUTS: INTENTIONAL ISLANDING OPERATION IN DISTRIBUTION NETWORKS

B. ENACHEANU, M. FONTELA, Ch. ANDRIEU, Ha PHAM, A. MARTIN, Y. BESANGER
GIE-IDEA
Laboratoire d'Electrotechnique de Grenoble – ENSIEG BP46
38402 Saint Martin d'Hères Cedex - France
enacheanub@leg.ensieg.inpg.fr

I. INTRODUCTION

Several countries have experienced electric system deregulation. The market deregulation is currently associated with deep changes in distributed resources (DR or DG) technologies and communication & information technologies (ICT). The massive connection of DR and the need to improve their profitability leads to new electric system management concepts. The article presents the possible use of DR to supply partially local distribution area, isolated from the interconnected electrical power system (EPS) during a blackout for instance.
This technical capacity may be achieved at various scales and may last several hours during a restoration process following a blackout. This intentional islanding may result of an ultimate saving action for a specific area of the EPS, or of a black start in a local area.
This specific EPS running mode leads to new kind of DR control and DNO operation tools, to a new fast adaptation of the local protection systems. Some existing areas in the distribution EPS may be relatively well adapted to manage the needed local agent. The size and the location of these possible cells are introduced in the paper.
The typical voltage level targeted in the paper is the medium voltage (MV). The main interest is to take profit of a local production capacity (interest for the network operator, the consumer and the producer) to increase the local security and availability. But this profit has a cost: local control and protection reinforcement and real time adaptation.
This paper gives information on some local area networks characteristics: possible topology flexibility, cell definition, need for a specific exploitation strategy (frequency and voltage control requirement), improvement needed for the protection system and for the local information system. The intentional islanding availability study is presented in the paper through a proposed methodology that may be automated in the long run. The approach proposed in this paper is essentially based on technical constraints. The methodology is applied to a study case and the results are illustrated using EUROSTAG software simulation. Finally, a few characteristics for the information system for the intentional islanding application are given. The works included in the article are integrated in the CRISP project (CRISP: Distributed Intelligence in Critical Infrastructures for Sustainable Power. Project funded by the European Community under the Fifth RTD Framework Program (2002-2005)).

II. OVERVIEW ON INTENTIONAL ISLANDING

As mentioned in the introduction the islanded EPS area may have various sizes, depending on the internal production capacity and its control characteristics, the internal consumption control means and demand characteristics.

A – State and transition

The paper deals with the stability and the steady-state of a given area during an intentional islanding. For this area and the included controlled components there is a need of a relatively centralized decision tool (remote coordination and control).
This intelligence refers to several local coordination purposes including DR controls, possible local demand controls, protection systems (public and DR devices) and is based on computing processors connected by communications means. The local information system allows the management and the coordination of the local voltage and frequency control means and of the protection systems, and plays a main role exchanging data with the hierarchical higher communication levels. When the state in islanded mode is checked and validated for various electrical conditions and intermediate EPS sizes, the question about transition from a state to another state have to be analysed. The two main transitions are:

1. Severe electrical conditions are detected and lead to an ultimate save for smaller local areas being able to work in intentional islanding: splitting transition.
2. When normal condition appears and is maintained around the island, a partial reconnection may be initiated after synchronization. After a general black-out, some additional local black-start capacities are required to begin the restoration or the local back-up process: concatenating transition.

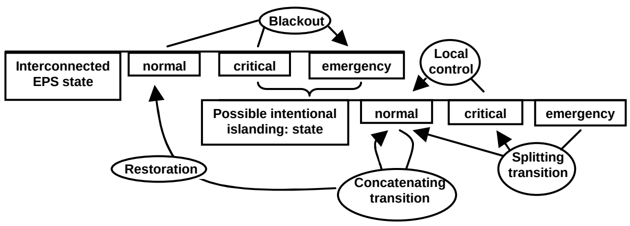


Figure 1: islanding state and transition

The figure 1 shows the general context for the studied islanding operation. The normal condition for the EPS is

assumed to be the total interconnection. During islanding different states are defined in a similar way (normal, critical and emergency condition) in order to orient the following decisions (control and transitions).
The next part deals with technical requirement (protections, V and f regulation...) for maintaining such an islanding state.

B – Protections, voltage and frequency control

The frequency control. Islanding operation mode requires frequency control capability similar to primary frequency control developed in the large plants connected to the transmission network (P/F droop) [1]. This kind of control enables a shared contribution of the various local DR and local controlled demand to power flow changes.
Another solution may be achieved with an isochronous generator as used in private installations (this generator support the whole transient variation in the local system). Nevertheless the interconnection of various DR by the public network owned by different actors leads to a more distributed control capacity. The droop regulation is well known and avoids fast and remote coordination: the frequency variation involves the required action expected for each DR and for each controlled consumer.
As for the large plant a small part of the power capacity may be reserved for mitigating frequency deviations: nearly 5% of the nominal power.
The main aspect is that the most important local DRs (relative to the local consumed power) are equipped with the adapted frequency control. The different DR units interfaced to the grid by synchronous machines or inverters can technically take part in it. The small generators dynamic parameters (small inertia and variation slope (MW/s)) make that the frequency control is different in comparison with the transmission system one. These characteristics must be taken into account in the network protections and frequency control settings. When a dynamic phenomenon occurs (demand variation for instance), the frequency moves and then is stabilized resulting in a new maintained frequency. In order to avoid a too large excursion in the normal frequency range, another control may be installed. It could be a coordinated optimal power flow (OPF), launched in a few seconds in order to update the local adequate balance. This OPF has to combine at the same time the resulting consequences on frequency and voltage magnitude. In the transmission system the disconnection is clearer for the action of active power on frequency and the action of reactive power on local voltage magnitude. In the distribution system, depending on the state of the EPS area (interconnected or islanded) the OPF may follow various control strategies.
During the islanded mode the apparent behaviour may be as the secondary frequency and power control installed in the large power plants. The main action is to recover the nominal frequency in the island after a given time period (nearly 1s or a few seconds). This local OPF need a local intelligence, and communication links between this agent and the involved controlled producers and consumers.

Voltage control. During the islanded mode the local DR units may have to maintain the voltage magnitude at the point of common coupling. During the interconnected mode the whole network (transmission system) and the tap-changer transformers are mainly contributing to the voltage magnitude in the distribution networks. The principle of voltage control for DR units is more complex than the one used in transmission network [1], it depends a lot on the running mode. Even during the interconnected mode the local synchronous machines and the local inverters can also contribute to act on the local voltage, according to their installed capacity, by controlling the active and the reactive power exchanged with the network.
The reactive power capacity of these sources is limited: the law in France makes the reactive power depends on the nominal output capacity (see French regulation of march 2003 about the distribution networks [2] and theoretical reactive limitation in [3]).
In the plants directly connected to the transmission level, the primary voltage control time-constant is nearly a hundred milliseconds. Depending on future protection systems installed around DR installations, a similar time constant is expected for the units installed in the distribution level for the islanded case.
The voltage amplitude has a more local influence than the frequency: the need of a specific coordination between the local units or the need of a specific distributed intelligence is obvious in order to maintain a normal voltage along the distribution feeders. As in the transmission system, a solution during islanded mode is to try to maintain the right voltages in certain given nodes of the system during dynamic phenomenon. The combined influence of active and reactive power leads to develop a fast OPF for steady-state operation.
The need for a local intelligence supervising and controlling a given area is highlighted. This *intelligence* should be able to coordinate the DR units in order to meet the voltage setting points in interconnected mode or in islanded mode.

Protection system. The traditional EPS switches in France installed along a feeder have no breaking capacity [4]. The breaking capacity is concentrated in the sending-end of the feeder in a circuit breaker. During a MV short-circuit all the DR units are quickly disconnected by specific protections [5]. These disconnecting protections are not adapted in the future to let contribute partially the DR to the system support or to maintain a stable supply of an islanded EPS area.
A future system must coordinate the DR unit breakers and feeder breakers in order to enable a given level of selectivity inside an islanded area and to take profit of the great number of fugitive faults or faults inside the customer installations.
This protection system may be adapted to the running mode (different need of system support in interconnected mode and in islanded mode), the fault current depending a lot of the mode and size of the islanded area.
During the fault clearing sequence due to fault occurring on the public feeder, all the DR units have to separate and certain of these units have to keep capacity to be re-connected very quickly. The fast re-connection asks for specific questions about the need of local synchronisation. Two solutions can be planned to adapt the protection system in the event of

intentional islanding:

- An economical solution: keeping the existing system and the network operator accepts a failure of the islanding network for a MV short current. Black start is then initiated if the faulty section is localized and is isolated.
- A more expensive solution consists in inserting other circuit breakers in the MV feeders and using a fast reconfiguration tool during a MV short circuit (to avoid temporary disconnection of most of the DR units).

III. PROPOSED METHODOLOGY TO STUDY THE ISLANDING FEASIBILITY

This paragraph deals with a methodology to study the feasibility of a maintained islanding. This methodology is presented in figure 2. The methodology includes several steps, the logical succession of these steps, contains exits (conditions necessary but not sufficient) to the main algorithm in order to eliminate the cases, in which the islanding is not possible, and so reduce the methodology evaluation time.

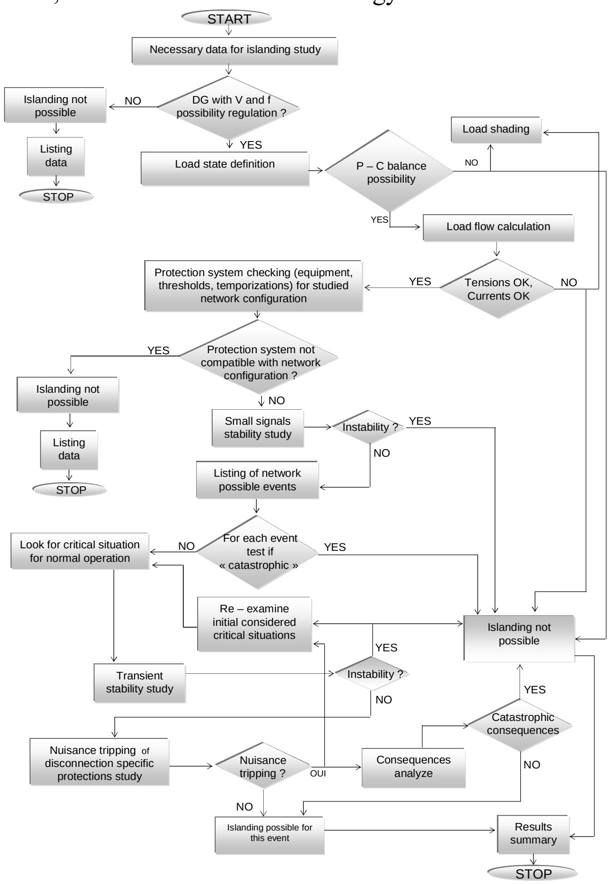


Figure 2: Intentional islanding feasibility study

The main phases of the algorithm are the following ones:

1. Learn the network architecture, the voltage and frequency control characteristics for each DR, load size and protections characteristics;
2. Test the existence of the V and f control capacity;
3. Load state definition ;
4. Load flow calculation ;
5. Check protection system ;
6. Small signals stability study ;
7. List the network possible events in the considered configuration;
8. Search for critical situation in normal operation;
9. For each event, transient stability study ;
10. Tests for unwanted operation of the specific DG disconnection protection ;
11. Analysis of unwanted operation and DG disconnection (DG protection);
12. Summary of results– islanding operation possibilities and limits for the analyzed architecture.

IV. STUDY CASE

The proposed methodology was applied to a study case. This study case, shown in figure 3, is composed by a MV feeder (between CB and S_2) connected to another MV feeder (supplied by another substation between S_2 and S_4). The system includes 3 DG units (synchronous machines): DG_1 (7.76 MVA), DG_2 (3.53 MVA), DG_3 (1.5 MVA) and the total load (P= 9.49 MW, Q= 3.48 MVAr) depends dynamically on voltage and frequency [3]. The load flow computations were acceptable for the bus voltages and line currents values at the expected demand. From a static point of view, the islanded operation is possible. Different short-circuits were evaluated in the system. The three – phase short-circuit currents in K_1 and K_2 (figure 3) are shown in table 1. The needed protection flexibility is clear for the MV level and less necessary for the supplied LV area.

	K_1	K_2	Short circuit current contribution
Interconnected	2.64	13.05	***upstream system***
Islanding	0.88	10.89	DG_1, DG_2, DG_3

Table 1: The short circuit current values (kA) for K_1 et K_2

The operating power reserve being $\Delta P_{DG1}+\Delta P_{DG2}$=1.26 MW, the islanded failures due to given events are identified:

- DG_1, DG_2, L_1, L_5 lost ;
- N10 and N14 load lost ;
- MV short circuit.

For the other events, the methodology, shown in figure 2, is followed. The simulations with EUROSTAG [6] show different performances for the islanded mode in the studied case [7]. This paper gives an illustration with 13.75 % load variation (meaning 103 % of the primary reserve), this event being critical. A larger load variation leads to a local synchronism loss (see figure 4). A fault is cleared faster than 200ms in a private installation. A few cycles are typical when the protection is achieved with fuses.

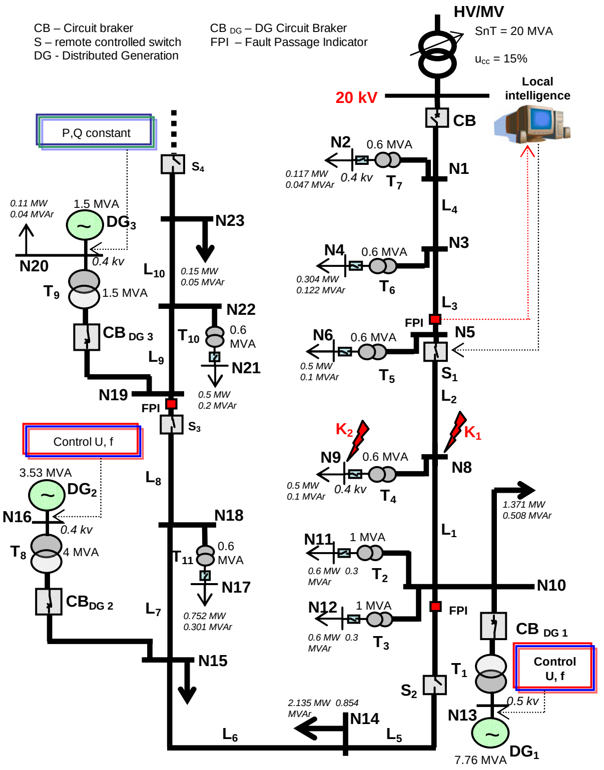


Figure 3: Single line diagram for the study system

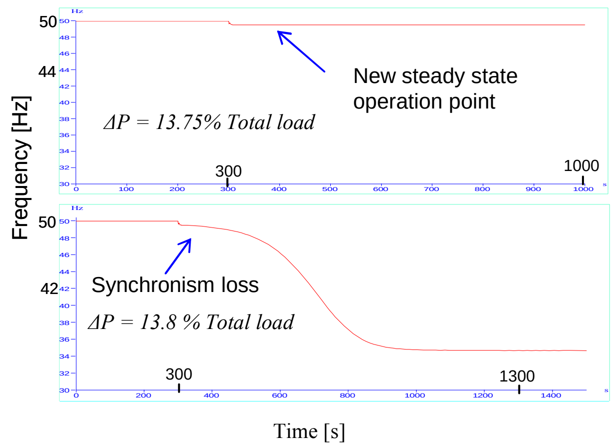


Figure 4: Frequency variation for two ΔP load variation cases

For a short circuit in N20 bus, the critical clearing time is evaluated to 200ms (see figure 6, DG_3 synchronism loss).

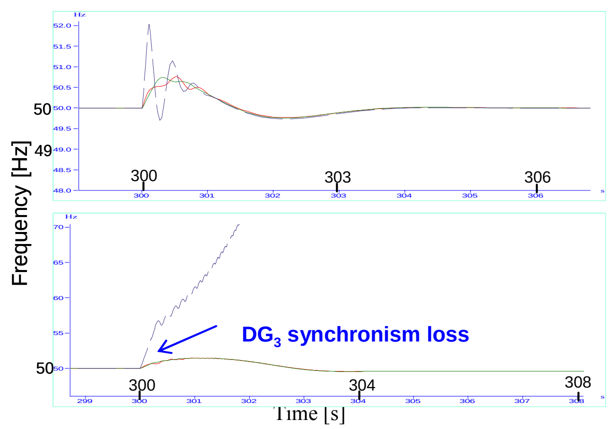


Figure 5: Fault in N20 cleared in 100 ms (top) or 200 ms (bottom)

The system eigenvalues calculation (figure 6) for 2% load variation gives negative values for the real part (small signals stability, [3]).

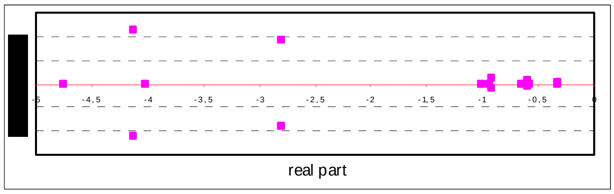


Figure 6: Small signal stability study – Eigenvalues: imaginary and real part

At the end of the study, a summary is proposed:

- Intentional islanding is possible from a steady-state point of view;
- Protection system need specific adaptation;
- Critical events for the given area and existing data are:
  - Maximal fast load variation: 103 % (1.304 MW),
  - Maximal clearing time 100 ms (MV fault);
- The L_7 line loss determines a two subsystems network separation: first sub-system which contains DG_1 and DG_2 can continue to function and the second sub-system which can not function (not a voltage and frequency control capacity, see figure 3).
- For the MV faults, the switch and the DG placement allows a possible reconfiguration and a partial load restoration (i.e. for a MV upstream of S_2 short circuit, DG is disconnected and a 39% load restoration is possible by DG_2 and DG_3 with S_2 open).

V. ICT REQUIREMENTS AND CHARACTERISITICS FOR ISLANDING OPERATION

For an intentional islanding the local protection system coordination requires a typical response time of a few hundreds of milliseconds. The radio frequency waves utilisation for a limited data communication volume is characterised by a similar time response (a few hundreds of milliseconds).

For our application, the DR units and EPS switches distribution and distances lead to this type of communication system. So, a solution for the control and for the decisional algorithms (real time operation and reconfiguration) must be achieved by taking into account simultaneously the electric and the ICT constraints.

The data communication characterization, developed in CRISP project, shows two typical time parameters: data transmission (file transmitted from a CPU to another one within nearly 350 ms) and communication process (total sequence of communication from connection to disconnection within nearly 400 ms). For a global time evaluation, the local data – processing is recorded and analysed. For a fault location and isolation application, the local data- processing time is nearly 10.5 ms with the following computer (Intel Celeron Processor 466 MHz, 320 MB SDRAM).

VI. EPS CELLS

As it was mentioned in the introduction, future electric networks will integrate a high amount of DR, changing traditional control and exploitation strategies. A new concept of MV cell is introduced for fitting well with the existing networks and devices (soft changes in the network) and enabling a powerful and fast reconfiguration among a given EPS area.
Two types of cells are previously defined joining one or several MV substations:
1/ A network cell level 1 consists in a group of electrical components including conductors, DR and loads in one or several distribution network feeders (the different feeders are linked by normally open switches (E), as indicated in figure 7). So, this cell level 1 is created by the concatenation of all the interconnected internal MV feeders. The boundaries of this cell are located at circuit breakers of MV substation.

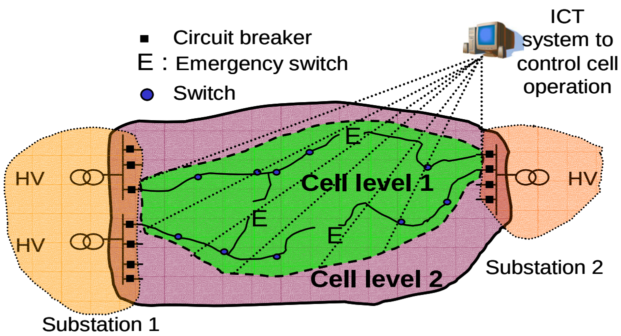


Figure 7: The « network cell » concept

Each substation includes several cells level 1 in general.

2. All these cells level 1 can be interlinked through the MV busbar inside the MV substations and, so, generate a cell level 2. An illustration is given in the figure 1 assuming that all the feeders are interlinked only between substation 1 and 2. The level 2 cell may be very large in urban system.
The definition takes into account technical constraints associated to existing distribution networks (the MV/LV substations play an essential role in the energy distribution and management at this voltage level). A simple view for the boundaries of the level 2 cell is the MV receiving-ends of MV substation busbar.

The *cell concept* refers not only to the EPS topology but also to the distributed part of intelligence associated: the cell has a function to achieve. Different missions may be assigned. When the cell includes a lot of applications (energy management, system support, autonomous control of voltage, flexible protection system, DR control, demand control), it could be then equipped in order to achieve the intentional islanding: this last and complex application must be seen as a possible future application.
This cell concept is general and will lead to a flexible MV network exploitation with DR insertion and variable production, a main point concerning the reconfiguration.
Future papers will deal with these applications.

VII. CONCLUSIONS

This paper introduces shortly a new concept of EPS cell which lays on existing electric infrastructures and a new kind of intelligent information infrastructure. This concept and associated applications will be developed in future papers.
For the study of an intentional islanding, a method has been proposed and used for a MV case. Some requirements for the voltage and frequency control, protection system in a network cell are given. The study results emphasize the need of a local agent (decisional ability) to enable an adaptive coordination of the protection system and frequency and voltage control means. The application was carried out with EUROSTAG simulations, for various scenarios and various network configurations. The aim is the feasibility study of an intentional islanding in a given area.
The real time constraints between the local control required and capacity of microwave ICT leads to think and combined electrotechnical analyses and communication constraints. This is a new approach of a high combination of theoretical physical evaluations with capacity of information flows.

VIII. REFERENCES

[1] P.Bornard, ”Réseaux d'interconnexion et de transport: réglage et fonctionnement“. Document 4090 “*Technique de l'ingénieur”*, traité Génie Electrique.

[2] Ministère de l'économie des finances et de l'industrie, Mars 17, 2003 ”Prescriptions techniques de conception et fonctionnement pour le raccordement a un réseau publique de distribution d'une installation de production d'énergie électrique“, Arrêté du 17 mars 2003.

[3] P. Kundur, 1994, “Power System Stability and Control” New York, Mc Graw-Hill, ISBN 0-07-035958-X

[4] R. Belhomme, Ph. Juston, P. Cholley, J.L. Fraisse, 2001 “Fonctionnement en regime îloté d'un réseau MT” CIRED Conference.

[5] EDF- GDF Service, December 2001**, “**Protections des installations de production raccordées a un réseau de distribution**“.** Guide technique de la distribution d'électricité.

[6] EDF (Electricité de France) and Tractebel Energy Engineering, EUROSTAG software.
http://rdsoft.edf.fr/poleindustrie/drd/rdsoft/home.nsf/AC_ACC_FR?OpenFrameSet

[7] B. Enacheanu, 2004 “Faisabilité du fonctionnement en îlotage d'un réseau électrique de distribution” MsD thesis INPG (Institut National Polytechnique de Grenoble).

Paper 11: *Advanced online tap changer control to counteract power system voltage instability*

Full bibliographic reference:

Z. Gajić, D. Karlsson, and M. Kockott: *Advanced online tap changer control to counteract power system voltage instability*, in Proceedings Fifth CIGRE Southern Africa Regional Conference, October 24-27, 2005, Somerset West, Western Cape, South Africa. (See also http://www.cigre.org/publications).

ADVANCED OLTC CONTROL TO COUNTERACT POWER SYSTEM VOLTAGE INSTABILITY

Zoran Gajić Daniel Karlsson Mike Kockott

zoran.gajic@se.abb.com

ABB Power Technologies, Substation Automation, SE-721 59 VÄSTERÅS, **SWEDEN**

SUMMARY

The main purpose of the automatic voltage regulator (AVR) for power transformers with on-load tap-changer (OLTC) is to keep the voltage on low voltage (LV) side of power transformer within a preset deadband. Originally AVR was designed to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an AVR shall react and change position of OLTC in accordance with LV side load variations. However, the AVR will as well react on abnormal voltage variations on the high voltage (HV) side of the power transformer. Sometimes such AVR behaviour is not desirable because it just further increases the total load on the HV system (i.e. transmission system). Especially, such behaviour shall be prevented during critical operation states of the transmission system, such as a slow power system voltage collapse.

The major power system blackouts throughout the world in 2003 have clearly illustrated the need for different modes of voltage control, since the requirements during normal operation conditions and abnormal conditions, sliding towards voltage instability, are very different. In this paper the focus will be on possibilities to improve tap-changer control in order to perform properly also during stressed situation in the power system.

Most of the current commercially available automatic voltage regulators (AVRs), just measure the LV side voltage of the power transformer in order to control OLTC position. Such a principle has a major drawback that typically speeds up a power system voltage collapse. However, some modern intelligent electronic devices (IEDs) used for such automatic control do have the capability to measure the power system voltage on both sides of the power transformer.

A scheme with such built-in feature can offer excellent performance of AVR scheme during large voltage variations on the transformer HV side. In the same time it can as well be used to improve time coordination of the OLTCs connected in series and to minimize the overall number of OLTC operations in the whole power system.

INTRODUCTION

When the load in a power network is increased the voltage will decrease and vice-versa. To maintain the network voltage at a constant level, power transformers are usually equipped with an on-load tap changer (OLTC). The OLTC alters the power transformer turns ratio in a number of predefined steps and in that way changes the secondary side voltage. Each step usually represents a change in LV side no-load voltage of approximately 0.5-1.7%. Standard tap changers offer between ± 9 to ± 17 steps (i.e. 19 to 35 positions).

The automatic voltage regulator (AVR) is designed to control a power transformer with a motor driven on-load tap-changer. Typically the AVR regulates voltage at the secondary side of the power transformer. The control method is based on a step-by-step principle which means that a control pulse, one at a time, will be issued to the on-load tap-changer mechanism to move it up or down by one position. The pulse is generated by the AVR whenever the measured voltage, for a given time, deviates from the set reference value by more than the preset deadband (i.e. degree of insensitivity). Time delay is used to avoid unnecessary operation during short voltage deviations from the pre-set value.

AUTOMATIC OLTC CONTROL PRINCIPLES FOR SINGLE TRANSFORMER

A typical AVR measures the busbar voltage (UB) at the power transformer LV side, and if no other additional features are enabled (i.e. line drop compensation) this voltage is used for voltage regulation. The voltage control algorithm then compares UB with the set target voltage (Uset) and decides which action should be taken.

Because this control method is based on a step-by-step principle, a deadband ∆U (i.e. degree of insensitivity) is introduced in order to avoid unnecessary switching around the target voltage. The deadband is typically symmetrical around Uset as shown in Figure 1. Deadband should be set to a value close to the power transformer's OLTC voltage step. Typical setting is 75% of the OLTC step.

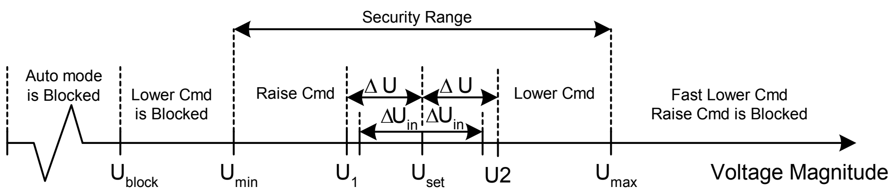


Figure 1: Typical AVR Voltage Scale for Automatic OLTC Control

During normal operating conditions the busbar voltage UB, stays within the deadband. In that case no actions will be taken by the AVR. However, if UB becomes smaller than U1 or greater than U2 (see Figure 1), an appropriate lower or raise timer will start. The timer will run as long as the measured voltage stays outside the inner deadband. If this condition persists for longer than a preset time, the appropriate LOWER or RAISE command will be issued. If necessary, the procedure will be repeated until the busbar voltage is again within the inner deadband.

The main purpose of the time delay is to prevent unnecessary OLTC operations due to temporary voltage fluctuations. The time delay may also be used for OLTC co-ordination in radial distribution networks in order to decrease the number of unnecessary OLTC operations. This can be achieved by setting a longer time delay for AVRs located closer to the end consumer and shorter time delays for AVRs located at higher voltage levels.

AUTOMATIC OLTC CONTROL PRINCIPLES FOR PARALLEL TRANSFORMERS

Automatic On-Load Tap-Changer Control of parallel transformers can be made according to three different methods:

I. Reverse Reactance method
II. Master – Follower method
III. Circulating Current method

Unlike the first method, the last two methods require exchange of signals and measured values between the transformers, or between the transformers and a central control unit. However, the drawback with the first method is that the voltage control will be affected by changes in the load power factor. The Master – Follower method is generally limited to applications with similar transformers, whilst the circulating current method, which is typically available in new numerical AVRs, also handles, in an elegant way, the more generic case with unequal transformers in parallel operation.

Two main objectives of voltage control of parallel transformers with the circulating current method are:

I. Regulate the LV side busbar voltage to the preset target value
II. Minimize the circulating current, in order to achieve optimal sharing of the reactive load between parallel operating transformers

The first objective is the same as for the voltage control of a single transformer while the second objective tries to bring the circulating current, which appears due to unequal LV side no load voltages in each transformer, into an acceptable value. Figure 2 shows an example with two transformers connected in parallel. If transformer T1 has higher no load voltage (i.e. UT1) it will drive a circulating current which adds to the load current in T1 and subtracts from the load current in T2. It can be shown that the magnitude of the circulating current in this case can be approximately calculated with the following formula:

$$\left|I_{cc\_T1}\right| = \left|I_{cc\_T2}\right| = \left|\frac{U_{T1} - U_{T2}}{Z_{T1} + Z_{T2}}\right|$$

Because transformer impedances are dominantly inductive it is possible to use only the transformer reactance in the above formula. At the same time this means that transformer T1 circulating current lags the busbar voltage almost 90^0, whilst transformer T2 circulating current leads the busbar voltage by almost 90^0. This also means that the circulating current is mainly reactive in nature, and it only represents reactive power that circulates between two transformers connected in parallel. Therefore by minimizing the circulating current flow through the transformers, the total reactive power flow through the parallel-connected transformer group is optimised as well. At the same time, at this optimum state the apparent power flow is distributed among the transformers in the group in direct proportion to their rated power.

Therefore an AVR, regardless of whether it is used for single or parallel transformer control, always reacts and changes OLTC position in accordance with LV side load variations. However, the AVR will as well react on abnormal voltage variations on the high voltage (HV) side of the power transformer. Sometimes such AVR behaviour is not desirable because it just further increases the total load on the HV system (i.e. transmission system). Especially, such behaviour shall be prevented during critical operation states of the transmission system such as a slow power system voltage collapse [1], [2] & [3].

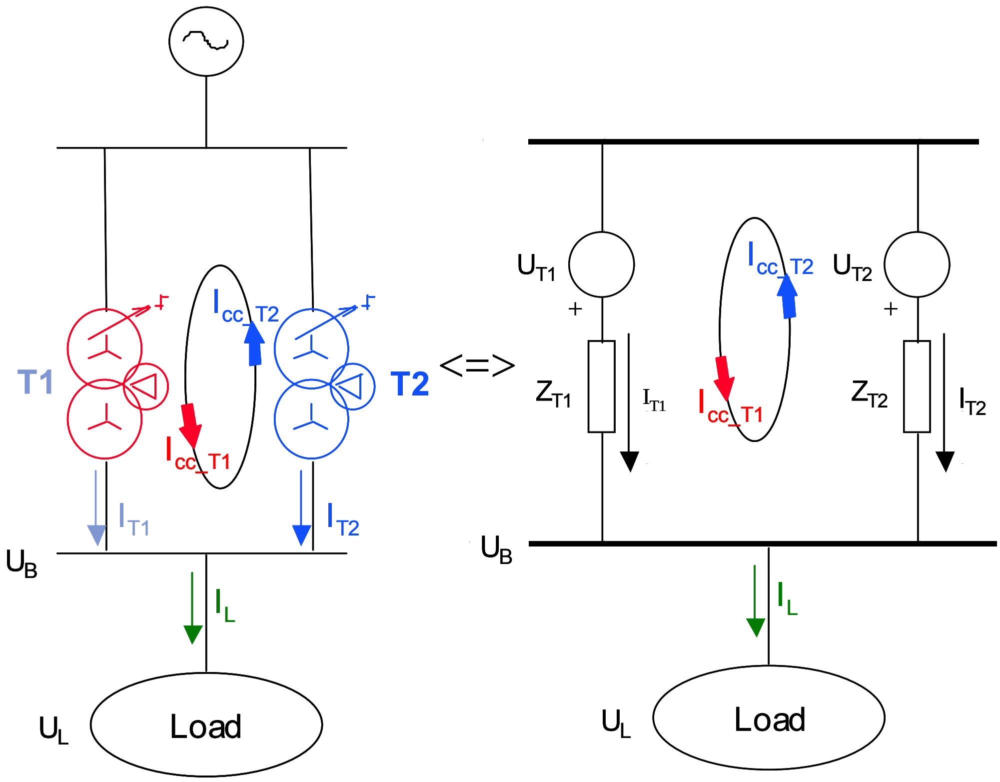


Figure 2: Equivalent scheme for two parallel transformers in accordance with minimizing circulating current method

KNOWN WEAKNESSES OF TRADITIONAL AVRs

The list of well-known weaknesses of traditional AVR is given here:

I. Radial active power flow from HV to LV side is pre-request for correct operation
II. Time coordination of cascading AVRs can be quite difficult task in order to minimize number of overall OLTC operation in a power system and still keep acceptable time delay for AVRs installed closest to the typical loads [4] & [5]
III. Quite inefficient way to control voltage for power transformers which interconnect two quite strong networks (i.e. between two transmission networks like 400/220kV autotransformers)
IV. Increase of voltage on LV power transformer side worsens the situation on the other side (reactive power flow increases from HV to LV side of power transformer)
V. LV side load recovery by AVR action during slow voltage collapse in power system [1]

However in this paper only the problems II. & V. will be addressed.

LESSONS LEARNED FROM SWIDISH BLACKOUT IN SEPTEMBER 2003

The major disturbances throughout the world in 2003 have clearly illustrated the need for different modes of voltage control, since the requirements during normal operation conditions and abnormal conditions, sliding towards instability, are very different. In the following, focus will be on possibilities to improve tap-changer control in order to perform properly also for disturbed conditions. Figure 3 shows HV side voltage and OLTC position for a power transformer connected between 400kV transmission system and 130kV subtransmission system, in the affected area, at the end of the Swedish blackout in 2003 [6]. The used AVR is designed only to keep the voltage at the low voltage side of the power transformer within certain limits, around the set point.

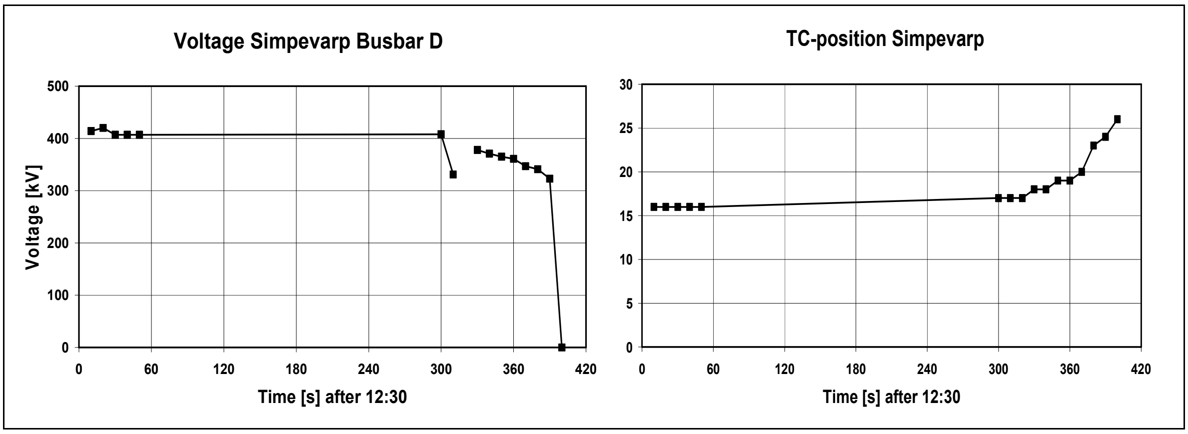


Figure 3: Transformer HV voltage and OLTC position recordings at the end of the Swedish blackout in September 2003

When the transmission side voltage decreases, the tap-changer position is increased by AVR in order to fulfill its task. As a consequence, the tap position increases nine steps within last 80 seconds of the blackout, keeping up the subtransmission voltage – and thereby the load – drawing more active and reactive power from the already weakened transmission system. Similar AVR behaviors have as well been reported during other blackouts, which happened in last 20-30 years all around the world.

