Survey of harmonic reduction techniques applicable as ancillary service of dispersed energy generators (DG)

Survey of Harmonic Reduction Techniques Applicable as Ancillary Service of Dispersed Generators (DG)

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Abstract—**Fundamental ways to reduce harmonics are: reduction of resonances, damping of harmonics and compensation of harmonics. Harmonic compensation is difficult to achieve, but can reduce harmonics to zero. However, if a rest distortion is allowed, harmonic compensation could be replaced for only harmonic damping. Harmonic damping by a resistive harmonic behavior of a power electronic converter of a dispersed generator (DG), is an attractive way of harmonic reduction. This damping can have effect on a total range of harmonics and cannot result in instabilities in the power system. The damping can be provided as an ancillary service of a power electronic converter in general. The resistance is virtual, therefore the energy involved is limited to losses in the converter. The effort to be taken, to implement this kind of ancillary service, is an extension in the control system of the converter, therefore costs can be kept minimal. There is however a contradiction with the needed measure for background harmonics, therefore harmonic reduction by damping must be limited to avoid wrong compensation for background harmonics, resulting in excessive currents through the distribution transformer, cables and/or lines.**

A combination with a series active filter on substation level, and harmonic damping dispersed over the distribution network, can avoid the wrong compensation for background harmonics, and be therefore an optimal solution for harmonic mitigation.

Index Terms—**Harmonic reduction, Damping of resonances, Ancillary service, Network impedance.**

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I. Introduction

THIS paper gives a survey of the techniques for reduction of harmonics. Fundamental ways are given to reduce harmonics by means of active and passive methods. Especially active ways are focused on, because they can be integrated into power electronic converters. Beside their prime task of converting power, these converters have thus the potential to deliver an ancillary service, namely: active harmonic reduction.

A harmonic reduction ancillary service of a grid coupled power electronic converter is most easy to implement if this is based on only current injection into the network. Small power electronic converters, up to about 5 kW, often make use of fast switching devices in the output section. Due to these fast switching devices, the converter is capable to control its output current not only for the fundamental frequency, but also in the harmonic frequency range.

The combination of a series active filter on substation level, together with a number of shunt active filters in the distribution network can bring a total package of mitigation. At one hand side a compensation of background harmonics by series active filtering and at the other hand side damping of harmonic propagation and harmonic current compensation by shunt active filtering. If a rest distortion is allowed, total compensation may not be needed and harmonic current compensation could be replaced for only harmonic damping, which has the advantage that it can have effect on a total range of harmonics and that there is no need for estimating the actual level of harmonics in the network. Beside this, there is no fear for instabilities involved with this system [Ryc 05a] and because the damping resistance is virtual, the energy involved is limited to losses in the power electronic converters.

II. Reduction of Harmonics

Figure 1, gives a survey of harmonic reduction techniques. In this chapter the three main ways of harmonic reduction, according to this figure are discussed in detail. The harmonics that are focussed on are those that lie in the range from the 2nd up to the 40th, because these are the harmonics in the area of concern, the area where harmonics can do harm [Std 01]. The most important cause of harmonic currents in a distribution network is the non-linear load.

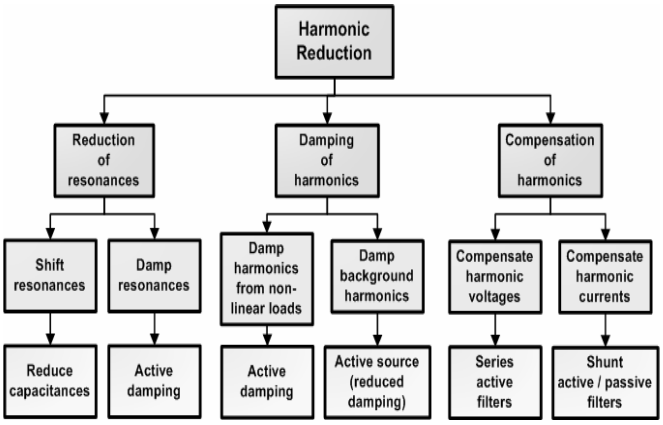

Figure 1, Survey of harmonic reduction techniques.

