HARMONIC REDUCTION AS ANCILLARY SERVICE BY INVERTERS FOR DISTRIBUTED ENERGY RESOURCES (DER) IN ELECTRICITY DISTRIBUTION NETWORKS

Peter HESKES
Energy research Centre of the Netherlands (ECN)
heskes@ecn.nl

Jorge DUARTE
Technical University of Eindhoven – the Netherlands
j.l.duarte@tue.nl

ABSTRACT

Can inverters for Distributed Energy Resources (DER) contribute to the reduction of harmonic in electricity distribution networks? In theory they can, however one must not underestimate the effort to be taken in practice, to override issues like reducing the output capacitance of the inverter itself.

In this paper computer simulations will give insight in requirements to be placed on inverters for DER, to let them contribute to the reduction of harmonics in electricity distribution networks.

INTRODUCTION

Inverters of today, although complying with emission standards, do contribute to harmonic voltage pollution in the electricity distribution network, because of their interaction on background pollution in the network [1,2]. Beside this, harmonic stability problems like resonance phenomena are observed in electricity distribution networks with large numbers of DER [3]. To avoid this harmonic emission and instability effects, special care must be taken to some topology aspects and the control of these inverters [4]. For this, the inverter must comply with requirements that are not driven by today's standards. Once these effects are under control, a start can be made to work on reduction of harmonics in electricity distribution networks.

COMPUTER MODELS OF DER INVERTERS

For this investigation, two basic computer models of an inverter were built. In these models only the current control loop was implemented. In practice an inverter has a fast inner control loop for controlling the output current, and a slow outer control loop to control the balance of input and output power. The latter loop was not modelled because of its slow response, compared to the area of interest. Figure 1 and 2 gives diagrams of both control loops of the two types of inverter models that were investigated. The difference between the two is the location of the current sensor in the circuit. In figure 1 the output filter is located <u>outside</u> the current control loop, and in figure 2 the output filter is located <u>inside</u> the current control loop and therefore compensated. In today's practice the output filter of a DER inverter is not compensated. Compensating the influence of the output filter has the advantage that the output capacitance of the inverter is strongly reduced. High output capacitances of DER inverters can cause a capacitive reactive power remainder in a distribution area with large numbers of DER, which is an unwanted situation [5].

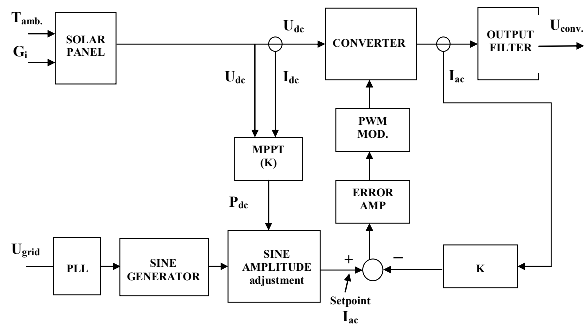

Fig. 1, Inverter-1 model with the output filter <u>outside</u> the current control loop.

When the output filter is located inside the current control loop, the grid impedance is directly a part of the control loop gain (1/Zgrid).

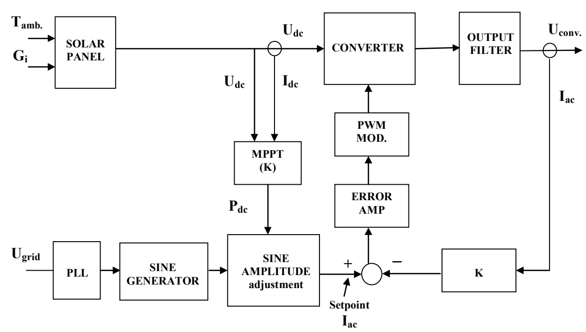

Fig. 2, Inverter-2 model with the output filter <u>inside</u> the current control loop.