ADVANCED AVR OPERATING PRINCIPLES

The main purpose of the automatic voltage regulator for power transformers with on-load tap-changer is to keep the voltage on low voltage side of power transformer within a preset deadband. Originally AVR was designed to compensate for the voltage drop across power transformer impedance caused by flow of the load current. Therefore an AVR shall react and change position of OLTC in accordance with LV side load variations. However, the AVR will as well react on abnormal voltage variations on the high voltage side of the power transformer. Often such reaction is not desirable because it just further increases total load on the HV system (i.e. transmission system). Especially, such behavior should be prevented during critical operation states of the transmission system, such as a slow power system voltage decrease, as shown in Figure 3. Typically modern commercially available AVRs just measure the LV side voltage of the power transformer in order to make decisions about OLTC position. Such a principle has a major drawback that typically speeds up a power system voltage collapse [1]. However, some modern intelligent electronic devices (IEDs) [7] used for such automatic control do have the capability to measure power system voltage on both sides of the power transformer, as shown in Figure 4. Additionally the total reactive power flow through the power transformer can be measured as well.

Voltage transformers are typically available on the HV side of the power transformer due to other reasons e.g. HV distance protection. By using a number of over- and undervoltage stages it is then possible to monitor HV side voltage magnitude and consequently influence the operation of the AVR or other equipment in the substation. For the best scheme security it is desirable to measure all three phase-to-earth voltages from the HV side, in order to take necessary action only when all three voltages are above or below the pre-set level. At the same time prolonged presence of negative or zero sequence voltage will indicate possible problems with HV VT. Therefore, operation of the AVR can be easily influenced, in the secure way, by the level of measured voltage on the HV side of the power transformer.

The following are some typical actions, which then can be taken:

I. Temporary AVR block (e.g. for 20 s).
II. HV shunt capacitor (reactor) switching.
III. AVR voltage set point change (typically reduction).
IV. Complete AVR block.
V. Undervoltage load shedding.

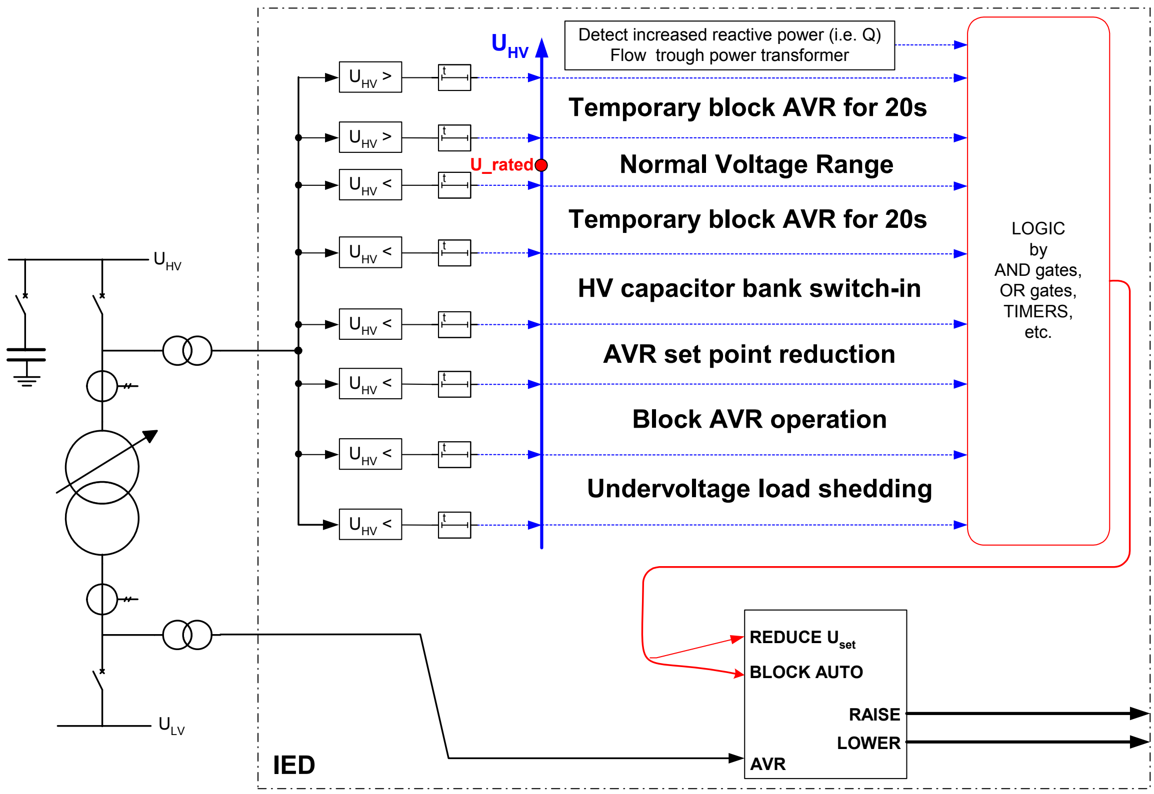


Figure 4: Proposal for an improved automatic on-load tap-changer control scheme.

Temporary block of local AVR for smaller voltage deviation on power transformer HV side can be actually used to drastically improve the cascading AVR time coordination in a power system. Small voltage variations on the HV power transformer side can be only corrected by the appropriate action of the upstream AVR. Therefore the local (i.e. downstream) AVR can be temporary block in order to give additional time to the upstream AVR in order to react and correct HV voltage magnitude. By doing so the operating time of all cascading AVRs can be set to the exact same value. Such scheme will as well guarantee faster voltage control at distribution loads than what is achieved today with traditional time coordination approach. At the same time the temporary blocking will guarantee operation of downstream AVR in case of failure of the upstream AVR. With such approach overall number of OLTC operations in complete power system can be minimized. At the same time this will represent cost benefit for the power utility regarding required OLTC maintenance.

When HV voltage drops to even lower value this might indicate the possible problems in the HV transmission system e.g. slow voltage collapse phenomenon. Therefore the proposed scheme can take certain precautions locally as for example:

I. HV shunt capacitor switching and shunt reactor disconnection, in order to try to increase voltage on the HV side of the power transformer.

II. AVR voltage set point reduction, in order to keep low voltage profile on subtransmission system and therefore cause reduction of total active and reactive power demand from HV transmission system.
III. Complete AVR block in order to prevent any OLTC automatic operation in order to prevent unwanted AVR operations during stressed condition on the HV side of power transformer.
IV. Finally undervoltage load shedding of pre-selected outgoing feeders on power transformer LV side can be performed in order to try to protect rest of the power system from complete blackout.

Which exact actions shall be taken depends on the particular power system characteristics, location of power transformer within the power system and type of load connected on power transformer LV side. Therefore a complete power system study must be performed in order to determine the optimum scheme setup. However, with help of graphical configuration tools, modern numerical IEDs can be tailor made to fulfill strict requirements of any power system operator and characteristics of the individual power system.

CONCLUSIONS

This paper focuses on new possibility for advanced automatic OLTC control strategy for power transformers. The main improvement from the traditionally used schemes is that the newly proposed scheme takes in consideration the voltage magnitude on the HV side of the power transformer. By doing that the overall coordination of series connected power transformers with OLTC can be much improved and in the same time performance of such AVR scheme will be much better during critical situations in HV power system e.g. slow voltage collapse phenomenon.

ACKNOWLEDGEMENT

The paper is based on work performed within the CRISP: distributed intelligence in CRitical Infrastructures for Sustainable Power, financially supported by the European Commission, contract nr. ENK5-CT-2002-00673: CRISP, which is gratefully acknowledged.

REFERENCES

[1] Taylor, C.W.: "Power System Voltage Stability", McGraw-Hill, 1993.

[2] Taylor, C.W.: "Concepts of Undervoltage Load Shedding for Voltage Stability", IEEE Transactions on Power Delivery, vol. 7, no. 2, pp. 480-488, April 1992.

[3] Ingelsson, Karlsson, Lindström, Runvik and Sjödin: “Special Protection Scheme against Voltage Collapse in the South Part of the Swedish Grid”, 1996 CIGRE Conference in Paris

[4] Mats Larsson: “Coordinated Voltage Control in Electrical Power Systems”, , Dissertation, Lund University, Sweden, December 2000.

[5] Daniel Karlsson: “Voltage Stability Simulations Using Detailed Models Based on Field Measurements”, PhD Dissertation, Chalmers University, Sweden, 1992

[6] "Elavbrottet 23 september, 2003 (Blackout 23 September, 2003)", Report Nr 1:2003, Senska Kraftnät, 2003-11-03, available on www.svk.se.

[7] "Application Manual for Power Transformer Protection and Control Terminal", ABB Document: 1MRK504037-UEN

Zoran Gajić; zoran.gajic@se.abb.com

SUMMARY OF AUTHORS' BIOGRAPHY

Zoran Gajić was born in Serbia, former Yugoslavia in 1965. He received his Diploma Engineer Degree with honours from University of Belgrade, Yugoslavia in 1990 and GDE in Computer Engineering from Witwatersrand University, Johannesburg-RSA in 1995. Since 1993 he has been working in the area of power system protection and control within ABB Group of companies, where he had various engineering positions. Currently he has a position of Protection Application Senior Specialist with ABB Power Technologies, Substation Automation in Sweden. He is a member of Cigré and IEEE. Currently he is the Convenor for Cigré, Study Committee B5, WG16. Zoran has published numerous technical papers in the relay protection area. His main working areas are computer applications for protection and control of electrical power systems, development of advanced protection algorithms for numerical relays and power system simulation. Zoran is co-holder of two patents.

Daniel Karlsson received his Ph. D in Electrical Engineering from Chalmers University in Sweden 1992. Between 1985 and April 1999 he worked as an analysis engineer at the Power System Analysis Group within the Operation Department of the Sydkraft utility. From 1994 until he left Sydkraft in 1999 he was appointed Power System Expert and promoted Chief Engineer. His work has been in the protection and power system analysis area and the research has been on voltage stability and collapse phenomena with emphasis on the influence of loads, on-load tap-changers and generator reactive power limitations. His work has comprised theoretical investigations at academic level, as well as extensive field measurements in power systems. Most recently Dr. Karlsson hold a position as Application Senior Specialist at ABB Automation Technology Products and now he is with Gothia Power. Through the years he has been active in several Cigré and IEEE working groups. Dr. Karlsson is a member of Cigré and a senior member of IEEE. He has also supervised a number of diploma-workers and Ph. D students at Swedish universities.

Mike Kockott was born in East London, South Africa. He graduated with a BSc in Electrical Engineering with honours from the University of Cape Town in 1980. After leaving university he entered into the SA Navy for his two-year period of National Service. After completion of his National Service, he joined Eskom where he worked from the beginning of 1983 until November 1999. His career began at System Operations where he calculated protection settings for transmission system equipment and performed post-fault investigations. He left System Operations as a Senior Engineer and joined the protection design department. At one time he held the position of Design Manager for all feeder related protection schemes. He later moved on to become a Senior Consultant. In 1996 he was appointed as the South African member to Cigré Study Committee 34. On leaving Eskom, he commenced employment with ABB in Sweden in January 2000. He currently holds the position of Protection Application Senior Specialist.

Paper 12: *Simulation study of DG effect on fault location methods in distribution networks*

Full bibliographic reference:

D. Penkov, B. Raison, C. Andrieu, L. Stoyanov, and J.-P. Rognon: *Simulation study of DG effect on fault location methods in distribution networks*, ELMA 2005 Conference, September 2005, Sofia, Bulgaria

Simulation Study of DG Effect on Fault Location Methods in Distribution Networks

D.Penkov, B. Raison, C. Andrieu, L. Stoyanov, J.-P. Rognon

Abstract: In this paper the results of simulation study for the estimation of Distributed Generation (DG) impact are presented. These are carried out in order to quantify the precision of a fault locating method in the worst case when these generators have a large penetration in the distribution network. Results are compared with those without DG and for different distributions in the network.

Keywords: Distributed Generation, Fault location

Introduction

Distribution networks are often subject to faults as a result of phase to ground, phase to phase or three phase short-circuits. These faults are dangerous, and provoke the circuit breaker's opening in order to be cleared. The clearing time depends on the fault nature, and on the fault persistence. A steady fault can not be cleared by the breaker's action and needs to be reviewed by the maintenance crew. In order to reduce the operation time, the fault should be located in advance by analytical means. These are based on voltage and current measurements on the substation, made in the meantime before the breaker's opening. Some methods for fault location could be found in [1]. These methods work well in the case of a one-source network. The Kyoto's protocol, (1997) [2], establishes new conditions in the networks for a 'green' energy. It means that all the countries which have signed it should have a green energy production also called Distributed Generation. That could be wind turbines, hydro turbines, photovoltaic panels for the solar energy and others [3]. These sources are good for the ecology, but their introduction in the networks requires changing lots of the guiding principles related to their exploitation and maintenance. Such a problem is the fault location in distribution networks. DG impact the locating precision through the fault currents they supply. As known these currents depend mainly on the short-circuit power of the generators, and the conductor's impedance. The short-circuit power is defined as the power that a generator is able to supply when a three phase fault is next to its output. Since this power is calculated for the nominal voltage of the machine, it is proportional directly to the current supplied during the fault. When it is to locate faults by measurements on the substation feeder only, the DG fault currents are going to modify those at the feeder. A higher short-circuit power of a DG source means a higher fault current supplied when a fault is and a possible greater impact on the fault signals. This effect has been studied for the fault location of three or two phase faults, taking place in a given distribution network when at least one 'green' generator is present. According to the position related to the fault location, one can distinguish two main situations:

- The feeder (main source) and the DG are both on the same side of the fault
- They are on the two sides of the fault location

This study can be extended to consider the short-circuit power ratio of the generators and the case of some generators dispersed over the network.

These three different criteria are studied in order to estimate the precision of a given fault-locating method. In the next four sections the method, the DG model, the network and program supply are presented respectively. Theory for DG impact is included in section 6. Results obtained for different situations described generally above are pointed out, and the appropriate conclusions made in section 7 and 8. Section 9 gives the main conclusions that could be tied out from this study.

Fault locating method

The method used for fault distance computation is based on the impedance measured on one faulted phase on the power transformer's secondary coil [4]. On the next figure a simplified scheme shows the fault situation:

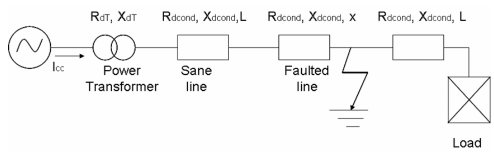


Fig.1. Simplified fault network scheme

The main equation for fault distance computation is:

$$(1)\quad (Rd_T + L.Rd_{cond} + x.Rd_{cond})^2 + (Xd_T + L.Xd_{cond} + x.Xd_{cond})^2 = k\left(\frac{U}{\sqrt{3}Icc}\right)^2$$

Where:

- *k –coefficient, depending on the type of fault, k=1, for a three phase fault, k=0.75 for a phase to phase fault.*

Such a one-end method is sufficiently precise since the considered currents are very high, compared to the load ones. A passive distribution ‘RL’ load can be considered as an open circuit for the three and double phase fault currents. The contact impedance between phases is considered to be zero. The method needs no additional changes to work properly for distribution networks with many taps. It is suitable for permanent faults, since the variables are complex values for the fundamental frequency.

The distribution network

The network is a 7MVA feeder, which has a total length of 55km, lines or cables. All the conductors have a length of 5 km, and the loads are 450MVA, power factor of 0.9 each. The network is developed for location purposes; the software that has been used is ARENE [5]. It has been developed and commercialized by the French utility EDF. The next figure shows the network topology and load distribution:

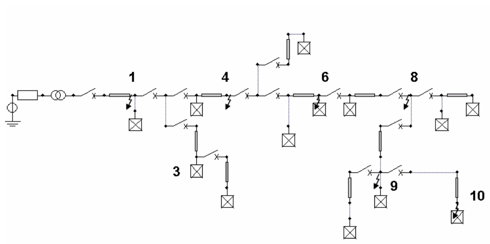


Fig.2. Studied distribution network

As it could be seen the load is equally distributed along the network. A brief description of the grid is given in the next table:

TABLE 1

Network parameters

Network part	Direct Resistance	Direct Reactance
Up Network	$R_{dHT} = 0.0266\Omega$	$X_{dHT} = 0.3989\Omega$
Transformer, 36MVA,63kV/20kV	$R_{dT} = 0.0463\Omega$	$X_{dT} = 1.664\Omega$
Lines	$R_{dL} = 0.2\Omega/km$	$X_{dL} = 0.299\Omega/km$
Cables	$R_{dC} = 0.203\Omega/km$	$X_{dC} = 0.1256\Omega/km$
Load	$R_{CH} = 2400\Omega$	$L_{CH} = 3.820H$

The short-circuit power of the main source is 180MVA. Faults are distributed on the points were an arrow is shown.

Distributed Generation model

A 0.4MVA Diesel Generator has been simulated. As this is not a real “green” energy generator it is necessary to explain why this generator has been chosen for the study. Normally there are two possible connections for a generator to the network grid: one is its “direct” connection – if the generated voltage and frequency match with those of the grid, and the second possible connection is by power electronics devices, when they do not match directly. The power electronic devices are “smart” devices – they have a control loop that is very fast and does not allow high currents. When a direct connection is used the high fault currents are allowed. That is the case when induction or synchronous generators are considered. The first ones are rapidly demagnetized by the voltage drop and not really able to provide a really high contribution to the permanent fault. Synchronous generators are more independent since they have their own excitation like permanent magnets or excitation circuit. That makes this type of generators the most “dangerous” in terms of fault current contribution and so the most suitable if one wants to study the DG effect on the fault location. Synchronous generators directly connected to the distribution grid are mostly hydro turbines. Their behaviour is similar to that of a diesel generator, but the last is more rapid in terms of reaction. So that kind of generator is chosen for the representation of the worst case of reaction to a fault. Here next is shown a simplified scheme of the used generator:

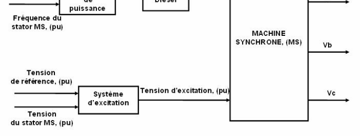


Fig.3. Diesel Generator

The excitation block is an IEEE standard Type 1 excitation, which description can be found in [6]. The Diesel engine model is developed and validated according to [6, 7, and 8]. The machine has 10% speed droop, and 400V out. The grid connection power transformer is Wye-Delta coupled.

Program supply

The program supply is important since the fault location is found by consecutive sum of the conductor's active and reactive impedance. The program supply has been developed in our laboratory for various distribution network studies [9]. It has three main blocks that react mutually. These are:

- Network description extraction – the topology of the grid and the parameters of the different conductors are read and stored in a dedicated data base
- Network course block – used for the fault locating algorithms test or for generation of useful data needed by other applications
- Visualization block – used for the network representation and fault location shift on a map.

The whole algorithm has been developed on MATLAB, [10], and a part of it translated in C-code for the purposes of the European project CRISP [11].

Here next the studied network is presented as rebuilt by the program:

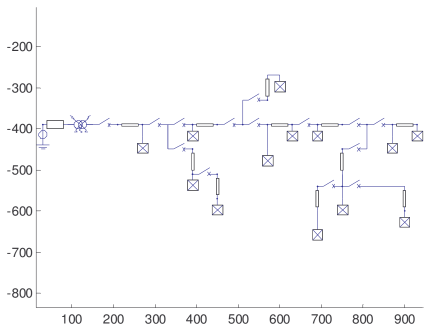


Fig.4. Studied network as seen in Matlab environment

During the network course the elements seen to be safe are coloured in cyan and those supposed to be faulted in red.

DG impact on fault location

In this section the simulation study is described. As mentioned before there are some study cases that represent the most usual situations. In order to achieve a better explanation the theoretical basis for this study are going to be presented bellow. On the next figure a three phase fault for a simplified network with DG is shown:

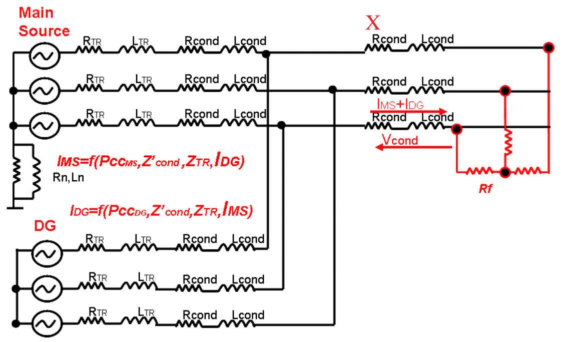


Fig.5. Theoretical situation for a three phase fault on network with DG

The length X of the common part for the main generator and the DG network is variable with the fault distance. For a three phase fault the KVL equations are:

(2) $$\begin{cases} V_{MS} = (Zd\_tr_{MS} + Zd_{MS}.L_{MS}).I_{MS} + (I_{DG} + I_{MS}).ZdcommX \\ V_{DG} = (Zd\_tr_{DG} + Zd_{DG}.L_{DG}).I_{DG} + (I_{DG} + I_{MS}).ZdcommX \\ Rf = 0 \end{cases}$$

Rearranging the equation with respect to X yields:

(3) $$X = \frac{1}{Zdcomm}.\frac{(Zd\_tr_{DG} + Zd_{DG}.L_{DG})((Zd\_tr_{MS} + Zd_{MS}.L_{MS})I_{MS} - V_{MS})}{V_{MS} - V_{DG} - (Zd\_tr_{MS} + Zd_{MS}.L_{MS} + Zd\_tr_{DG} + Zd_{DG}.L_{DG})I_{MS}}$$

meaning that a measurement of the fault current on the substation should be sufficient to find the fault location. However for the purposes of this study the formula is to be used as is (1), without taking into account the DG contribution.

For a double phase to phase fault, considering the phase to phase voltages, the fault distance is the following:

(4) $$X = \frac{1}{Zdcomm}.\frac{(Zd\_tr_{DG} + Zd_{DG}.L_{DG})(U_{MS} - 2(Zd\_tr_{MS} + Zd_{MS}.L_{MS})I_{MS})}{U_{DG} + 2(Zd\_tr_{MS} + Zd_{MS}.L_{MS} + Zd\_tr_{DG} + Zd_{DG}.L_{DG})I_{MS} - U_{MS}}$$

Since for phase-to-phase faults the fault currents are not totally identical, a mean absolute value has been taken for the fault distance calculation. Once again it should be noticed that the fault location is going to be found by applying the original formula in order to evaluate the DG's impact.

Fault simulations and locating results

As it was said the simulation study is to be carried on following three main criteria:

- The fault position in respect to the generators
- The short circuit power of the DG
- The DG distribution over the network

Practically the simulations were performed in the following manners:

1. Fixed generator - various fault positions, (DG on p.6)
2. Fixed generator – various fault positions and DG powers
3. Two generators fixed –p.6 and p.3 - (sum power equal to maximal simulated) - various fault positions

Let us recall that the inserted generator has an apparent power of 0.4MVA and the total load on the feeder is 7MVA.

Three phase faults

Table 2 presents the results obtained for the first case study:

TABLE 2

Fault location results with 1DG

Fault point	Real distance, km	Fault current for urban, A	Calculated Distance, km	Fault current for rural, A	Calculated Distance, km
1	5	3974,7	5,0121	3101,4	5,0062
4	10	2940,5	9,9874	2114,8	9,9692
6	15	2305,4	14,903	1605,8	14,842
8	20	1886,7	19,8	1303,4	19,512
9	25	1589,4	24,761	1088,1	24,404
10	30	1378	29,546	940,06	29,06

On the next figure the computational error is shown:

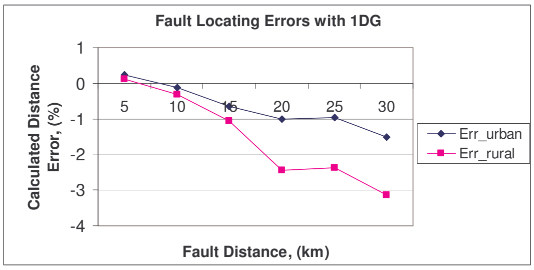


Fig.6. Fault Location Error

where the error is calculated as:

$$(5)\quad \varepsilon = \frac{D_{calculated} - D_{real}}{D_{real}}.100$$

As it could be seen the error in fault location is relatively small. The error is increased after the 15-th km, when the DG has a common path with the main source. The DG provides some fault current that decreases that of the main source. The computed fault distance is thus increased. For a better illustration the errors when there is no DG in the network being rural or urban, are shown on the next figure:

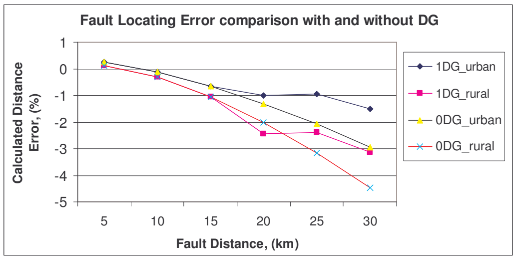


Fig.7. Fault location error comparison

The computed distance error is reduced due to the DG. Its influence is stronger with the shared network path. The “correction” is in the range of 2%. However this situation changes when the DG short-circuit power is bigger. On the next figure the results for different DG powers are shown. The DG power was increased by connecting other DG of the same size to the same connection point 6. For this type of connection is more realistic than a greater source, the “green” generators are not supposed to be small units [12]:

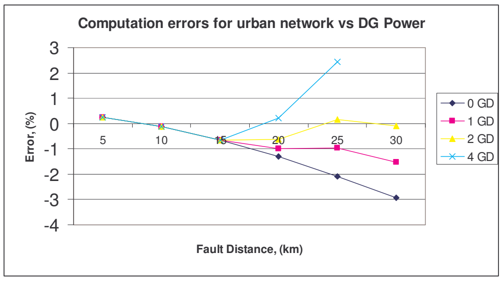


Fig.8. DG Power influence for urban network

Each added DG increases the calculated fault distance after the 15-th km. The locating error is smaller when 2DG are connected but when they double the error is increased to positive and for the 30km the obtained distance is greater than that of the network and no solution is found. Four DGs is the worst situation for the presented fault locating results, which remain however acceptable, with the error of 3-5% maximum. Such a DG connection is very rare, to say not realistic at the moment, the generated power is too much for the network. On the next figure the results for a rural type of network are shown:

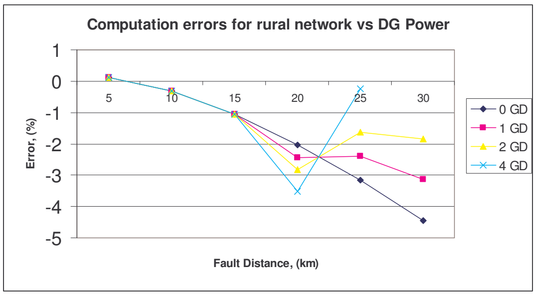


Fig.9. Error for a rural type of network

The results here are more pessimistic. The maximum error without DG is 4.3% while it is about 3% for the urban grid. The difference is result of the smaller cable reactance which increases the fault current and so the load effect of the bifurcations upstream to the fault position is thus reduced in urban network. The DG decrease the error, however on the 20km fault point that is next to the DG the influence is negative.

The case of two generators connected on two different points shows the influence of their distribution over the network for the same fault. The next figure illustrates this phenomenon:

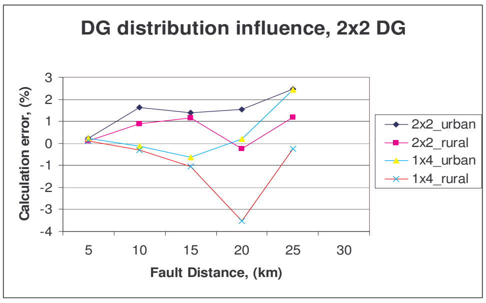


Fig.10. DG dispersion influence

Obviously the error is depending on the network type urban or rural. As it could be seen the DG dispersion on the network increases the error, due to the fact that they stand on the two ends of the network and deliver fault current for nearly all fault positions. But downstream the second DG group the error is greater than it is for one DG group of equal power connected on the same place. That is due to the longer path shared by the first DG group and the main source which induces a smaller fault current from the last. So the worst place for fault location remains the 30km where the two DG groups deliver both fault currents.

Double phase-to-phase faults

The same studies were performed for double faults. On the next figure results for the first case study are shown:

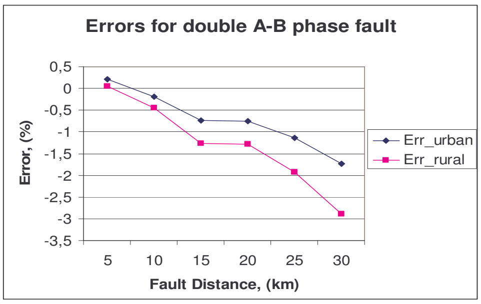


Fig.11. Errors in fault distance computation for double fault

The computed distance decreases with the fault distance. The range is the same as previously for the three phase faults. The point of 15 km is special for there is a DG connected. As previously, the DG fault current maintains the error in proximity of the fault but its influence is limited 10 km downstream. The DG power increase has an influence on fault location in urban network as follows:

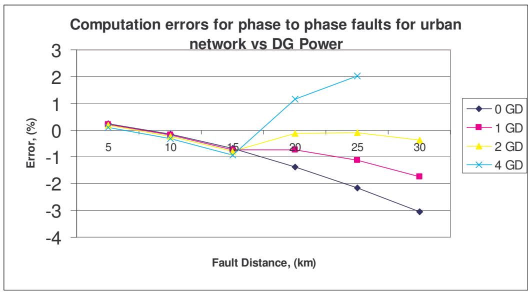


Fig.12. Results for urban network

The effect is greater for a double phase fault. It modifies the results even before the connection point, where DG and main source have no shared path. That is because they remain “connected” by the third safe phase. Its current induces some voltage on the two faulted phases. The DG insertion increases this voltage. Next are the results for a rural network:

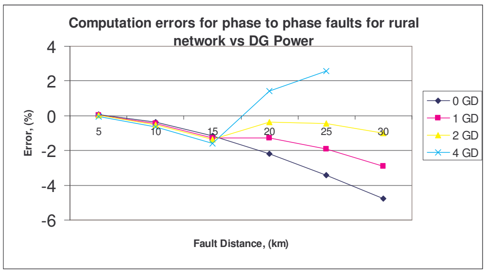


Fig.13. Results for rural network

As previously mentioned the error is greater but the tendencies remain the same.

The influence of the DG distribution on the fault location is visualized on the next figure:

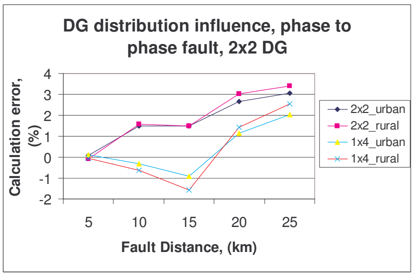


Fig.14. DG dispersion influence

The fault location results are similar to those obtained for three phase faults. The DG distribution increases the error. This effect is reduced when the fault is too far from the DG but their influence remains important.

Conclusion

In this paper results for fault location of phase to phase or three phase faults in distribution network containing Distributed Generators are presented. A method based on one end data has been applied. The DG influence is depicted and commented. It is relatively small but not negligible. The DG distribution over the network increases the fault location error, since this implements a greater network path to be shared with the main source. Reducing their effect seems to be possible by connecting them on one point, which is preferably to be at the feeder, or they should have a dedicated feeder. The network type, urban or rural, impact is also studied and shows better results for smaller cable impedances which induce a greater fault current and so reduce the load effect.

References

[1] M. Saha, R. Das, P. Verho, D. Novosel, Review of Fault Location Techniques for Distribution Systems. Power Sytems and Communications Infrastructures for the future, Beijing, September 2002

[2] Entrée en vigueur du protocole de Kyoto – Que laissera la date de 16 février 2005 dans nos mémoires ? , ACTU Environnement, 17.02.2005

[3] B. Multon, Production d’énergie électrique par sources renouvelables, Techniques de l’ingénieur, Traité Genie Electrique, D4005, 2001

[4] B. de Metz-Noblat, F. Dumas, G. Thomasset, Calcul des Courants de court-circuit. Cahier Technique No.158, Schneider Electric, www.schneider-electric.com

[5] www.rdsoft.**edf**.fr/ARENE.html

[6] G.S. Stavrakakis, G.N. Kariniotakis, A General Simulation Algorithm for the Accurate Assessment of Isolated Diesel-Wind Turbines Systems Interaction Part I: A General Multimachine Power System Model and Part II: Implementation of the Algorithm and Case-studies with Induction Generators, IEEE Transactions on Energy Conversion, Vol.10, No.3, September 1995

[7] G. Claeys, Modélisation de la production indépendante dans les réseaux de distribution, Phd Thesis, LEG, 2001

[8] D. Penkov, Simulation d’un centre de production adapté aux réseaux isolés pour les pays en voie de développement électrique, DEA, LEG, 2003

[9] D. Penkov, Le parcours et la visualisation de réseaux électriques pour la localisation de défauts, JCGE Montpellier, 2005

[10] www.mathworks.com

[11] C. Andrieu, B. Raison, D. Penkov, M. Fontela, S. Bacha, N. HadjSaid, Fault Detection, Analysis and Diagnostics in High-DG Distribution Systems. EESD Project ENK8-CT-2002-00673 CRISP, 2002

[12] J.-F. Canard, Impact de la génération dispersée dans les réseaux de distribution, Phd Thesis, LEG, 2000

D. Penkov *– PhD student in the Laboratoire d’Electrotechnique de Grenoble (LEG), INPG, France*

e-mail: penkov@leg.ensieg.inpg.fr

B.Raison *– Associate professor in the Ecole Nationale Supérieure d’Ingénieurs Electriciens de Grenoble,*

e-mail: Bertrand.Raison@leg.ensieg.inpg.fr

C.Andrieu *– Research Engineer in Schneider Electric*

e-mail: christophe.andrieu@leg.ensieg.inpg.fr

L.Stoyanov *– student master degree in LEG,*

e-mail: stoyanov@leg.ensieg.inpg.fr

J.-P. Rognon *–professor in in the Ecole Nationale Supérieure d’Ingénieurs Electriciens de Grenoble*

e-mail :rognon@leg.ensieg.inpg.fr

Paper 13: *Microeconomic distributed control: Theory and application of multi-agent electronic markets*

Full bibliographic reference:

J.M. Akkermans, J. Schreinemakers, and J.K. Kok: *Microeconomic distributed control: Theory and application of multi-agent electronic markets*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Microeconomic Distributed Control: Theory and Application of Multi-Agent Electronic Markets

Hans Akkermans
Free University Amsterdam VUA
Business Informatics, and AKMC
Amsterdam, The Netherlands
Hans.Akkermans@akmc.nl

Jos Schreinemakers
Free University Amsterdam
Business Informatics FEW/BI
Amsterdam, The Netherlands
jos@cs.vu.nl

Koen Kok
ECN
TSC, PO Box 1
Petten, The Netherlands
j.kok@ecn.nl

Abstract

We discuss the theoretical foundations of distributed large-scale control. Our approach is to integrate multi-agent microeconomic market theory with control theory, such that online adaptive control is economically optimal at the overall systems level. A central result is the derivation of a general market theorem that proves two important properties about this agent-based microeconomic control: (1) computational economies with dynamic pricing mechanisms are able to handle scarce resources for control adaptively in ways that are optimal locally as well as globally ('societally'); (2) in the absence of resource constraints the total system acts as collection of local independent controllers that behave in accordance with conventional control engineering theory. We further derive some analytical results for the market-based control outcome, the clearing price, and hierarchical versus decentralized emergent control. Our agent-based microeconomic control theory is applicable to several different types of control, and it provides the theoretical underpinnings for a wide range of industrial distributed large-scale control applications, for example in power networks and energy management.

