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Massive coordination of residential embedded electricity generation and demand response using the PowerMatcher approach

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Abstract:

Different driving forces push the electricity production towards decentralization. The projected increase of distributed power generation on the residential level with an increasing proportion of intermittent renewable energy resources poses problems for continuously matching the energy balance when coordination takes place centrally. On the other hand, new opportunities arise by intelligent clustering of generators and demand in so-called Virtual Power Plants. Part of the responsibility for new coordination mechanisms, then, has to be laid locally. To achieve this, the current electricity infrastructure is expected to evolve into a network of networks (including ICT(Information and Communication Technology)-networks), in which all system parts communicate with one another, are aware of each other's context and may influence each other. In this paper, a multi-agent systems approach, using price signal-vectors from an electronic market is presented as an appropriate technology needed for massive control and coordination tasks in these future electricity networks. The PowerMatcher, a market-based control concept for supply and demand matching (SDM) in electricity networks, is discussed. The results within a simulation study show the ability to raise the simultaneousness of electricity production and consumption within (local) control clusters with cogeneration and heat-pumps by exchanging price signals and coordinated allocation using market algorithms. The control concept, however, can also be applied in other business cases like reduction of imbalance cost in commercial portfolios or virtual power plant operators, utilizing distributed generators. Furthermore, a PowerMatcher-based field test configuration with 15 Stirling-engine powered microCHP's is described, which is currently in operation within a fieldtest in the Netherlands.

Background

Traditionally, 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. One of the consequences of liberalisation is that power networks are being utilized with decreasing reserve capacity and investment capital preferably has a much shorter payback time horizon. This leads to an increase of smaller capacity installations operating in a distributed manner. Embedding small-scale renewable energy resources, with intermittent production, on the other hand, poses another challenge to match supply and demand of electricity in real-time at several levels in the grid. State-of-the-art information processing hardware and communication technology networks (ICT) form part of the solution for coordination and concerted control of demand and supply of electricity in these distributed environments ([1],[2],[3]).

An ongoing change in the worldwide energy supply is this 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. Driving forces behind the growing penetration of DG are [4-7]: environmental concerns, deregulation of the electricity market, diversification of energy sources, energy autonomy, and energy efficiency.

The growing share of DG in the electricity system may evolve in three distinct stages:

- **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 [6],[7].) During the second and third stage of DG growth, the lower parts of the electricity grid are expected to evolve 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 this scenario, 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.

This paper describes a novel control concept for automatic matching of demand and supply in electricity networks with a high share of distributed (co-)generation on the residential level. In this concept DG, demand response, and electricity storage are integrated using the advanced ICT technology of distributed control. The control concept opens the possibility to introduce massive scale **distributed coordination** additional to the existing **central coordination**, when the share of distributed generation increases. The coordination mechanism has the aim to increase the portion of DG that can be accommodated under normal operational conditions in the power grid.

ICT for distributed coordination

As a result of the electricity evolution, described above, the electricity infrastructure will become more and more inter-linked with ICT-infrastructure components. The architecture and algorithms 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 markets. 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.

The PowerMatcher approach is based the computer science technologies Multi-agent Systems (MAS) and Electronic (Virtual) Markets [8-10]. The combination of these two technologies results in a combination of properties, interesting from the viewpoint of coordination in electricity networks:

- 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. For instance, for a temperature control system in a dwelling, the deviation from the set-point temperature is a measure for the steepness of theprice-response.

- 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. In the PowerMatcher approach, from the appliance only a volume/price curve is sent to the coordinator/auctioneer; the auctioneer only spreads the allocations of the resource.

- 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 an intermediate or 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.

Of course, 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 as a whole must be secure, i.e. hardened against hackers and cheaters.

The PowerMatcher 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. The supply-demand mechanism is explained in figure 1. Articulation of the demand response is translated into a demand curve; ability or uncertainty to shift generation is modeled into a supply curve bid. Supply and demand meet at an equilibrium point, which gives the price.

The electronic market is implemented in a distributed manner via a tree-structure of so-called *SD-Matchers*, as depicted in Figure 2 and adopted from [1,2]. 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.