In contrast with the Inverter-1 concept, sufficient phase and gain margins must be obtained in the Inverter-2 concept, to guaranty stability with the expected variations on the grid impedance. Another method is to guaranty this, is to (automatically) measure the grid impedance over a wide frequency spectrum and adjust the control loop gain with this information [6].

In a distribution network the grid impedance is dominated by the series circuit of a resistance and an inductance [2].

Local loads can be seen in parallel with this L-R series network. In practice, local inductive loads do not have influence on the phase and gain margin of the Inverter-2 control loop, but resistive and capacitive loads do have. Therefore in this investigation the grid impedance at the Point of Common Coupling (PCC) was modelled by a network according to figure 3.

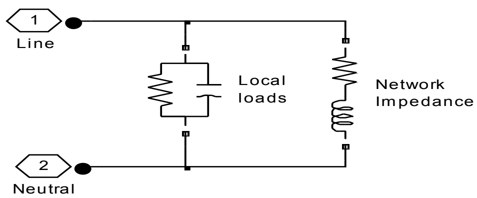

Fig. 3, network impedance with local loads of importance.

The transfer function $H_{grid}(s)$ from inverter-2 output voltage to inverter-2 output current of the circuit in figure 3, is expressed in formula (1). The transfer function of the 'network impedance with local loads' compensation $H_{comp}(s)$, implemented in the control loop of Inverter-2, is expressed in formula (2).

$$H_{grid}(s) := C_{load}\cdot s + \frac{1}{R_{load}} + \frac{1}{R_{netw.} + L_{netw.}\cdot s} \qquad (1)$$

$$H_{comp}(s) := \frac{1}{C_{load}\cdot s + \frac{1}{R_{load}} + \frac{1}{R_{netw.} + L_{netw.}\cdot s}} \qquad (2)$$

To be able to compare the performance of the two different control loops, the open loop gains as function of the frequency of both Inverter-1 and -2, were equalized, see figure 4.

The characters of the output impedances of the inverter types are about the same, namely capacitive. For Inverter-1, it can be expected that the capacitor in the output filter is dominating in the output impedance. This because of the high impedance of the inverter part before the output filter, see figure 5. The output impedance of the inverter part is high for lower frequencies (non-ideal current source). For higher frequencies, the output filter inductor impedance is dominating and isolates this non-ideal current source.

In today's practice the output capacitances of DER inverters are much higher than that of modern domestic appliances with electronics. In a dwelling with a DER inverter of 2kW or more coupled to the grid, the total capacitance at the PCC can be tripled. This can lead to an unwanted capacitive reactive power remainder in a distribution area with large numbers of DER. These capacitances can also come into resonance with the leakage induction of the distribution transformer [2, 5], see figure 6. Beside this resonance fenomenon, an inverter can respond strongly on pollution of the grid voltage [4].

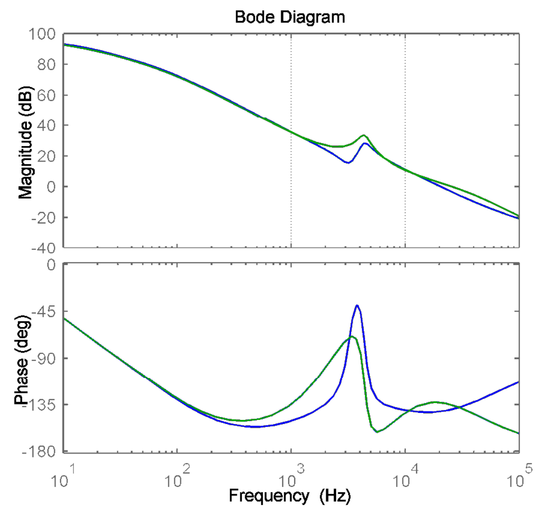

Fig. 4, open loop Bode diagram. The equalized open loop gains, achieve a comparable performance of both Inverters. Blue = Inverter-1, green = Inverter-2.