CRIS-2004 (version May 2004)
Keywords: Networked Computer Systems, Distributed Control, Agents, Computational Techniques

1. Introduction

The aim and contribution of this paper is the development of a systems-level theory of large-scale intelligent and distributed control. Large-scale industrial control in network settings, enhanced by forms of distributed intelligence, provides an example of real-world applications involving large numbers of interacting software agents. Then, we are not just interested in a theory of individual agent design, but foremost in a social theory that explains and predicts the emergent outcomes of the agent society *as a whole*. For service as well as security reasons, it is required that certain guarantees on properties and behaviours can be demonstrated at the overall *systems* level. A formal and fundamental theory at the systems level is thus a necessity. Nonetheless, such a fundamental 'bottom-up' theory of distributed intelligence underlying large-scale control applications is in its infancy.

The theory developed in this paper allows for a wide range of practical applications. It subsumes the agent research applications and simulations that have been carried out especially under the heading of market-based control (see e.g. [1] and the individual papers herein; and [2, 3, 4]). A practical example of this type of application is climate control of buildings with many office rooms. As depicted in Figure 1, offices (represented by agents) are attached to a pipe through which cold air is transported and distributed to the individual office rooms. Incidentally, this control problem originated from a XEROX PARC office building in California, where the aim was to improve energy management by a market approach during the Summer period [2].

In addition, the present work allows for more demanding and sophisticated applications. Several specializations of the theory presented in this paper have been practically implemented and tested in simulation studies as well as real-world field experiments by means of our HomeBot agent concept (see e.g. [5, 6, 7, 8, 9]). Current investigations concern a variety of industrial applications of distributed intelligence in the area of ICT-based network control for distributed power generation and energy resources (DG/DER), including (i) peak shaving by decentral load management in power networks; (ii) smart agent-based comfort and energy management in large buildings and sites; (iii) real-time demand-supply matching, in a liberalized business setting, through power exchange e-markets at diverse time scales and geographical and grid levels; (iv) intelligent load shedding schemes in emergency conditions; (v) so-called 'vir-

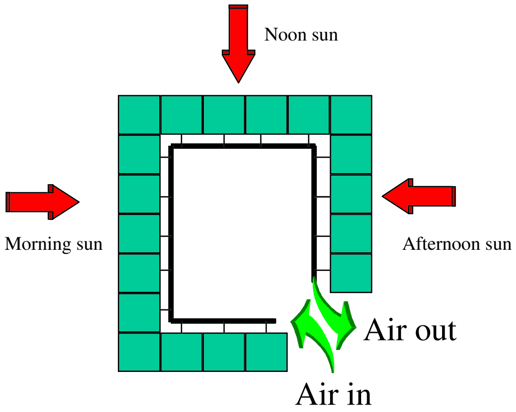


Figure 1. Multi-agent control problem for smart self-managing buildings.

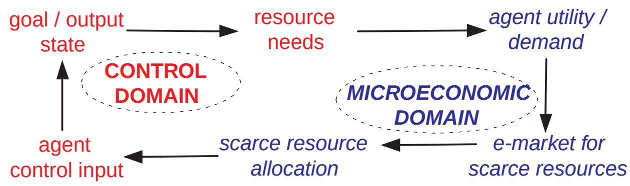


Figure 2. Handling of scarce resources in a society of control agents.

tual power plant' concepts; (vi) demand-response online strategies and services.

Our theory is based upon a unification of formalisms from microeconomic theory and control theory. First, we outline a conceptual framework how one can unify these rather different types of theory in a natural and general way (Sec. 2). A central result is our derivation (Sec. 3) of a general equilibrium market theorem for multi-agent based control. It provides a microeconomic extension of conventional control theory that shows how computational economies with dynamic pricing mechanisms can achieve system control goals — in an emergent fashion, by forms of adaptive distributed intelligence — that are both individually and globally optimal. We then consider some special cases that allow to derive analytical results (Sec. 4), for the market outcome, the equilibrium price, and their impact on individual agent control strategies. The theory presented in this paper answers several outstanding questions in the literature regarding decentralized vs. hierarchical forms of control. It also has various generalizations to distributed solutions for advanced forms of optimal and adaptive control that are beyond the scope of this paper. This is discussed in Sec. 5.

2. Unification of Microeconomic Markets and Control Theory

Consider an interactive society of a large number of agents, each of which has an individual control task. What kind of control strategies will interactively emerge from this agent society, and how good are these with respect to both local and global control performance criteria? There are two, very different but both well-formalized, theories that can be brought to bear to model this problem setting: control theory and microeconomic theory. The conceptual picture, then, is that agents are negotiating and trading with each other on a marketplace in order to acquire the resources that they need to achieve their individual control action goals, as indicated in Figure 2.

Microeconomic theory is able to tell us, presupposing given agent utilities or demands, at what price needed resources can be acquired, and what their allocation over the agents will be. However, it lacks the notion of a goal: the purpose or reason for which the resources are put to use by the agents (and this will ultimately determine what and how many resources are needed and demanded) falls outside the scope of market economic theory. This is, scientifically speaking, a weak (and therefore rather ideological) point of free market approaches: utility and its maximization is posited as a first principle, but agent utility — hence the amount of resources required — is simply *assumed* to exist as an exogenous quantity. It is therefore not operationalized or derivable *within* the context of microeconomics.

This is a crucial point, however: in dealing with our physical environment it is usually not at all clear how many resources we need to fulfil our control goals. The smart building management example illustrates this very clearly: no inhabitant of a building will ever be able to tell us how much cooling power is actually needed in order to maintain a comfortable climate given a certain weather situation. Defining agent utility and demand for such an application does turn out to be highly non-trivial technically [6]. This point, in that it is often unclear in the eyes of the individual agents what their resource demands should be in relation to their actual goals, is a general and moreover very practical problem characteristic, but it remains unsolved in microeconomic theory.

Control theory, however, gives an operational handle on this important issue. It tells us what the amount of resources (the input variable) must be if we want to reduce the deviation (the output or error state variable) from a desired goal state of the system (the setpoint). Controller design means quantitatively specifying this input-output, i.e. resource-goal, relationship. As there are many different types of controllers, this can be done in several ways [10, 11]. The simplest way to do this is so-called PID control, the type of

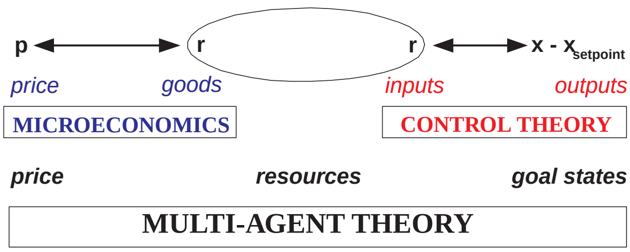


Figure 3. Microeconomics and control engineering unified in multi-agent theory.

control considered by almost all previous multi-agent studies (in assuming that individual agents represent PID controllers). An exception is our field experiments with comfort management in smart buildings [6, 7, 9], which employed a, model-based and predictive, form of optimal control. As we will show in this paper, microeconomic control of large-scale networked systems is a specific form of online adaptive control.

What is common to all types of control is that they embody some mechanism to compute the needed goal-resource relation. On the other hand, control theory lacks the notion of an economy of resources that is able to adequately allocate scarce resources in a societal context. This is a gap that can be filled by microeconomic theory, since it gives us a way to compute the resource-price relation. If we combine microeconomic and control theory, we are able to treat the complete goal-resource-price triad for control in a distributed fashion, enabling a full cost-benefit calculation for resources desired in the light of individual agent goals. Our agent theory thus forms the unification of these two theories, as depicted in Figure 3.

3. Microeconomics of Markets for Control

3.1. PID control agents and the systems level

Here, we will specifically develop the microeconomic control theory in formal detail for one significant class of local controllers, namely, PID control. The assumption is that each individual agent represents a local PID controller. The building control problem (Figure 1) is a case in point: commercial building management systems include a large number of local PID controllers. The issue we want to solve is to derive what the system as a whole will look like if all local controllers are communication networked, and especially how it will react globally as well as locally if control resources are scarce at the systems level.

The general equation expressing the PID control strategy is

$$r(t) = K^P x(t) + K^I \int_0^t dt' x(t') + K^D \tfrac{d}{dt} x(t). \tag{1}$$

Here, $r(t)$ is the input resource variable, $x(t)$ is the output state error variable, and the K are the gain constants. In market terms, $r \in \Re$ implies that we are dealing with an infinitely divisible resource. Earlier agent studies of market-based control typically used a special case of Eq. (1), viz. integral controllers ($K^P = K^D = 0$).

Now, let us consider a large collection $\alpha = 1, \ldots, N$ of independent local PID controllers (in the building example, one local controller for each room in the office building; so N may run in the hundreds or even thousands). Each local controller follows the PID control rule of Eq. (1), which can be more concisely written in operator notation as

$$r_\alpha = \mathcal{O}_\alpha x_\alpha, \tag{2}$$

where $\mathcal{O}_\alpha$ is a linear operator operating on the local error state variable x_α. As a matter of convenience, we do not indicate the dependence on t explicitly.

Interpreted in agent terms, the PID control rule Eq. (1) and its alternative form Eq. (2) state the resource amount r_α that a controller agent α needs if it wants to achieve its goal state (setpoint) by eliminating the state error x_α. The PID control rule thus defines the agent's local demand function without taking possible resource constraints into account. If, on the other hand, the total resource is constrained, it is traded on an automated marketplace that thus serves as a resource allocation mechanism. Economic issues such as this scarce-resource situation are not addressed in conventional control, and this is the added value of our market-based approach. This is formalized below.

3.2. Market theorem for agent-based microeconomic control

We assume an agent society in which each individual agent α represents a local independent controller, which has to negotiate with other agents in a marketplace in order to obtain its desired resource r_α. In particular, there may occur a situation of scarce resources, in the sense that the total available resource at a certain time t is smaller than the sum total of the requested resources $\sum_{\alpha=1}^{N} r_\alpha$ as given by Eqs. (1) or (2). In this new constrained situation, how are the available resources going to be distributed, what is the optimal situation for each agent locally, how does its new local control strategy look like, and what is the global control strategy that emerges in this agent society?

Definition 3.1 *Let each independent local PID controller be represented by an agent α, whereby its utility function is defined by*

$$u_\alpha = f_\alpha(r_\alpha), \tag{3}$$

where f_α is a strictly concave function of r_α that is twice continuously differentiable (on a suitable interval $|r_\alpha| \leq |R^{unc}|$), and that has its maximum at the local resource value $r_\alpha = \mathcal{O}_\alpha x_\alpha$ as given by the PID control equations Eq. (1) or, equivalently, Eq. (2). In f_α one may also include a money term (a constant in r_α, representing the 'numeraire' good or rest of the economy outside r_α) which makes the utility function quasilinear.

Furthermore, suppose that the total available resource is scarce, so that we have [1]

$$0 \leq \sum_{\alpha=1}^{N} r_\alpha = R^{max} \leq \sum_{\alpha=1}^{N} \mathcal{O}_\alpha x_\alpha \overset{def}{=} R^{unc}. \quad (4)$$

Finally, let all agents be self-interested utility maximizers and let them be competitive (i.e. price takers). [2]

The latter equation says that R^{unc} is the total 'free' demand of all agents taken independently, as implied by the sum total of the PID control equations in a situation with an unconstrained supply of resources. But, there may be a smaller cap R^{max} on the total available resource if it has to be shared by the agent society (as is the case with the cooling power in the smart building example). The total demand R^{unc} by the individual agents in the unconstrained case derives from local information (according to Eq. (2)), whereas the resource limitation to R^{max} is the result of a supposed external action or situation. One has the design freedom to choose *any* agent utility function f_α within the confines of Definition 3.1.

Theorem 3.1 *Assuming the agent utility functions and behaviours given by Definition 3.1, the following statements hold:*

A. *There exists a resource allocation r^*_α that is a global maximum to the optimization problem: $\text{Max} \sum_{\alpha=1}^{N} f_\alpha(r_\alpha)$ subject to the resource constraint $\sum_{\alpha=1}^{N} r_\alpha = R^{max}$, and this global maximum is unique.*

B. *The* same *resource allocation r^*_α is* identical *to the competitive equilibrium of a market in which each individual agent maximizes its utility $f_\alpha(r_\alpha)$ within its budget, whereby the market is clearing (i.e. $\sum_{\alpha=1}^{N} r^*_\alpha = R^{max}$) and p^* is the market clearing price.*

C. *The resource allocation r^*_α obtained as outcome of this competitive equilibrium market is Pareto optimal (i.e. there exists no other allocation that is better or neutral for* all *agents).*

Proof. Statement A follows directly from Definition 3.1 and standard optimization theory (see for example Ibaraki and Katoh [12], Ch. 2; Fletcher [13], pp. 216-218; Mas-Colell et al. [14], pp. 50-51, 314-327, 945, 962). A standard method to find the constrained maximizer in an optimization problem is to set up the Lagrangian $\mathcal{L}$ for problem A, as follows

$$\mathcal{L} = \sum_{\alpha=1}^{N} f_\alpha(r_\alpha) + p\left(R^{max} - \sum_{\alpha=1}^{N} r_\alpha\right), \quad (5)$$

and solve the equations $\frac{\partial \mathcal{L}}{\partial r_\alpha} = 0$ and $\frac{\partial \mathcal{L}}{\partial p} = 0$. The latter immediately yields the constraint equation $\sum_\alpha r_\alpha = R^{max}$. The former gives $\frac{\partial f_\alpha}{\partial r_\alpha} = p$ for all α: the marginal agent utilities all have the same value p at equilibrium. The resource allocation r^*_α that satisfies these equations solves the *(global)* optimization problem of statement A. Now, following the definition of (partial) competitive equilibrium (e.g. [14], p. 314-318) and including the agent budget constraints, we find that the *local* utility maximization problem for each individual agent on the market of statement B is:

$$\text{Max } [f_\alpha(r_\alpha) - p^* \cdot r_\alpha + \text{const}_\alpha]. \quad (6)$$

As a result, the *same* first-order equations hold for the market problem B and the optimization problem A, whereby at the market clearing point the resource constraint holds. Hence, the Lagrangian parameter p equals the market clearing or equilibrium price p^*, and the optimal resource allocation r^*_α of problem A is also the solution to the competitive equilibrium market problem of statement B. This proves statement B. Statement C now immediately follows from the first fundamental theorem of welfare economics ([14], pp. 325-327). □

Our market theorem for agent-based control is a key contribution of this paper. It has weaker assumptions and is much stronger than the corresponding result in [4]. It also holds in the *multicommodity* case (hence, for the case of state-feedback control). In fact, it expresses a rather general statement about the relationship between global optimization and competitive market problems. The optimization problem of statement A reflects how a central controller, that oversees all local control agents, will look at the situation in a hierarchical, top-down manner. In contrast, the market problem of statement B represents the situation through the eyes of the individual agents in a bottom-up and emergent fashion. Our market theorem then shows that there is an *outcome equivalence* between the two approaches. Moreover, statement C says that the resulting resource allocation r^*_α is optimal both locally and globally, in

1 Depending on the physics of the problem, R^{unc} might be either positive or negative. Here we have assumed a positive R^{unc} for simplicity. If it happens to be negative, the statements and derivations that follow still hold (just introduce auxiliary resource variables that are the negatives of the above ones).

2 Competitiveness in microeconomic theory means that agents take prices as externally given (exogenous; reflecting their limited market power, for example due to a very large number of agents on the marketplace), so that they are not able to directly influence or set the market clearing price (as is the case in a monopoly or oligopoly situation).

other words, it is optimal for each agent individually as well at the agent society level.

3.3. Market protocols for agent-based microeconomic control

For a practical implementation of electronic markets for multi-agent control tasks, any suitable resource-oriented market protocol will do, such as a (quasi)Newton-type algorithm discussed in detail by Ygge and Akkermans [15]. This algorithm has actually been used in our field experiments of agent-based comfort management in large buildings [7, 9]. One then searches for the equilibrium resource allocation r^*_α, updated in each market round by the auctioneer agent; each control agent submits its marginal utility $\frac{\partial f_\alpha}{\partial r_\alpha}$ which may be interpreted as its *bid price*. This protocol also lends itself to anytime, bounded-rationality, approaches that are relevant under time-critical conditions, and also to strict peer-to-peer (less computationally fast, but more network robust) versions.

Yet another possibility is to employ an extended, multicommodity version of the combinatorial tree-based COTREE and CONFAST algorithms, cf. [16]; they are discrete, communication sparse, and can handle non-concave utility functions.

Alternatively, standard price-oriented market protocols are also possible, for example Wellman's WALRAS algorithm [17, 18]. Then, we search for the equilibrium value of p, whereby p is interpreted as the *going market price* which is updated in each bidding round by the auctioneer agent, and the control agents submit their demand r_α. The price-oriented protocol requires an explicit equation for the agents' demand function. It can therefore not be directly used if we start from the givens in Definition 3.1 (since the demand is only implicitly given in the chosen expression for f_α). Note, however, that in Definition 3.1, we could alternatively have started directly from the agent demand function instead of from its utility function: $r_\alpha(p) = g_\alpha(p)$, whereby g is continuously differentiable and equal to $\mathcal{O}_\alpha x_\alpha$ for $p = 0$. Then a price-oriented market algorithm is most suitable. The simplest demand function that satisfies the requirements of our market theorem is a linear function, and this is justified on the basis of Eq. (2). In conclusion, a broad range of good possibilities exists from which we can select a suitable market protocol for control.

4. Some Analytical Results for a Society of PID Control Agents

The general statements of the previous section can be extended to analytical results if we consider some special cases that throw further light on the characteristics of microeconomic control by PID agents. Namely, the simplest utility function that satisfies the requirements of Theorem 3.1 is a quadratic one (we note that simple utility functions like these *do* make practical sense in real-life applications such as smart buildings [4, 6]):

$$u^Q_\alpha = -\frac{1}{2c_\alpha}(r_\alpha - \mathcal{O}_\alpha x_\alpha)^2, \qquad (7)$$

where $w_\alpha \stackrel{\text{def}}{=} 1/c_\alpha$ is a weight factor > 0 that may be different for each agent. The weight factor may be used to express individual preference differences (a higher w makes the utility function sharper and a lower one makes it broader, so that the agent less/more easily makes concessions in its utility maximization) and/or to express some social hierarchy (the CEO's boardroom is probably seen as more important to serve than the junior underassistant's office); c can be seen as a measure for the agent's willingness to make concessions. The differences in strictly physical characteristics (such as size) are already catered for through the $\mathcal{O}_\alpha x_\alpha$ term in the utility equation.

This form of the utility function allows us to analytically solve the Lagrangian equations for the constrained market optimization:

$$\frac{\partial \mathcal{L}_Q}{\partial r_\alpha} = 0 \;\Rightarrow\; r_\alpha = \mathcal{O}_\alpha x_\alpha - c_\alpha \cdot p_Q \qquad (8)$$

Through this equation we have actually derived an explicit expression for the agent's demand function when available resources are scarce (compare with Eq. (2) for the unconstrained case). Using the resource constraint equation and Eq. (4) then gives the market outcome at equilibrium:

$$p^*_Q = \frac{(R^{unc} - R^{max})}{\sum_{\alpha=1}^N c_\alpha}, \qquad (9)$$

and

$$r^*_\alpha = \mathcal{O}_\alpha x_\alpha - \frac{c_\alpha}{\sum_{\alpha=1}^N c_\alpha}(R^{unc} - R^{max}). \qquad (10)$$

The latter equation is actually a generalized version of the central control solution constructed by [4].

There are some special cases of Eq. (10) that are of interest to show explicitly. The first case is that all agents are equal in the sense of having equal weights:

$$\forall\alpha : c_\alpha = 1 \;\Rightarrow\; r^*_\alpha = \mathcal{O}_\alpha x_\alpha - \frac{1}{N}(R^{unc} - R^{max}), \quad (11)$$

and

$$p^*_Q = \frac{1}{N}(R^{unc} - R^{max}). \qquad (12)$$

This equation says that if all agents are equal, they all have to take the same *absolute* cut in resources.

A second interesting case is when the agents' preferences are proportional to their unconstrained demand $\mathcal{O}_\alpha x_\alpha$. Then we get

$$\forall \alpha : c_\alpha = \mathcal{O}_\alpha x_\alpha \;\Rightarrow\; r^*_\alpha = \mathcal{O}_\alpha x_\alpha \left(\frac{R^{max}}{R^{unc}} \right). \qquad (13)$$

Note that in this case we have

$$\forall \alpha : c_\alpha = \mathcal{O}_\alpha x_\alpha \;\Rightarrow\; p^*_Q = \left(\frac{R^{unc} - R^{max}}{R^{unc}} \right). \qquad (14)$$

This is another elegant result: if all individual preferences are proportional to free demand, each agent gets the same *relative* cut in resources. In control terms, all PID gain constants are multiplied with the same factor < 1, equal to the overall relative resource reduction.

The above analytical results are useful in their own right, because we have the agent design freedom to choose the utility function. Hence, it is convenient to take the simplest one (viz. the quadratic form) that does the job. In addition, they are helpful in the microeconomic interpretation of large-scale distributed control.

Namely, by looking at the proof of Theorem 3.1 and the subsequent discussion on market protocols in Sec. 3, it follows that the Lagrangian multiplier p is naturally interpreted as the going market price. and its value at the optimal resource allocation r^*_α equals the market equilibrium price p^*.

If we apply this interpretation to the above analytical results, we see that the market clearing price for constrained PID control is proportional to $(R^{unc} - R^{max})$, in other words, to the 'cut' applied to or shortage in the total available resource. In the unconstrained case, the equilibrium price is zero (which is natural because the resources then are 'for free', in other words, there is no premium price on top of a given external price). Thus, the unconstrained situation of conventional control (independent, non-communicating local controllers) is the limiting case of the constrained control problem, where there is no resource cut. We also see that the reduction of the resource for each agent relative to its initial 'free' demand (according to the standard PID control rule) is proportional to the resource shortage.

5. Implications and Generalizations

5.1. Top-down hierarchical control or bottom-up decentralized markets?

Let us reconsider Equation (10). It has the form of a PID control rule extended with a term reflecting resource constraints. By summing over α it is easily seen that it incorporates the resource constraint (both sides always sum to R^{max}). Moreover, it also covers the unconstrained case (because then $R^{max} = R^{unc}$, so that the term with the weight factors w equals zero, and we are left with Eq. (2)).

Hence, Equation (10) actually gives the recipe for the design of a *central* controller that behaves under resource constraints in a way *equivalent* to the *decentralized market* approach to PID control [3, 4] . These equations show that a hierarchical central controller needs global access to the following information: (1) all local PID control rule information (i.e. all $\mathcal{O}_\alpha x_\alpha$, in order to be able to construct R^{unc}); (2) all local weights w_α; (3) the value of R^{max}. This formalizes what Huberman and Clearwater's 'omniscience' means. The central controller then can correctly instruct each local controller with the proper (changed) PID rule when the total resource is constrained, and can simply leave them alone in the unconstrained case. This extends the previous partial results by [4] to general PID control.

We note that the direct explicit construction of the central controller fully depends on whether an analytical solution of the constrained optimization equations can be found. This is only possible due to the special choice of a quadratic utility. It is *not* straightforward or even possible in the general case, whereas the decentralized market approach will *always* work properly (according to Sec. 3). Thus, the distributed microeconomic approach to control is more flexible and more generally valid than hierarchical control.

This completes our general theory of microeconomic control as applied to large-scale PID control. It also settles some conjectures and outstanding questions in the literature regarding the capabilities and added value of market-based control versus central conventional control. In brief, we have demonstrated:

- For resource-constrained large-scale PID control, we have shown how to construct a Pareto-optimal agent-based market solution (Sec. 3, market theorem statement B and C).
- There also exists a central hierarchical controller of which the outcome is identical to the multi-agent based solution (Sec. 3, market theorem statement A).
- The computational economy can always be constructed in the general PID case, and suitable market protocols have been given (Sec. 3). In contrast, a direct explicit construction of the central controller is only possible in a few special cases (Sec. 4). In the general case, a computational market approach is needed (or at least a functionally equivalent optimization algorithm).

5.2. Distributed intelligence: Microeconomic control as an online adaptive strategy

It is noteworthy to point out that the market-based control solution effectively controls the local PID controllers, but generally it is not *itself* a PID controller. (This is only true in the special case of quadratic utility functions and linear demand functions of the control agents, see Sec. 4).

In essence, microeconomic control is a special type of as *adaptive* control. It embodies an, online and self-organizing, adaptation of the local control strategies when overall resource limitations come into play. The results of this paper have been derived for the general case of PID control. They can, however, be generalized to other, more sophisticated types of control (outlined in Sec. 2). This will be demonstrated in forthcoming papers. For example, all results of the present paper readily carry over to state-feedback control, whereby the market is turned into a multicommodity market.

Our distributed microeconomic approach is also applicable to optimal control whereby a chosen performance index is optimized over a whole time period. In that case, the negotiation rounds are inherently intertwined with iterative internal optimization computations by each local control agent, which is on its turn responsible for a (possibly large) multidimensional dynamic subsystem. Moreover, each such subsystem itself may be handled in a fully decentralized fashion, by representing each local variable (single dimension) by an agent. This leads to a coupled hierarchy of computational economies, and this is actually a quite natural architecture in advanced application scenarios, such as the management of multi-building sites or city neighbourhoods, or online demand response and supply-demand matching of power over several regions at the national and international level. These are currently all very relevant applications of distributed intelligence, both from a business, policy, and technical perspective. A hierarchical control approach then ceases to be possible at all, whereas distributed agent-based microeconomic control offers an effective as well as conceptually natural decentralized computational framework.

Thus, the microeconomic control theory of this paper can be generalized in several directions, representing a diversity of other, richer or more comprehensive agent societies for control:

- multiple state dimensions and control variables can be handled simultaneously;
- different types of control design and strategy can be covered, whereby ‘conventional’ control theory is preserved and integrated into the agent actions;
- dynamic physical environments and models, including nonlinear ones, can be treated;
- a mix of markets and hierarchies for control is possible;
- forms of bounded rationality may be covered (e.g. satisficing, anytime market algorithms, relevant for scenarios dealing with emergencies or critical events);
- different kinds of agent intentionality can be handled — including utilities that are not strictly self-interested, thus going beyond the societal limitations of competitive markets.

6. Conclusion

In sum, our agent-based microeconomic control approach yields a formalism plus a decentralized, bottom-up computational framework that enables new forms of large-systems control that are:

1. optimal,
2. adaptive,
3. economically aware.

It has been designed such that it takes full advantage of existing control engineering and theory. It provides the theoretical underpinnings for, and subsumes, multi-agent based control applications developed so far. It moreover generalizes to computational economies for other types of control, thus providing the formal foundation for an even wider range of distributed intelligence applications in large-scale industrial control.

Acknowledgments. This work was partially supported by the European Commission in the context of the EU-SUSTDEV Project No. NNE5-2001-00906 called CRISP (Distributed Intelligence in CRitical Infrastructures for Sustainable Power).

References

[1] S.H. Clearwater (Ed.). *Market-Based Control — A Paradigm for Distributed Resource Allocation*. World Scientific, Singapore, 1996.

[2] S.H. Clearwater and B.A. Huberman. Thermal markets for controlling building environments. *Energy Engineering*, 91(3):25–56, 1994.

[3] B.A. Huberman and S.H. Clearwater. A multi-agent system for controlling building environments. In V. Lesser, editor, *Proceedings of the First International Conference on Multi-Agent Systems (ICMAS'95)*, pages 171–176, Menlo Park, CA, June 1995. AAAI Press / The MIT Press.

[4] F. Ygge and J.M. Akkermans. Decentralized markets versus central control: A comparative study. *Journal of Artificial Intelligence Research*, 11:301–333, October 1999. Available from http://www.jair.org.

[5] F. Ygge, J. M. Akkermans, A. Andersson, M. Krejic, and E. Boertjes. The HomeBots system and field tests: A multi-commodity market for predictive load management. In *Proceedings of the Fourth International Conference on The Practical Application of Intelligent Agents and Multi-Agent Technology (PAAM99)*, pages 363–382, April 19–21 1999.

[6] E. Boertjes, J.M. Akkermans, R. Gustavsson, and R. Kamphuis. Agents to achieve customer satisfaction — the COMFY comfort management system. In *Proceedings Fifth International Conference on The Practical Application of Intelligent Agents and Multi-Agent Technology (PAAM2000)*, pages 75–94, Blackpool, UK, April 2000. The Practical Application Company Ltd.

[7] R. Kamphuis, C. Warmer, W. Zeiler, W. Wortel, J.M. Akkermans, and J. Jelsma. SMART — experiences with e-services for smart buildings. In F.-N. Pavlidou, editor, *Proc. IEEE 6th Int. Symp. on Power-Line Communication and its Applications (ISPLC-2002, Athens, 27-29 March 2002)*, Thessaloniki, Greece, 2002. Aristotle University of Thessaloniki and IEEE. CD-ROM available from IEEE.

[8] J.M. Akkermans. Being smart in information processing — technological and social challenges and opportunities. In M. Musen, B. Neumann, and R. Studer, editors, *Intelligent Information Processing*, pages 1–12, Norwell, MA, 2002. Kluwer Academic Publishers. Keynote IIP-IFIP World Computer Congress, Montreal, August 2002.

[9] J. Jelsma, A. Kets, R. Kamphuis, and W. Wortel. SMART field test: Experience of users and technical aspects. Technical Report ECN-C–02-094, Energy Research Centre of The Netherlands ECN, Petten, The Netherlands, October 2002.

[10] K-J. Åström and B. Wittenmark. *Computer-Controlled Systems - Theory and Design*. Prentice Hall, Englewood Cliffs, NJ, 1990. ISBN 0-13-168600-3.

[11] K. Ogata. *Modern Control Engineering*. Prentice-Hall, Englewood Cliffs, NJ, 1990. Second Edition, ISBN 0-13-589128-0.

[12] T. Ibaraki and N. Katoh. *Resource Allocation Problems—Algorithmic Approaches*. The MIT Press, Cambridge, MA, 1988.

[13] R. Fletcher. *Practical Methods of Optimization*. John Wiley & Sons, 1987. Second Edition.

[14] A. Mas-Colell, M. Whinston, and J. R. Green. *Microeconomic Theory*. Oxford University Press, 1995.

[15] F. Ygge and J.M. Akkermans. Resource-oriented multicommodity market algorithms. *Autonomous Agents and Multi-Agent Systems*, 3(1):53–71, 2000. AAMAS Journal Special Issue Best Papers of ICMAS'98.

[16] P. Carlsson, F. Ygge, and A. Andersson. Extending equilibrium markets. *IEEE Intelligent Systems*, 16(4):18–26, 2001.

[17] M.P. Wellman. A market-oriented programming environment and its application to distributed multicommodity flow problems. *Journal of Artificial Intelligence Research*, 1:1–23, 1993.

[18] J. Cheng and M.P. Wellman. The WALRAS algorithm—a convergent distributed implementation of general equilibrium outcomes. *Computational Economics*, 12:1–24, 1998.

Paper 14: *Distributed intelligence for supply/demand matching to improve embedding of distributed renewable energy sources*

Full bibliographic reference:

I.G. Kamphuis, P. Carlsson, C.J. Warmer, J.C.P. Kester, and J.K. Kok: *Distributed intelligence for supply/demand matching to improve embedding of distributed renewable energy sources*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

DISTRIBUTED INTELLIGENCE FOR SUPPLY/DEMAND MATCHING TO IMPROVE EMBEDDING OF DISTRIBUTED RENEWABLE ENERGY SOURCES

René Kamphuis (*), Per Carlsson (+),Cor Warmer (*), Josco Kester (*) and Koen Kok (*)

(*) ECN, Energy research Centre of the Netherlands, Unit Renewable Energy in the Built Environment, Westerduinweg 3, P.O. Box 1, 1755 ZG Petten, The Netherlands, [kamphuis, warmer,kester,j.kok]@ecn.nl

(+) EnerSearch AB and Uppsala University, office: Computer Science, Lund University, P.O. Box 118, S-221 00 Lund, Sweden, per.carlsson@enersearch.com

Introduction

Electricity distribution infrastructures are based on a hierarchical, top-down flow and distribution of power. The infrastructures were designed and economically validated with accounting models of energy companies that typically had a time horizon of 20 to 50 year. A consequence of liberalisation is that power networks are being utilized with decreasing reserve capacity and investment capital in this sector preferably has a much shorter time horizon than this.

Due to these changes, flexible, middle-size distributed power generation is becoming more attractive. Standards are being developed for using information networks to couple numbers of such medium sized installations forming a virtual power plant [1], which operates on the power market or has a contract for supplying power on demand (e.g. driven by market prices).

This, together with recent problems with power delivery in California and the large-scale power failures of 2003 in both North Eastern USA and in parts of Europe, gives a renewed interest in distributed generation (DG). In parallel we see an interest in demand side management (DSM) and ICT related opportunities to reverse to a more active role of the demand side in the form of demand response resources. Given the rules of re-regulated energy markets more and more brokerage, wholesale and retail companies are becoming active on energy markets where supply and demand side parties meet bilaterally and on markets with different time-ahead periods.

Price Volatility and End User Dynamics

The price volatility of the APX (Amsterdam Power eXchange)-market compared to the prices charged to, two-tariff, end customers are depicted in Figure 1. The short axis refers to the price development over a day; the long axis to day-numbers in 2003.

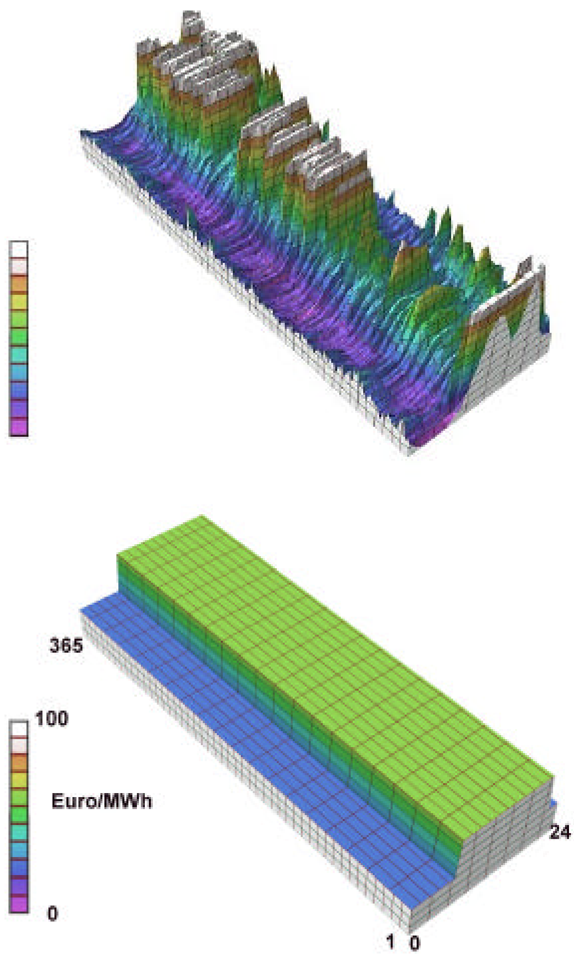


Figure 1 *Price volatility in 2003 at the Amsterdam APX-market and end user prices; both graphs are on the same color-scale*

There are substantial variations in the day-ahead APX-prices over both season and time-of-day. In winter, there are peaks around 5-6 PM. In summer, the demand for cooling is becoming apparent in the first week after summer holidays have ended. The effect of the problems with power supply in the

Netherlands in the second half of august of 2003, when code Red was issued with prices reaching 1800 €/MWh, can not be seen figure as it would have been 18 times as large.

The APX spot market mainly is used to bring market parties together for contracting the last 10-15 percent of the total required load. The extreme price spikes are a result of competition for a relatively small amount of power on a market with low surplus capacity.

The figure also shows the double tariff consumer prices. End users are not exposed to the top-level APX-spikes. Apart from mobilizing peak power production capacity, operating demand response resources might alleviate the spiking burdens [2].