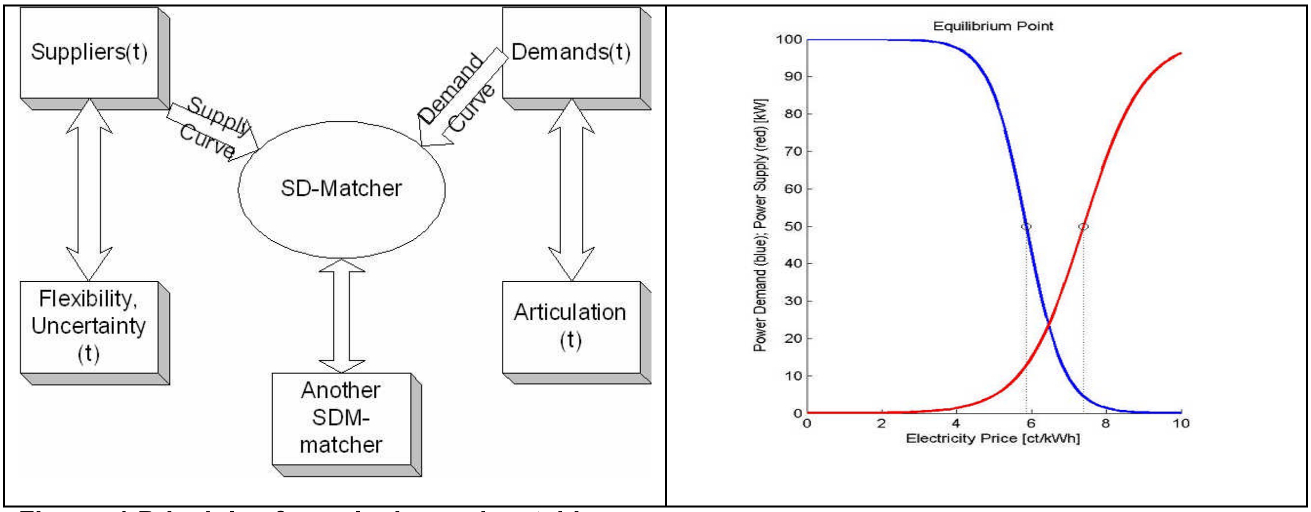

Figure 1 Principle of supply-demand matching

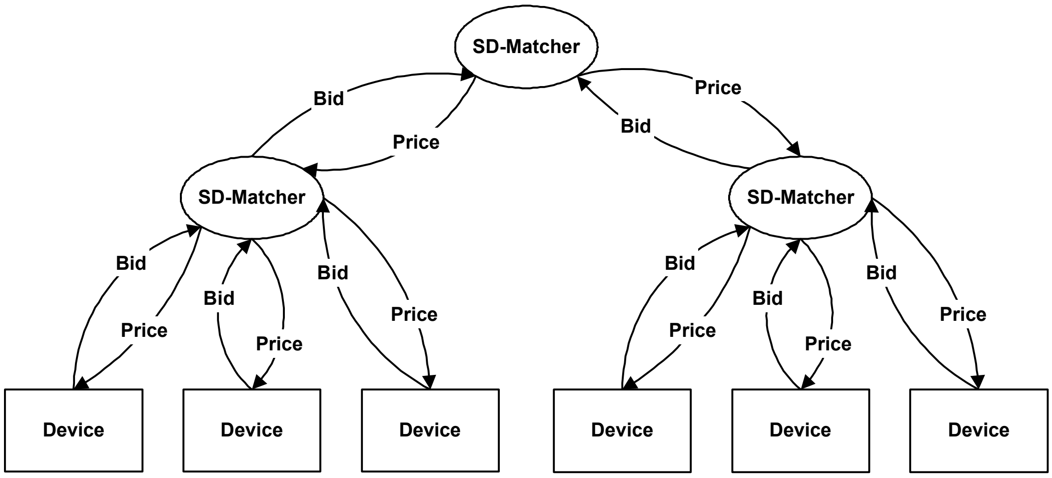

Figure 2: Hierarchy of supply & demand matchers in the PowerMatcher concept. The SD-Matchers implement a distributed electronic market.