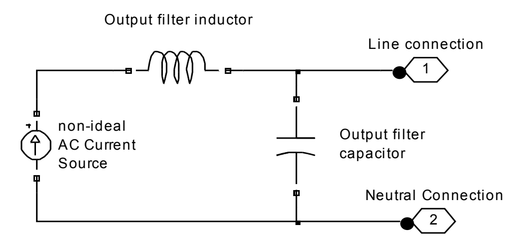

Fig. 5, the output impedance of Inverter-1 is dominated by the output filter capacitor.

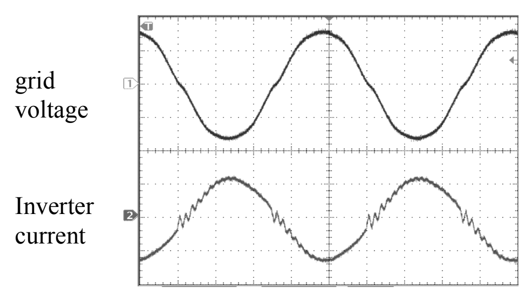

Fig. 6, resonances in the electricity network, pushed by pollution of the network voltage. This result was measured under laboratory conditions at ECN.

Inverter-2 has the advantage that the active output capacitance is from a different order of magnitude. For this inverter, the active capacitance is a reduction of the physical capacitance, caused by the control loop. In figure 7 the output impedance of both inverters are plotted in a Bode diagram. It can be noticed that the reduction of the output capacitance in Inverter-2, is more than 20dB.

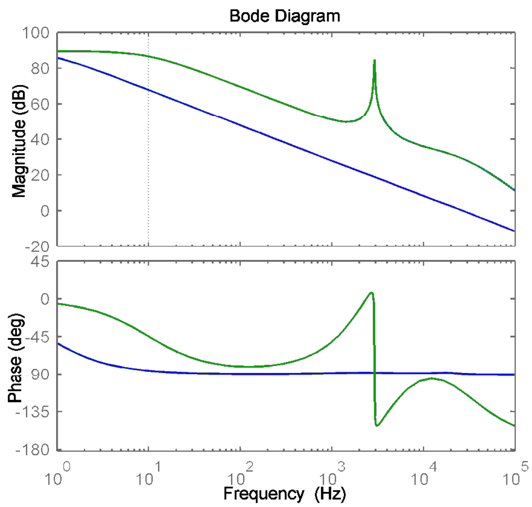

Fig. 7, output impedance Bode diagram for small signals. The output impedance, of the two inverters has a capacitive character, the active capacitance of the green plot is over 20dB lower, this can be marked as an advantage. Blue = Inverter-1, green = Inverter-2.

SIMULATION OF A SMALL ELECTRICITY NETWORK

Fig 8, gives a simplified diagram of the used Matlab/Simulink model of a small electricity network, connected to two inverters and a load. Both inverters can be connected or disconnected from the network in this model.

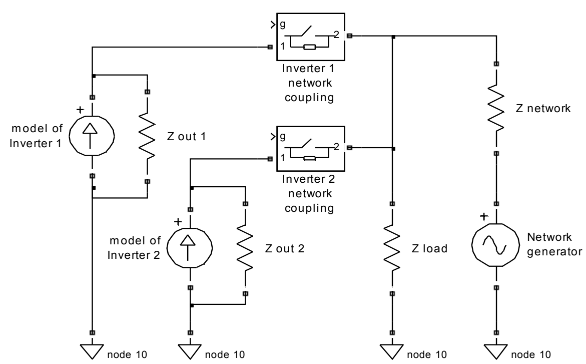

Fig. 8, a simplified diagram of the Matlab/Simulink model of a network connected to the two inverters and a load.

Simulation results from this model will be discussed hereafter. The time plots herewith are result from simulations with the Matlab/Simulink model. All time plots shows the Network voltage, wich is the voltage over Z_{load}, the Network current, wich is the current trough $Z_{network}$ and the Inverter-1 and -2 current, which is the current trough the coupling switches. During the simulations, the Network Voltage was strongly polluted with a number of harmonics, but still complying with the standard for the quality of the voltage at the PCC, namely EN 50160. Further during the simulations, Z_{load} was held pure resistive.

