Ancillary Services for Minimizing the Impact of Resonances in Low Voltage Grids by Power Electronics based Distributed Generators

P.J.M. Heskes, J.M.A. Myrzik, *Member, IEEE* and W.L. Kling, *Member, IEEE*

***Abstract*-- This paper proposes a solution for the minimization of the impact of resonances due to parallel capacitances in the grid. This solution is a combination of two additional (ancillary) services of power electronics converters, namely Virtual Parallel Capacitance Reduction (VPCR) and Virtual Resistive Harmonic Damping (VRHD). VPCR is an ancillary service that lets a power electronics converter generate a current to compensate currents through capacitances placed in parallel with the grid, for a frequency range that includes the fundamental and a number of harmonics. VRHD is an ancillary service that gives a power electronics converter a resistive behavior for a number of harmonics. This action will bring extra damping to resonances in the grid.**

Results of laboratory validated computer simulations with a model of a small single-phase inverter for DG, will give insight in the effect of the two ancillary services, VPCR and VRHD that are implemented.

***Index Terms*— Grid Resonances, Harmonic Interaction, Active Damping, Ancillary services, Power Quality.**

I. Introduction

Most small inverters for DG of today show a sinusoidal output current and with that a low harmonic current emission, therefore they easily comply with the applicable harmonic current emission standards of today and from that point of view they don't contribute to voltage pollution in the LV distribution grids. However in another way they can cause harmonic voltage pollution in these grids, because of possible resonances due to the interaction of the output filter capacitance of the inverter and the grid inductance. Grid resonances can amplify harmonic voltages and become problematic in future grids with large numbers of power electronics based appliances, because of the increase of parallel capacitances connected to the grid. It should be mentioned that inverters for DG have relatively large output capacitors. An inverter of a few kW can bring a large contribution to the total in parallel connected capacitances at the point of connection, therefore a good starting point is to let the inverter compensate the current through its output capacitance for the fundamental frequency and a number of harmonics. Because the inverter has the potential to generate a current for compensating currents through one or more in parallel connected capacitances, this feature is marked as an ancillary service. In this work, this service is called "Virtual Parallel Capacitance Reduction (VPCR)". For correct compensation, parallel capacitors of other loads must be located close to the output feeders of the inverter that offers this ancillary service.

A second measure to minimize the effect of resonances is an ancillary service that is called "Virtual Resistive Harmonic Damping (VRHD)". VRHD gives the inverter a resistive behavior for the harmonic frequency range. This will bring extra damping to resonances in the grid [1].

The combination of the two ancillary services, VPCR and VRHD, is an approach that is very effective for minimizing the impact of resonances in the LV distribution grid [2]. This combination contains two measures, firstly VPCR is virtually shifting the resonance towards a higher frequency range where the propagation is limited, preferably above the 25^{th} harmonic, and secondly VRHD damps the resonance peak to a lower level. VRHD will also bring damping to the harmonic currents coming from non-linear loads in the distribution grid.

In this paper computer simulations with a laboratory validated model will give insight in the two ancillary

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services VPCR and VRHD. The ancillary services could be implemented in almost all appliances with a power electronics based front end (i.e. a power electronics based converter that is directly connected to the grid), but because a small inverter for DG has a relatively large output filter capacitance, such an inverter is used in this work. With this ancillary service inverter, especially VPCR effects can be easily noticed.

Figure 1 shows a part of a LV distribution grid with a number of ancillary service inverters at several Points of Connections (PoC).

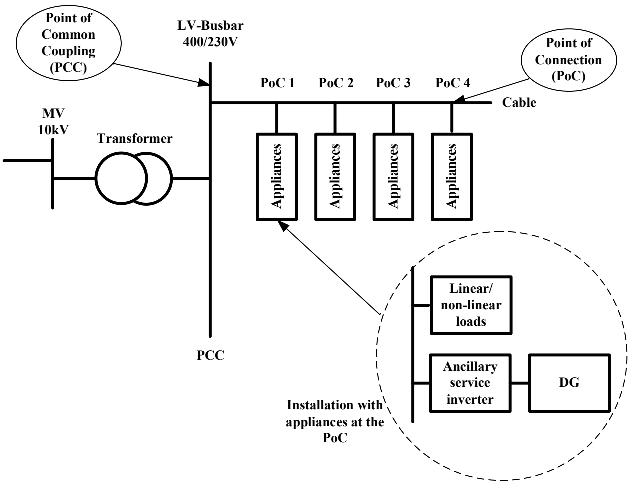

Figure 1: Part of a LV distribution grid with a number of ancillary service inverters.