Device agent types and strategies

From the viewpoint of supply and demand matching, devices can be subdivided according to 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, the device agent 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, 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, whose operation objective is to keep a certain temperature within two limits. Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power).

- **Electricity storage devices:** conventional batteries or advances technologies like flywheels and super-capacitors coupled to the grid by a bi-directional connection. The agent bidding strategy is 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. 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. Device constraints and user constraints are to be dealt with and introduced in a very cautious way. E.g. micro-CHP can't be operated with too many on/off subsequent cycles in order to save overall operating time. Adequate feedback has to be given to users to meet socio-economic and acceptance requirements of partly autonomously operating devices. Using this technology may not lead to major changes in lifestyle of users without any reward.

Simulation Case

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. 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.

Each home has a Home Energy Management gateway, which implements the local energy management strategy of the house. 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.

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Figure 3 and 4 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 25th 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 3 is 58% lower in the SDM-controlled case. This means that predictability of the cluster as a whole is increased by the automatic matching of demand and supply.

Figure 4 further nicely illustrates, that the internal price development on the internal device market acts as a coordination incentive.

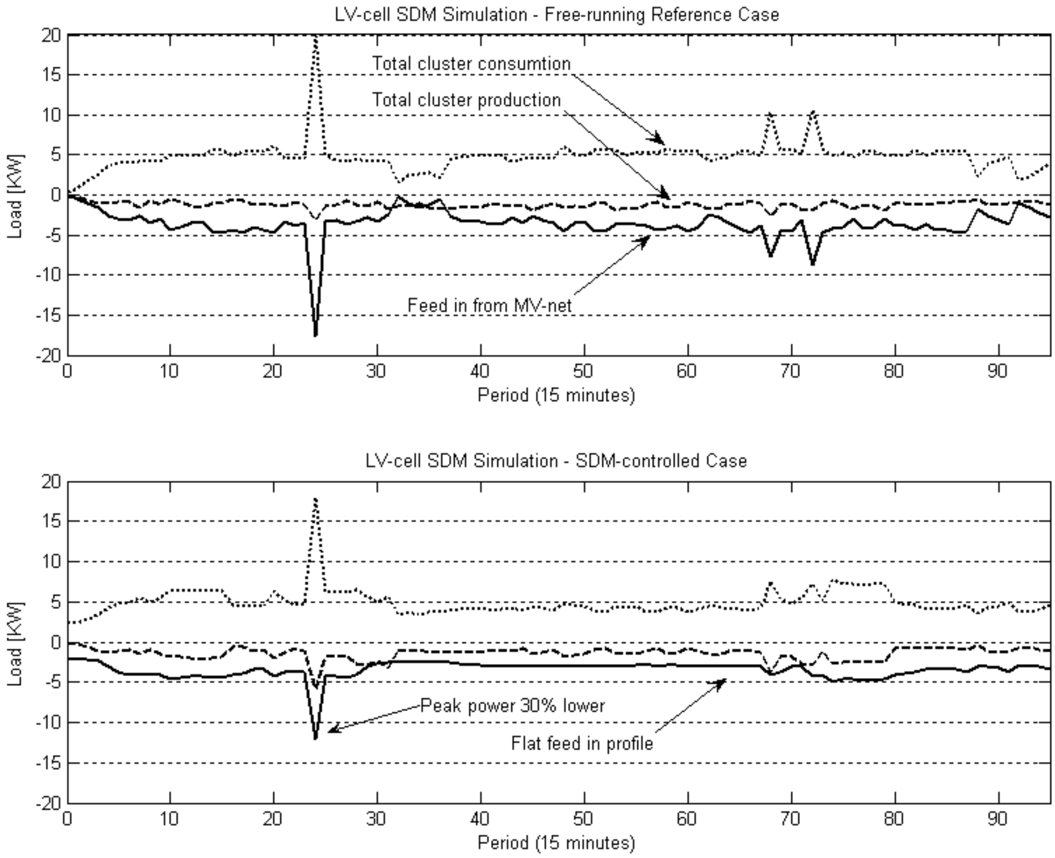

Figure 3: The result of a typical simulation run for the LV-cell simulation (see text).