In the US the activity of hedging risks of supply using demand response resources has become a additional market mechanism for mitigating risks (as are derivative markets for stocks).

Parties delivering more or less than the programmed amount are charged with a penalty proportional to the price formed the day before. Apart from a volume market there is a capacity market. The capacity is charged on availability and actual delivery. Programme responsible parties are charged upon their surplus or deficit by the TSO and receive a fine/incentive as well according to the grid-code, which is defined on a per country basis.

This article treats the implications of above-mentioned developments mainly in the light of

- Information and communication technology,
- Operational issues with respect to supply-demand matching at different aggregation levels in the grid, and
- Their effects on market price formation and customer interaction.

We describe the context of part of the activities in the EU-supported CRISP-project [3,4] in defining the broader context and scenarios for supply and demand matching in a distributed setting. Furthermore, it discusses a bottom-up approach to matching of electricity supply and demand. Hierarchical clustering enables bottom-up balancing leading to less imbalance from lower levels upwards. The idea behind these clusters is depicted in Figure 2.

In such supply/demand matching (SDM) schemes both uncertainty on the behaviour of some actors (e.g. RES) and other fluctuations in production and consumption is met utilising the dynamics of other actors. On demand side, typically some 40 % of the total power consumption has such characteristics that it could be utilised to balance the behaviour of other actors. In the electricity market only a quarter of this amount would suffice to cut the spikes of Figure 1 by half. In this article a further description of necessary ICT, market design and preliminary results from implementations are given.

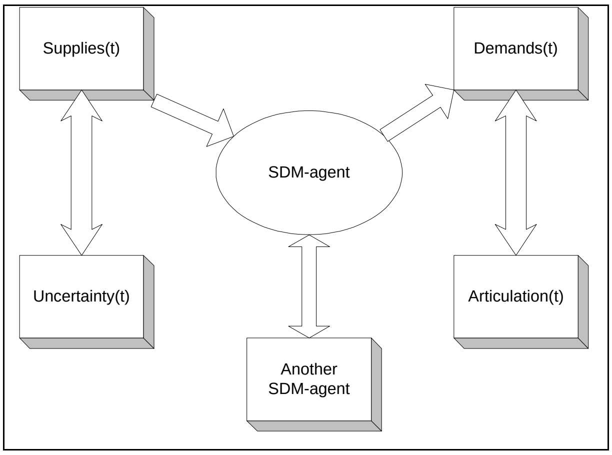


Figure 2 *Supply/demand matching*

Bottom-up approaches for Supply Demand Matching (SDM) as compared to DSM (Demand Side Management)

Renewable Energy Sources

Due to their low predictability and intermittency of production most renewable energy resources can have problems with full exposure to these mechanisms. Renewable energy systems (RES) in a distributed setting currently only use the power grid bi-directionally as a buffer for exchange of electricity; they have to adapt to other installations in the total power infrastructure for maintaining uninterrupted operation and for power quality aspects. RES are more or less tolerated, from a power system point of view, instead of being an active contributor to total grid stability. This is reflected in power pricing, regulatory issues and market aspects.

In view of the above problems, when a more than marginal amount of RES is introduced in a DG setting, these energy producing systems have to be "interrelated" in an intelligent way in order to empower them optimally; distribution networks have to become active at all levels [5].

Bottom-Up operation

Optimisation of the operation of a mixed power supply and demand infrastructure, for instance in the context of a residential area, is quite different from traditional top-down control of power grids. It requires access to operational information from a large number of power network nodes deep in the hierarchy of the network (from the demand side as well as from the supply side). To manage such a network, a bottom-up architecture has to be applied. This is particularly true when an increasing amount renewables is present.

Furthermore, a supply and demand planning model that is more dynamic than what we have today will be required. One of the main issues to handle will be what real-time or expected demand urges what supply of electricity to insert in the network. The EPRI Electricity Technology Roadmap [6] envisions a new mega-infrastructure of energy and information networks, built to meet these challenges. This infrastructure is thought to be partly customer-managed.

DSM and SDM

In the days before deregulation of electricity markets, the approach to demand side management problems was a top down approach. This was obviously the first choice in a world with vertically integrated energy utilities and with utility – customer relations that where quite different from the relations on a liberalised energy market. They involved residential customers as well as industrial ones in schemes aiming at peak load reduction. A common base for the schemes was that the initiative to take action was in the hands of the utility.

When it came to residential customers the approach was to shut down or reduce thermal loads such as tap water heating and building heating for a couple of hours. On the industrial side the experience is that solutions have to be tailored for the individual customer. With good knowledge on consumption patterns as well as the supply situation this could be sufficient e.g. to reduce the need to install new production capacity [7].

On a liberalised market it is both more difficult to achieve some of the benefits of top-down DSM actions that involve consumer side participation, and at the same time we have new alternative approaches. It is harder to achieve some benefits of the top down approaches by the simple reason that the vertical integration of the sector has been loosened and hence it is harder both to set up such systems and to make use of them.

Bottom-up approaches to SDM may not rely on deregulation, but they fit well into a deregulated setting, as the initiative can be moved from the control room of the utility into the hands of small scale actors. The actors of interest are consumers and small scale local producers.

Today's communication and computation capabilities are open for new approaches to SDM, among them bottom-up approaches such as price-reactive optimisation and electronic markets.

The role of buffers in SDM

An abstract model of the control strategy problem of a B-Box (Buffer-box; an abstraction of a ICT network node to handle buffered resources) is presented in Figure 3. An input resource (e.g.natural gas) can be converted directly to an internal resource (e.g. heat) or fuel co-generation (e.g. heat and electricity). A number of computational techniques for solving the strategy problem have been developed and an optimal algorithm was derived using a packet trajectory optimization algorithm. The algorithm is able to optimize the buffer control strategy in time-of-use and/or volume-based pricing situations for each of the resources. The algorithm is scalable and may be used to calculate the strategy one day-ahead in 15-minute intervals within a short amount of computational time. An example of such an application is residential cogeneration.

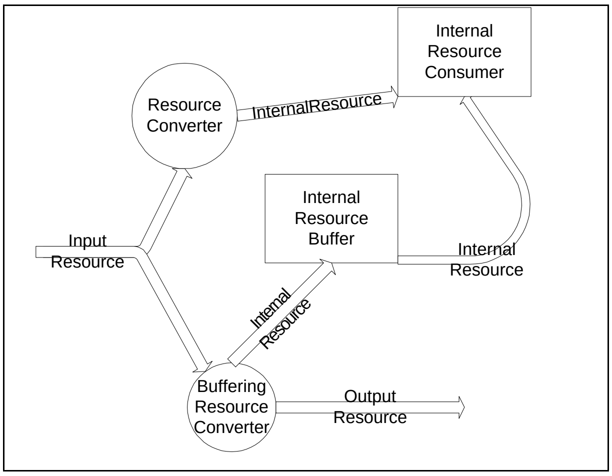


Figure 3. *System description of the B-Box buffer model*

In Figure 4 the buffer control strategy is depicted for such cogeneration in a residential setting for a typical winterday. The resource needed is indicated by the dotted blue line and follows a heat demand approximately adapting to the inhabitant's behaviour and the outside temperature in a winter situation.

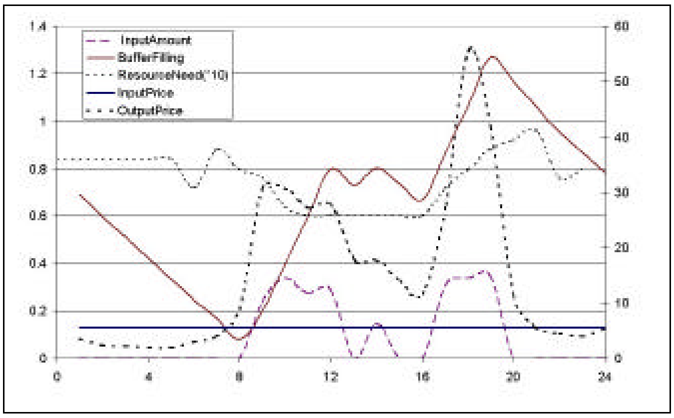


Figure 4. *Cogeneration in a residential setting*

The InputPrice is based on consumption of natural gas, the InputResource. The InputAmount is the amount of gas used. The OutputPrice is taken from APX-data in November 2003 (shown in Figure 1). The input resource price is shown as the straight blue line below on the graph. The internal resource need is the heat demand In the figure, the X-axis is the time in hours, the left Y-axis denotes amounts of resources (in GJ) and the right Y-axis the prices in €ct/GJ. As might be expected, the buffer is filled automatically during output price peak periods and emptied to fulfil the heat demand during the night.

Residential electrical heat production and heat storage.

Using the same data as in the previous section, the control strategy of a heat pump in combination with heat storage is shown in Figure 5. Electricity now is the input resource. Input and OutputPrices are the same in this case. Electricity is used during night time to fill the heat buffer. During the day the buffer is emptied. A similar strategy can be used to control hot tap water generation in a boiler.

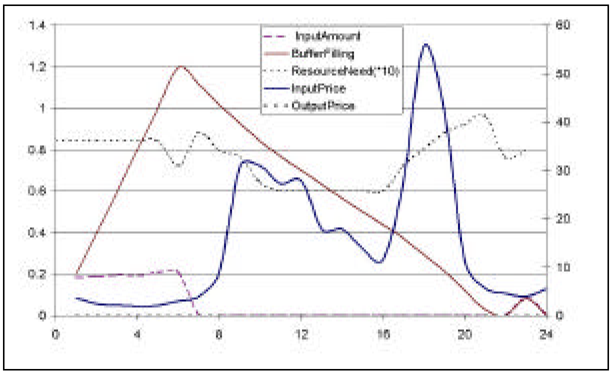


Figure 5 *Price driven heat-pump operation combined with heat storage*

CHP in the Horticultural sector

In the horticultural sector CHP has been used throughout during the 90's. In Figure 6, the situation is sketched for the winter period with accompanying electricity prices and heat demands. In spring and autumn cost effective buffer management in this sector is more difficult in view of current fuel and electricity prices and power requirements.

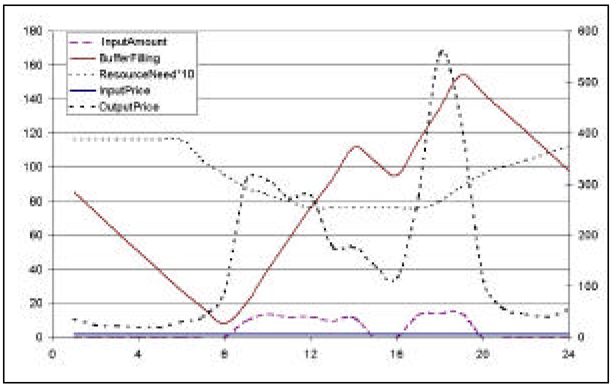


Figure 6 *CHP buffer control in the horticultural sector*

Thus, electricity price driven operation of cogeneration can be combined with effective heat delivery when using appropriate buffers. In all cases, possible cost reductions are possible, if articulated time-dependent tariff schemes are utilized. Exposure to market price signals can be introduced in these types of installations for optimisation.

Price Reactive Optimisation

When to produce or consume energy can be viewed as an optimisation process. A simple example is that the heating or cooling system of a room optimises its behaviour with respect to the objective to stay close to a predefined temperature.

A price reactive consumer adds dynamic prices as a new parameter of the optimisation. Hence, the objective of the optimisation becomes more complex, as he now tries to stay close to the set temperature at as low cost as possible. To do this in practice, the consumer has a need for new technology aiming at these goals.

A system of software agents could be used to perform the optimisation. Such a system can be constructed such that it scales well to handle e.g. climate systems in both small scale and large, complex buildings [8]. External input needed for the optimisation is information on dynamic prices. Among what is needed beside this is metering capabilities that match the resolution of the dynamic power prices used as input for the optimisation.

For a consumer the advantage of price-reactive optimisation is that he has the opportunity to reach his goals at a lower cost. In the same way, a local producer might be able to profile his production such that his returns increase.

From a power system viewpoint the gain is in changes in the behaviour of the same actors. That is, due to their changes in behaviour there is less strain on peak hours and an increase in net demand during low cost periods.

Surprisingly the main drawback of price-reactive optimisation comes when it is introduced as a large scale SDM tool. Power markets of today rely on knowledge on consumption patterns. Energy suppliers have an essential knowledge on the patterns of their customers and how their behaviour varies with factors such as time of year, day of week, weather, etc. Large scale price-reactive optimisation makes these patterns much harder to estimate as market prices starts influencing end user behaviour.

On the other hand, a natural step is to let the changes in behaviour influence market prices, that is, to introduce new participants on dynamic power markets such as day-ahead power markets. Price-reactive optimisation might not give a solution to SDM problems at a large scale, but it might well be a first step in the direction of electronic power markets.

Electronic Power Markets

Dynamic power markets of today such as day-ahead markets and market structured balancing services acting on time scales down to a few minutes before real-time are not constructed to handle large numbers of actors. SDM based on active market participation by small-scale actors to benefit from their dynamics without the drawbacks of price-reactive optimisation needs other market design approaches. Electronic markets seem to be the most promising alternative due to their inherent optimisation possibilities by the possibility of mapping optimisation onto market algorithms, which are suited for distributed applications.

In short, an electronic market is a market where software agents act on the market representing physical world actors. Their behaviour is based on factors such as user preferences, properties of technical systems, forecasts on e.g. weather and market prices, etc. As in the case of price-reactive optimisation some systems that an agent comprises could from another viewpoint be seen as extensions of e.g. control systems such as climate control systems.

Electronic Markets

A division line between market mechanisms goes between mechanisms designed for single-commodity markets[1] and those designed for multi-commodity markets. Note that e.g. day-ahead power markets where a number of time slots are traded simultaneously but where it is not possible to express any dependencies between time slots technically are single-commodity markets.

Electronic markets and auctions have been used and suggested for quite a few different resource allocation problems. Among them we find diverse areas such as transportation of cargo [9], bandwidth on the Internet [10], and supply chain formation [11].

The advantages of using electronic markets instead of other techniques vary with the application area. When it comes to power markets the main arguments for electronic markets are the possibility to *introduce participation of small scale actors* on dynamic markets such as day-ahead markets and market based balancing services, and that electronic markets can be a way to *enhance opportunities to express preferences* on the market (with multi-commodity markets).

A multi-commodity market mechanism ideally gives opportunities to express both substitutability and complementarities between commodities. That is, it is possible to express XOR-bids and bids on combinations of commodities. In practice, if there are no restrictions on these possibilities; the algorithmic problem of establishment of equilibrium prices turns out to be hard. Hence an understandable mechanism with sufficient flexibility that still is computationally efficient is of high interest.

[1] We use the notation of a single-commodity market referring to a market that strictly speaking handles two commodities, the one in focus of the trade and money.

The CONSEC Mechanism

We have developed a mechanism for electronic power markets and similar, the CONSEC mechanism. The mechanism is tailored for markets with time-dependent goods such as dynamic power markets. That is, it utilises that the closer the goods are in the ordering the more interdependent they are. In this way the limited set of opportunities to express substitutability and complementarities between commodities that is offered is tailored for the kind of markets we have in mind.

A detailed presentation of the mechanism can be found in [11]. In short, the idea is to utilise that e.g. a power market is a market with time-dependent goods. That is, the traded commodities are naturally ordered such that the closer they are in the ordering, the more interdependent they are.

From the viewpoint of the bidder the mechanism can give a number of possibilities, depending on how the market is organised. Besides the possibility to bid on single commodities, a hierarchy of blocks of consecutive time periods are defined, Figure 7. For each of the blocks the bidder may submit bids on the same (positive or negative) resource for the duration of the block (i.e. expressing complementarities), and he may submit adaptive "anytime bids", bids expressing substitutability between the time slots of the block. The objective when submitting an adaptive bid is to buy when the price is low or to sell when the price is high.

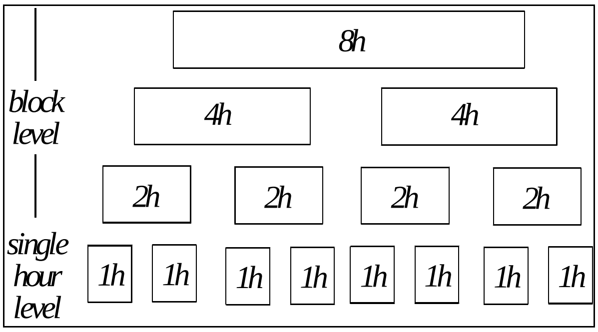


Figure 7 *A market using the CONSEC mechanism is organised in a hierarchical bidding structure. Within each bidding block it is possible to express both substitutability and complementarities between the traded time periods. Here a market with eight hours.*

Bids for the same resource over the time slots of a block are there to give opportunities related to processes that e.g. have start-up costs that give that they have to run for a certain period when started. Adaptive buying bids raise the consumption during low cost hours, and adaptive selling bids raise the production during high cost hours.

CONSEC and Power Markets

This gives that in a power market setting the bidding opportunities offered by CONSEC are clearly advantageous compared to e.g. day-ahead power markets of today.

First of all, as CONSEC is an electronic market mechanism well suited for distributed computing[2], it is possible to use it for power markets where consumption and small scale production play an active role. The gain of this and the opportunities to express substitutability and complementarities as described in the previous section is in enhanced utilisation of participants' dynamics in a way that enhances the knowledge on outcome instead of weakening it. Contrary to peak load shaving and price-reactive optimisation there is no risk that new peaks are introduced when the new actors start playing an active role on the market and in the price formation.

From a power system viewpoint a mechanism with these properties is highly interesting, and it is easy to see why; when actors are able to express their preferences more accurately the dynamics of theirs will be utilised to a higher degree than on today's power markets.

Power infrastructure network layers

To realise the above-described types of applications a more extensive information exchange networks and computational resources at network nodes are necessary. Depending on the type of distributed generation, different properties may characterise the power supply in a electricity distribution network :

- Most renewable energy resources, such as wind energy and solar power, are dependent on local weather circumstances and are subject to relatively large uncertainties. When they are applied on a large scale, this may have a substantial influence on the balance between predicted and actually available supply on different timescales ahead, locally as well as on higher levels.
- Management of combined heat and power (CHP) units is often based on the heat demand of the premise or area supplied with heat or the horticultural activity. Depending on the heat demand they either deliver electricity at different capacity levels, or they are not delivering any power at all and use a central heating installation.
- The usage of CHP-units can also be based on power demand, e.g. by adapting to peak demand e.g. at the premise or within the local distribution network. Heat buffers may be used in this case to store the heat excess.

In a distributed environment, traditional load management or demand side management does not cover the full planning scope and is not pre-emptive. A need for enhanced automated, autonomous supply and demand management becomes apparent. The concept of supply and demand matching is a way to control the power balance within the distribution network. Application of this service requires the development of active, distributed and intelligent networks as sketched in the next paragraphs.

This development is paralleled by current ICT-enabled metering projects. In Italy, a large (30 million) rollout of intelligent meters with bi-directional communication possibilities to end-customers is in the implementation phase now. In this project prices per installation are in the order of 70 Euro. Apart from automated metering, additional benefits come from automation of back-office activities, obtaining real-time data for day-ahead estimations of power usage, reduced tampering and the possibility for extended service offerings. In the Italian configuration, the intelligent meters exchange data using power-line communication to near transformer stations. At these stations, the wireless GSM network further transfers the data. Significant in this respect is the partnering relation between the utility company, Enel, and the largest software provider in the world, IBM. Primary objectives of the project include a need to understand customers better, more accurate and timely billing, less disruptions and shortages and better monitoring of network availability and efficiency. Automated Meter Management (AMM) further opens the gate to a large number of utility operated on-demand customer applications using the back-office application information.

Intelligent, active networks – an innovative approach

Distributed and intelligent solutions require an additional focus, apart from the power network, onto the information and communication (ICT) network and the application area, which is represented by a service network through which distributed and intelligent services can be deployed. Figure 8 depicts this three-layered network in our approach.

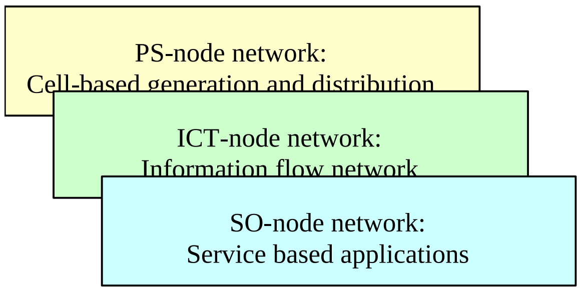


Figure 8: *Three-layered network approach for intelligent applications on the power network*

The PS (Power System)-node network consists of the traditional power delivery infrastructure, including producers and consumers on the transmission and distribution grid. The network consists of hardware,

[2] The mechanism can be organised utilising the principles of the COTREE algorithm [12].

including existing dedicated ICT systems for real-time operation and control.

The ICT-node network also is a hardware network, which enables free information flows between all network nodes, supports local intelligence and knowledge of business processes at each node, and is built upon the PS-node network. The ICT-node network can be seen as an enhancement of the dedicated operation and control systems within the PS-node network, whereas at the same time it delivers basic functionality for the energy services.

The SO(Service Oriented)-node network is a functional network, which consists of the software components that together constitute one or more services or applications that control the PS-node network through the ICT-nodes network. The precise location of these processes in the network, then, is an implementation issue.

Cell-based grid operation

The power grid itself can be organised as a cell-based distribution network, which consists of hierarchies (Middle Voltage or MV and High Voltage or HV) of generation-distribution cells. This network of generation-distribution cells constitutes the Power System Node network, or PS-Node network. Supporting the necessary information flow to facilitate the proper operations of the PS-Node network we have a communication and information exchange infrastructure, the ICT-Node network. The interaction between the cells within the PS-Node network is handled by a collection of service based applications, the SO-Node network.

In the future cell-based power grid the energy flow will change from 'plant to consumer' HV $\rightarrow$ LV $\rightarrow$ MV (top-down delivery) to 'customer to customer' (peer-to-peer) energy exchange networks within the LV and MV network. Production units will become small and be placed at the household level.

In order to control the cell-based power grid SCADA and central load control will be enhanced by autonomous control systems and local supply and demand matching. The control topology will change from top-down to bottom-up. In such an architecture agent models, operating in smart node networks, will become a natural way of control instead of processes based on data and communication.

Operation of the cell-based power grid will lead to increased dynamic balancing needs within LV and MV cells, also because large scale RES integration will make supply less predictable. In previous paragraphs we have shown how a market approach based on electronic market mechanisms can contribute to the tuning of supply and demand within cell-based power grids.

Note that two extremes are sketched here. In reality the traditional grid is already moving. The resulting situation will be a hybrid one. However, we are interested in the implications of decentralisation on network operation. We see a transition from passive networks towards active networks, firstly in order to control the reliability of the power network, but also in order to enable supply and demand matching as proposed in this article. Through this transition we are able to organise the generation-distribution cells such that they interact in an optimal way to meet supply-demand conditions. Emphasis will change from profit / kWh for the utility towards profit / information / kWh for the energy service company.

Requirements for intelligent networks

Intelligent networks as sketched above have to satisfy a large number of requirements in order to rely on them for business operation. We will mention briefly a number of them without going too much into detail.

A number of technical requirements for communication are apparent, dependent on the type of application: latency requirements will vary from milliseconds (fault analysis) to tens of seconds for business applications; for most applications broad bandwidth will not be required; error rate and loss of messages require robust solutions and fallback scenarios for individual nodes and parts of the network.

ICT-layer requirements include always on connection, preferably between all nodes in the network; standardised distributed inter-process communication; distributed processing capacity; hot-pluggable components. The safety and reliability of power distribution should under no circumstances be endangered due to failure in the ICT network.

Functional requirements will vary for each application. We can formulate general requirements for services deployment, such as hot-configurability of network topology and nodes and configuration management for software components.

Dependability and security issues not only lead to network security requirements, but also information security and business protection requirements. Ensuring dependability and security however is not enough. As stressed before, failures in any part of any network should not endanger power safety and reliability. But it should also limit consequences for business applications, especially with respect to financial losses and customer dissatisfaction. This can either be done by increasing reliability of the ICT- and SO-infrastructure (which is more than just the network) or by increasing robustness of applications.

Conclusions

In this document, market-oriented online supply-demand matching has been treated from a number of views.

- The impact of introduction of more DG-RES into the electricity grid has been dealt with especially looking at the different characteristics of electricity and energy suppliers and demanders. The concept of Supply/Demand matching, representing an innovative way of using ICT for bottom-up optimisation is shown to provide for a valid framework for grid-operation.

- The role of buffering in supply and demand matching has been discussed and illustrated with a number of sample cases, in which the potential of real-time price driven optimisation, taking care of the context of other user processes, has been shown.
- Electronic markets and the CONSEC market-algorithm for tailoring software agents, operating in a limited context, ‘market’-environment (to be discriminated from current nation-wide markets) are discussed.
- The role of ICT in these kinds of grids has been treated and the software and hardware architectural issues have been discussed and the role of modern agent technology has been discussed. Four sample cases are defined, which may yield results to judge the impact of these new tools and tune their application.

References:

[1] IEEE P1547 Draft Standard for Interconnecting Distributed Resources with Electric Power Systems. See http://grouper.ieee.org/groups/scc21/1547/1547_index.html

[2] J.M. Akkermans and J. Gordijn, Eds. Business models for Distributed Energy Resources in a Liberalized Market Environment. EnerSearch AB, Malmö, 2004. www.enersearch.com

[3] Kamphuis, R. *et al*. “Market-oriented online supply-demand matching.” Deliverable 1.2 in the framework of the CRISP project. March, 2004. www.ecn.nl/crisp

[4] Warmer, C.J. et al. “ Requirements specifications of intelligent ICT simulation tools for power applications.” Deliverable 2.1 in the framework of the CRISP project. October, 2003. www.ecn.nl/crisp

[5] M.J.J. Scheepers and A.F. Wels, “New approach in electricity network regulation: an issue on effective integration of distributed generation in electricity supply systems”, SUSTELNET-project, 2003.

[6] EPRI, Electricity Technology Roadmap, 1999 Summary and synthesis. EPRI, 1999.

[7] Larsson, L. et al. “Projekt MINTOP”, project report on a Sydkraft project on peak load reduction. Malmö, 1998 (in Swedish).

[8] R. Kamphuis, C. Warmer, and J.M. Akkermans: SMART - Innovative services for smart buildings. In ISPLC-2001, Proceedings of the 5th International symposium on Power-Line Communications and Its Applications, pp. 231-236. Lund University, Sweden, 2001.

[9] Rasmusson, L. “Pricing virtual paths with quality-of-service guarantees as bundle derivates”, submitted to IEEE/ACM Trans. on Networks, June 2001.

[10] Walsh, W. E., Wellman, M. P., and Ygge, F. “Combinatorial auctions for supply chain formation”, Second ACM conference on Electronic Commerce, pp 260-269, Minneapolis, 2000.

[11] Carlsson, P., and Andersson, A. “A flexible model for tree structured multi-commodity markets, submitted.

[12] Andersson, A., and Ygge, F. “Managing large scale computational markets”, in H. El-Rewini (ed.), Proceedings of the Software Technology track of the 31st Hawaiian International Conference on System Sciences (HICSS31), pp 4-14, IEEE Computer Society, Los Alamos 1998.

Paper 15: *Dynamic protection of software execution environment*

Full bibliographic reference:

P. Mellstrand and R. Gustavsson: *Dynamic protection of software execution environment*, in Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures, Grenoble, France, October 2004 (available from http://www.leg.ensieg.inpg.fr/cris2004/ or www.ecn.nl/crisp).

Dynamic Protection of Software Execution Environment

P. Mellstrand[1], **R. Gustavsson**
<per.mellstrand@bth.se>, <rune.gustavsson@bth.se>
School of Engineering, Blekinge Institute of Technology, Sweden

Introduction

Proper operations of software and software systems are crucial requirements of reliable operations of power grids. This fact has been manifested in recent blackouts in US-Canada and Europe, e.g., blackouts in Italy and Sweden-Denmark. The final report by a U.S.–Canadian task force[1] on the August 14, 2003 blackout in Northeast North America reports a number of findings related to this worst outage in North American history affecting over 50 million people.

One of the findings was buried in a massive piece of software compiled from four million lines of C and C++ code and running at FirstEnergy Corporation in Ohio. The code was GE Energy's XA/21Energy Management System (EMS) used at the control center of FirstEnergy. After about eight weeks of hard and difficult software and event analysis related to the cause chains of the events leading to the blackout, a hitherto unknown bug in the one million lines of code belonging to XA/21's Alarm and Event Processing Routine was found. The bug caused a "race condition" due to improper handling of interactions between two processes having access to a common data structure. This coding error allowed a simultaneous write access for the two processes that in turn led to the alarm event application getting into an infinite loop and spinning and eventually to the collapse and blackout of the power grid.

Later analysis showed that the bug had a window of opportunity measured in milliseconds. Furthermore, the XA/21 system had up to this failure had an excess of three million online operational hours in which the bug has not been triggered. There are some lessons that can be drawn here:

- The software fault itself – race condition – is a well-known problem in interaction between processes and should not have appeared if "good software practises" had been followed.
- The complexity of millions of lines of code software makes it highly possible that there are bugs that remain undetected even after long time of use.
- It is in practise impossible to validate by testing that large software systems are free of bugs, not the least due to the fact that by networking the systems new and completely unforeseen interaction between software might appear.

In fact, collapses of critical infrastructures due to software bugs happen quite often, even if the scale and damage are less than the example given above. In fact, we had the ARPAnet (Internet) collapse in the 80's and the AT&T (telecom) collapse in the 90's.

Of course, we should strive for producing and maintaining as bug free software systems as possible, not the least because software is the active glue of the increasingly networked society. But given the lessons learned, we should also compensate for the shortcomings of static methods of creating bug free software systems (design and testing) by introducing dynamic protection mechanisms. This complementary approach is advocated in this paper.

In short, we propose a runtime environment whereby we can:

- Dynamically change program execution protection mechanisms based on runtime conditions (e.g., protection against a vulnerability in a given context).
- Log program runtime behaviour allowing us to have a more informed maintenance and debugging situation.

The remaining part of the paper is organised as follows. The following section Background introduces and discusses basic concepts such as function and vulnerable calls, different risk assessments related to function calls, and the role of domain-specific rules. The bottom line is to identify and implement mechanisms that prevent programs from being exploited, not to prevent an exploited program from performing malicious actions. The latter task is the focus of virus and worm protection schemas.

Dynamic Inspection is addressed in the following section, where we describe the differences between static and dynamic tools, and describe the technical foundations used to create dynamic tools. Following that, we describe the plibc system, which is a rule-based dynamic inspection system that lets an administrator control the software execution environment. We describe the technical design decisions made in the plibc system, and the different protection characteristics of the system.

[1] Funded by EC grant ENK8-CT-2002-00673, Distributed Intelligence in Critical Infrastructures for Sustainable Power, "CRISP"

In the Experiments section we present our results from experimentation with the plibc system on a large high-privileged program, and how currently known and possible future problems with this program can be handled by dynamically modifying the execution environment. Following Experiments, in the section Performance Benchmark we share our results from a performance benchmark measuring the overhead imposed by using the plibc system in a worst-case scenario.

The paper ends with a section on Conclusions and Future Work and a list of References.

Background

Much general-purpose software is used today in business sensitive or critical environments, for which the software was not originally designed. In these environments, there are typically different requirements on the software execution properties than what might normally be the case. For example, software used on a closed intranet to monitor device output might have high requirements on reliability and logging of erroneous states, but lesser requirements on performance and fully supporting standards that are only partially used.

Due to the way many operating systems handle privileges, and the way much software is written, it is often necessary to execute software with high privileges, even in these critical environments. Executing software with high privileges impose a risk to the system, should the program malfunction it would still keep the high privileges and could cause significant damage to the system. Such malfunction could occur for many different reasons, for example as the result of a programming error ("bug") in the software. In some cases, these programming errors can be exploited by an adversary to cause even more serious damage to the system.

Software programs communicate with their execution environment by means of functions. Even if a program is written in an object-oriented language the communication with the operating system and other software is usually done by means of functions, following the conventions of the C programming language. Essentially all software executing on Unix or Unix-like operating systems, and all software executing on Windows communicate with the operating system through a number of functions, commonly referred to as an Application Programmers Interface, or API. These functions follow a well-defined interface, and their exact implementation is not important for most programs.

Due to the different standards that govern the interfaces between programs and the operating system environment, some functionality offered by the environment to a program is exposed through sub-optimal function interfaces and the use of these functions can result in vulnerabilities in the executing program. Typically, these functions are safe to use if used exactly as intended, but small programming mistakes can result in incorrect calling of one of these functions and hence result in an exposed vulnerability in the program.

It is often not possible to tell if the use of a specific function is safe until all runtime information, such as the values of parameters and variables are known. In addition, other properties from the environment can be important when determining which calls are safe under given circumstances. For example, a critical system may require very stringent validation of the execution environment, which halt the program should any potentially insecure state be detected, while other supporting systems can execute with less a less restrictive policy.

In this paper, we present a method to execute software according to an environment-specific policy that determines which operations the software is allowed to perform. By using this method, it is possible to disallow potentially dangerous calls under certain administrator-defined conditions, to log program execution, and to redirect calls to alternative implementations. In contrast to other policy-based methods, this method does not work on an operating system kernel level, but in user level inside the program, making a more fine-grained control of function calls to system libraries possible.

Dynamic Inspection

Inspecting programs during execution, dynamic inspection, has the advantage over static inspection methods that the actual state of the program is always known. When a function call is made from the program it is possible to analyse the actual parameters sent from the program to the function, as well as the value of other variables used in the program. A dynamic inspector can also use other process information, such as the process' privileges and file system root as basis for taking different actions.

Dynamic inspection is done at the actual time of execution, and inside the executing program, so it is important that the inspector does not impose vast overhead on the program, and does not introduce new vulnerabilities during inspection. A vulnerability in the inspection may result in as severe problems as if the vulnerability were in the program itself.

Plibc is a rule-based dynamic inspection tool designed to allow control of program execution based on domain-specific policies and run-time conditions. Using plibc it is possible to protect a program by defining rules that allow or disallow execution of particular functions based on runtime-conditions. Plibc can also be used to modify a program to conditionally use an alternative implementation for a function call or to change parameters to a function.

The rule language used in plibc is designed to allow flexible rules without allowing high-risk features that could lead to vulnerabilities in the run-time rule evaluation. In the following sections, we describe the design of plibc, present a performance evaluation and argue that the use of the plibc tool increases system protection with negligible performance overhead.

The Plibc System

The plibc system consists of three components; the dynamic inspector, the rule compiler and user-defined rules. The user-defined rules set actions that the dynamic inspector will take when certain runtime states occur in an executing program. The rule compiler is used to transform the rules from a human-readable format to a binary format used by the dynamic inspector.

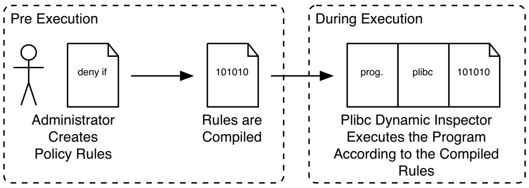


Figure 1: The plibc components and system interaction.

When using plibc to protect a program the first step is to write the rules that should be applied by the dynamic inspector. These rules are written in a special-purpose script language designed specifically for plibc. The rule file is then compiled into a binary form by using the rule compiler. Using a separate compiler step results in faster loading of protected programs and removes the need for a complex parser in the dynamic inspector.

The dynamic inspector intercepts function calls made from the program in an efficient way, and applies user-specified rules to determine which actions to take. The dynamic inspector operates entirely inside the protected program, but is completely transparent to the program. The protected program does not need to cooperate with the dynamic inspector in order to be protected, and the dynamic inspector analyzes the programs state without interfering with the normal program execution. The dynamic inspector is the largest component of plibc and is divided into two main parts, the rule evaluator and a large number of hook functions.

When a call is made from the protected program to a library, such as the C library, the call is intercepted by a hook function. The hook function reconstructs run-time information for the function, prepares a high-level environment, and invokes the rule evaluator. The rule evaluator applies each user-defined rule for the given function, which may perform a variety of different operations, and eventually make a decision of how the call should be handled.