In figure 9, both Inverter-1 and -2 were switched off. Due to the resistive load, the Netvork Current and the Network Voltage has the same harmonic distortion level.

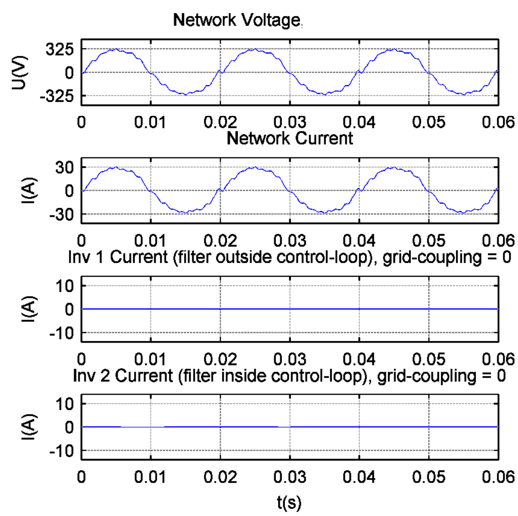

Fig. 9, both Inverter-1 and -2 were switched off. Note that the Netvork Current and the Network Voltage has the same harmonic distortion level.

In figure 10, both Inverter-1 and -2 were switched on. Note that the output current of Inverter-1 is polluted, this was caused by the pollution of the Network Voltage, in combination with the output capacitance. The current of Inverter-2 is not perceptible polluted, so it seems that this current shape is quite ideal.

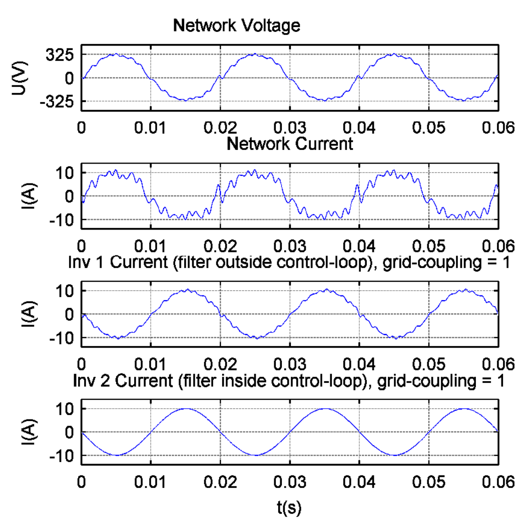

Fig. 10, both Inverter-1 and 2 were switched on. The harmonic distortion of the Network Current has increased to a much higher level.

The Fundamental of the Network Current is lowered from 30A to 10A amplitude, however the absolute harmonic content has not much changed, therefore the (relative) harmonic distortion of the Network Current has rased to a much higher level.

In figure 11, Inverter-1 was replaced by another sample of Inverter-2, so two inverters with a low output capacitance were placed in the model. As can be seen, both Inverter currents are not perceptible polluted. Although quite ideal inverters were used here, again the harmonic distortion of the Network Current has increased to a much higher level.

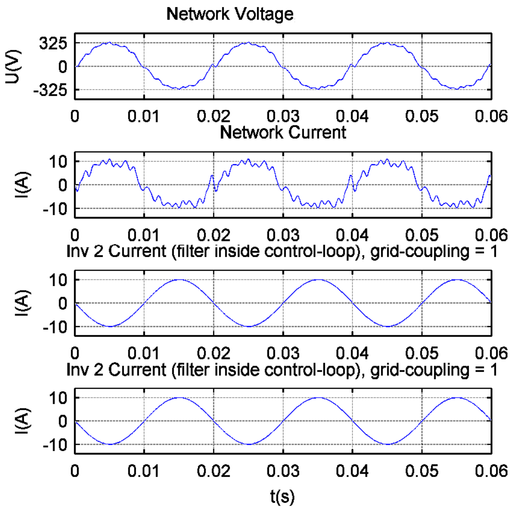

Fig. 11, two types of Inverter-2 were placed in the model.