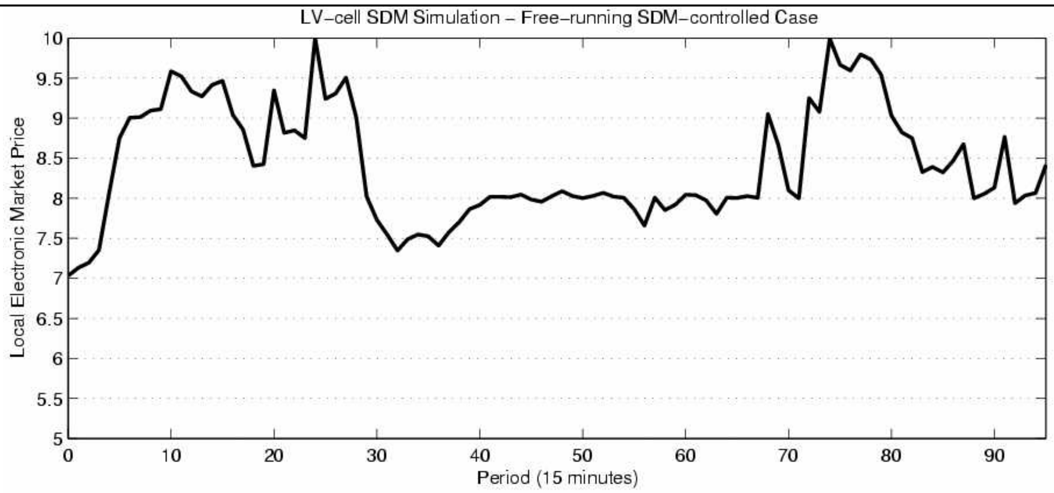

Figure 4: Internal price formation development during the internal market simulation

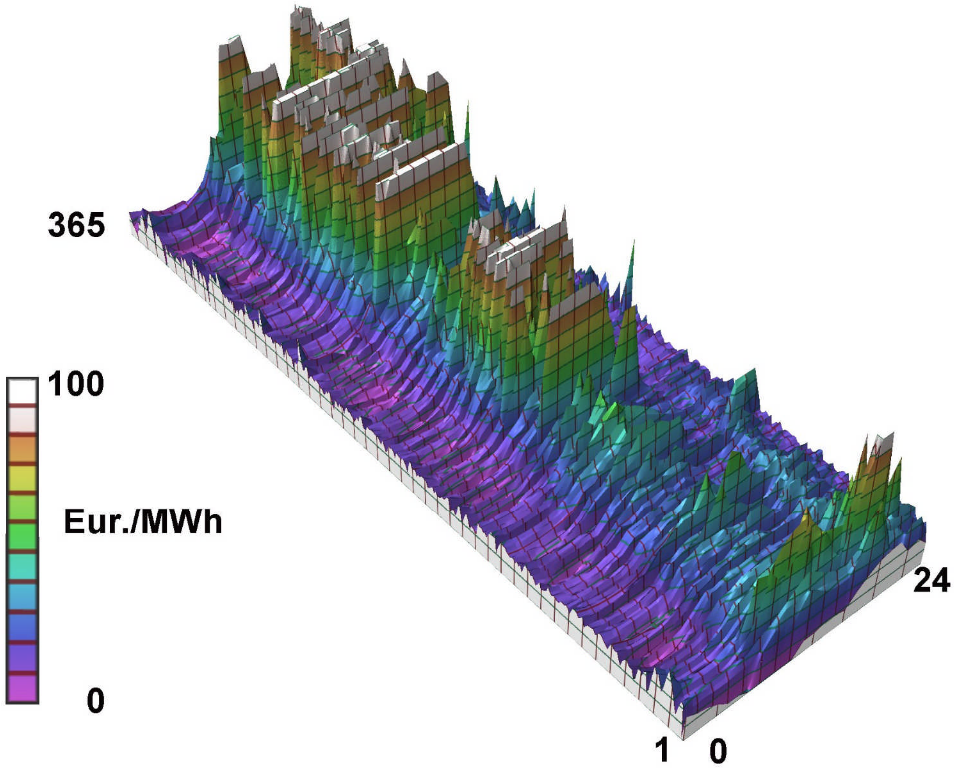

Figure 5 Price development on the APX-market in 2003 as a function of wallclock time and daynumber