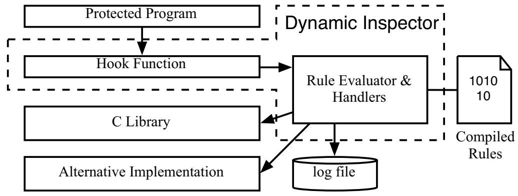


Figure 2: A function call is intercepted, evaluated, and actions are taken.

The user-defined rules execute conditionally based on the run-time state in the program, and can perform actions such as logging call details, modify function parameters and change execution flow. When all rules for the function have been evaluated, one of the following actions is taken based on the last rule that matched the call.

Always allow calls to this function. If there are no matching rules for this function, or if the rules are constructed to always allow this function to be called, this action is retuned to the hook function. The hook function will cache this decision and the rule evaluator will not be invoked for this function again.

Allow this call. If the rules for this function have been applied to the current state and the call have been deemed secure this will be retuned to the hook function which will allow the call this time, but invoke the rule evaluator the next time this function is called.

Terminate the program. A rule can force program termination. This is useful when a potentially dangerous state is found in a program running with high privileges. The hook function will invoke a special low-level termination routine that will safely terminate the program without relaying on any possibly compromised high-level functions.

Redirect this call. A call can be transparently transferred to another function than the program intended. This is typically used to force use of slower but more secure implementations under certain circumstances determined by the user-provided rules.

Redirect all calls to this function. A call can be permanently mapped to an alternative implementation, which means that the rule evaluator will not be invoked for this call again.

Intercepting Function Calls

The dynamic inspector requires the protected program to be re-linked to inspect the calls made from the program. Re-linking a program means that the extern symbols used in the program are bound to addresses in the dynamic inspector. There are two fundamental ways to do this re-linking:

1) By static linking which means that the program is recompiled from source code and linked with the dynamic inspector[2], or
2) By using the dynamic linker in the system, which will provide on-the-fly re-linking of a program just prior to executing it.

Neither static linking nor the concept of using the dynamic linker to inject a library into a program is new, dynamic linking is discussed in most operating system textbooks, and we will not discuss the details of how this is done, but assume that the reader is somewhat familiar with these technologies. The result from using either of these techniques is that a "hook function" in the dynamic inspector will be called instead of the function the protected program intended to call.

Hook Functions

A hook function is a small function that is called each time the program intended to call another particular function (the hooked function). If a previously cached result is available, the hook function transfers the call to this location. If no such cached result is available, the hook function constructs an environment under which the rule evaluator can be executed, executes the rule evaluator, and effects the decision made by the evaluator.

To call the rule evaluator the hook function must obtain runtime information for the function that was hooked and prepare so that the rule evaluator can be called without destroying any state, such as parameters and environment, sent from the program to the hooked function. The runtime information is required to match the right rules to the function, and to know how to handle the call if allowed by the rules. The hook function itself is written in assembly language to ensure it does not modify any such state while preparing to call the higher-level rule evaluator. The runtime information obtained by the hook function and sent to the rule evaluator is:

- name of the hooked function,
- parameters sent to the function, and
- pointer to the cache for this function.

Obtaining Run-Time Information. When compiling a program some information from the source code is removed by the compiler, and other information is transformed to a form more suitable for the execution environment. For example, the name of a function is normally preserved in the executable but only in a form optimized for use by the runtime linker. The runtime linker translate the name of a function to the address where the corresponding machine code is, and information about function names is saved in a format which is optimized for this type of lookup only. In some cases, function names are removed in a program (stripped binaries), but this information is always preserved in libraries, which is sufficient for the dynamic inspector. The hook function need to perform the reverse lookup, that is, given the address that is currently executing determine which function the program called.

To do an address-to-function lookup a single address can be used in only one function, which means that a given hook function can hook only one function. If a single hook function was used for several functions it would not be possible to determine which of these functions the program intended to call. This means that there has to be a separate hook function for each library function, which is also the case in plibc. As this requires many hook functions, each hook function in plibc is optimized for size to reduce the total memory overhead in the protected program. The advantage of using multiple hook functions is that data for each function can be stored inside the respective hook function. This technique is used by the dynamic inspector to store function names, which can be retrieved very fast in run-time.

The hook function also retrieves the parameters sent from the program to the function. The calling convention does not contain information about how many, or the type of, parameters that are sent in a function call, so the hook function handles parameters in a generic way by saving a pointer to the first argument. If a particular rule requires information about a specific parameter this can be decoded by the rule evaluator given information about which parameters the function take.

The last piece of information sent by the hook function is a pointer to a cache. If the rule evaluator determines that this function is safe to call regardless of the runtime state, a pointer to the function is saved in the cache. If set, the hook function will use the cache for all following calls to the function, which leads to a very small overhead for safe calls.

Rule Evaluator

The rule evaluator finds the correct rule set for a function and executes each rule in the set determining which actions to take, depending on the rules and runtime state in the program. A rule can trigger arbitrary actions such as logging the call, modifying parameters, or make decisions of how to handle the call. The rules used by the evaluator are written in a script language, compiled with a special compiler and the resulting binary file is read by the dynamic inspector when a program starts to execute.

A rule file used by plibc contains a sorted list of function names that have rule sets attached, and the corresponding rules for each function. Only functions that have non-empty rules are saved which means that in a typical usage scenario several hundred functions have hooks but less than fifty have non-empty rules and needs to be considered by the rule evaluator. For example, in the experiment with DHCPD, less than twenty of the 800 possible

[2] Technically only a re-linking with the library is needed, but access to the original object files are required

functions had non-empty rule sets. Functions that do not have rules are always allowed and this result is cached by the hook function for faster execution.

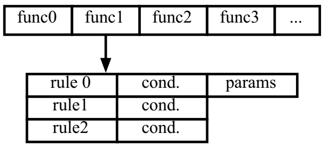


Figure 3: Layout of rule sets and rules during execution.

Each rule has a condition and an action, and optionally a predicate and parameters. The condition is one of “always”, “never”, “if” and “if not” with the obvious meanings. If the condition is “if” or “if not” the predicate function is called by the rule evaluator to determine whether the rule should execute or not. The rule handler is executed with the optional parameters, and returns an action to the evaluator. The possible actions are “continue rule evaluation”, “allow call”, “deny call” and “redirect call”. It is in the rule handler that arbitrary actions such as logging are implemented. A rule may also change the execution environment of the program when invoked, as we will show later in our experiments. If the last rule returns “continue rule evaluation”, the call is permitted. A rule does not have any variables or other state.

Plibc defines several generic predicates and rule execution handlers that are sufficient for many rule sets, but it is also possible to write more specialised predicates and handlers in C that can be used by the dynamic inspector. This feature is useful in special-purpose legacy programs where customized data inspection is necessary. These C functions can safely call hooked library functions without trigging the hooks, as this could otherwise lead to a problematic situation of recursion.

The rule evaluator optimises unconditional rules, which reduces the overhead time for these calls, but as we will show later, the overhead in plibc even without optimised rules, is typically not a problem.

Rule Language Security

The language used to define rules is a simple script language, but still requires parsing to translate into a machine-readable format. The translation of human-readable rules to a machine-readable format is done in a separate compiler that can be executed on a different computer from the one executing the dynamic inspector and the protected program.

Using a separate compiler gives both performance and security benefits, as parsing is slow and there have been many vulnerabilities found in parsing code. The parsing code used in the dynamic inspector to read the compiled rules is small, fast and uses no static buffers. This is to further reduce the risk of vulnerabilities in the runtime handling of rules. The rules used in plibc cannot have any state so a state build-up in the rule evaluator not possible. In addition, there is no support for loops or other repetition in a rule set, which means that a rule set cannot loop forever. The dynamic inspector also performs several sanity-checks on a compiled rule file before loading, and refuses to load too large files or files with suspicious permissions. Because of the limited script language and the extended security checks performed by the dynamic inspector, it is highly unlikely that a correct program given hostile rules should perform any dangerous operation.

Plibc makes no provision for verifying itself or extensions written in C, so these must be verified with other methods.

Extending the Plibc System

The plibc system is designed in a modular way, which makes it easy to add new components to the system. The rule system can easily be extended with new predicates that test different aspects of the runtime state, and with handlers that modify the execution in some way. The standard predicates and handlers are sufficient for many cases, but when dealing with special-purpose programs is might be necessary to extend the plibc system.

It is also possible to extend which functions that plibc can hook. The hook functions in the dynamic inspector are created when plibc is built, using the systems C library as a template, creating a matching hook function for each function in the library. Thanks to this process, it is trivial to extend the plibc system to hook other libraries that might be interesting to examine during execution, such as xlib, glib or libpam.

Experiments

To experiment with plibc rules in a real-world setting we performed a series of experiments on Internet Systems Consortiums DHCPD [2]. ISC DHCPD is a widely spread daemon used to configure network settings for client hosts on a network dynamically. Due to the DHCP protocol and the way privileges are handled on a UNIX system the DHCPD daemon constantly executes under super-user privileges.

ISC DHCP version 3.0 contains a security problem known as a ”format string” vulnerability. A format string vulnerability means that the program can be tricked into using data provided by a non-trusted party in such a way that the data is interpreted by a function, which might lead to execution of attacker-provided code. Details about the vulnerability in DHCPD were first published by NGSEC in May 2002 [3] and are further discussed on the BugTraq security forum [4] and in a CERT Advisory [5]. There is a published proof-of-concept that makes DHCPD execute attacker-provided code with super-user privileges on the BugTraq forum.

Format string attacks are well known in the security community and can be tackled in different, non-optimal ways. One way is to remove the vulnerable parts of these functions, but these capabilities are required by many programs, and removing them also clearly violates the ANSI requirements. Another way of tackling format string vulnerabilities is to use a pre-processor hack to count the arguments sent by the program and later match this with the format string. This technique requires recompilation of the program to protect, and can not be used on all programs due to the way the pre-processor works.

Experiment Design

The purpose of the experiment was to see how the plibc system could be used to create an environment that protected DHCPD from format string vulnerabilities, without affecting other programs, and without make the protection specific for the only published proof-of-concept attack that is available. The main idea was to use plibc to hook all functions vulnerable to format string attacks, and attach different rule sets to these functions and test the publicly known exploit against the executing program. We also wanted to determine the number of calls made to these hooked functions during normal execution, so we performed a test with normal clients and a rule set that logged all relevant calls. The following test cases were used;

Baseline. DHCPD was executed without plibc.

Denying Rule set. To test a typical situation where a call should be denied we designed a rule set that allowed DHCPD to call functions that are vulnerable to format string attacks if, and only if:

- The program executed without super-user privileges, or
- The format string used does not contain “%n” or “%hn”.

In this case we knew that the first rule would never match as the program always executes with super-user privileges, but decided to use this rule for illustrative purposes. In the experiment all ten functions in the printf family[3] were hooked with a rule set, looking like the one below for vsnprintf:

```
allow vsnprintf if not euid 0

deny vsnprintf if param-match 3 "%n"

deny vsnprintf if param-match 3 "%hn"
```

The first rule allows calls to the function (“vsnprintf”) if the program is not running under super-user privileges (the effective user id, or euid, is non-zero). The second and third rules deny the call if parameter three, which is the format string, contains “%n” or “%hn” respectively.

[3] printf, fprintf, sprintf, snprintf, asprintf, vprintf, vfprintf, vsprintf, vsnprintf and vasprintf

Patching Rule set. We also designed a rule set to log the call and patch the parameters sent from DHCPD if a possible format string attack was detected. The following type of rules were used:

```
log vsnprintf "pisp" if param-match 3 "%n"

log vsnprintf "pisp" if param-match 3 "%hn"

replace-param vsnprintf 3 ptr ¬
    "call protected by plibc" ¬
    if param-match 3 "%n"

replace-param vsnprintf 3 ptr ¬
    "call protected by plibc" ¬
    if param-match 3 "%hn"
```

In this rule set the first two rules log the “vsnprintf” call with relevant parameters if the third parameter matches “%n” or “%hn” respectively. The third and fourth rules change the format string parameter if “%n” or “%hn” is found.

Logging Rule set. To determine the number of calls made from DHCPD to hooked functions during normal execution we also used a rule set that logged all calls to these functions.

Results and Analysis

Executing the test for the baseline case resulted, as expected, in injection of hostile code that could execute with super-user privileges.

When using the denying rule set DHCPD was terminated by plibc, and the program state was saved in a file (core dump). This was also an expected result as the “%n” and “%hn” directives are used in essentially all format string vulnerabilities, and these were analysed for all vulnerable functions. DHCPD was terminated just before executing the “vsnprintf” function and no hostile code was ever executed. An investigation with a debugger of the saved core file reveals the chain of calls that lead to the point where the program would normally have been compromised. This information can often be used to trace the root problem in the vulnerable program.

```
# gdb dhcpd dhcpd.core
(gdb) bt
#0  0x280f6ac1 in kill_me () from /libpc.so
#1  0x25 in ?? ()
#2  0x8086560 in print_dns_status
(status=19, uq=0xbfbfde08) at print.c:1369

(Call frames #3 - #16 removed)
```

Using the patching rule set DHCPD continues to execute normally when attacked, but some messages sent to the system log are changed to “call protected by plibc”. The reason for this is that the attack against DHCPD targets only logging functions and when plibc modifies the parameters sent to “vsnprintf” the function is no longer attackable.

Modifying parameters in runtime is not always a good thing. If the program is written in such a way that it depends on a function to modify data pointed to by a parameter, and the parameters sent to the function are modified at runtime the state of the program may be changed in a way the program cannot handle. This situation can also occur if the program is dependant on a state modification done by the function that no longer will be done if the parameters are changed. When hooking functions in the C library, the interface for the function is known and it is possible for an administrator to make a balanced decision of which actions to take if a dangerous call is made. In many cases it is more secure to use a "deny" rule that kills the program than to modify parameters in runtime, but under certain circumstances, such as when it is important that the program continues to execute, it is useful to modify parameters in runtime.

The logging rule set was executed in a different environment, with one thousand normal DHCP requests sent on an otherwise quiet network. The purpose of this experiment was to determine the number of calls DHCPD makes to hooked libc functions. The total number of calls made was 163950, including a small number of calls made when the daemon started up and shut down. As the exact number of calls made for each request is not interesting in this case, we did not separate calls made during start up and shut down from those made to serve requests, but conclude that on average 163950 / 1000 ≈ 164 calls were made to handle a request. In the next section, we present a performance benchmark of plibc on different systems.

Performance Benchmark

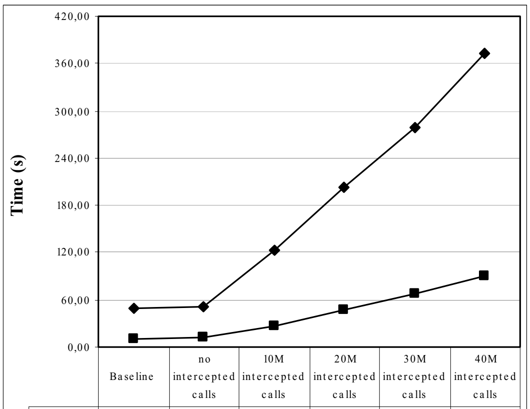
To benchmark the performance overhead imposed by using the plibc system we used a small program that repeatedly called four functions from libc. This represents the worst-case scenario for the dynamic inspector as the test program itself contains no logic, but constantly make calls that are intercepted by a hook function, and each time a hook function is called a small delay occur. If there is a non-optimizeable rule set for the function, a full rule evaluation must be done for each call made. The test was executed so that each of the four libc functions was called 10 million times, and using the following test settings;

Baseline. Test was executed without any plibc interference to determine normal execution time.

No intercepted calls. Test was executed with plibc active but without any rules. In this setting, the hook functions cache the results from the first rule evaluation and use this for all following calls to the same function. This test was to determine the minimum overhead imposed when using plibc.

10M, 20M, 30M and 40M functions intercepted. The test was executed with plibc active and using a simple but non-optimizable ruleset for 1, 2, 3 or 4 functions, resulting in full rule evaluation of 10 million, 20 million, 30 million or 40 million calls respectively. This test was to determine the overhead introduced when a call is intercepted and handled with a full rule evaluation.

The tests were executed on two different systems, a 400Mhz Pentium II and a 2.8 GHz Pentium 4, both running FreeBSD 4.9. The results from this benchmark are shown in Figure 4.



	Baseline	no intercepted calls	10M intercepted calls	20M intercepted calls	30M intercepted calls	40M intercepted calls
P2 400MHz	49,04	50,59	123,06	202,01	277,68	372,59
P4 2.8GHz	11,21	11,39	27,03	46,95	67,15	89,71

Figure 4: Execution time in seconds for the different test cases.

From this benchmark we draw two conclusions. The first conclusion is that there is a low static overhead imposed by using plibc. The overhead in this worst-case scenario on the Pentium II system is three per cent, and on the Pentium 4 it is one per cent. These results are expected as the hook functions are implemented in assembly and a cached call only requires four machine code instructions overhead.

The second conclusion is that the overhead imposed by plibc is linear to the number of calls that require a full rule evaluation. From the results we can see that the average overhead for a full rule evaluation was less than eight microseconds on the Pentium II system and less than two microseconds on the Pentium 4.

Comparisons

There are several techniques available that increase program security by modifying the execution environment, or that provide an alternative execution environment for programs. In this section, we compare the plibc system with other techniques, in terms of security, performance and integration time. In most cases can these techniques be used together to create a good in-depth protection for a program, but in other cases are the techniques mutually exclusive.

Pre-processor methods. By using the C pre-processor it is possible to extract some information during the pre-processing stage of compilation, and later use this information in run-time to verify that certain parameters have not changed. This technique is for example used in the Immunix Linux distribution [6] to protect against format-string attacks. Because of the dependency on the C pre-processor, it is only usable for programs written in C and possibly C++, and for programs that can be recompiled from source code. In addition, as this method relies on special macros to extract information all protected programs need to be recompiled from source, should a new vulnerability become known. The biggest advantage of using the macro approach when protecting against format string vulnerabilities is that the actual number of parameters sent from the program to the function is known. This means that the protection can be made more fine-grained and permit potentially unsafe calls to be made in a safe way. On the other hand, macros are not transparent to the protected programs, and programs that use certain kind of conditional compilation directives cannot be compiled as the macros make these programs break the C language specification.

There is a runtime performance overhead when using this pre-processor technique, as the real state in the executing program must be verified against the saved known-good value. This check typically require verifying each parameter sent from the program to the function, and will require about the same time as a full function interception in the plibc dynamic inspector.

To conclude the comparison, we believe that the macro approach provides a good protection against format-string attacks, and possibly some other types of related attacks, but cannot be used to enforce other policies in programs. Using the macro-based approach also requires access to the source code for programs that should be protected, and these programs must be recompiled should a new type of vulnerability be discovered.

Static removal or modification of functionality. Another method to increase the executing environments' resistance to vulnerabilities is to remove possibly dangerous code from system libraries. We believe that this is the best method available if the functionality can be removed without breaking any regulatory standards. Unfortunately, due to the way functions are standardized it is often not possible to do this and still maintain compatibility with the standard and already developed programs.

In some cases, a more resistant implementation of an existing interface can be used, which then provide programs with a more secure environment. If such an alternative implementation does not impose too much overhead, the best option is to unconditionally use it in the library for all calls. However, if the alternative implementation does not fully conform to the standard, or if it imposes a vast performance overhead, it might only be possible to use it in the most dangerous situations. In this case, plibc can be used to inspect the environment and change execution of the program to use the more secure implementation when needed.

If the modifications to the system libraries are only removal of functionality, it is likely that there will be no performance overhead. If more stable implementations are used it is likely that this will affect the execution performance negatively, but it is difficult to tell to which degree.

Kernel-based approaches. There are a number of operating system kernel assisted modifications that can be done to increase the protection of the execution environment. With exception of OpenBSD's W^X memory protection[7], all popular kernel-based methods, such as chroot and jail, restrict what a potentially exploited program is allowed to do. As the kernel can determine which low-level operations are allowed and which are not, and as there is no way to circumvent this protection, we believe that this is a good approach to increase the in-depth protection for a system.

The purpose of using plibc is to prevent a program from being exploited, not to restrict what an already exploited program is allowed to do, as this is not possible from user-land. In many cases, several types of protection can be combined, for example using plibc and chroot for a critical program. Because of the different types of protection offered by kernel-assisted methods and pure userland-methods such as plibc, it is difficult to compare these methods. As the kernel-assisted methods operate outside the program, any performance overhead they impose is not easily measured inside the program.

Interpreted languages and sandboxes. Interpreted languages typically execute the interpreted program in a very limited environment, called a sandbox. In some cases, such as Java, the interpreter itself has a strong notion of security, and allows pieces of interpreted code to execute with different permissions inside the sandbox, or in different sandboxes. Interpreted languages typically also have more runtime information available than a compiled C program has. The limited execution environment and the additional runtime information make it easier to provide a strong protection in the environment, which is also often the case for interpreted languages.

While it is beyond the scope of this article to discuss the relative merits of compiled versus interpreted languages, we conclude that due to the large differences in execution environment, programs developed in interpreted languages have different security characteristics than those developed in compiling languages. Generally, there is more runtime information available in interpreted languages, which provide a good protection against certain types of attacks. On the other hand, interpreted programs are typically vulnerable to other types of attacks and execute a magnitude slower due to interpreter overhead compared to compiled programs.

In some cases, it might be a good approach to use an interpreted language to increase the security in the execution environment, but using this approach also greatly affects other system properties. By using plibc to protect a compiled program, it is possible to use runtime information in the program to make good security decision that increase the protection in the execution environment without imposing large performance overhead.

Conclusion and Future Work

Software plays an important role in all information networks, and hence for almost all non-trivial information processing systems. Malfunctioning software can cause large problems, even for critical infrastructures, such as the electrical power grid.

Static methods, i.e. methods that are not used during program execution, are often the only methods used to increase the dependability in software. By using static methods, it is possible to find certain types of problems, but experience from recent events clearly illustrates that more software protection mechanisms are needed. In this paper we have described how dynamic methods, i.e. methods used during execution of the program, can be used to increase the protection for a program by modifying the execution environment.

We have described plibc, a dynamic rule based system used to apply domain specific rules that modify an executing programs environment. By modifying the environment, it is possible to execute programs in a more secure way, and to apply a domain-specific policy that prevents a program from performing unwanted operations. In our experiments with plibc we have seen that it is possible to increase the dependability in existing software without large modifications and that the performance overhead is linear to the number of runtime inspections done.

Our plans on further work include a larger test of the plibc system in the BTH security laboratory to determine which type of rules are most efficient and how logging can be used to determine potential dangerous states. Also we plan on integrating plibc with a system for separating privileges, which will make it possible to execute unreliable code with lesser privileges, without any support needed from the program.

References

[1] U.S. – Canada Power System Outage Task Force: Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, April 2004. https://reports.energy.gov/
[2] Internet Systems Consortiums Dynamic Host Configuration Protocol Distribution (ISC DHCPD), http://www.isc.org/
[3] NGSEC Advisory “NGSEC-2002-2”, May 2002, Available from http://www.ngsec.com
[4] Buqtraq ID 4701, “ISC DHCPD NSUPDATE Remote Format String Vulnerability”, May 2002, http://www.securityfocus.com
[5] CERT Advisory “CA-2002-12”, May 2002, Full Advisory Available from http://www.cert.org
[6] Cowan, C. et al., “FormatGuard: Automatic Protection From printf Format String Vulnerabilities”, Proceedings of the 2001 USENIX Security Symposium, http://www.usenix.org
[7] OpenBSD 3.3 Introduced “W^X” protection, further information is available in the release notes http://www.openbsd.org/33.html

Paper 16: *A tractable mechanism for time dependent markets*

Full bibliographic reference:

P. Carlsson, A. Andersson, and F. Ygge: *A tractable mechanism for time dependent markets*, in Jen Yao Chung and Liang-Jie Zhang (Eds.), Proceedings CEC-2003 – IEEE International Conference on E-Commerce, pages 31-34. IEEE Computer Society, Los Alamitos, CA, June 2003 (http://www.computer.org).

A Tractable Mechanism for Time Dependent Markets

Per Carlsson
EnerSearch and
Dept. of Information Techn.
Uppsala University, Sweden
Per.Carlsson@cs.lth.se

Arne Andersson
Dept. of Information Techn.
Uppsala University, Sweden
arnea@csd.uu.se

Fredrik Ygge
Trade Extensions and
Dept. of Information Techn.
Uppsala University, Sweden
ygge@csd.uu.se

Abstract

Markets with time dependent goods are special cases of multi commodity markets. An application area of high interest is day-ahead power markets. If these are to be opened for consumer side bidders and local production bidders, the number of actors on the market grows dramatically, and new market mechanisms and algorithms are needed. Another interesting application area with many similarities is bandwidth markets.

The design of large flexible markets with time dependent goods is a computational challenge. In this paper we present a computationally tractable mechanism for time dependent markets. By a number of predefined bid types, it offers useful flexibility to the bidders. We present the market mechanism and the corresponding matching algorithm together with some analysis of its behaviour.

1 Introduction

In time dependent markets, such as power markets, a set of consecutive time slots are often traded simultaneously. However, although the participants may have various types of dependencies and constraints between the time slots, there is typically no, or very weak, support for the expression of such dependencies. In this article, we propose a trading mechanism that allows for a fairly large flexibility in expressing time dependencies, at the same time as it is computationally tractable. The computational aspects are important since the most general way to allow the expression of time dependencies is by a combinatorial auction, which presents us with an NP-hard computational problem. Therefore, it is interesting to have a trading mechanism which (i) allows for sufficient flexibility, (ii) is natural and understandable for participants, and (iii) has a low computational complexity.

Our mechanism has some carefully selected combinatorial features that increase the market flexibility compared to markets where each time period is treated as an independent good. The gain is that it enables participants to express preferences more accurately and an improved market outcome.

2 Main Idea

We consider a market for a set of consecutive time slots (hours). A bid is assumed to be given as a continuous (positive or negative) demand function, expressing one of following:

1. *hourly bids*: separate bids for each hour. If there are k different time periods (hours), all hourly bids may be aggregated into k demand functions, see Figure 1,
2. *block bids*: bids on the same volume each hour. All block bids may be aggregated into a single demand function,
3. *adaptive consumer bids*: bids describing a consumer demand that is not related to any specific hour; the consumer is prepared to buy whenever the price is low enough. All adaptive consumer bids may be aggregated into a single demand function,
4. *adaptive producer bids*: Corresponding to the adaptive consumer bids.

Each bidder can give $k + 3$ different demand functions, hence we say that there are $k + 3$ *bidding tracks*.

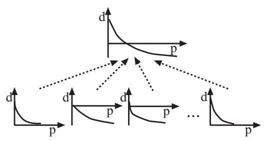


Figure 1. The demand functions of each separate bidding track are aggregated into one, giving full information on supply and demand of the system.

Proceedings of the IEEE International Conference on E-Commerce (CEC'03)
0-7695-1969-5/03 $17.00 © 2003 IEEE

The four types of bids allow for a fairly flexible market. Compared to a fully implemented combinatorial market, the hourly bids correspond to single bids, block bids correspond to traditional combinatorial bids expressing synergies, and the adaptive bids corresponds to XOR bids, expressing complementarity.

3 Problem Formulation

We state the problem as follows:
Given one market with the four bid types, compute

- a price p_i^* for each hour i, and
- an allocation of the adaptive bids,

such that supply meets demand, i.e. to determine a price vector p^*:

$$\begin{array}{l} p^* = \{p_1^*, p_2^*, \ldots, p_k^*\} \\ s.t.\ \forall i: d_i(p_i^*) + t_{ap,i}(p^{max}) + t_{ac,i}(p^{min}) - t_b = 0, \end{array} \quad (1)$$

where $p^{min} = min_i\ (p_i^*)$ and $p^{max} = max_i\ (p_i^*)$.

The existence of a solution is shown in a technical report [2], in the following we show how to compute the solution. Prerequisites used are that demand is continuous and decreasing in price, and that the goods traded on the adaptive sub-markets are divisible.

As said above, supply and demand bids are assumed to be given as continuous (positive and negative) demand functions, expressed as sample vectors. The bids are aggregated along the separate tracks, giving a set of demand functions, one for each track. These functions give full information on supply and demand and an equilibrium can be calculated without any further communication. An equilibrium is expressed as a set of prices where the excess demand for each hour on the market as a whole, but not necessarily on each bidding track, is zero. The outcome of the trade depends on a trade or reallocation between on one hand the hourly sub-markets and on the other the block and the adaptive tracks.

4 Algorithm

On a high level, the algorithm can be described as a binary search over the volume t_b reallocated between the block the hourly tracks. For each iteration in the loop a set of equilibrium prices (relative t_b) of the hourly and adaptive tracks is determined.

For the notations in the algorithm description we need some definitions. First the demand functions.

Definition. 4.1 *Let d_b be the demand function defined by the aggregated demand on the block sub-market, d_i the aggregated demand of hour i, d_{ac} the aggregated adaptive consumer demand, and d_{ap} the aggregated adaptive producer demand.*

The resources reallocated between sub-markets are expressed as follows.

Definition. 4.2 *Let t_b be the resource reallocated from the block sub-market to the hourly sub-markets (the same resource for all hours). Let $t_{a,i}$ be the resource reallocated between any one of the adaptive actors and hour i. Further, let $t_{ac,i}$ be the adaptive consumer demand allocated to hour i, and $t_{ap,i}$ the corresponding producer demand, and let t_c be the resource reallocated between the adaptive tracks.*

The dynamics of the set of prices is expressed as follows:

Definition. 4.3 *Let $p_b(t_b)$ be the equilibrium price of the block market when t_b is reallocated from the block to the hourly sub-markets. Let $p_i(t_b, t_{a,i})$ be the equilibrium price of hour i with t_b as before and $t_{a,i}$ traded with one of the adaptive actors, and let $p_{\forall h}(t_b, t_a)$ be $\sum_{\forall i} p_i(t_b, t_{a,i})$.*

The following algorithm gives a strategy for the search for an optimum. Details on the computations follows the algorithm description.

Algorithm 4.1 (Determination of prices) *{*
pick a value on t_b; *(I)*
while ($|p_{\forall h}(t_b, t_a) - p_b(t_b)| > \epsilon_1$){
for all i set the material balance to t_b; *(II)*
compute adaptive demand; *(III)*
determine $p_{\forall h}(t_b, t_a)$ & $p_b(t_b)$; *(IV)*
if($p_{\forall h}(t_b, t_a) - p_b(t_b) > \epsilon_1$) raise t_b; *(V)*
if($p_{\forall h}(t_b, t_a) - p_b(t_b) < -\epsilon_1$) lower t_b;
}
announce prices;
}

4.1 Algorithm Details

We give the details on the algorithm step by step:

(I) **Excess block demand level.** The excess demand on the block market, t_b, is the main search variable of Algorithm 4.1. Pick a start value on t_b.

(II) **Adjustment of the material balance.** The material balance line of the hourly actors is adjusted to compensate for t_b, see Figure 2. By the adjustment, the equilibrium price changes for the hour under observation. In Figure 2, $p_i(0, 0)$ equals the equilibrium price with no trade between sub-markets, and $p_i(t_b, 0)$ is the equilibrium price when t_b is traded with the block but no trade has taken place with any adaptive actor.

(III) **Determination of the adaptive demand.** The reallocation between time dependent actors and time independent ones requires some special attention. Any

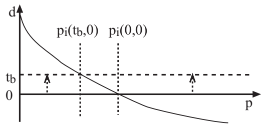


Figure 2. In the search for a total market equilibrium the hourly demand has to balance an excess demand on the block. Graphically this could be viewed as moving the material balance line in the plot from zero to t_b.

reallocation between time dependent actors bound to different time periods has to be avoided. To prevent it, the search for an optimal allocation is based on parts of their demand functions only. For for each hour we define two new demand functions as follows:

Definition. 4.4 *For all prices p we define the function d_i^+ and d_i^- as follows: $d_i^+(p) = max(d_i(p) - t_b, 0)$, and $d_i^-(p) = min(d_i(p) - t_b, 0)$.*

We define two new aggregate demand functions expressing all positive and negative hourly demand, respectively:

Definition. 4.5 *For all prices p and hours i we define $d_{\forall h}^+ = \sum_i d_i^+(p)$ and $d_{\forall h}^- = \sum_i d_i^-(p)$.*

The equilibrium prices related to the two adaptive sides are determined using a binary search based aggregation of (i) $d_{\forall h}^+$ and d_{ac}, and of (ii) $d_{\forall h}^-$ and d_{ap}, respectively. If the outcome is that $p^{min} > p^{max}$, this is not sufficient.Then a reallocation between the adaptive actors is introduced. In this case, the volume reallocated between adaptive actors, t_c, is determined with an additional binary search.

It is obvious that if there is a reallocation, it can reduce the price of more than one high demand hour, and raise the price of more than one low demand hour.

(IV) **Determination of prices, including $\mathbf{p_{\forall h}(t_b, t_a)}$.** Determine the price for each hour i, $p_i(t_b, t_{a,i})$. From the set of hourly equilibrium prices $p_{\forall h}(t_b, t_a)$ is computed as it is expressed in Definition 4.3[1].

(V) **Breaking condition.** When the difference between $p_{\forall h}(t_b, t_a)$ and $p_b(t_b)$ is sufficiently small to be considered zero the search is ended and the set of prices is fixed.

[1]The prices $p_{\forall}(t_b, t_a)$ and $p_b(t_b)$ could be expressed in two ways, either the price for a resource level during the whole block or on hourly scale. On an hourly scale $p_{\forall h}(t_b, t_a)$ should equal the average hourly price, and the block price, $p_b(t_b)$, should be expressed on an hourly scale.

We conclude that the final equilibrium price within a specific hour is depending on both its own demand and a reallocation between this hour and (i) the block and (ii) at most one of the adaptive sub-markets.

4.2 Algorithm 4.1 Determines an Equilibrium

Algorithm 4.1 determines an optimal price vector, p^* of Eq. (1), and does this efficiently. Once the aggregation of bids is done, the algorithm is independent of the number of actors.

Theorem 4.1 *Within a predefined finite resolution in prices, Algorithm 4.1 determines an equilibrium covering hourly bids, block bids, and the adaptive bid types.*

With s_1 and s_2 the size of the search space in volume and prices, respectively (in a proper resolution), and bids on h hours simultaneously, the computational complexity of the algorithm is $\mathcal{O}(h \log s_1 \log s_2)$.

The proof is given in the technical report [2].

5 Example

To show the behaviour of the algorithm we set up a small example with a two hour block size and walk through one step of the iteration. The enumeration of the example is the same as in the algorithm description.

(I) At this iteration step, the block excess demand, t_b is set to four. As a consequence, the equilibrium price of the block market changes, see Figure 3.

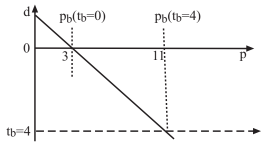


Figure 3. The demand function of the block. When the excess demand is changed from zero to (minus) $t_b = 4$, the block price is changed from 3 to 11. Step (I).

(II) The demand functions of the hourly tracks are affected by this and the material balance line of the hourly demand functions is updated, Figure 4.

(III) From this it is possible to calculate the hourly positive and negative demand, $d_{\forall h}^+$ and $d_{\forall h}^-$, c.f. Definition 4.4 and 4.5 and Figure 5. The demand function of the adaptive producers is aggregated with $d_{\forall h}^+$, and the

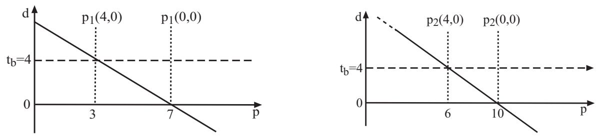


Figure 4. The demand functions of the hours. When the material balance line is changed, the equilibrium prices change too. Step (II).

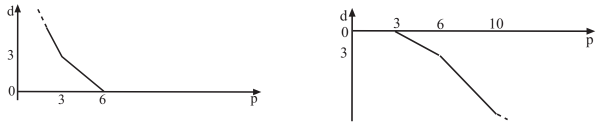


Figure 5. The positive and negative demand of the hourly tracks, $d^+_{\forall h}$ and $d^-_{\forall h}$, are used in the trade with the adaptive actors, Step (III).