II. ANCILLARY SERVICES INVERTER

In this section the VPCR and VRHD ancillary services are firstly computer simulated with a Matlab/Simulink inverter model and afterwards implemented in the Digital Signal Processor (DSP) control system of a hardware inverter by means of automatic code generation [3]. This hardware inverter is then used in laboratory experiments for the validation of the computer simulations.

To see the effects of VPCR and VRHD, simulations are done on a network model that has a practical behavior for the frequency range of interest, i.e. up to the 40^{th} harmonic according to the standard for the quality of voltage [4]. For all the modeling work only single- phase systems are studied, this means connections between a line and the neutral. Unbalance issues are not taken into account in this work. Because the used converter switching frequencies are much higher than the frequencies involved with the control system, an average model could be used [5].

Because the purpose of the computer simulations is an investigation on the lowest frequency resonances with the validated inverter model, all grid impedances are simplified and represented as first order systems with only resistance and inductance. Capacitances of cables are not taken into account, because they are neglectable compared to the inverter capacitances and parallel capacitances of loads, therefore cables are modeled as a resistive-inductive system [6].

Most of the ancillary services inverter performance results in this work are output impedances, presented in a Bode plot. Output impedance as a function of harmonic frequencies expresses the interaction between harmonic current and voltage, and numerous aspects can be concluded from these plots, e.g. the grid feeding character for harmonic frequencies and the contribution to parallel resonances in the grid.

The studied inverter model in this work is based on a grid-feeding system like small PV-inverters in general are. These systems dump their power to the grid irrespective of grid conditions [7]. Because the focus of this work is on the interaction between the inverter and the grid, only the grid interfacing part of the inverter is described. Figure 2 shows the inverter's basic block diagram with focus on the grid interfacing part.

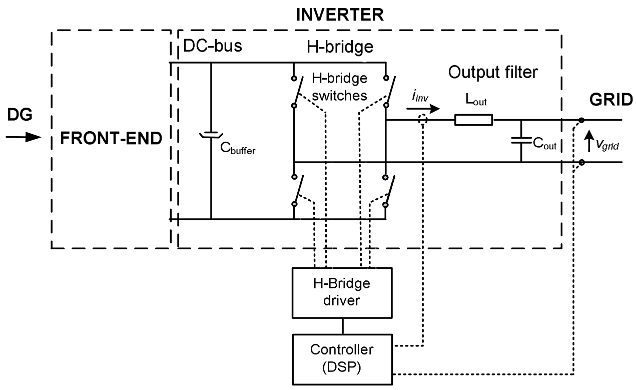

Figure 2: The inverter's basic block diagram with focus on the grid interfacing part.

In the following sections successively the topology, the control system and the ancillary services are discussed.

A. The inverter topology

The used topology for the ancillary services inverter simulation model is a Voltage Source Converter (VSC). A VSC characterizes itself with a low output impedance (i.e. the impedance of the converter seen from the grid). This low impedance is mainly due to the low impedance of the buffer capacitor and the H-bridge switching components, and the output impedance is dominated by the output filter. Therefore in the harmonic frequency range of interest in this work, the output impedance of the circuit of Figure 2 varies from inductive to capacitive and in between the system resonates with a high impedance, all due to the dominating effect of the output filter. In Figure 3 the buffer capacitor together with the inverter's H-bridge of Figure 2 is replaced by a controllable voltage source.

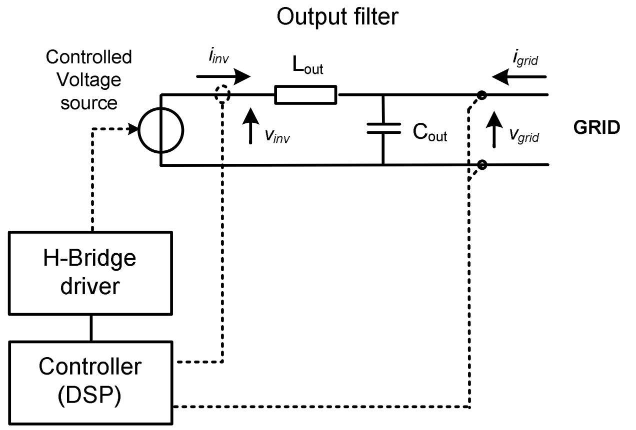

Figure 3: The inverter modeled as a controlled voltage source with output filter.