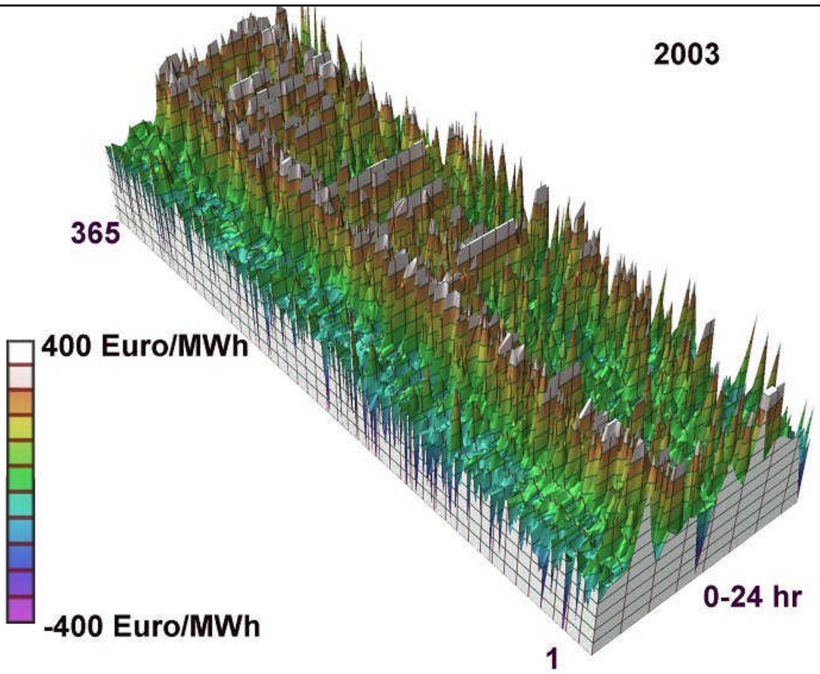

Figure 6 Imbalance (over/underrealisation compared to the programme) cost per MWh as a function of time in 2003

Utilizing distributed coordination for operating virtual power plants on markets

The flexibility in micro-CHP operation utilized by clustering in a VPP can be put into value in different ways. One might think of:

- Trading the output of the VPP on the day-ahead power market (e.g. the Dutch APX or the Scandinavian NordPool). Figure 5 shows the highly variable price development on the APX power market in the Netherlands. Actual price peaks were above 2000 Euro/MWh. The peaks round mid-day in august and at the end of the afternoon during winter provide opportunities for flexible electricity generating capacity and demand.

- Trading the output of the VPP on the imbalance or spinning reserve market. Figure 6 shows a similar 3D-plot for the imbalance market in the Netherlands. If demand/generation shiftability fits into the timeframe of this market, considerable benefits may be gained.

- Support the local distribution system operator (DSO). For instance, by reducing the local peak demand of low-voltage grid segments, to defer reinforcements in the grid infrastructure (e.g. substations and cables).