In figure 12, the two types of Inverter-2 were extended with a harmonic compensation loop. It can be noticed that the harmonic distortion levels of all the currents in the network seems to be equal.

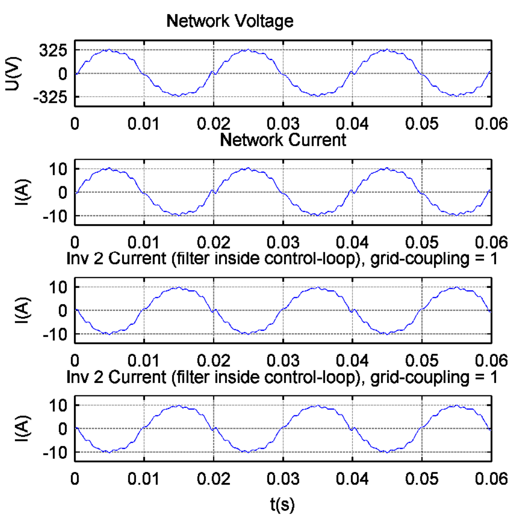

Fig. 12, the two types of Inverter-2 were extended with a harmonic compensation loop. All harmonic distortion levels in the network are compareable.

CONCLUSIONS

In today's situation inverters for DER show a high output capacitance, wich can lead to unwanted situations. The first step to improvement is to build inverters with a low output capacitance, for instance by compensation of the output filter with a control loop. Use of this types of inverters seems to be ideal, however harmonic background pollution of the network voltage can lead to a much higher level of harmonic distortion in the network current on understation level. A further step is needed to overcome this situation. This can be harmonic reduction as ancillary service by inverters for DER in electricity distribution networks.

ACKNOWLEDGMENT

This work was supported in part by SenterNovem under Grant EOSLT01021.

REFERENCES

[1] J.H.R. Enslin; W.T.J. Hulshorst; A.M.S. Atmadji (KEMA, The Netherlands), P.J.M. Heskes; A. Kotsopoulos (ECN, The Netherlands), J.F.G. Cobben; P. Van der Sluijs (NUON, The Netherlands), 2004, "Harmonic Interaction Between Large Numbers of Photovoltaic Inverters and the Distribution Network", IEEE Transact. on Power Electronics Vol.: 19, No. 6.

[2] J.H.R. Enslin, W.T.J. Hulshorst, J.F. Groeman (KEMA, The Netherlands), P.J.M. Heskes (ECN, The Netherlands), 2003, "Network Interaction Considerations of Photovoltaic Rich Networks". Cigre 2003.

[3] H.E Oldenkamp, I. de Jong (Oke-Services, The Netherlands), P.J.M. Heskes, P.M. Rooij, H.H.C. de Moor (ECN, The Netherlands), 2004, "Additional Requirements for PV inverters necessary to maintain utility grid quality in case of high penetration of PV generators", 19th European PV Solar Energy Conference, Paris, France.

[4] P.J.M. Heskes (ECN, The Netherlands), J.H.R. Enslin (KEMA, The Netherlands), 2003, "Power Quality Behaviour of Different Photovoltaic Inverter Topologies", PCIM-2003, Nürnberg, Germany.

[5] J.F.G. Cobben (TU/e, The Netherlands, Continuon, The Netherlands) , W. Kling (TU/e, The Netherlands), P.J.M. Heskes (ECN, The Netherlands), H.E. Oldenkamp (OKE-Services, The Netherlands), 2005, "Predict the level of harmonic distortion due to Dispersed Generation", Cired 2005.

[6] K. Visscher, P.J.M. Heskes (ECN, The Netherlands), 2005, "A method for operational grid and load impedance measurements", International Conference on Future Power Systems, FPS 2005.