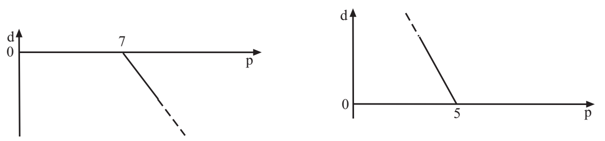


Figure 6. The demand functions of the adaptive producers and consumers.

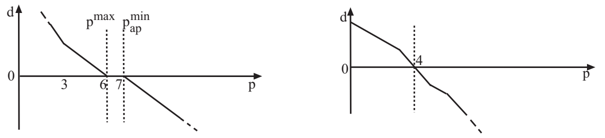


Figure 7. Left pane: A gap between the highest buying price, p^{max}, and the lowest selling price, p^{min}_{ap}, gives that no adaptive producer trade takes place. Right pane: An equilibrium price of 4 is established in the trade between hours and adaptive consumers. This affects any hour i with $p_i(t_b, 0) < 4$. Step (III).

demand of the adaptive consumers is aggregated with $d^-_{\forall h}$, Figure 6 and Figure 7.

In Figure 7 we see that there is a gap between the highest consumption price of the hourly markets and the lowest production price of the adaptive producers, hence no reallocation is performed. On the other hand, a reallocation takes place between the aggregated hours and the adaptive consumers (in this case involving h_1 and the adaptive consumers).

(IV) As an effect of the trade with the block and with the adaptive consumers, the equilibrium price of h_1, $p_1(t_b, t_{a,1})$, is changed first from seven to three and then to four. The price of h_2 is affected by the trade with the block, and changes from ten to six, but it is not affected by any trade with the adaptive actors.

In this iteration $p_{\forall h}(t_b, t_a) = 4 + 6 = 10$. The equilibrium price on the block market, $p_b(t_b)$, is 11, Figure 3.

(V) Since $p_{\forall h}(t_b, t_a) < p_b(t_b)$, t_b is to high, and in next iteration step $t_b^{max} \leftarrow t_b$ and $t_b \leftarrow t_b^{min} + (t_b - t_b^{min})/2$.

6 Concluding Remarks

In this paper we presented a computationally tractable mechanism for time dependent markets. By a number of predefined bid types, it offers useful flexibility to the bidders. The capabilities are easy to understand and the mechanism is computationally tractable.

The market mechanism has properties that are highly relevant in e.g. day-ahead power markets [1, 3] and bandwidth markets [4, 5]. In a power setting, the big advantage of the mechanism (compared to the power markets of today) comes with the possibility to set up electronic markets with a huge number of participants. With a direct market participation of small size actors (formerly represented by distributors) the market outcome can become considerably more efficient.

Acknowledgement: The paper is based on work performed within the CRISP project (distributed intelligence in CRitical Infrastructures for Sustainable Power), financially supported by the European Commission, contract nr ENK5-CT-2002-00673:CRISP, which is gratefully acknowledged.

References

[1] S. Borenstein, M. Jaske, and A. Rosenfeld. Dynamic pricing, advanced metering and demand response in electricity markets. (Available from http://www.ef.org), 2002.

[2] P. Carlsson, F. Ygge, and A. Andersson. A tractable mechanism for time dependent markets. Technical Report 2003-027, Department of Information Technology, Uppsala University, April 2003. (Available from www.it.uu.se/research/reports/).

[3] R. H. Patrick and F. A. Wolak. Using customer demands under spot market prices for service design and analysis. Technical Report WO 2801-11, EPRI, 2001. (Available from http://www.rci.rutgers.edu/~rpatrick/hp.html).

[4] L. Rasmusson. Evaluating resource bundle derivatives for multi-agent negotiation of resource allocation. In J. Liu and Y. Ye, editors, *E-Commerce Agents*, number 2033 in LNAI, pages 154–165, Berlin Heidelberg, 2002. Springer Verlag.

[5] L. Rasmusson and G. Paues. Network components for market-based network admission and routing. Technical report, Swedish Institute of Computer Science, SICS, Kista, Sweden, 2002.

Paper 17: *A flexible model for tree-structured multi-commodity markets*

Full bibliographic reference:

P. Carlsson and A. Andersson: *A flexible model for tree-structured multi-commodity markets*, Electronic Commerce Research journal, to appear (2005).

A Flexible Model for Tree-Structured Multi-Commodity Markets

Per Carlsson*
EnerSearch and Uppsala University,
Office: Computer Science Department, Lund University, Box 118,
SE - 221 00 Lund, Sweden,
Email: Per.Carlsson@cs.lth.se

Arne Andersson
Uppsala University,
Box 311, SE - 751 05 Uppsala, Sweden,
Email: arnea@csd.uu.se

Accepted for publication in Electronic Commerce Research

Abstract

In this article we study tree-structured multi-commodity markets. The concept is a way to handle dependencies between commodities on the market in a tractable way. The winner determination problem of a general combinatorial market is well known to be NP-hard.

It has been shown that on single-unit single-sided combinatorial auctions with tree-structured bundles the problem can be computed in polynomial time. We show that it is possible to extend this to multi-unit double-sided markets. Further it is possible to handle the commodities of a bundle not only as complements but as perfect substitutes too. Under certain conditions the computation time is still polynomial.

Keywords: multi commodity markets, electronic markets, computational markets, equilibrium markets, resource allocation, power markets, bandwidth markets, computational complexity.

* **Acknowledgement:** This article is based on work performed within the CRISP project (distributed intelligence in *cr*itical *i*nfrastructures for *s*ustainable *p*ower), financially supported by the European Commission, contract nr ENK5-CT-2002-00673:CRISP, which is gratefully acknowledged.

1 Introduction

Actors on markets where multiple commodities are traded simultaneously typically have dependencies between the traded commodities (complementarities and substitutability). Hence, market mechanisms that support the expression of these dependencies are highly interesting from an actors' perspective. Traditional simultaneous multi-commodity markets, single unit auctions as well as two-sided markets give no or very limited support for the expression of dependencies between commodities. Examples of situations where this is an issue are day-ahead power markets (e.g. the Nordic Nord-Pool market) and the often discussed radio frequency auctions (as run by e.g. the FCC)[16].

The economical efficiency of a competitive market depends on the actors' possibilities to express their true valuations. The more they are able to express their valuations in terms of complementarities and substitutability between commodities, the higher is the potential efficiency of the market. Hence, the outcome of markets where there are practically no opportunities to express dependencies may be clearly sub-optimal.

To reach optimal economical efficiency on the market the ideal would be to allow all possible combinatorial bids expressing synergies and substitutability. Given that the participants act price-takers, this would open for to compute an optimal price vector and corresponding allocation (assuming that they exist). The bad news is that this gives a computational problem that is known to be NP-hard, i.e. the worst case computational complexity is too high. Hence, there is a conflict or tradeoff between economical and computational efficiency.

Since the winner determination problem of the general combinatorial auction is computationally hard, a number of simplifications and special cases have been studied in the literature [11, 16, 17]. One natural case is tree-structured markets where any two bundles either are disjoint or one is a proper subset of the other. As pointed out by Rothkopf et al [16], for a single-unit single-sided auction this type of bid structure can be handled with a polynomial time algorithm.

In this article we study more general tree-structured market mechanisms[1] handling multi-commodity, multi-unit markets. As in the market described by Rothkopf et al, we allow for complementarities to be expressed for tree-structured bundles. However, we also allow the following more general types of bids:

- *Multi-unit bidding.* A bid on a predefined bundle is expressed as a demand curve, which implies a multi-unit market.
- *Two-sided market.* A demand curve can be buy, sell, or both.

[1]We use the notion of a *market mechanism* to denote the rules of the market, whereas *market protocol* includes the behaviour of the actors on the market.

- *Bidding for substitutes.* Bidding for substitutes (XOR-type of bids) normally implies that the winner determination becomes computationally intractable even for tree-structured bids. We show that the problem is solvable in subexponential time also when a bidder is allowed to express that the commodities in a bundle are perfect substitutes, i.e. the volume in the bid's demand curve is on the total allocation over the commodities within the bundle.

1.1 Motivation for Tree-Structured Markets

There are a number of reasons for studying markets with tree-structured bidding. Two of these arguments are:

- *Expressibility vs. complexity.* Tree-structured bids are signifficantly more expressive than plain single-commodity bids. In our case, we manage to handle both complemtens and substitutes. Compared to arbitrary combinatorial bids, the possibility to compute winner determination in polynomial time makes an important difference. All in all, we achieve a tradeoff between expressibility and computational complexity.

- *A natural structure.* A hierarchical structure of commodities is natural and easy to understand. For example, in many of today's systems for e-Sourcing, such as online B2B auctions a terminology of "lots", grouped into "categories" is very common, which clearly reflects an underlying tree-structure.

1.2 Structure

In the following section we present a small result on single-unit auctions. Then we move on to multi-unit markets in Section 3. We give a sketch of a market mechanism for tree-structured markets. After this we move to the main result of this article, presented in Section 4. Here we present a novel approach to tree structured markets that does not only handle bundling of complementarities on a multi-unit market, but it handles substitutes too. In Section 4.2 we present the main idea of the mechanism. In Section 4.3 we move to a more precise problem formulation. After this we present an algorithm solving the problem in Section 4.4, more detailed information on the algorithm is given in an appendix. Experiences gained from a first test implementation are discussed in Section 4.5, after this we draw some general conclusions in the final section.

2 Improving the Results of Rothkopf et al

In a tree-structured single-unit single-sided market each commodity corresponds to a leaf, and each multi-unit bundle corresponds to an internal node. There are no unary nodes and therefore the total number of nodes is at most $2n-1$, n being the number of commodities. Under the assumption that we know the best bid on each bundle we only need to consider at most $2n-1$ bids, and we can express the complexity in terms of n regardless of the number of bids.

Under these conditions Rothkopf et al presented an $\mathcal{O}(n^2)$ time algorithm for winner determination [16]. However, with a simple algorithm the computations can be performed in linear time. We assume this to be folklore, but since we have not found it in the literature we here provide a proof sketch.

Given a tree representing the bid structure we store one number in each node, representing the best bid value on the bundle. The winner determination is computed during two tree traversals:

1. Perform a postorder traversal of the tree, do the following at each non-leaf node: If the sum of the children values is larger than the value stored in the node, mark the node's bid as replaced and replace the value with the sum of the children.

2. Make a partial preorder traversal and do the following at each visited node: If the value in the node is not marked as replaced include it in the set of winning bids, else proceed to its child nodes.

3. Present the set of winning bids.

Both traversals require $\mathcal{O}(n)$ time.

We summarise this with the following observation:

Observation 2.1 *The winner determination problem of tree-structured single-unit single-sided markets can be solved in time linear in the number of commodities.*

An example is given in Figure 1. The values inside the nodes represent the highest bid on the corresponding bundle. A value to the left of the node corresponds to a replacing value found during the first traversal. The nodes of the winning combination, i.e. the topmost nodes with non-replaces values, are highlighted with a double ring (37, 12, 10, 7, and 50 summing to 116).

3 Multi-Unit with Demand Curves

On a two-sided multi-commodity, multi-unit market with demand curves the opportunities of the bidder are richer than in the above auction. Furthermore, computationally it presents us with a more complex problem. Here,

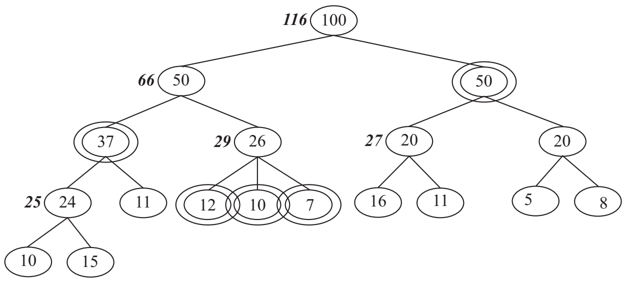


Figure 1: *Illustration of the linear winner determination algorithm for single unit single sided markets.*

the bidder expresses his demand for individual commodities as well as for predefined bundles as a function of price, and supply is expressed as negative demand. (A bundle bid expresses the same demand for all commodities of the bundle.) We assume that each demand function is a piecewise linear function over a predefined, evenly distributed set of prices. Furthermore, we assume that the function is continuous and decreasing in price.

A set of equilibrium prices can be established using a resource oriented algorithm. As with the single unit auction we build the bundle tree, with each node representing a predefined bundle. All nodes hold an aggregate excess demand function based on the demand of all bidders. The root of the tree corresponds to a bundle including all commodities. We determine the total demand for this bundle in a binary search. At each step of the search, we recursively solve the complete problem for each sub-tree. The goal is to establish a set of prices for the individual commodities, that renders an equilibrium with respect to the demand expressed in all nodes of the tree.

Example. Consider a two commodity market where it is possible to express a (positive or negative) demand for each commodity separately, and for the combination, Figure 2. This creates three submarkets. Treated separately, the equilibrium prices of the three submarkets are $\{4, 4.5, 3\}$ (dashed line *'a'* in the figures). This set of prices is clearly not efficient as the average price of the commodities is higher than the bundle price. Instead, asserting a negative excess demand of 1 on the bundle, balanced by a corresponding positive demand for each single commodity (*'b'* in the figures), we end up with a new price vector $\{3, 4, 3.5\}$, where the average of the single commodities equals the bundle price, i.e. an optimal set of prices.

If the bundle tree e.g. is a balanced binary tree the height of the tree is $\log n$. If the size of the search space over the above excess demand is s, the binary search of a node requires $\lceil \log(s+1) \rceil$ search steps. The total complexity satisfies:

$$T(1) = \lceil \log(s+1) \rceil$$

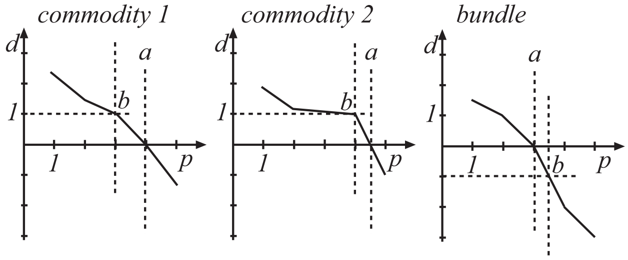


Figure 2: A small market example, determination of equilibrium prices. For each submarket *'a'* is the local equilibrium price, and *'b'* indicates the equilibrium price after adjusting so that the average price of the single commodities equals the bundle price.

$$T(n) = \lceil \log(s+1) \rceil \left(2T\left(\frac{n}{2}\right) \right) = n \lceil \log(s+1) \rceil^{1+\log n} = \\ = \mathcal{O}\left(n^{1+\log \lceil \log(s+1) \rceil} \log s \right),$$

where $T(n)$ is the total number of comparisons and $\lceil \log(s+1) \rceil$ is the number of comparisons in one binary search. In the above we assume n to be an even power of two. From this we derive that the time complexity is polynomial given that s is constant. This gives the following theorem:

Theorem 3.1 *The worst case time complexity of solving an n commodity multi-commodity, multi-unit market with demand curves structured as a balanced tree is*

$$\mathcal{O}\left(n^{1+\log \lceil \log(s+1) \rceil} \log s \right)$$

where s is the size of the excess demand space.

Proof. The complexity is given by the recursion above. □

Details are left to Section 4 where we discuss a mechanism that also handles substitutes.

4 Main Result

4.1 Allowing Substitutes

Finally we add the possibility to bid for perfect substitutes. That is, the volumes in a bid is on the total allocation over the commodities in the bundle.

The intuition behind is that when the commodities within the bundle are perfect substitutes for the bidder, a buyer prefers to pick among the lowest price commodities, and in a similar way a seller prefers to sell at highest possible price. In a practical situation a bidder typically submits this type of bids as a complement to his other bids.

The practical usefulness of this type of bids is clear but it introduces a number of computational problems. A first approximation of a market solution that would enhance the market possibilities in this direction is presented in previous work [7] and illustrated in Figure 3.

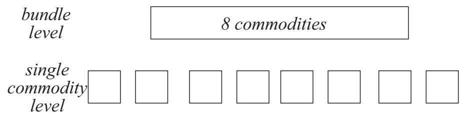


Figure 3: *The bidding possibilities offered by the market mechanism proposed in earlier work [8].*

The rest of this article is devoted to solving the problems of a tree-structured market allowing bids on substitutes, a market mechanism — the CONSEC[2] mechanism — Figure 4, and an algorithm description.

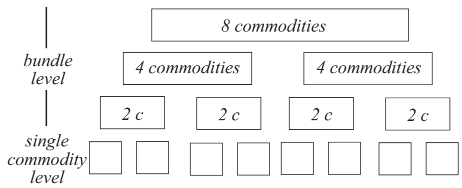


Figure 4: *The tree-structured market mechanism that is presented in this article. In this example a market with eight commodities organised in a binary structure.*

4.2 Main Idea

We consider a multi-commodity market organised in a hierarchical tree structure of commodity bundles, Figure 4.

A bidder could submit multiple bids according to the following:

1. *single bids*: demand curve for each commodity,
2. *bundle bids*: demand curve for a bundle, the same volume for each included commodity,
3. *substitute buy bids*: a curve describing a consumer demand that could be arbitrarily distributed over a bundle (the consumer preference is to buy at lowest price),

[2] CONSEC, a tree-structured market mechanism for e.g. a set of CONSECutive time periods.

4. *substitute sell bids*: symmetric to the substitute buy bids.

Demand is assumed to be continuous and decreasing in price.

The tree can be organised in different ways, with arbitrary degree in each node. As an example consider a market with n commodities, where n is an even power of two. If this market is organised a binary tree structure of bundles, each bidder can give up to $4n-3$ different bids (demand functions), hence we say that there are $4n-3$ *bidding tracks* (one single track for each commodity/leaf node, and three tracks for each bundle/internal node, type one and type two – four in the list above, respectively).

Please note that all demand functions of a track may be aggregated into a single function giving the excess demand of the track as a function of price, see Figure 5. This aggregation is outside the scope of this paper, standard techniques are presented in e.g. [9, 10, 2].

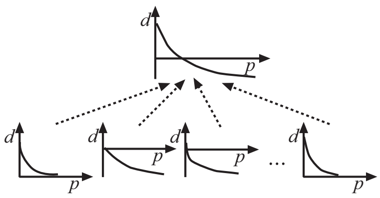


Figure 5: *The demand functions of each separate bidding track are aggregated into one, giving full information on supply and demand of the system. Supply is expressed as negative demand.*

The four bids types allow for a fairly flexible market. Compared to a fully implemented combinatorial market, the single bids are similar, bundle bids correspond to traditional combinatorial bids expressing synergies, and the substitute bids corresponds to XOR bids.

As shown below, although we combine single bids, bundle bids, and XOR-type of bids, the market can be handled optimally in a computationally efficient way.

4.3 Problem Formulation

Given a market with the bid types presented above, compute

- a price p_i^* for each commodity i, and
- an allocation for the substitute bids,

that renders an equilibrium, i.e. the excess demand for each commodity on the market as a whole is zero, but it might well be non-zero on individual bidding tracks.

With demand expressed as above, Section 3, the bids of the separate tracks are aggregated giving a set of demand functions, one for each track. These functions give full information on supply and demand and an equilibrium can be calculated without any further communication.[3]

4.3.1 Definitions

The market is organised in a tree structure, hence it is convenient to refer to single commodities as leaf nodes and bundles of commodities as internal nodes (or bundle nodes). We define the following (aggregate) demand functions describing the demand of all bidding tracks:

Definition. 4.1 *Let*

- $d_j(p)$ *or* d_j *be the main demand function of node* j *as a function of a price* p*,*
- $b_j(p)$ *or* b_j *be the buying demand with the commodities of bundle node* j *viewed as perfect substitutes, and*
- $s_j(p)$ *or* s_j *be the corresponding selling demand.*

Note that b_j and s_j are only defined for bundle nodes.

We define the following demand that is expressed in the interaction between nodes in the market tree:

Definition. 4.2 *Let*

- d_j^{ch} *be the (positive or negative) demand of node* j *that it expresses towards its children, and that they all have to meet,*
- d_j^{min} *be the (negative) excess demand of node* j *induced by the minimum price set by the parent, that it expresses towards the parent, and*
- d_j^{max} *the corresponding (positive) excess demand induced by the maximum price set by the parent.*

Finally we define the following price notations:

Definition. 4.3 *Let*

- p_j^{min} *be the minimum price imposed by node* j *on its child nodes,*
- p_j^{max} *the corresponding maximum price,*
- p_j *be a price of node* j*, for a bundle node it is defined as the average price of the children.*

We now move on to a formal specification of the problem, proof of existence of an equilibrium, and in Section 4.4 an algorithm that computes an equilibrium.

[3]This holds under the assumption that the optimal solution is within the price span of the given bids.

4.3.2 Formal Specification of the Problem

The problem is to determine a price vector p^*

$$p^* = \{p_1^*, p_2^*, \dots, p_n^*\} \tag{1}$$

s.t.

$\forall$ leaf nodes j with parent i:

$$d_j\left(p_j^*\right) + d_i^{ch} - d_j^{min} - d_j^{max} = 0, \tag{2}$$

$$p_i^{min} \leq p_j^* \leq p_i^{max} \tag{3}$$

$\forall$ bundle nodes j with parent i and children v, w:

$$d_j\left(p_j^*\right) + d_i^{ch} - d_j^{ch} = 0, \tag{4}$$

$$b_j + d_v^{min} + d_w^{min} - d_j^{min} = 0, \tag{5}$$

$$s_j + d_v^{max} + d_w^{max} - d_j^{max} = 0, \tag{6}$$

if a bundle node has more than two children the equations are adjusted to take all of them into account. Figure 6 and 7 illustrate the equations (without the notational assumption that a bundle node has no more than two children).

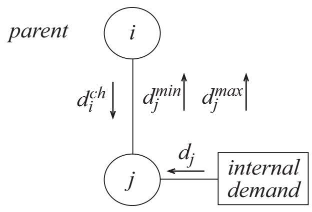


Figure 6: *The demand for resources related to a leaf node of a market tree. The arrows indicate the origin of each demand. With parent node i,* d_i^{ch} *is a demand that this node has to meet; if either the minimum or the maximum price influences the node, the induced excess demand is expressed towards the parent. With this the node is in equilibrium, c.f. Eq. (2).*

It should be noted that for bundle nodes the constraint that $p_i^{min} \leq p_j^* \leq p_i^{max}$ is secured by the definition of p_j as the average price of its children, with no child price outside the boundaries.

4.3.3 The Existence of an Equilibrium

The nodes of the market tree interact with both higher and lower levels of the hierarchy to enhance the market outcome. The root of the system and leaf nodes are special cases with limited interaction.

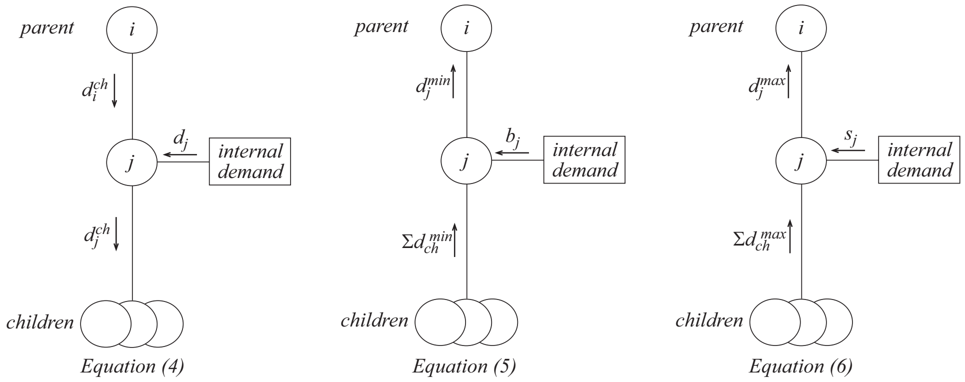


Figure 7: *The demand for resources related to a bundle node as given by Eq. (4) – Eq. (6). The arrows indicate the origin of each demand. To maintain an equilibrium the internal bundle demand, d_j together with the demand of this node on its children d_j^{ch} has to meet the demand of the parent node, d_i^{ch}. Further, the children's demand, $\sum d_{ch}^{min/max}$, induced by $p_j^{min/max}$ is balanced by $\left(b_j - d_j^{min}\right)$ and $\left(s_j - d_j^{max}\right)$, respectively. If $p_j^{min} > p_i^{min}, d_j^{min} = 0$, and if $p_j^{max} < p_i^{max}, d_j^{max} = 0$.*

In order to prove the existence of an equilibrium for the system, we prove the existence of an equilibrium for an arbitrary node.

Lemma 4.1 *For an arbitrary node j with parent i, given*

- *a (positive or negative) demand expressed by the parent d_i^{ch},*
- *a minimum price p_i^{min}, and*
- *maximum price p_i^{max}*

there exists

- *a price p_j,*
- *a (negative) excess demand d_j^{min} generated by the minimum price, left for the parent to meet, and*
- *a corresponding (positive) demand d_j^{max} generated by the maximum price,*

setting the node in balance with respect to the input variables. As a side effect the system rooted in the node is set in balance too.

Proof.
Leaf nodes, Eq. (2): An equilibrium in the node is obtained with a price

p_j such that $d_j(p_j) + d_i^{ch} = 0$. The existence of such a p_j follows from continuous and decreasing demand.

If $p_j < p_i^{min}$ an imbalance is created when setting $p_j = p_i^{min}$. The local balance can be restored by setting $d_j^{min} = d_i^{ch} + d_j\left(p_i^{min}\right)$. Everything is symmetric in p_i^{max} and d_j^{max}.

This fulfils Eq. (2) and the node is in equilibrium, c.f. Figure 6.

Bundle nodes: The notion of an equilibrium in a bundle node is different from a leaf node. Where a leaf node has a single demand function, affected by both d_i^{ch}, p_i^{min}, and p_i^{max}, a bundle node has three different demand functions d_j, b_j, and s_j, interacting with d_i^{ch}, p_i^{min}, and p_i^{max} respectively, c.f. Figure 7.

Eq. (4): The equation expresses an equilibrium regarding bundle demand (i.e. a demand for the same resource over all commodities of the bundle). In the equation d_i^{ch} is fixed. Let p_j be the average price of the children as in Definition 4.3, given d_j^{ch}. By continuous and decreasing demand we have that an increase in d_j^{ch} gives a higher p_j, and hence a lower $d_j\left(p_j\right)$. Hence there exists a price p_j, such that $d_j(p_j) + d_i^{ch} - d_j^{ch} = 0$. As p_j is given by the average price of the system rooted in the node, this system is in balance too when this price is established.

Eq. (5): The equation expresses an equilibrium regarding the effects of minimum prices and buying demand with substitutability. This demand is not affected by the bundle price p_j, but the minimum price of the child nodes.

With children v, w, there exists some lowest price p_j^{lowest} of the system rooted in node j, such that the buyer demand with substitutability of this node is in balance with the demand, $d_v^{min} + d_w^{min}$, expressed by its child nodes (independent of p_i^{min}, the minimum price given by node j's parent). Depending on whether $p_j^{lowest} > p_i^{min}$ or $p_j^{lowest} \leq p_i^{min}$, we get two cases:

1. $p_j^{lowest} > p_i^{min}$: this implies that $b_j(p_i^{min}) + d_v^{min} + d_w^{min} > 0$. Let $p_j^{min} = p_j^{lowest}$ and $d_j^{min} = 0$, and
2. $p_j^{lowest} \leq p_i^{min}$: this implies that $b_j(p_i^{min}) + d_v^{min} + d_w^{min} \leq 0$. Let $p_j^{min} = p_i^{min}$ and $d_j^{min} = b_j(p_i^{min}) + d_v^{min} + d_w^{min}$,

in both cases there exists p_j^{min} and d_j^{min} such that $b_j(p_j^{min}) + d_v^{min} + d_w^{min} = 0$.

Eq. (6): Everything is symmetric when it comes to maximum prices, Eq. (6).

The node is in equilibrium when all three of Eq. (4) – Eq. (6) hold, i.e. then the node and the system rooted in it is in balance given d_i^{ch}, p_i^{min}, and p_i^{max}.

All together this gives the lemma. □

From this lemma we get the following theorem on the existence of an equilibrium.

Theorem 4.1 *There exists a price vector* $p^* = \{p_1^*, p_2^*, \ldots, p_n^*\}$*, rendering an equilibrium on a* CONSEC *market.*

Proof. We have from Lemma 4.1 that for a given triplet $(d_i^{ch}, p_i^{min}, p_i^{max})$, given by its parent node i, there exists a price such that Eq. (2) holds for an arbitrary leaf node, and such that Eq. (4) – Eq. (6) hold for an arbitrary bundle node. In both cases this constitutes a local equilibrium of the node.

In particular, with a zero demand from the outside on the root node (which covers all commodities), and without restricting minimum and maximum prices at the same node, we have an equilibrium of the whole market when this node is in equilibrium, as an equilibrium in one node is based on its child nodes being in equilibrium recursively. □

From this we move on to the algorithm that we suggest for establishment of a market equilibrium.

4.4 Algorithm

We describe the algorithm from the viewpoint of an arbitrary bundle node j with parent i. Given a triplet consisting of (i) the demand from the parent node, (ii) a minimum price, and (iii) a maximum price it returns a corresponding triplet consisting of (i) an equilibrium price, (ii) a negative excess demand induced by the minimum price, and (iii) a positive excess demand induced by the maximum price. The algorithm mainly consists of a nested exponential-and-binary search.[4] Each exponential-and-binary search starts at the value of the last iteration.

Algorithm 4.1 (Equilibrium Search) :
double[] findEquilibrium$(d_i^{ch}, p_i^{min}, p_i^{max})$*{*
do an exponential-and-binary search in d_j^{ch}
starting from the value of the previous call,
at each step in the search:{
do an exponential-and-binary search in p_j^{min}
starting from p_i^{min}*, and*
do an exponential-and-binary search in p_j^{max}
starting from p_i^{max}*,*

[4] In an exponential-and-binary search we start by performing an expanding inverted binary search, followed by an ordinary binary search within the boundaries defined by the first search.

at each step of the searches:{
*/*recursive call*/*
$\forall children:$
findEquilibrium$(d_j^{ch}, p_j^{min}, p_j^{max})$*;*
use return values for these evaluations:
} until Eq. (5 & 6) are fullfilled
} until Eq. (4) is fullfilled
return $\{p_j, d_j^{min}, d_j^{max}\}$*;*
}

In practice the breaking conditions are that the solutions are sufficiently close to optimal.

We give some further details on the algorithm in Appendix A, where we describe the algorithm in terms of a few Java style methods.

The root node and a leaf node are special cases. By definition *a leaf node* does not have any children and it does only have a single demand function. Hence it establishes an equilibrium price corresponding to the given demand from the parent node. If this price is lower than the imposed minimum price or higher than the maximum price it is adjusted and any excess demand generated by this adjustment is expressed towards its parent. To set a full market in balance *the root node* is set in balance, by definition with no demand from above and no restricting minimum and maximum prices.

4.4.1 Algorithm 4.1 Computes an Optimal Set of Prices

What we need to prove is that Algorithm 4.1 computes a set of prices as in Theorem 4.1.

Theorem 4.2 *Algorithm 4.1 correctly computes a set of prices* $p^* = p_1^*, p_2^*, .., p_n^*$ *as in Theorem 4.1, and hence it establishes an equilibrium on a* CONSEC *market.*

Proof.
Leaf nodes: For an arbitrary single commodity node j with parent node i, the actions of the algorithm consists of the parent expressing a demand, d_i^{ch}, a minimum and a maximum price, p_i^{min} and p_i^{max} respectively. Based on this input the node computes a price p such that $d_j(p) + d_i^{ch} = 0$ or in practice $\left|d_j(p), -d_i^{ch}\right| < \epsilon$ for some sufficiently small $\epsilon > 0$. If $p < p_i^{min}$, $p \leftarrow p_i^{min}$ and $d_j^{min} \leftarrow d_j(p_i^{min}) + d_i^{ch}$ to compensate for this. If the maximum price is exceeded, a corresponding action is taken. By this Eq. (2) is fullfilled for the given input, and the node is in balance.
Bundle nodes: For an arbitrary bundle node j with parent node i, given a triplet $(d_i^{ch}, p_i^{min}, p_i^{max})$ the algorithm performs a three dimensional search in a nested loop. The goal is to set a new triplet $(d_j^{ch}, p_j^{min}, p_j^{max})$ for its children

(with $p_j^{min} \geq p_i^{min}$ and $p_j^{max} \leq p_i^{max}$) such that Eq. (4) – Eq. (6) hold at node j for the given input triplet. As stated in Theorem 4.1, continuous and decreasing demand gives that such a triplet exists. As above, in practice the search will be ended when sufficiently close to the solution. The recursive approach gives that when the equilibrium is reached in the node, the same holds for all nodes rooted in j.

When the root node of the system is in balance, the whole system is in balance, and this concludes the proof. □

4.4.2 The Complexity of Algorithm 4.1

The complexity of this market mechanism is highly dependent on the depth of the market tree.

The bad news is that the worst case computational complexity of interesting markets could be to high to be practical. An example is the market of Figure 8, that could be a natural extension of e.g. today's day-ahead power markets. Our test implementation, far from fine tuned, indicates that a straight-forward binary search implementation that does not utilise prior knowledge in an iteration step is hardly practical. It is easy to understand why, as the probability is high to reach a running time close to the worst case.

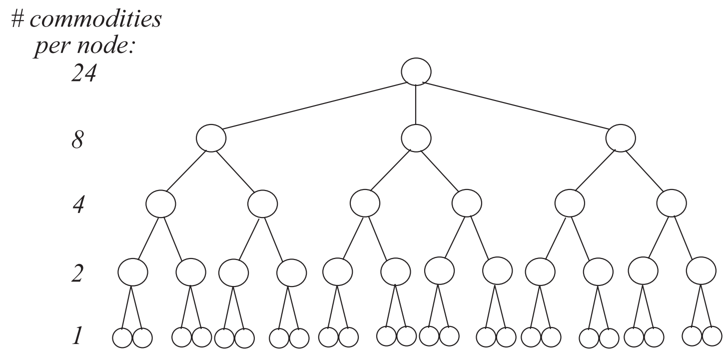


Figure 8: *A market where 24 commodities are traded simultaneously, could for example be organised with three eight commodity market structures that have a common root node. A day-ahead power market is a good example of a real-world market where this fits well.*

On the other hand *the good news* is that algorithms that utilise expontential-and-binary search, as the one we suggest, has shown to be fast in practice when it comes to the same problem instances.

The analysis of the computational complexity presented here does not take the advantages of the exponential-and-binary search of Algorithm 4.1 into account, but is based on the simple binary search approach. When it comes to worst case behaviour, this is correct, if we would try to give a theoretical evaluation of the average behaviour it would not.

In the worst case, the establishment of a local equilibrium of a bundle node renders a full nested binary search in the three search variables, with recursive calls of the child nodes at each search step.

Let s_1 and s_2 be the size of the search spaces in volume and prices, respectively (given in a resolution such that the deviations from the true optimum are sufficiently small). Then the worst case local search cost of a bundle node is $2\lceil\log(s_1+1)\rceil\lceil\log(s_2+1)\rceil$ comparisons (one search in bundle demand, with a nested parallel search in minimum and maximum prices). The corresponding cost of a leaf node is $\lceil\log(s_1+1)\rceil$, as there is a sole search for a price corresponding to the given demand expressed by the parent node (here the work related to minimum and maximum prices is constant). With an explicit inverse demand function the work of a leaf node reduces to a constant time operation.

The total worst case cost depends on the depth of the market tree. The deepest tree structure that makes sence is a binary tree, where we get the recursion:

$$\begin{aligned} T(1) &= \lceil\log(s_1+1)\rceil \\ T(n) = (2\lceil\log(s_1+1)\rceil\lceil\log(s_2+1)\rceil)\left(2T\left(\frac{n}{2}\right)\right) &= \\ = (4\lceil\log(s_1+1)\rceil\lceil\log(s_2+1)\rceil)\left(T\frac{n}{2}\right) &= \\ = (4\lceil\log(s_1+1)\rceil\lceil\log(s_2+1)\rceil)^{\log n}\log(s_1+1) &= \\ = \mathcal{O}\left(n^{(4+\log\lceil\log(s_1+1)\rceil+\log\lceil\log(s_2+1)\rceil)}\log s_1\right), \end{aligned}$$

on a binary structured market where n commodities are traded. As in Section 3, $T(n)$ is the total number of comparisons and n is assumed to be an even power of two.