To achieve a grid-feeding system, a high output impedance is needed for the 50Hz fundamental and to improve harmonic and transient performance, also for a wider frequency range that includes a number of harmonics. A current feed-back control as depicted in Figure 4 can provide for this high output impedance while using a VSC.

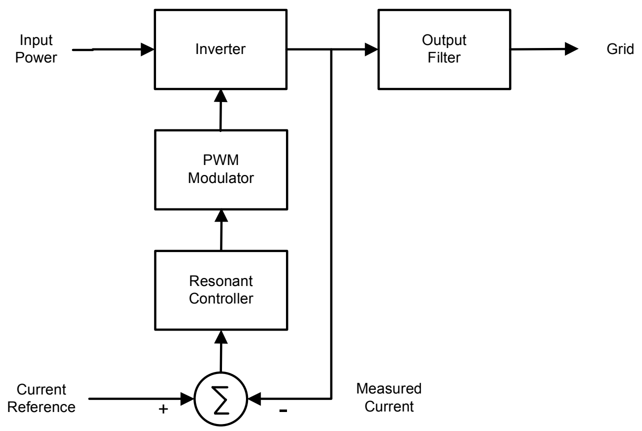

Figure 4: An inverter with a current feedback control system.

Building a control system that performs well at various grid impedances, can easily be done if the only concern would be the 50Hz fundamental, however controlling also a range of harmonics is not an easy task. In today's practice, DSP based controllers are used in switching converters. Although these controllers can easily contain very complex systems, PWM transport - and sample delays reduces the attainable performance in bandwidth [8], [9].

Also grid impedance variations have a large influence on the attainable control performance of grid connected power electronics converters [7]. To achieve a robust system in terms of stability at various grid impedances, damping of the interaction between the output filter and grid impedance, with a special control loop is a good option [10], [11]. For the ancillary services performance simulations, a practical Dutch grid impedance value of a single-phase low voltage connection is chosen from [12], see the used Thevenin scheme of the grid in Figure 5 and the corresponding values below:

- R_{grid} = 0.25 Ohm,
- L_{grid} = 0.25 mH.

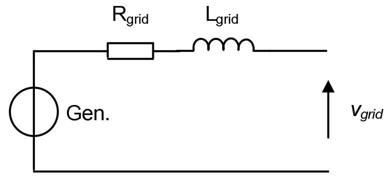

Figure 5: Thevenin scheme of a single-phase low voltage grid connection used in the simulations.

B. *The inverter control system*

The block diagram of Figure 6 gives the total control system of the inverter with VPCR and VRHD control, this control system measures voltage and current of the inverter system (see Figure 3) and drives the PWM modulator. As can be seen also in Figure 6 a so called "u_L-compensation" feed-forward loop is added to the system for output inductor voltage drop compensation.

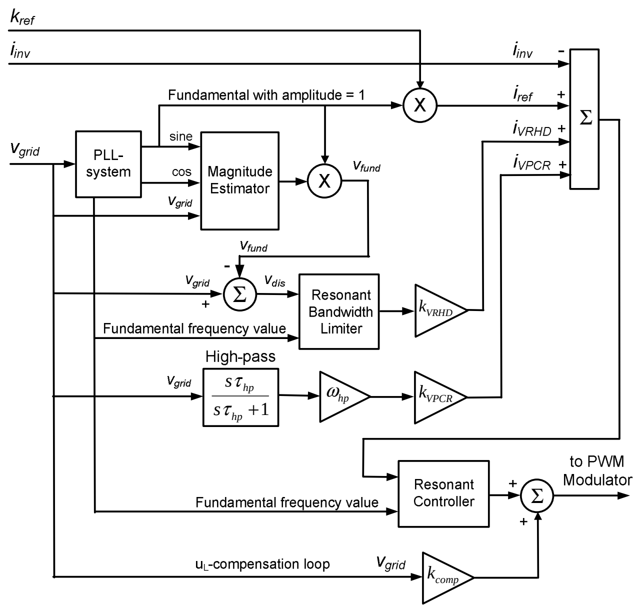

Figure 6: The total control system of the ancillary services inverter with VPCR and VRHD control and u_L-compensation.