Fieldtests in a Virtual Power Plant setting

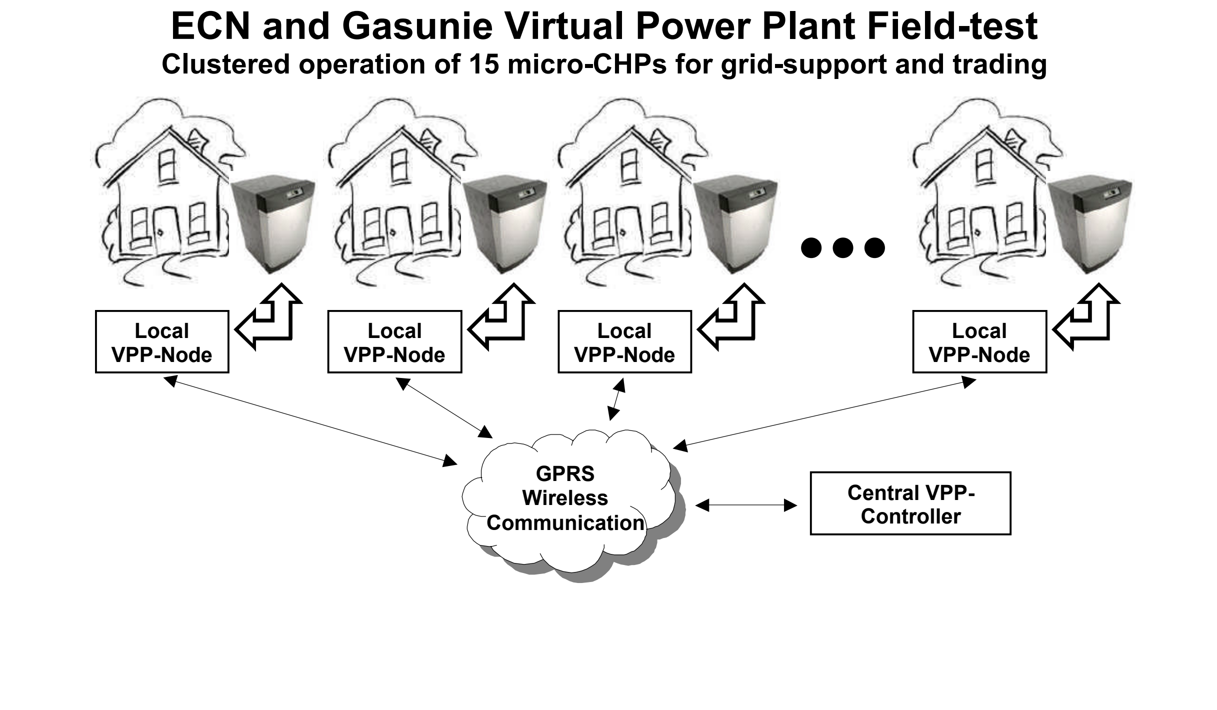

Figure 7 Fieldtest configuration with micro-CHPs

Currently a fieldtest with 15 Stirling based CHP's is in the process of rollout (see fig 6). The Dutch natural gas company Gasunie is undertaking a rollout and measurement program of domestic micro-CHP installations. A measurement project of approximately 50 microCHP installations is started. WhisperGen type installations are placed at the premises of people employed by Gasunie and a number of cooperating Dutch electricity retail companies. The primary goal of this field test is to monitor the installation in typical Dutch households and to gain user experiences. The current available micro-CHP systems are heat-demand driven, i.e. they produce heat and electricity at moments of heat demand, either from room heating or warm tap water usage. Uncoupling the electricity production from the heat demand can raise the value of produced electricity. This can be done by utilizing the inherent heat buffering capacity of the building and the warm tap water buffer. The electricity and heat functions of the CHP can be uncoupled further by adding a device for heat (or electricity) storage.

In the first half year of 2006, Gasunie and ECN cooperate to add an ICT-infrastructure and local intelligence to a series of 15 of the before-mentioned 50 microCHP's. Goal of this field test is to demonstrate the ability to act as a cluster in a Virtual Power Plant (VPP) setting to attribute to a common control goal. The PowerMatcher control concept forms the core software of this VPP.

The field test VPP is designed to support the local distribution system. Due to the open character of the control concept, flexible electricity loads (i.e. demand response) can easily be added to the system in later stages of the field trial. The field test runs under auspices of the Smart Power System-consortium, a Dutch industrial and research conglomerate developing technology and business cases for microCHP based virtual power plants.

Conclusion

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 that can contribute to a solution to 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 a distributed control mechanism. Due to device reactions on price fluctuations, the simultaneousness between production and consumption of electricity 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. Two field experiments with the technology show very encouraging results as to the actual implementation and the use of price signals for smooth concerted operation of the devices due to the market equilibration mechanism. Proper socio-economic considerations are to be dealt with when constructing utility functions to be used in the agents and to assure acceptance and minimal lifestyle changes.

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