This gives the following theorem on the complexity of Algorithm 4.1:

Theorem 4.3 *The worst case complexity of Algorithm 4.1 on an n commodity market is*

$$\mathcal{O}\left(n^{(4+\log\lceil\log(s_1+1)\rceil+\log\lceil\log(s_2+1)\rceil)}\log s_1\right)$$

where s_1 and s_2 are the sizes of the search spaces in volumes and prices, respectively.

Proof. The complexity is given by the recursion above. □

It is possible to speed up computations by an explicit representation of the inverse demand function of leaf nodes. By this $T(1)$ is reduced to a constant time operation and we get the following complexity:

Theorem 4.4 *The worst case complexity of Algorithm 4.1 on an n commodity market, with an explicit representation of the inverse demand of leaf nodes is*

$$\mathcal{O}\left(n^{(4+\log\lceil\log(s_1+1)\rceil+\log\lceil\log(s_2+1)\rceil)}\right)$$

where s_1 and s_2 are the sizes of the search spaces in volumes and prices, respectively.

Proof. Given by the recursion above, but with $T(1)$ as a constant operation. □

In practice the algorithm runs significantly faster than this due to (i) the choice to utilise prior knowledge in an iteration, and (ii) the search in minimum and maximum prices only taking place when a local price has to be calculated.

4.5 Test Implementation and Design Experiences

We have written a first test implementation of the algorithm in Java. The implementation gave valuable insight into the practical consequences of algorithm structure and complexity. Our goal with this test implementation was to achieve some practical experience of the algorithm. A natural next step would be to evaluate the market outcome using our market mechanism compared to the market outcome of alternative approaches. This kind of evaluations are left for future research.

The advantage of exponential-and-binary search over plain binary search was clearly demonstrated by a first preliminary Java implementation. With a plain binary search approach there was no problem solving instances with an eight commodity binary structured market tree (c.f. Figure 4) with bids expressed in sample vectors holding 1000 sample prices each. Moving to a corresponding 24 commodity market gave a running time in the order of hours.[5] (The market was structured with a root node holding three such eight commodity sub-markets, Figure 8.) The introduction of an exponential-and-binary search reduced the running time of such instances to a practical level, c.f. Table 1.

Another idea is to use a dynamic programming approach, introducing caching at lower levels. In our implementation the time – space tradeoff was not worthwhile, but it might still be an alternative in some settings. We also note that tree-structured algorithms are well suited for parallel computing.

[5]The test implementation was run on a three GHz PC, Windows XP, and Java J2SE 1.4.2.

Table 1: *Running time of the algorithm with sample arrays of 1000 price levels, eight and 24 commodity market setups. In this test the algorithm was run ten times with each market setup, each one with a new set of bids.*

# commodities	# samples in array	average running time
8	1000	one second
24	1000	half a minute

We find the running times fully practical as a typical setting for such a market, such as a day-ahead power market is not that time critical. Markets that are more time critical probably handle a smaller number of commodities. An example might be a balancing service in power grids, organised as a market.

A second and in many ways more interesting implementation is under development within the CRISP project.[6] This implementation will be used in a market algorithm library and for simulations of supply – demand matching in power grids.

5 Conclusions

In this article we present a number of results ranging from tree-structured single-unit auctions to tree-structured multi-unit multi-commodity markets. The main result is a market mechanism suitable for e.g. markets handling time dependent commodities, the CONSEC mechanism. By a number of predefined bid types, it offers useful flexibility to the bidders. The article presents useful abstractions, holding the combinatorial capabilities on a low level. A reason to keep the combinatorial capabilities of a market mechanism down is to keep it easy to understand and to make it easy to convince oneself that the pricing mechanism is correct. Furthermore, there are complexity reasons with respect to communications as well as to computations to do this.

The main computational (and communicational) task of the mechanism is the aggregation of demand. With the combinatorial capabilities of the mechanism expressed as independent tracks (bids on single commodities, bundle bids and substitute bids) the computational complexity of this part does not grow more than linear in the number of bidding tracks. The aggregation of bids is outside the scope of this article, standard techniques are presented in e.g. [9, 10, 2]. We have shown preliminary results on scalability in the number of commodities traded. Scalability in the number of participants is out of scope of this article as it depends on the aggregation of bids.

[6]See http://www.ecn.nl/crisp for a presentation of the project.

A real world market setup of a large CONSEC market would likely be a highly distributed market, i.e. most of the information needed for market computation is spread over the network. Since the input to Algorithm 4.1 is aggregated demand, it is natural to distribute a possibly heavy part of the computation — the aggregation — over the network. By this, the communicational load is diminished radically.

In earlier work we have looked into distributed resource allocation and resource allocation with non concave objective functions, [2, 3, 1], even applicable on markets with non-continuous demand [6]. In this article we have assumed continuous demand. Non-continuous demand on multi-commodity markets is left for future work.

An assumption of ours that may be hard for some actors entering bids for substitutes is that their bids are assumed to be divisible, i.e. as soon as the price of more than one commodity of the bundle equals the minimum (maximum) price, their allocations might be split over these commodities. In practice we assume that the number of actors entering bids for substitutes is large relative the volumes traded, hence the goods can be handled as divisible. The case with non-divisible goods introduces conceptual pricing problems as well as computational problems, and is beyond the scope of this article.

The market mechanism has properties that are highly relevant in e.g. day-ahead power markets [5, 13] and bandwidth markets [14, 15]. In a power setting, the big advantage of the mechanism (compared to the power markets of today, such as the Nordic NordPool [12] and the Dutch APX [4]) comes with the possibility to set up electronic markets with a huge number of participants. When a direct market participation of a large number of presumably small size actors (formerly represented by distributors) is introduced the market outcome can become considerably more efficient. To reach this, one has to enhance the possibilities for actors on the market to express dependencies and constraints between the traded time slots, we believe our mechanism to be an interesting alternative when it comes to this.

The combinatorial possibilities given by the market mechanism enriches the possibilities of the actors. While being easy to understand and computationally feasible, it scales well to markets with a huge number of participants.

A Algorithm Details

In this appendix we give a high level outline of the implementation of the algorithm. We give it in terms of a few Java style methods. Some supportive methods performing the actual search and recursive calls are left out of the description.

When the nodes have received the aggregated bids of their bidding tracks, the environment calls the *findEquilbrium* method of the tree's root node with a zero demand, and minimum and maximum prices set to equal the borders of the search space (these are for simplicity assumed to be sufficiently low and high, respectively). When this call returns, equilibrium prices have been established and all that remains is to compute the allocation of substitute bids (this simple computation is not described).

Algorithm A.1 (Hierarchical Binary Search) :
{
rootNode.findEquilibrium(0, lowestValue, highestValue);
compute corresponding allocations of substitute demand;
announce prices & allocations;
}

The *findEquilibrium* method of a bundle node (Method A.1) performs a search in the demand that it imposes on its children, i.e. this search is resource based. The goal of the search is to find a price such that — given the input and its own bundle demand — it is in equilibrium with the system rooted in the node.

Each search step of the *{exp, bin}SearchMb* methods involves a call of the *searchMinPrice* method. Starting at the current value, the *expSearchDemand* method decides on search direction and moves in that direction to establish lower and upper borders of an ordinary binary search. At each iteration the step length is doubled. The exponential-and-binary search phase is followed by an ordinary binary search within the defined borders until the breaking condition is fulfilled (i.e. the difference between bundle price and average single commodity prices is less than a predefined small $\epsilon > 0$).

The return value of the *findEquilibrium* method holds information on the equilibrium price of the node, and what excess demand it expresses towards the parent due to the imposed minimum and maximum prices. (The excess demand variables are set by the *search{Min, Max}* methods, respectively.)

As in Section 4.4, the parent node of current node is denoted i, and the node itself j.

Method A.1 (Find Equilibrium, Bundle Nodes) *:*
double[] findEquilibrium(double d_i^{ch}*, double* p_i^{min}*, double* p_i^{max}*){*

```
  double[] borders ← expSearchDemand(d_i^ch, p_i^min, p_i^max);
  return binSearchDemand(d_i^ch, p_i^min, p_i^max, borders);
}
```

The goal of the *seachMinPrice* method is to set the local minimum price of the child nodes, such that buying demand for substitutes and/or the excess demand variable meet the demand of theirs. The first check of the *seachMinPrice* method (Method A.2) is whether the imposed minimum price renders a positive or negative excess demand. If it is strictly positive, the local buyer demand for substitutes at the imposed minimum price is greater than the corresponding excess demand of the child nodes. Hence a local minimum price has to be established that gives a zero excess demand. A negative excess demand at the imposed minimum price is left for the parent node to take care of. The search for a higher local minimum price is similar to the search of the previous method.

Method A.2 (Search in Minimum Price) *:*

```
double[] searchMinPrice(double d_j^ch, double p_i^min, double p_i^max){
  double[] retVal ← searchMaxPrice(d_j^ch, p_i^min, p_i^max);
  if(acDemand(p_i^min)+retVal[1]>0){
    /*search for a higher local minimum price*/
    double[] borders ← expSearchMinPrice(d_j^ch, p_i^min, p_i^max);
    retVal ← binSearchMinPrice(d_j^ch, p_i^max, borders);
  }
  return retVal;
}
```

The *searchMaxPrice* method (Method A.3) is similar to *searchMinPrice*. The supporting method *callSubSystems* performs a call of the *findEquilibrium* method of all child nodes using the locally defined values on this nodes demand, minimum price, and maximum price. Furthermore, the method is used to summarise the return values.

Method A.3 (Search in Maximum Price) *:*

```
double[] searchMaxPrice(double d_j^ch, double p_j^min, double p_i^max){
  double[] retVal ← callSubSystems(d_j^ch, p_j^min, p_i^max);
  if(apDemand(p_i^max)+retVal[2]<0){
    /*search for a lower local maximum price*/
    double[] borders ← expSearchMaxPrice(d_j^ch, p_j^min, p_i^max);
    retVal ← binSearchMaxPrice(d_j^ch, p_j^min, borders);
  }
  return retVal;
}
```

The *findEquilibrium* method of a leaf node (Method A.4) is straightforward. With a simple binary search the price matching the demand of the parent is established as the equilibrium price of the node. If this price is lower than the minimum price or higher than the maximum price, the equilibrium price is set to equal the minimum or maximum price, respectively. The excess demand generated by this operation is exported with the return value of the method.

Method A.4 (Find Equilibrium, Leaf Nodes) *:*

double[] findEquilibrium(double d_i^{ch}*, double* p_i^{min}*, double* p_i^{max}*){*
  *double[] retVal;/*initialised with zero values*/*
  double $p \leftarrow$ *binSearchDemand(*d_i^{ch}*);*
  if($p < p_i^{min}$*){*
    retVal[1] $\leftarrow d_j(p_i^{min}) + d_i^{ch}$;
    $p \leftarrow p_i^{min}$;
  }
  if($p > p_i^{max}$*){*
    retVal[2] $\leftarrow d_j(p_i^{max}) + d_i^{ch}$;
    $p \leftarrow p_i^{max}$;
  }
  retVal[0] $\leftarrow p$;
  return retVal;
}

With an explicit inverse demand function (that could be pre-compiled) the computational work of a leaf node reduces to constant time work.

There are a lot of details left out in this description, we still want to give it to present the major outline of an implementation of the algorithm.

References

[1] A. Andersson, P. Carlsson, and F. Ygge. Resource allocation with wobbly functions. *Computational Optimization and Applications*, 23(2):171–200, 2002.

[2] A. Andersson and F. Ygge. Managing large scale computational markets. In H. El-Rewini, editor, *Proceedings of the Software Technology track of the 31th Hawaiian International Conference on System Sciences (HICSS31)*, volume VII, pages 4–14. IEEE Computer Society, Los Alamos, January 1998. ISBN 0-8186-8251-5, ISSN 1060-3425, IEEE Catalog Number 98TB100216. (Available from http://www.enersearch.se/~ygge).

[3] A. Andersson and F. Ygge. Efficient resource allocation with non-concave objective functions. *Computational Optimization and Applications*, 20:281–298, 2001.

[4] http://www.apx.nl.

[5] S. Borenstein, M. Jaske, and A. Rosenfeld. Dynamic pricing, advanced metering and demand response in electricity markets. (Available from http://www.ef.org), 2002.

[6] P. Carlsson, F. Ygge, and A. Andersson. Extending equilibrium markets. *IEEE Intelligent Systems*, 16(4):18–26, July/August 2001.

[7] P. Carlsson, F. Ygge, and A. Andersson. A tractable mechanism for time dependent markets. Technical Report 2003-027, Department of Information Technology, Uppsala University, April 2003. (Available from www.it.uu.se/research/reports/).

[8] P. Carlsson, F. Ygge, and A. Andersson. A tractable mechanism for time dependent markets. In jen Yao Chung and Liang-Jie Zhang, editors, *CEC 2003, IEEE International Conference on E-Commerce*, pages 31–34. IEEE Computer Society, Los Alamos, June 2003.

[9] T. Ibaraki and N. Katoh. *Resource Allocation Problems — Algorithmic Approaches.* The MIT Press, Cambridge, Massachusetts, 1988.

[10] N. Katoh and T. Ibaraki. Resource allocation problems. In D.-Z. Du and P.M. Pardalos, editors, *Handbook of Combinatorial Optimization*, volume 2, chapter Resource Allocation Problems, pages 159–260. Kluwer Academic Publisher, 1998.

[11] N. Nisan. Bidding and allocation in combinatorial auctions. In *EC'00, Proceedings of the 2nd ACM conference on electronic commerce*, pages 1–12. The Association for Computing Machinery, New York, USA, 2000.

[12] http://www.nordpool.no.

[13] R. H. Patrick and F. A. Wolak. Using customer demands under spot market prices for service design and analysis. Technical Report WO 2801-11, EPRI, 2001. (Available from http://www.rci.rutgers.edu/~rpatrick/hp.html).

[14] L. Rasmusson. Evaluating resource bundle derivatives for multi-agent negotiation of resource allocation. In J. Liu and Y. Ye, editors, *E-Commerce Agents*, number 2033 in LNAI, pages 154–165, Berlin Heidelberg, 2002. Springer Verlag.

[15] L. Rasmusson and G. Paues. Network components for market-based network admission and routing. Technical report, Swedish Institute of Computer Science, SICS, Kista, Sweden, 2002.

[16] M. H Rothkopf, A. Pekec, and R. M. Harstad. Computationally manageable combinatorial auctions. *Management Science*, 44(8):1131–1147, August 1998.

[17] M. Tennenholtz. Some tractable combinatorial auctions. In *AAAI/IAAI 2000 Proceedings*, 2000.

Paper 18: *PowerMatcher: multiagent control in the electricity infrastructure*

Full bibliographic reference:

J.K. Kok, C.J. Warmer, and I.G. Kamphuis: *PowerMatcher: multiagent control in the electricity infrastructure*, in Proceedings of the Fourth International Joint Conference on Autonomous Agents & Multi- Agent Systems AAMAS'05, ACM, New York, NY, July 2005 (ACM Order nr. 607054), Industrial Track Volume, pages 75 – 82.

PowerMatcher:
Multiagent Control in the Electricity Infrastructure

J.K. Kok, C.J. Warmer, I.G. Kamphuis
Energy research Center of the Netherlands (ECN)
Sustainable Energy in the Built Environment
P.O. Box 1, 1755 ZG, Petten, The Netherlands
{j.kok, warmer, kamphuis}@ecn.nl

ABSTRACT
Different driving forces push the electricity production towards decentralization. As a result, the current electricity infrastructure is expected to evolve into a network of networks, in which all system parts communicate with each other and influence each other. Multi-agent systems and electronic markets form an appropriate technology needed for control and coordination tasks in the future electricity network. We present the PowerMatcher, a market-based control concept for supply and demand matching (SDM) in electricity networks. In a presented simulation study is shown that the simultaneousness of electricity production and consumption can be raised substantially using this concept. Further, we present a field test with medium-sized electricity producing and consuming installations controlled via this concept, currently in preparation.

Categories and Subject Descriptors
I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence – *multiagent systems, coherence and coordination*.

I.2.1 [**Artificial Intelligence**]: Applications and Expert Systems – *industrial automation*.

General Terms
Algorithms, Economics, Experimentation.

Keywords
Multi-agent systems, multi-agent control, electronic markets, electricity infrastructure, electrical power systems automation.

1. Background

1.1 Evolution in the electricity net
Several different forces drive a change in the current worldwide energy supply. The portion of electricity in the total energy supply mix is expected to rise substantially [17]. Another ongoing change is the growing penetration of distributed electricity generation. Distributed Generation (DG) can be defined as a source of electric power connected to the distribution network or to a customer site ("behind the meter"). This approach is fundamentally distinct from the traditional central plant model for electricity generation and delivery.

Fourth International Joint Conference on Autonomous Agents & Multi-Agent Systems, *AAMAS'05*, July 25-29, 2005, Utrecht, Netherlands
ACM 1-59593-094-9/05/0007

Driving forces behind the growing penetration of DG are [18, 20]:

1. Environmental concerns. Producers of sustainable – or 'green' – electricity are to a large extent distributed generators. Photovoltaic solar cells and wind turbines are examples of these generators. Apart from large-scale wind farms, these generators are connected to the (low-voltage) distribution network or "behind the meter" at customer sites. Governmental aims to increase the portion of sustainable energy in the national energy mix have been translated into incentives and tax policies to promote the uptake of renewable energy sources in European countries as well as in other parts of the world.
2. Deregulation of the electricity market. As a result of the deregulation, the long-term prospects for large-scale investments in power generation are unclear at this moment. As a result of this, a shift of interest of investors from large-scale power generation plants to medium and small-sized generation can be seen. Investments in DG are lower and typically have shorter payback periods than those of the more traditional central power plants. Capital exposure and risk is reduced and unnecessary capital expenditure avoided by matching capacity increase with local demand growth.
3. Diversification of energy sources. Diversification of energy sources is a way to reduce the economic vulnerability to external factors. In particular, a higher portion of sustainable energy in the energy mix reduces the dependency on fossil fuels from politically unstable regions. The European energy need, for instance, is largely imported from outside the EU. As energy demand continues to grow, this external dependence could grow from 50 to 70% in 25 years or less.
4. Energy autonomy. A sufficient amount of producing capacity situated in a local electricity network opens the possibility of *intentional islanding*. Intentional islanding is the transition to stand-alone operation during abnormal conditions on the externally connected network, such as outages or instabilities, e.g. during a technical emergency. In this manner, autonomy can be achieved on different scales, from single buildings to wide-area subsystems.
5. Energy Efficiency (i). In general, distributed generation reduces energy transmission losses. Estimates of power lost in the long-range transmission and distribution systems of western economies are of the order of 7%. By producing electricity in the vicinity of where it is consumed, transport

losses are avoided. There is, however, a concern that in cases where the local production outgrows the local consumption the transmission losses start rising again. But in the greater part of the European distribution network we are far from reaching that point.

6. Energy Efficiency (ii). Heat production out of natural gas can reach higher efficiency rates by using combined heat-power generation (CHP) instead of traditional furnace burners. CHP is a growing category of distributed generation, especially in regions where natural gas is used for heating. In Northern Europe, for instance, CHP is already commonly used in heating of large buildings, green houses and residential areas. The use of micro-CHP for domestic heating in single dwellings is expected to rise steeply in the next 10 to 20 years.

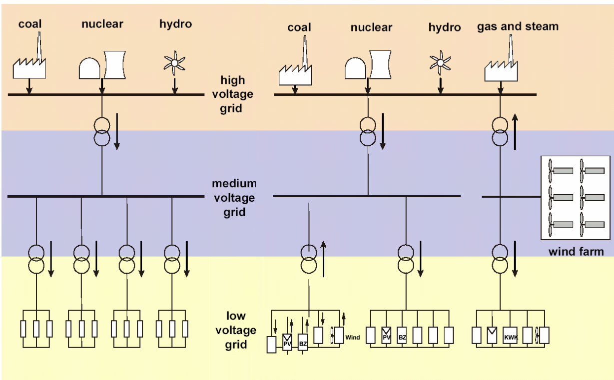


Figure 1: The traditional (left) and the future electricity infrastructure. In the future situation a substantial part of the electricity will be fed into the network at medium and low-voltage sub-networks [19] (original drawing courtesy of ISET).

The growing share of DG in the electricity system may evolve in three distinct stages [20]:

- **Accommodation.** Distributed generation is accommodated in the current market. Distributed units are running free, while centralized control of the networks remains in place.
- **Decentralization.** The share of DG increases. Virtual utilities optimize the services of decentralized providers through the use of common ICT-systems. Central monitoring and control is still needed.
- **Dispersal.** Distributed power takes over the electricity market. Local low-voltage network segments provide their own supply with limited exchange of energy with the rest of the network. The central network operator operates more like a coordinating agent between separate systems rather than controller of the system.

In specific parts of the world there are already signs of the decentralization stage (see for instance [21, 22].)

1.2 Need for new coordination mechanisms

During the second and third stage of DG growth, the structure of the current electricity grid evolves from a hierarchical top-down controlled structure into a network of networks, in which a vast number of system parts communicate with each other and influence each other. In the current electricity infrastructure energy and control information both mainly flow down and money flows up. In a DG-dominated electricity grid, energy, control information, and money will flow in all directions. A combination of distributed generation, electricity storage, demand response, real-time electricity prices and intelligent control opens the possibility of optimization regarding economics, dependability and sustainability.

As distributed generation gradually supplants central generation as the main electricity source, **distributed coordination** will supplant **central coordination**. The standard paradigm of centralized control, which is used in the current electricity infrastructure, will no longer be sufficient. The number of system components actively involved in the coordination task will be huge. Centralized control of such a complex system will reach the limits of scalability, computational complexity and communication overhead.

In addition to the described technical evolution of the electricity infrastructure, there is an ongoing evolution in the market structure. The electricity supply will no longer be in the hands of a small group of big players, but be spread out over a vast number of market players, big ones as well as small ones. This will give rise to new business models in (distributed) electricity production and consumption [5]. In regions with a highly deregulated energy system, like the Scandinavian countries, the United Kingdom, The Netherlands and some USA states, coordination mechanisms based on market-economic principles have been introduced at a central level, i.e. high up in the grid hierarchy. Market mechanisms are used for planning of large-scale production via day-ahead power exchange trading, and for real-time balancing via spinning-reserve auctions held by the Transport System Operators (TSOs). The coordination mechanisms for the low-end of the grid hierarchy, that become necessary during the second and third stage of DG growth, need to comply with the constraints given by the changing market structure. Consequently, these control mechanisms must be based on market-economic principles as well.

2. MAS for power management

2.1 ICT-Requirements

As a result of the electricity evolution as described above, the electricity infrastructure will get more and more inter-linked with ICT-infrastructure. The architecture and algorithmics of this ICT-infrastructure must be adapted to the technical structure of the (future) electricity net and the connected producing and consuming installations, but also to the structure of the liberalized energy market. This ICT-architecture and associated algorithms must be designed using a strong system-wide viewpoint, but must also consider stakes of local actors in the system. In other words, there is a need for a multi-actor coordination system, which optimizes global system objectives (like stability, power quality, and security of supply), in coherence with the interests of local actors in the form of installations for electricity production, consumption, and storage. These local actors vary greatly in characteristics defined by process type, purpose and size, and so do their specific constraints and objectives.

The resulting requirements of the ICT-infrastructure needed for the expected electricity evolution are:

- The ICT-architecture must be flexible, open and extensible.
- The coordination system must exceed boundaries of ownership. The total system includes the electricity network itself, central and distributed generators, electricity storage systems and electricity consuming

systems. These system parts are owned by a vast number of parties, varying from public authorities, via companies, to private individuals.

- In this multi-actor system the stakes on the global level as well as those of individual actors must be taken into account. Control of distributed generators, electricity consuming installations and electricity storage, needs to be based on local information specific for the purpose and characteristics of the device. The power to take decisions on local issues must stay with each individual local actor.
- In a liberalized market setting, control (and local decisions) must be based on economical grounds.
- Communication between system parts must be uniformed and stripped from all local information. This is needed to reach the required flexibility and openness as stated in the first point, but also for reasons of privacy and trade secrecy.

Naturally, the total resulting system (the electricity infrastructure plus the ICT infrastructure) must be dependable, since the power grid is a critical asset in the modern society. Most developed countries currently have a highly dependable electricity supply, and any changes to the system must not weaken it but rather strengthen it. Further, the system must be secure, i.e. hardened against hackers and cheaters[1].

2.2 Meeting the requirements

Multi-agent systems (MAS) and electronic (virtual) markets provide the key technology necessary to meet the ICT requirements as described in the previous paragraph, for the following reasons:

- In multi-agent systems a large number of actors are able to interact, in competition or in cooperation. Local agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of an individual agent can be low, the intelligence level of the global system is high.
- Multi-agent systems implement distributed decision-making systems in an open, flexible and extensible way. Communications between actors can be minimized to a generic and uniform information exchange.
- By combining multi-agent systems with micro-economic principles, coordination using economic parameters becomes possible. This opens the possibility for the distributed coordination process to exceed boundaries of ownership. The local agent can be adjusted by the local stakeholder, and does not fall under the rules and conditions of a central authority.
- Using electronic markets a *Pareto efficient* system emerges, i.e. a system that optimizes on a global level, while at the local level the interests of all individual actors are optimally balanced against each other.

3. Earlier research

The combination of MAS and electronic markets yield distributed rational decision-making. For a good overview of the state of the art in this field, we refer to Sandholm [6]. The work on MAS and electronic markets for energy management as described in this paper builds further on earlier research on market-based control and market-based resource allocation for flow resources. Although these two research topics are closely interrelated, we treat the relevant work in these areas separately.

3.1 Market-based control

In market-based control, a large number of agents are competitively negotiating and trading on an electronic market, with the purpose to optimally achieve their *local* control action goals. In [12] the first agent research applications and simulations carried out under the heading of market-based control were brought together. Most early research was aimed at climate control in office buildings with many office rooms, where local control agents compete in the allocation of cool (or hot) air. (See e.g. [13, 14, 15, 16]).

Recently, a systems-level theory of large-scale intelligent and distributed control was formulated [1, 3]. This theory unifies microeconomics and control theory in a multi-agent theory, and subsumes the agent research applications and simulations as described above. A central result is the derivation of a general market theorem that proves two important properties about agent-based microeconomic control: (1) computational economies with dynamic pricing mechanisms are able to handle scarce resources for control adaptively in ways that are optimal locally as well as globally ('societally'); (2) in the absence of resource constraints the total system acts as collection of local independent controllers that behave in accordance with conventional control engineering theory.

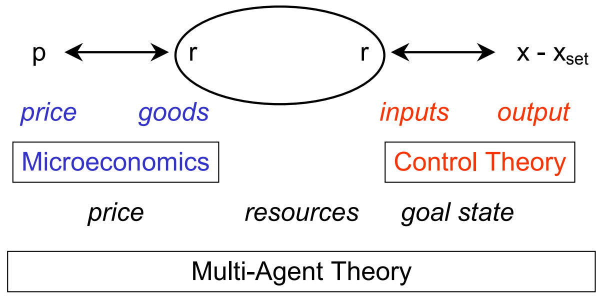


Figure 2: Microeconomics and control engineering unified in multi-agent theory [1].

3.2 Market-based resource allocation

Resource allocation in energy management systems is part of a special type of allocation problems, namely allocation of *flow resources*. An early paper on the use of market algorithms for power load management was published by Ygge and Akkermans [7].

Generally, market algorithms for solving flow-resource problems have two scalability problems: one regarding the number of participants in the market and the other regarding the interdependency in the participant's demand over time. Ygge and Akkermans solved the first problem. In their solution to the problem, the demand functions[2] of the individual agents are aggregated in a binary tree. Because of this, the computational complexity of the market algorithm becomes $O(\lg p)$, where p is the number of participants in the market. Furthermore, this opens the possibility for running the optimization distributed over a series of computers in a

[1] In this paper, we do not address the important issues of ICT security and dependability directly. We will treat these issues in future publications. For related work on this topic, we refer to [23, 24].

[2] In energy flow systems, supply can be seen as negative demand. Throughout this paper the term *demand* can be replaced by *supply* in case of electricity production.

network in a way that fits nicely to power systems architectures [8, 9].

The second scalability problem, the one regarding the interdependency in the participant's demand over time is harder to solve in such a way that the usability in the power field remains intact. One way of dealing with this problem is to ignore it and just suppose there is no interdependency between electricity used in different time periods. Then, a single-commodity market algorithm can be used, where the commodity is the amount of energy to consume in one time period. Then, the trading agents must totally rely on market price predictions in order to utilize flexibility in their demand over time. On the other end of the scale one could consider a multi-commodity market algorithm in which agents can formulate demand functions that are fully interdependent among the commodities. Here the commodities are amounts of energy to consume in a series of consecutive time periods. In this case the search space in which the market equilibrium must be found scales with $O(c^n)$, where n is the number of time periods and c a constant related to the resolution with which prices are expressed. This poses no practical problems as long as the number of time slots (n) is kept low (say, $n<5$). This scalability problem was partly solved by Carlsson and Anderson who propose a market algorithm that can handle demand functions which are tree-structured in the time-domain [10, 11]. Agents are able to express dependencies between bids in different time periods, but in a limited number of ways. This method reduces the search space dramatically and, thus, the scalability with respect to the number of time periods, at the cost of a reduced flexibility in the agent bids

4. PowerMatcher

4.1 Basic concept

The PowerMatcher is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption. In the PowerMatcher method each device is represented by a control agent, which tries to operate the process associated with the device in an economical optimal way. The electricity consumed or produced by the device is bought, respectively sold, by the device agent on an electronic exchange market [2].

The electronic market is implemented in a distributed manner via a tree-structure of so-called *SD-Matchers*, as depicted in Figure 3. An SD-Matcher matches demand and supply of a cluster of devices directly below it. The SD-Matcher in the root of the tree performs the price-forming process; those at intermediate levels aggregate the demand functions of the devices below them. An SD-Matcher cannot tell whether the instances below it are device agents or intermediate SD-Matchers, since the communication interface of these are equal. The root SD-Matcher has one or more associated market mechanism definitions, which define the characteristics of the markets, such as the *time slot length,* the *time horizon*, and a definition of the *execution event* (e.g. "every whole quarter of an hour", "every day at twelve o' clock"). When an execution event occurs, the root SD-Matcher sends a request to all directly connected agents to deliver their bids. The device bids are aggregated at the intermediate matchers and passed on up-wards. The root SD-Matcher determines the equilibrium price, which is communicated back to the devices. From the market price and their own bid function each device agent can determine the power allocated to the device.

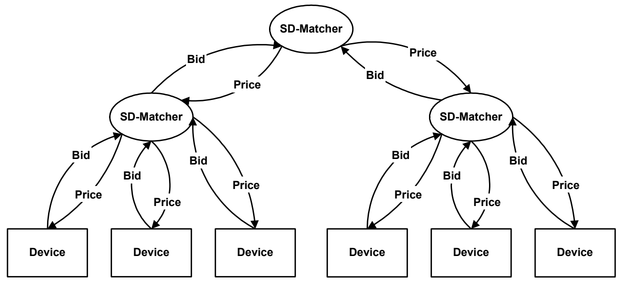


Figure 3: Hierarchy of supply & demand matchers in the PowerMatcher concept. The SD-Matchers implement a distributed electronic market.

4.2 Device agent types and strategies

From the viewpoint of supply and demand matching, devices can be categorized by their type of controllability into the following classes:

- **Stochastic operation devices:** devices like solar and wind energy systems of which the power exchanged with the grid behaves stochastically. In general, the output power of these devices cannot be controlled. For its bidding function the device agent must rely on short-term power predictions. Furthermore, it must accept any market price.
- **Shiftable operation devices:** batch-type devices whose operation is shiftable within certain limits, like (domestic) washing and drying processes. Processes that need to run for a certain amount of time regardless of the exact moment, like swimming pool pumps, assimilation lights in greenhouses and ventilation systems in utility buildings. The total demand or supply is fixed over time.
- **External resource buffering devices:** devices that produce a resource, other than electricity, that is subject to some kind of buffering. Examples of these devices are heating or cooling processes, which operation objective is to keep a certain temperature within two limits. Changing standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (Figure 4). Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power). Appliance of additional heat buffering devices can increase the operation flexibility of this type of devices substantially.
- **Electricity storage devices:** conventional batteries or advances technologies like flywheels and super-capacitors coupled to the grid by a bi-directional connection. Grid-coupled electricity storage is widely regarded as an enabling technology for increasing the penetration of distributed generation technologies at reasonable economic and environmental cost [19]. Grid-coupled storage devices can only be economically viable if their operation is reactive to a time-variable electricity tariff, as is present in the PowerMatcher concept. The device agent must try to buy energy at low prices and sell it later at high prices.

- **Freely-controllable devices:** devices that are controllable within certain limits (e.g. a diesel generator). The agent bidding strategy is closely related to the marginal costs of the electricity production.
- **User-action devices:** devices whose operation is a direct result of a user action. Domestic examples are: audio, video, lighting and computers. From the agent point of view these devices are comparable to the stochastic operation devices: their operation is to a great extent unpredictable and the agent must accept any market price to let them operate.

In all described device categories, agent bidding strategies are aimed at carrying out the specific process of the device in an economically optimal way, but within the constraints given by the specific process. Note that this self-interested behavior of local agents causes electricity consumption to shift towards moments of low electricity prices and production towards moments of high prices. As a result of this, the emergence of supply and demand matching can be seen on the global system level.

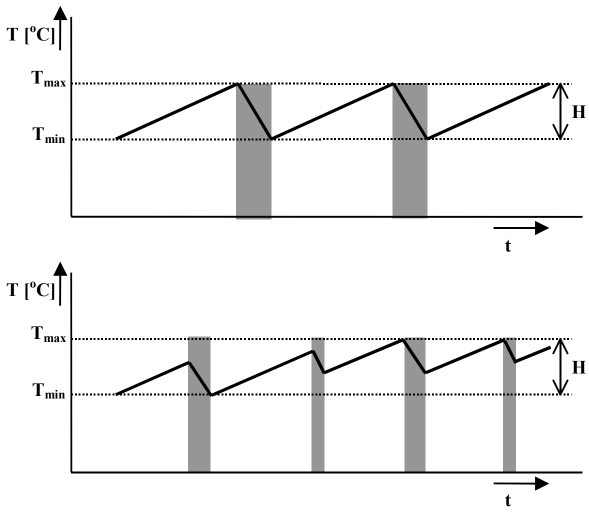


Figure 4: Operation shifting in a cooling process whilst obeying process state limits.

5. Simulation Case

5.1 Case description

In a simulation study the impact of distributed supply and demand matching applied in a residential area was investigated. In the study, a cluster of 40 houses, all connected to the same segment of a low-voltage distribution network (an LV-cell) were simulated. Each house has a *Home Energy Management* (HEM) box, which implements the local energy management strategy of the house (Figure 5). The HEM-box incorporates the intermediate SD-Matcher functionality, together with energy performance feedback to the user, and the possibility for the user to set cost and task preferences. The latter makes it possible to set agent parameters of devices without a user interface.

Within the LV-cell an exchange agent implements the root SD-Matcher. The LV-cell is externally connected to a medium voltage network. Through this connection power can be obtained form and delivered to other parts of the distribution network. The electricity surplus of the cluster is delivered to an external electricity supplier, which delivers electricity to the cluster in case of local shortage. The external supplier can either be a full player on the local electronic market or set tariffs for delivery and retribution. In the latter case, the external tariffs are not influenced by the local price formation, and, typically, the retribution price will be lower than the delivery price. Then, the equilibrium price on the local electronic market will be bounded by the external tariffs.