For the total control system, only two signals needs to be measured, namely the current through the output inductor of the inverter i_{inv} and the grid voltage v_{grid}, the only output of the control system goes to the PWM modulator. A very important part of the control system is the Phase Lock Loop (PLL) system, the base of this system is a voltage controlled oscillator and a phase-sensitive detector in a loop. The PLL system generates from a grid voltage signal with possible pollution v_{grid}, the following signals: a sine and cosine function with the same frequency as the grid voltage fundamental, and the fundamental frequency value. The sine and cosine functions are used to estimate the fundamental magnitude value from the grid voltage v_{grid}. The sine function is also used to generate a current reference signal i_{ref} that is in-phase with the grid voltage, by multiplying this sine function with k_{ref}. Giving k_{ref} is a positive value will let the inverter deliver real power to the grid. The fundamental voltage v_{fund} is used to calculate the grid voltage pollution v_{dis} by subtracting v_{fund} from v_{grid}, see equation (1).

$$v_{dis} = v_{grid} - v_{fund} \tag{1}$$

The fundamental frequency value output from the PLL is used to tune the fundamental and harmonic resonators. The used PLL system and the fundamental magnitude estimator are made of building blocks from the Matlab/SimPowerSystems toolbox library [3].

Just as in many control systems the inverter's output current i_{inv} is fed back with a negative sign and summated with the reference i_{ref} to create an error signal to drive a controller. Extra in this system are two additional inputs i_{VPCR} and i_{VRHD} to this summation coming from the VPCR and VRHD control.

In the following sections the ancillary service functions VPCR and VRHD are explained in more detail.

1) VPCR controller

The goal of VPCR is to virtually reduce the inverter's output capacitor, this is done by compensating the current through this capacitor. In Figure 7 the VPCR controller is copied out of the total control system of Figure 6. This VPCR control uses the v_{grid} signal to calculate the current through the output capacitor C_{out}, this can be done because v_{grid} equals the capacitor voltage, see Figure 3. The calculated current through the output capacitor i_{VPCR} is added to the requested inverter output current i_{ref} (see Figure 6), with this action the capacitor current is compensated and the output capacitance virtually reduced.

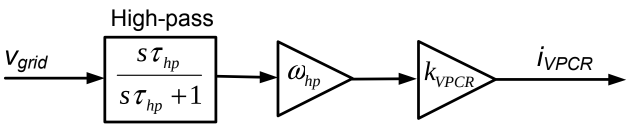

Figure 7: The VPCR control system of the inverter.

The relation between v_{grid} and the current through C_{out} is shown in Equation (2). Equation (3) shows how to calculate the current through C_{out}.

$$X_{C\,out} = \frac{v_{grid}}{i_{C_{out}}} = \frac{1}{sC_{out}} \tag{2}$$

$$i_{C\,out} = v_{grid}\, sC_{out} \tag{3}$$

Building a pure differentiator is not possible in practice and not needed, therefore a high-pass filter is used. To give this high-pass filter a unity gain at ω = 1, the filter output is multiplied with a gain that equals the value of the high-pass filter cutoff frequency ω_{hp}, see Equation (4). ω_{hp} is the reciprocal of τ_{hp}. The high-pass filter cutoff frequency ω_{hp} is chosen beyond the inverter's bandwidth.

$$i_{VPCR} = v_{grid}\,\frac{s\tau_{hp}}{s\tau_{hp}+1}\,\omega_{hp}\,C_{out} \tag{4}$$

Finally the constant k_{VPCR} equals the capacitor value from which the current is compensated, see Equation (5).

$$k_{VPCR} = C_{out} \tag{5}$$

2) VRHD controller

The goal of the VRHD control is to let the inverter behave as a (virtual) resistor, but only for harmonic frequencies, therefore the output impedance needs to be controlled. Seen from the grid the output impedance is (see Figure 3):

$$z_{out} = \frac{v_{grid}}{i_{grid}} \tag{6}$$

Because the output capacitor current is compensated by the VPCR control loop, $-i_{inv}$ equals i_{grid}, therefore the following counts by approximation:

$$z_{out} = -\frac{v_{grid}}{i_{inv}} \tag{7}$$

$$i_{inv} = v_{grid}\,\frac{-1}{z_{out}} \tag{8}$$

$$i_{VRHD} = v_{grid}\, k_{VRHD} \tag{9}$$

$$k_{VRHD} = \frac{-1}{z_{out}} \tag{10}$$

The calculated current i_{VRHD} is added to the requested inverter output current i_{ref} (see Figure 6), with this action the inverter's output impedance can be controlled.

In Figure 8 the VRHD controller is copied out of the total control system. This VRHD control needs to damp only the grid voltage distortion and of course not the fundamental, therefore the fundamental voltage v_{fund} is subtracted from the grid voltage v_{grid} to estimate the distortion voltage v_{dis}.

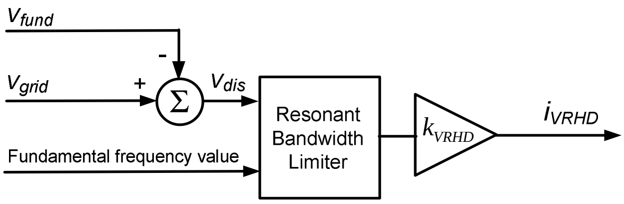

Figure 8: The VRHD control system of the inverter.

To avoid poorly defined damping at frequencies other than the harmonics a resonant bandwidth limiter is added to the VRHD controller, see Figure 8. This resonant bandwidth limiter works with multiple resonators. At the resonant peaks the limiter has a gain of 0 dB and a zero phase shift, see Figure 9.

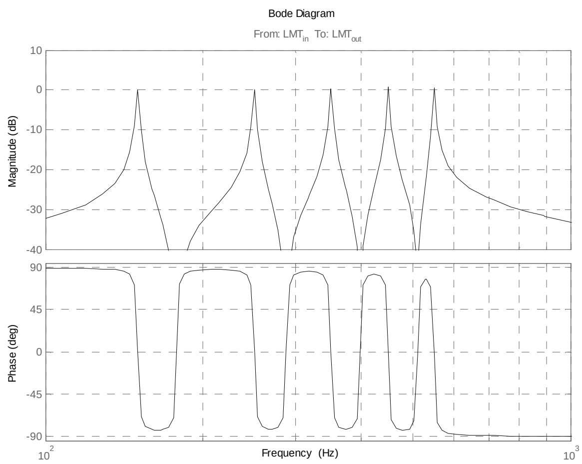

Figure 9: Bode transfer function plot of the resonant bandwidth limiter of the VHRD control system.

III. Validated Simulations in the Frequency Domain

In this section practical simulations in the frequency domain of the inverter's output impedance are given, these results are presented in Bode plots. The inverter's output impedance is calculated from time series of measured voltage and current, with the laboratory setup of Figure 10.

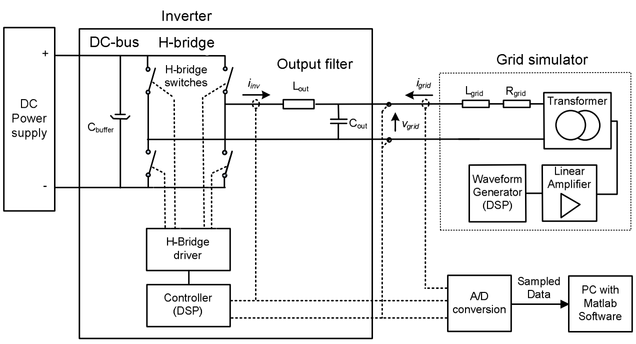

Figure 10: Laboratory setup.

The output impedance plots give an impression of the performance of the inverter's control system. Both computer simulation results as well as related experimental results are presented in this section, for validation.

In the used simulations the grid voltage v_{grid} is polluted with a flat spectrum, containing all harmonics up to the 40^{th}. Time series of the grid voltage v_{grid} and the grid current i_{grid} are used to calculate the inverter's output impedance, only for harmonics from the 2^{nd} to the 40^{th}. Results from computer simulations are presented as a solid line connecting all the harmonic impedances, results from the laboratory measurements are presented as dots. For comparison both the computer simulation results and the related experimental results are presented in one figure.

In this work attention is paid to the inverter's controlled performance as well as the uncontrolled performance. After some Bode plots of the basic control system, successively the ancillary services VPCR and VRHD are activated, to notice the difference.