Half of the 40 simulated dwellings are heated by heat pumps (electricity consumers), the other half by micro-CHP units (small-scale combined heat-power, producers of electricity and heat). The micro-CHPs are also used for production of hot tap water. Washing machines are operated as shiftable operation devices with a predefined operational time window; electricity storage is present in the form of batteries; stochastic operation devices are present in the form of photovoltaic (PV) solar cells and small-scale wind turbines; and user-action devices are represented as lights.

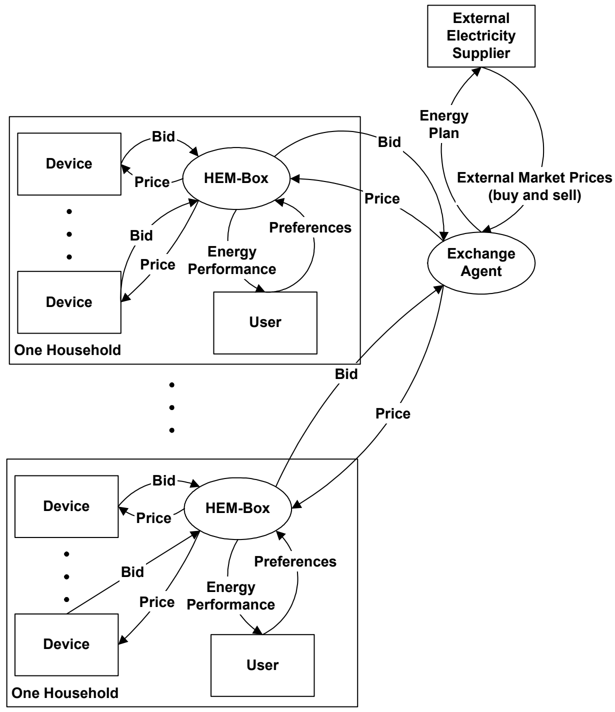


Figure 5: Set-up of the LV-cell simulation (see text).

5.2 Simulation result

Figure 6 and Figure 7 show the result of a typical simulation run for the LV-cell simulation case. In both plots the total consumption and the total production in the cluster have been summed into a single plotline, while production is regarded as negative consumption. The top plot shows the reference case in which all devices are free running. In this case all heating devices are on/off controlled, washing machines start their operation at the start of their operational time window, and batteries are excluded due to the absence of a real-time price signal according which they can be operated. In the bottom plot the SDM-controlled case is shown. Interesting features are:

- Around the 25^{th} 15 minutes period there is a peak in electricity demand caused by the simultaneous starting of a number of heatpumps. Although there is also a small peak in local production at that moment, the greater part of the electricity needed to meet the peak demand is delivered from the external connection to the mid-voltage network. In the SDM-controlled case the peak in external feed-in is 30% lower, due to the reaction of different devices to the price peak on the electronic market at that moment. Consuming device agents shift part of their operation to other moments in time, producing agents shift as much as production as possible to this moment, and battery agents react by switching to discharging mode. In this particular case, consumption reduction accounts for 50% of the peak reduction, battery discharging accounts for 37%, and production increase causes another 13%. From the viewpoint of electricity distribution systems, this is an important result. The highest expected peak demand of a low-voltage net segment determines the capacity the coupling transformer and the network cables or lines. Reducing the peak demand lowers network investments in case of building new sub-networks, and defers network reinforcements in case of demand increase in existing nets.

- Introducing supply and demand matching results in a more flat and smooth profile of the electricity fed in from the mid-voltage network. Fluctuations in local consumption and local production are damped, and the mutual simultaneousness in the remaining fluctuations is high. The standard deviation of the feed-in from the MV-net in Figure 6 is 58% lower in the SDM-controlled case.

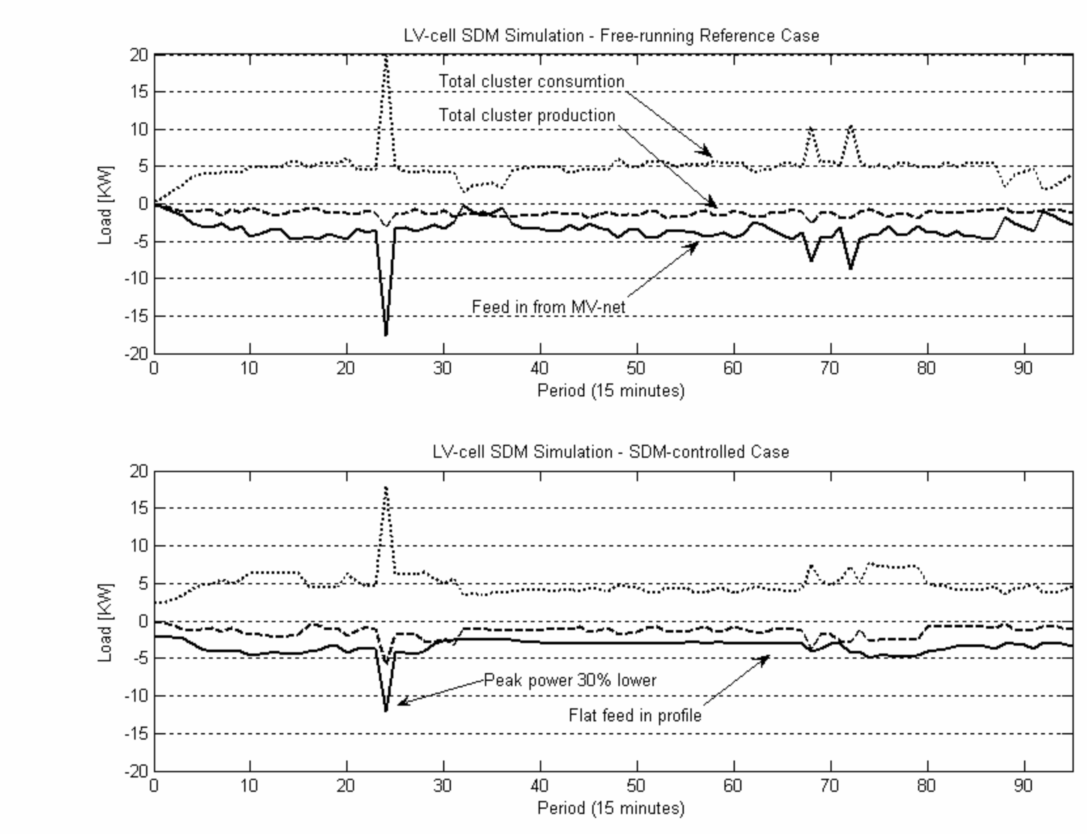


Figure 6: The result of a typical simulation run for the LV-cell simulation (see text).

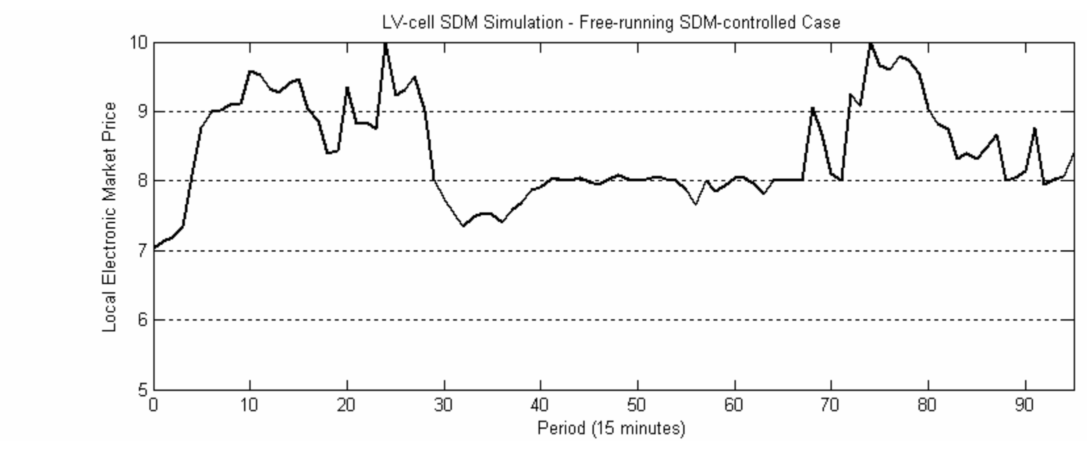


Figure 7: Price development on the electronic market.

6. Field experiment

6.1 Background: balancing responsibility

In countries with a deregulated energy market like the United Kingdom, The Netherlands and the Scandinavian countries, the bigger market parties (those that make use of the transport services of the independent network operators) are obliged to make daily plans for production, transport and consumption of electricity. These plans have to be handed in at the so-called transport system operator (TSO), the operator of the high-voltage electricity network. In The Netherlands these plans have to be handed in before 12:00 hours and plan the 24-hours period starting at the next midnight with a resolution of 15 minutes.

The TSO uses all these plans to ensure the stability of the electricity network. For the sake of this stability, it is important that every balancing responsible party sticks to her own plan. To enforce this, each party that has a deviation from his plan (*imbalance*) is charged for it. These charges are referred to as *imbalance costs*.

6.2 Reducing imbalance costs by SD-Matching

Balancing responsible parties with a high share of wind energy in their production portfolio are faced with extra costs due to the stochastic behavior of wind energy production. Within the EU-funded research project CRISP, a field experiment is currently being prepared in which the aggregated imbalance of a cluster of medium-sized electricity producing and consuming installations is minimized by using the market-based control concept of the PowerMatcher.

The objective of the field experiment is formulated as: “real-time monitoring and control of electricity supply and demand in a commercial setting to avoid short term market imbalance due to intermittent renewable energy sources”. Secondary aim of the experiment is to test the ICT elements needed for implementation of Supply and Demand Matching mechanisms in a real-life environment.

The experiment will run for a full year from April 2005 onwards. The first results of the experiment are expected to be available mid July 2005.

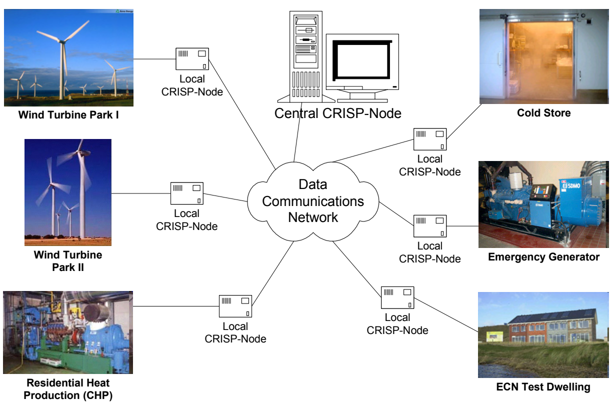


Figure 8: Set-up of the CRISP Supply and Demand Matching field experiment.

7. Conclusion

7.1 Future Research

Future research will include:

- Assessment of different business cases in which the PowerMatcher is beneficial to stakeholders at a local level as well as at a global level. Simulation and implementation studies for selected business cases.
- Investigation of different market configurations:
    - Time-ahead planning by using multi-commodity market algorithms.
    - Stacking of market mechanisms with different characteristics, e.g. a day-ahead market mechanism with 24 one-hour timeslots combined with an hour-ahead market of four slots of 15 minutes.
- Investigation of the use of MAS and electronic markets for *virtual power plants* (VPPs). VPPs are aggregations of small and medium-sized electricity producing and consuming devices acting as a normal conventional power plant.

7.2 Conclusions

Various drivers push the production of electrical power in the current electricity infrastructure towards decentralization. Multi-agent technology and electronic markets form an appropriate technology to solve the resulting coordination problem. The PowerMatcher concept proposed in this article is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation.

The presented simulation case shows that this concept is capable of utilizing flexibility in device operation via agent bids on an electronic power market. Via agent reactions on price fluctuations, the simultaneousness between production and consumption of electricity by devices in a sub-network is increased. As a result, the net import profile of the sub-network is smoothed and peak demand is reduced, which is desired from a distribution network operational viewpoint. Further, a field experimental setup in which the PowerMatcher concept will be tested in a real-life environment is presented.

Acknowledgments. The work presented in this paper was partially supported by the European Commission in the context of the EUSUSTDEV Project No. NNE5-2001-00906 called CRISP (Distributed Intelligence in CRitical Infrastructures for Sustainable Power).

8. References

[1] J.M. Akkermans, J.F. Schreinemakers, J.K. Kok, “Microeconomic Distributed Control: Theory and Application of Multi-Agent Electronic Markets”, *Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures*, Grenoble, October 2004.

[2] I.G. Kamphuis, P. Carlsson, C.J. Warmer, J.C.P. Kester and J.K. Kok, “Distributed Intelligence for Supply/Demand Matching to Improve Embedding of Distributed Renewable Energy Sources”, *Proceedings of CRIS 2004 – 2nd International Conference on Critical Infrastructures*, Oktober 25-27, 2004, Grenoble, October 2004.

[3] J.M. Akkermans, J.F. Schreinemakers, J.K. Kok, "Emergence of Control in a Large-Scale Society of Economic Physical Agents", *Proceedings of the AAMAS'04 Conference*, 2004.

[4] J.M. Akkermans, C.J. Warmer, J.K. Kok, J.C.P. Kester, I.G. Kamphuis and P. Carlsson "ELEKTRA: The DER Electronic Market Power Game - An Interactive Experience with advanced Information and Communication Technologies for DER Management", *Proceedings of IRED – First International Conference on the Integration of Renewable Energy Sources and Distributed Energy Sources*, Brussels, December 2004.

[5] J. Gordijn and J.M. Akkermans, "Business Models for Distributed Energy Resources in a Liberalized Market Environment", *Electrical Power Systems Research Journal*, accepted for publication in 2005.

[6] T.W. Sandholm, "Distributed Rational Decision Making", in: G. Weiss (ed.), *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, MIT Press, Cambridge, 2000.

[7] Fredrik Ygge and Hans Akkermans, "Power Load Management as a Computational Market", *Proceedings of ICMAS*, 1996.

[8] F. Ygge and J.M. Akkermans, "Resource-Oriented Multi-Commodity Market Algorithms", *Autonomous Agents and Multi-Agent Systems*, Vol 3, pages 53-72, 2000. (Special Issue Best Papers of ICMAS-98).

[9] F. Ygge, "*Market-Oriented Programming and its Application to Power Load Management*", Ph.D. Thesis, ISBN 91-628-3055-4, Lund University, 1998.

[10] P. Carlsson, and A. Anderson, *"A Flexible model for Tree-Structured Multi-Commodity Markets"*, Technical Report, EnerSearch and Department of Information Technology, Uppsala University, 2004. (Submitted for journal publication.)

[11] P. Carlsson, *"Algorithms for Electronic Power Markets"*, Ph.D. Thesis, Uppsala University, Sweden, 2004.

[12] S.H. Clearwater (Ed.). *Market-Based Control - A Paradigm for Distributed Resource Allocation*. World Scientific, Singapore, 1996.

[13] S.H. Clearwater and B.A. Huberman. Thermal markets for controlling building environments. *Energy Engineering*, Vol 91, Nr 3, pp. 25–56, 1994.

[14] F. Ygge and J.M. Akkermans, "Decentralized Markets versus Central Control - A Comparative Study", *Journal of Artificial Intelligence Research*, Vol. 11, pp. 301-333, 1999.

[15] I.G. Kamphuis, C.J. Warmer, and J.M. Akkermans, *"*SMART - Innovative services for smart buildings", in ISPLC-2001, *Proceedings of the 5th International Symposium on Power-Line Communication and Its Applications*, pp. 231-236, Lund University, Sweden, 2001.

[16] F. Ygge, J.M. Akkermans, A. Andersson, M. Krejic, and E. Boertjes, "The HomeBots System and Field Test – A Multi-Commodity Market for Predictive Power Load Management", in *Proceedings 4th Int. Conf. on the Practical Application of Intelligent Agents and Multi-Agent Technology PAAM-99* (London, 19-21 April 1999), pages 363-382, The Practical Application Company Ltd., Blackpool, UK, 1999.

[17] KEMA, "Electricity Technology Roadmap – Technologie voor een Duurzame Samenleving", KEMA, april 2002.

[18] ENIRDGnet, *"Concepts and Opportunities of Distributed Generation: The Driving European Forces and Trends"*, ENIRDGnet project deliverable D3, 2003.

[19] European Commission, Directorate-General for Research (Brussels), *"New Era for Electricity in Europe – Distributed Generation: Key Issues, Challenges and Proposed Solutions"*, European Communities, Office for Official Publications, Luxembourg, 2003.

[20] International Energy Agency IEA, *"Distributed Generation in Liberalised Electricity Markets"*, International Energy Agency, Paris, 2002.

[21] R. Bitch, "Decentralised Energy Supply Options in Industrialised & Developing Countries", *World Power 2000*, Siemens AG, pp. 61-65, 2000.

[22] D. Cohen, "Using Real-Time Web Technology to Manage DE Networks", *Distributed Power 2001*, Intertech, Nice, France, 2001.

[23] P. Mellstrand, R. Gustavsson, "Dynamic protection of software execution environment", *Proceedings of CRIS 2004 – 2nd International Conference on Critical Infrastructures*, Oktober 25-27, 2004, Grenoble, October 2004.

[24] J. Van de Vyver, G. Deconinck, R. Belmans, "Improving Dependability in the Electricity Network by Integrating Communication in the Control Strategy using a Distributed Algorithm", *Proceedings of CRIS 2004 – 2nd International Conference on Critical Infrastructures*, Oktober 25-27, 2004, Grenoble, October 2004.

Paper 19: *ELEKTRA: the DER electronic market power game - an interactive experience with advanced Information and Communication Technologies for DER management*

Full bibliographic reference:

J.M. Akkermans, C.J. Warmer, J.K. Kok, J.C.P. Kester, I.G. Kamphuis, and P. Carlsson: *ELEKTRA: the DER electronic market power game - an interactive experience with advanced Information and Communication Technologies for DER management*, in Proceedings First International Conference on the Integration of Renewable Energy Sources and Distributed Energy Resources, OTTI, Brussels, December 2004, pages 198-203.
(See also www.conference-on-integration.com and www.IRED-cluster.org).

ELEKTRA: The DER Electronic Market Power Game
- An Interactive Experience with advanced Information and Communication Technologies for DER Management

Hans Akkermans [1,3], **Cor Warmer** [2], **Koen Kok** [2], **Josco Kester** [2], **René Kamphuis** [2], **and Per Carlsson** [1]

[1] *EnerSearch*, Carl Gustafs väg 1, SE-205 09 Malmö, Sweden; www.enersearch.com
[2] *ECN*, Unit DEGO, PO Box 1, 1755 ZG Petten, The Netherlands; www.ecn.nl/crisp
[3] *Free University Amsterdam VUA*, FEW/Business Informatics, De Boelelaan 1081a, NL-1081 HV Amsterdam, The Netherlands; www.cs.vu.nl/bi
Contact: E: Hans.Akkermans@akmc.nl; T: +31 20 444 7718

Abstract. *We have developed an electronic market power game called ELEKTRA, on the occasion of the 1st International Conference on the Integration of Renewable Energy Sources and Distributed Energy Resources in Brussels, 1-3 December 2004. It simulates the power trading market of a large-scale virtual power plant consisting of many Distributed Energy Resource (DER) devices. Thus, it offers a hands-on interactive experience regarding innovative information and communication (ICT) technologies now under development that help manage and optimize large numbers of DER equipment through e-market mechanisms.*

Why electronic markets for DER?

Suppose you are a DER device, such as a Combined Heat and Power (CHP) installation producing electricity while heating a large office, or a cooling installation in need for electricity in order to control the temperature in a cold store. Today, the overproduction of electricity of the CHP is normally sold at low prices to an external party, your electricity utility. In contrast, the cold store will probably purchase its electricity at high prices from its utility. This discrepancy between the low retribution prices and the high delivery prices, however, opens up the opportunity for mutually beneficial *local electricity trading* between the CHP and the cold store, especially if the CHP is able to deliver its electricity when the cold store actually needs it. The possibility of direct local trading would save money for each DER device. If not just two but a large number of DER participants take part in the trade, a *market* emerges. This is not a trading mechanism that is in place today, but the use of advanced ICT is now making this kind of service into a realistic option.

By means of ICT the trade between the DER parties can be computerized and organized as an *electronic power exchange market*, where prices are established according to the supply and demand of power. They will be better than the normal buy/sell prices for DER production/consumption: each party usually has flexibility in its production or consumption pattern allowing it to attribute different prices to different loads. If you are in urgent need of electricity (e.g. the cold store reaches its maximum allowed temperature) you tend to pay more than when you can wait for some time. In the cold store, for example, you can gain time by using the cold store as a buffer. Electronic power markets make it actually possible for DER devices to exploit this production/consumption flexibility, and so widen the range of strategic options DER devices have at their disposal: not only buy/sell from the utility or national power exchange, but alternatively trade locally with other DER at self-chosen and self-controlled time slots, and any mix of these strategies. This feature makes e-markets into an attractive new mechanism, because they enable DER management in the power network at a larger scale and at lower cost than today.

The ELEKTRA game

In the ELEKTRA game we simulate such an electronic power market in a simple interactive way. Conference participants represent DER devices and construct and submit the market bids for „their" DER device. The ELEKTRA market software then calculates the resulting market price, after which a next round of market bidding begins.

The game consists of the following steps (cf. Figure 1):

1. Participants are aggregated into groups, each member of the group representing one DER device on the electronic power market with a defined task (e.g. keep the temperature between 20°C and 22˚C). Each group may be seen as a Virtual Power Plant (VPP).
2. Each VPP group is coordinated by a group leader (in fact, the VPP node), who functions as the VPP's communication channel to the auctioneer that leads the e-market. The system as a whole thus acts like a Large-Scale Virtual Power Plant (LSVPP). The auctioneer coordinates the LSVPP electronic power market, and operates the DER e-market system on a computer.
3. Each participant within a VPP group has a voting form on which s/he can choose a bidding strategy for his/her DER device for the next period (of, say, 15 minutes). It is allowed to interact with your neighbours within the group. Strategic discussion is part of the game (but of course, you don't have that much time, because the e-market moves on and has a deadline for each round...). For simplicity and speed, the voting options for each DER device are a few predefined strategies 1, 2, 3, ... that may be likened to simple stock exchange trading strategies, from conservative to speculative.
4. The VPP group leader gathers all individual votes from the group, counts the votes, and assembles one aggregate VPP vote from it. This is done according to a prefixed rule that bears some similarity to how votes in parliamentary elections may be aggregated. The group leader then forwards the VPP vote to the auctioneer, who enters the vote into the ELEKTRA e-market software system.
5. After all votes have been cast, the ELEKTRA computer system calculates the resulting market price for electricity for the next period (of, say, 15 minutes), as well as the state update of each DER device for that period.

6. This new going market price and the new state of each DER device, transmittted by the group leader to the VPP members, constitute the starting point for the next bidding round of the DER e-market (return to step 3).

In this way participants, after some rounds, get a quite good feel how an electronic power market actually works *and* how they should act on it in order to get the most out of it.

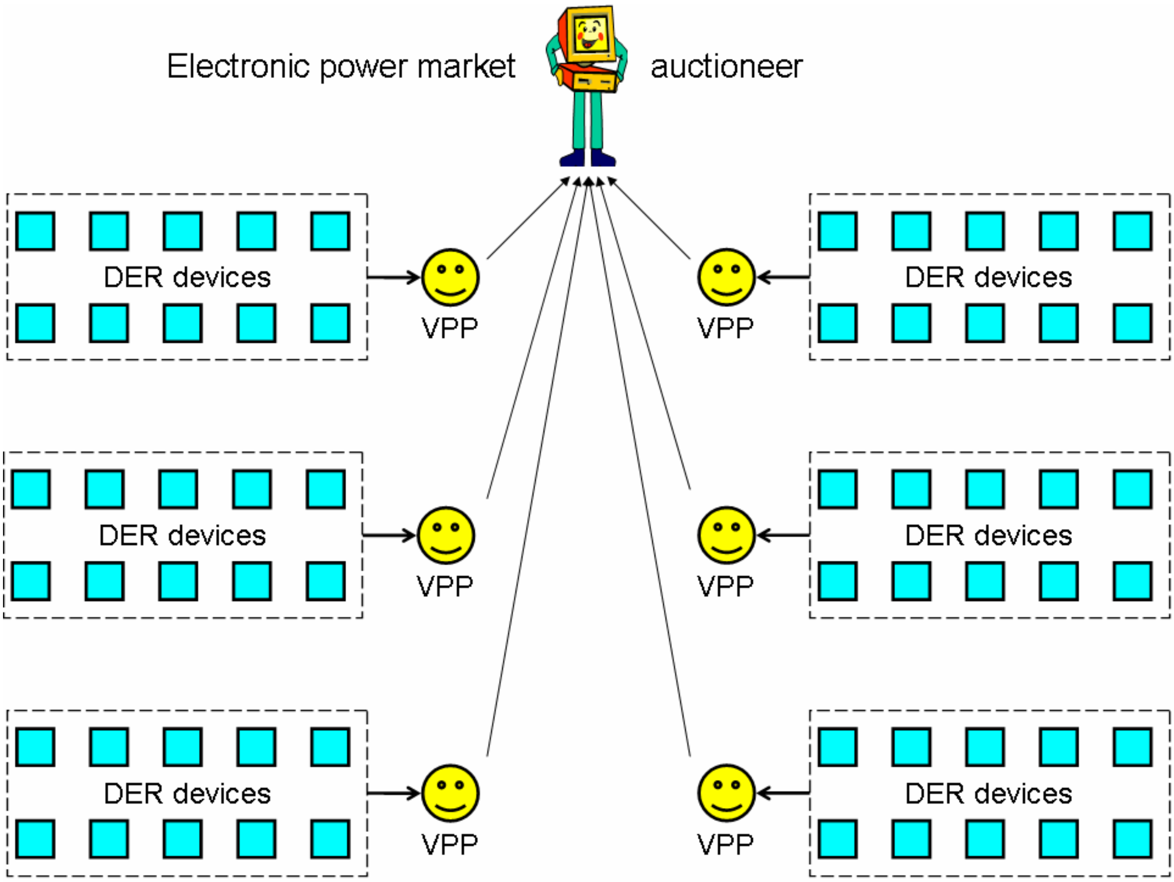


Figure 1: DER Virtual Power Plants and their electronic market.

The ELEKTRA e-market power game can be (and has been) easily adapted to different settings of conferences and meetings. Also, we will make available a version of the game downloadable from the Internet, on the CRISP project website at www.ecn.nl/crisp/elektra. This version allows you to play the electronic market game personally on your own PC, against many built-in computerized agents that represent different DER devices on the market. A screenshot impression of the game is shown in Figure 2.

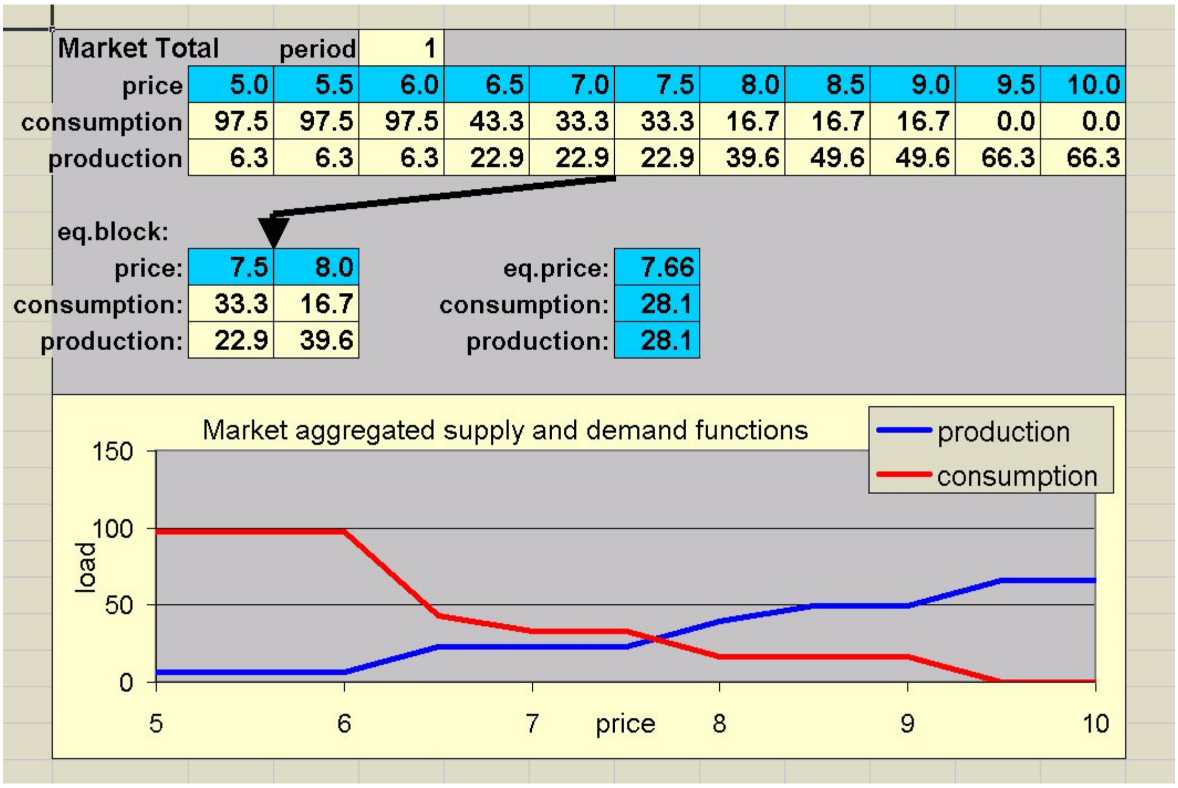


Figure 2: Screenshot of the ELEKTRA e-market power game.

Some of the technological background

The ELEKTRA game is a simplified but illustrative representation of e-market technologies for DER management that are currently developed and tested in the EU project CRISP. It demonstrates a rather realistic set up of how DER can be aggregated in the future into Virtual Power Plants and how they will act and trade on power markets. ELEKTRA in essence has the format of a human auction. However, with modern ICT methods this format can be fully computerized into an automated electronic market. In that case, DER devices are not represented by persons but by dedicated pieces of software known as software agents.

Software agents represent a new type of Information Systems architecture particularly suited for distributed applications as you have them in networked environments such as Intranets, Internet/World Wide Web, or the electricity grid. Agents offer ways to embed intelligent systems techniques in large distributed Information Systems. A definition and overview of the characteristics of agents is given in Figure 3.

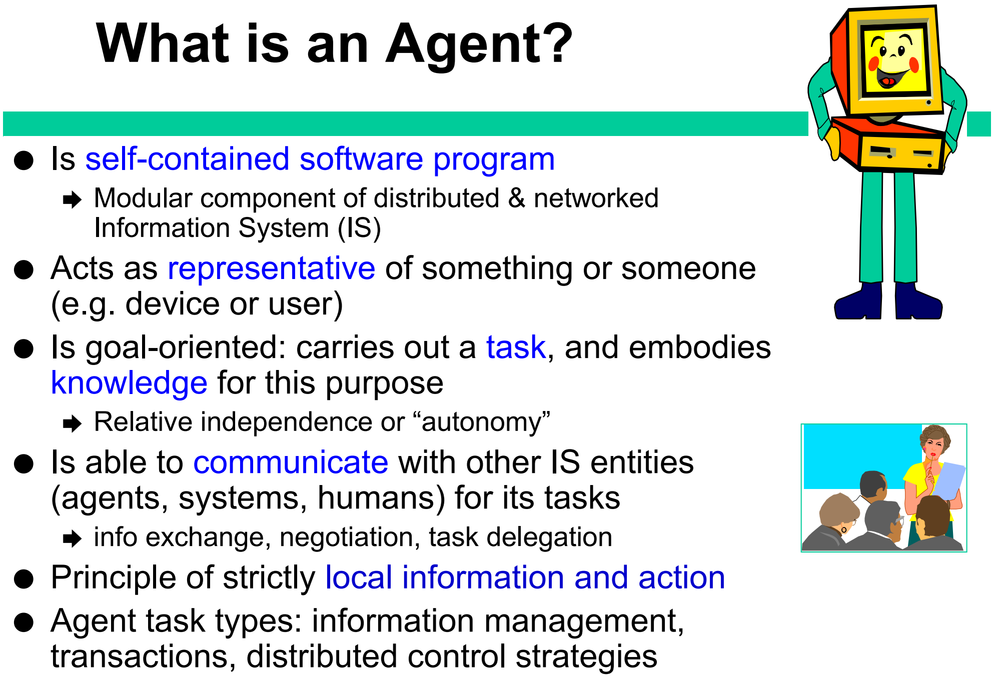


Figure 3: Definition and characteristics of software agents.

Software agents act on electronic markets very much in the way humans do on auctions: they assess their situation and goals, construct and submit bids, respond to the going market prices, and from there try and optimize their situation.

Markets and auctions are, following the theory of micro-economics, mechanisms that optimize the allocation of resources (such as power and money) over a large numbers of actors in a distributed way. When to produce or consume energy can be viewed as an optimisation process. A simple example is that the heating or cooling system of a room optimizes its behaviour with respect to the objective to stay close to a predefined temperature. However, markets add a dimension to this: price information. So, the optimization is not only about getting optimal functionality, but doing so at minimum cost or maximum profit: *price-reactive optimization*.

Price-reactive optimization is the foundation of novel *demand response* strategies. The key difference with the old top-down demand-side management schemes is this price responsiveness of local equipment, coupled to the possibility of two-way communication that enables bottom-up schemes in which DER devices are proactive on a market. In addition, we can treat „supply response“ on the same footing, and combine it with demand response into online, dynamic and price-responsive, *supply-demand matching* strategies.

To carry out price-reactive optimization in a computerized way, most well-known numerical optimization or operations research techniques are not really suited, because they have been developed typically with centralized, closed-system and offline settings in mind. This is not going to work in the open Internet-based environments of today. New agent-based e-market techniques and algorithms are therefore developed and tested that handle fully distributed and online situations with dynamic prices. This is the technological contribution by projects such as CRISP.

For consumers the advantage of price-reactive optimisation by means of electronic markets is that they have the opportunity to reach their goals at a lower cost. In the same way, local producers might be able to profile their production such that returns increase. From a power system viewpoint the gain is in changes in the behaviour of these same actors. Namely, due to their changes in behaviour (as a result of price incentives) there is less strain on peak hours and an increase in net demand during low cost periods.

Further information on electronic markets for DER

Further information on electronic power markets and agents can be found at the following references and sites.

[1] EU Project CRISP: www.ecn.nl/crisp.

[2] René Kamphuis, Per Carlsson, Cor Warmer, Josco Kester, and Koen Kok: *Distributed Intelligence for Supply/Demand Matching to Improve Embedding of Distributed Renewable Energy Sources*, CRIS-2004 Conference (www.leg.ensieg.inpg.fr/cris2004/).

[3] Hans Akkermans, Jos Schreinemakers, and Koen Kok: *Microeconomic Distributed Control: Theory and Application of Multi-Agent Electronic Markets*, CRIS-2004 Conference (www.leg.ensieg.inpg.fr/cris2004/).

[4] Dan Andersson, Peter Elmersson, Åke Juntti, Per Carlsson, Zoran Gajić, Daniel Karlsson, and Sture Lindahl: *Intelligent Load Shedding to Counteract Power System Instability*, CIGRE-2004 Conference.

[5] EPRI study on Auction Agents for the Electric Power Industry (1999): www.agentbuilder.com/Documentation/EPRI/; White paper: http://www.agentbuilder.com/Documentation/EPRI/epri.pdf

[6] R. Gustavsson: *Agents with Power*, Communications of the ACM, Vol. 42, No. 3 (March 1999), pages 41-47.

[7] Fredrik Ygge and Hans Akkermans: *Decentralized Markets versus Central Control - A Comparative Study*, Journal of Artificial Intelligence Research Vol. 11 (1999), pp. 301-333 (http://www.jair.org). (Related work, see: http://www.enersearch.com).

[8] Fredrik Ygge and Hans Akkermans: *Resource-Oriented Multi-Commodity Market Algorithms*, Autonomous Agents and Multi-Agent Systems (AAMAS) Journal Vol. 3 (March 2000) pages 53-72.

Acknowledgment. This work has been partially supported by the European Commission in the context of the IRED and CRISP projects.

Distributed Intelligence in Critical Infrastructures for Sustainable Power

ENK5-CT-2002-00673