A. Basic inverter control

In this section the effect of the basic inverter control is discussed. In the first plot the inverter's output impedance is given without any control active, hereafter the u_L-compensation loop is activated for 50%. The reason for implementing only 50% u_L-compensation and not 100% has to do with keeping the total control system stable for various grid impedances. Finally the current control loop is activated as well.

In Figure 11 the inverter's output impedance Bode plot is given for the situation without any control loop active. This figure clearly shows a parallel resonance between L_{out} and C_{out} , this is because the inverter impedance Z_{inv} is very low due to the VSC concept of the inverter.

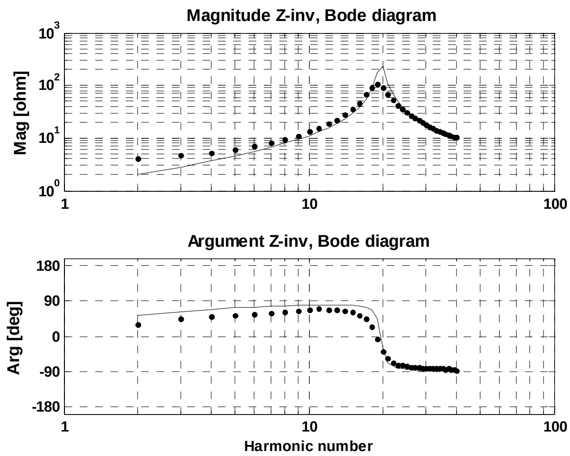

Figure 11: Bode plot of the inverter's output impedance without any control.

In Figure 11 also can be noticed that the simulation results (solid line) differ from the experimental results (dots), because the latter one has more resistance and therefore also more damping. For frequencies lower than the 19^{th} harmonic, the inverter's output impedance shows an inductive-resistive behavior, because the phase angle tends to +90°. For frequencies higher than the 19^{th} harmonic, the inverter's output impedance shows a capacitive behavior, this is indicated by the phase angle that goes to -90°.

In Figure 12 the Bode output impedance plot is given with the 50% u_L-compensation loop active. With this loop activated, the parallel resonance between L_{out} and C_{out} is damped to a much lower peak level, compared to Figure 11.

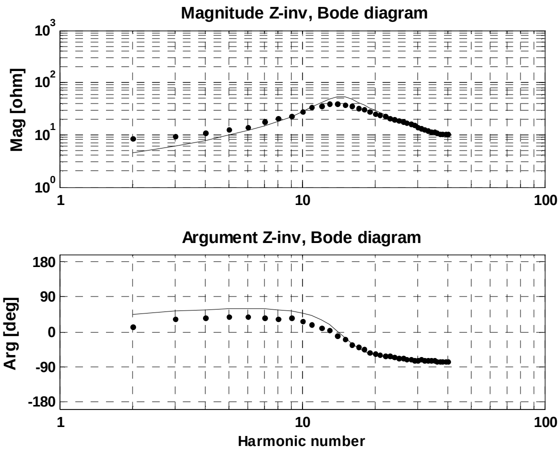

Figure 12: Bode plot of the inverter's output impedance with only u_L-compensation.

The resonance frequency in Figure 12 is virtually shifted from about the 19^{th} to about the 14^{th} harmonic, this is due to the virtual increase in inductance of L_{out} with a factor two, as a result of the activated 50% u_L-compensation loop.

In Figure 13 the Bode output impedance plot is given with the current control loop activated in addition to the u_L-compensation loop.

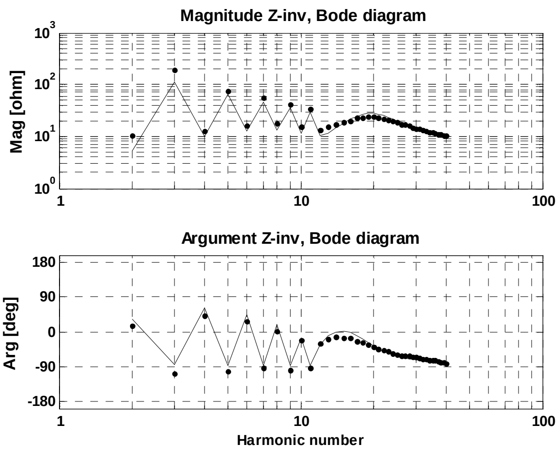

Figure 13: Bode plot of the inverter's output impedance with current control and u_L-compensation.

The current control loop has mainly effect on the fundamental and the 3^{th}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonic, due to the resonator control system. Because of this the inverter has a high impedance for these harmonic frequencies. Therefore the output impedance on these harmonics equals the impedance of the output capacitor C_{out}. There is however also some effect beside these resonance peaks, therefore other harmonic impedances are affected as well.

With the activation of both the u_L-compensation and the current control loop the ancillary services inverter has its basic configuration, the Bode plot of Figure 13 shows thus the impedance on harmonic frequencies for this basic configuration, measured at the output feeders.

B. Ancillary services VPCR and VRHD

In this section the output impedance Bode plots are discussed of the basic inverter with the ancillary services VPCR and VRHD activated successively.

In Figure 14 the Bode plot of the inverter's output impedance is given with the ancillary service VPCR activated. Compared to the output impedance plot of the basic configuration (see Figure 13) the magnitude of the capacitive impedance has strongly increased, due to VPRC (see Figure 14). This indicates a virtual reduction of the parallel capacitances. The ancillary service VPRC has mainly effect on the fundamental (not shown here) and the 3^{th}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonic, because the VPCR performance depends on the current control performance.

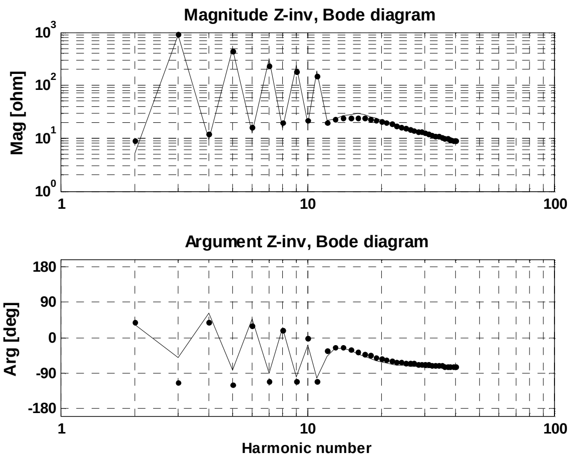

Figure 14: Bode plot of the inverter's output impedance with activated VPCR.

In Figure 15 the inverter's output impedance Bode plot is given with the ancillary service VRHD activated in addition to VPCR. The ancillary service VRHD has mainly effect on the 3^{th}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonic, because also the VRHD performance depends on the current control performance, beside this the VRHD controller has an extra resonant bandwidth limiter to avoid poorly defined damping at frequencies other than the harmonics supported by the resonant controller of the current control system. Because of this strongly limited effect of VRHD to the 3^{th}, 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonic, only on these harmonics, the inverter's output impedance equals the pure resistive value of 10 ohms, as adjusted.

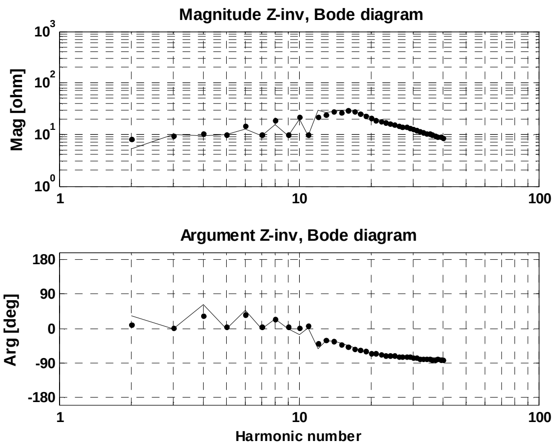

Figure 15: Bode plot of the inverter's output impedance with activated VPCR and VRHD.

With the activation of both the ancillary services VPCR and VRHD, the ancillary services inverter has its full performance operation mode. The Bode plot of Figure 15 shows the impedance on harmonic frequencies for this operation mode, measured at the output feeders.

IV. Discussion

An inverter for DG that offers the ancillary services VPCR and VRHD can contribute to a power quality improvement, but are there any design consequences and what about the effect on efficiency and dynamic range?

For both services, a compensation current has to flow between the inverter and the grid, through the output filter inductor. To let this current flow, the inverter has to superimpose compensation voltages on the fundamental voltage. Because these compensation voltages have to overcome the voltage drop across the output filter inductor, the magnitudes can be significant, especially in the higher harmonic order range. Beside this, also a small voltage drop due to resistive losses will be present.

Concerning the dynamic range, the ancillary services VPCR and VRHD with its compensation current, ask for a higher DC-bus voltage of the inverter, in order to achieve a higher dynamic range of the PWM modulator.

Concerning efficiency, the ancillary services VPCR and VRHD with its compensation current, will cause voltage drops due to resistive losses. Although these resistive losses are expected to be small, they have to be incorporated in the efficiency calculation of the inverter Therefore the losses due to the ancillary services VPCR and VRHD, will slightly reduce the total inverters efficiency.

In this work the effect off the ancillary services VPCR and VRHD on efficiency and dynamic range are not being quantified, therefore to learn more about this subject, more research need to be done.

V. Conclusions

In this paper two ancillary services for minimizing the impact of resonances in the grid are studied. Both services can be implemented in power electronics based converters, they are named "Virtual Parallel Capacitance Reduction (VPCR)" and "Virtual Resistive Harmonic Damping (VRHD)".

VPCR is an ancillary service that generates an additional current to compensate currents through capacitances that are placed in parallel with grid connected appliances. VPCR works in a frequency range that includes the fundamental and a number of harmonics. VRHD is an ancillary service that gives the converter a resistive behavior for a number of harmonics.

A single- phase inverter for DG with the ancillary services VPCR and VRHD is computer simulated and validated with a hardware model in a laboratory. Results of the validated simulations show that the two ancillary services perform as expected, especially the combination of the two ancillary services is very useful to minimize the effect of resonances in the LV distribution grid, because VPCR is virtually shifting the resonance towards a higher harmonic frequency range and VRHD damps the resonance peak to a lower level. VRHD will also bring damping to harmonic currents coming from non-linear loads in the distribution grid.

These two ancillary services can be implemented in power electronics based inverters for DG, as presented in this paper. The actual working range however depends on the performance of control system.

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VII. AUTHORS’ BIOGRAPHIES

Peter J.M. Heskes received the Electronic Engineer degree from the HTS, The Hague, The Netherlands, in 1980. From 1980 to 1999, he was with a large Dutch electronic-product manufacturer for the military and professional market. He started there as a Product Designer and became a Product Manager of the power-electronic department. His work was related to power electronic converters. In 2000, he started as a Project Coordinator with Intelligent Energy Management at the Energy Research Centre of the Netherlands (ECN), Petten, the Netherlands. His current work is related to power electronic converter technology in grid connected distributed energy systems. From the beginning of 2007 he combines his work at ECN with a position as a Ph.D. student at the Electrical Power Systems group of the Eindhoven University of Technology. His research interests are power quality issues with the coupling of power electronic converters of distributed energy systems, to the electricity network.

Johanna M.A. Myrzik was born in Darmstadt, Germany in 1966. She received her MSc. in Electrical Engineering from the Darmstadt University of Technology, Germany in 1992. From 1993 to 1995 she worked as a researcher at the Institute for Solar Energy Supply Technology (ISET e.V.) in Kassel, Germany. In 1995 Mrs. Myrzik joined the Kassel University, where she finished her PhD thesis in the field of solar inverter topologies in 2000. Since 2000, Mrs. Myrzik has been with the Eindhoven University of associate professor in the field of residential electrical infrastructure. In 2009 Johanna Myrzik joined the Technical University of Dortmund where she holds a professorship on energy efficiency. Her fields of interests are: power electronics, renewable energy, distributed generation, electrical power supply.

Wil L. Kling (M’95) was born in Heesch, The Netherlands in 1950. He received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, The Netherlands, in 1978. From 1978 to 1983 he worked with Kema and from 1983 to 1998 with Sep. Since then he is with TenneT, the Dutch Transmission System Operator, as senior engineer for network planning and network strategy. Since 1993 he is a part-time Professor at the Delft University of Technology and since 2000 he is also a part-time Professor in the Electric Power Systems Group at the Eindhoven University of Technology, The Netherlands. From December 2008 he is appointed as a full-time professor and a chair of Electrical Energy Systems group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability. Mr. Kling is involved in scientific organizations such as Cigre and IEEE. He is the Dutch Representative in the Cigre Study Committee C6, *Distribution Systems and Dispersed Generation.*