A. Character of linear and non-linear loads

A load is called to be linear if Z_{load} is linear, this is valid if (1), (2) and also according to the superposition rule (3) counts [Coo 72]:

$$U_1 = I_1.Z_{load} \tag{1}$$

$$U_2 = I_2.Z_{load} \tag{2}$$

$$(U_1 + U_2) = (I_1 + I_2).Z_{load} \tag{3}$$

For systems in general counts, that a linear system can be modeled as the sum of independent linear subsystems, for each harmonic frequency. These linear subsystems are independent because the n^{th} harmonic voltage only affects the n^{th} harmonic current. With a nonlinear system, the n^{th} harmonic voltage affects a number of harmonic currents, and therefore the subsystems are not independent [Bos 06].

1) Modeling of nonlinear loads

The harmonic currents that nonlinear loads draw from the network, are independent of other loads and the overall network. Therefore, to make it possible to do calculations with these kinds of loads, harmonic currents of a nonlinear load can be modeled as currents sources in parallel with the load; one single source for each harmonic [Col 99]. The sign of the current sources is so defined that current flows into the load, as if the load draw these harmonic currents from the network. Figure 2 gives a model of a linear and nonlinear load.

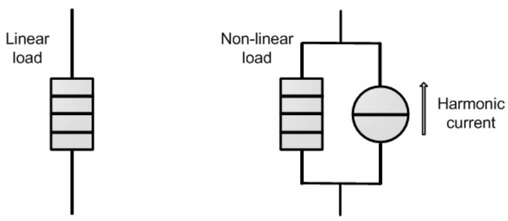

Figure 2, model of a linear and nonlinear load.

B. Reduction of resonances

The reduction of resonances contains two measures, firstly shifting the resonance out of the harmonic area of concern, and secondly damping the resonance peak to a lower level, see the survey in figure 1. Small grid coupled inverters for dispersed generators (DG) often show a high output capacitance for filtering out switching frequency currents towards the electricity network. For example in residential districts with high concentrations of solar inverters, a high capacitive load to the network can rise up parallel and series resonances [Ens 04], see the simplified network model of figure 3.

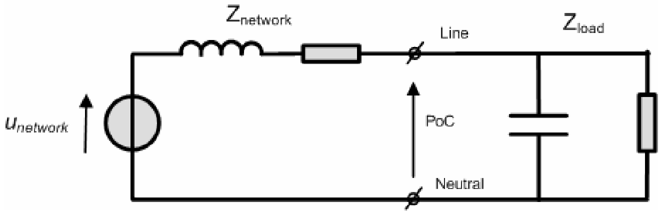

Figure 3 , simplified network model with a lumped large number of resistive and capacitive loads, in this situation parallel and series resonances can rise up.

1) Shifting of resonances

The first method mentioned in the survey of figure 1 is to avoid that a possible resonance can rise up in the frequency area of concern. In situations where distribution networks are not having high capacitive loads, the possible resonances are in general in higher frequency ranges than the harmonic area of concern. In this higher frequency range harmonics will not be propagated far in the network, because of the damping effects of cables and transformers [Sai 03].

Figure 4 gives a Bode impedance plot with a parallel resonance generated from simulation of the simplified network of figure 3, were Z_{load} stands for a lumped large number of resistive loads and beside this, capacitive loads from output filters of inverters for DG. Also the effect of (virtually) reducing the output capacitance of these inverters is shown in this figure [Hes 07].

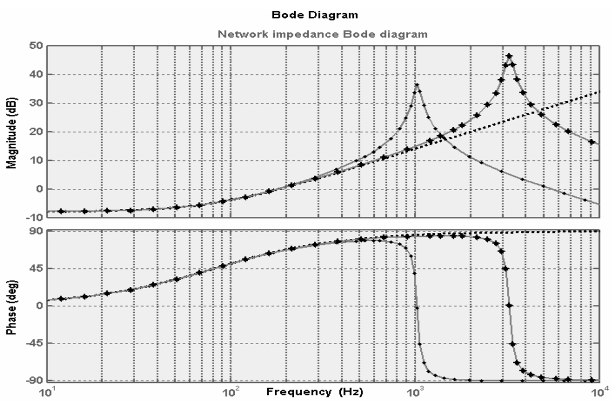

Figure 4, Bode impedance plot with a parallel resonance, dotted line: Unloaded network, line with dots: High cap. inverter load, line with asterisk: Low cap. inverter load.

2) Damping of resonances

The second measure for the reduction of resonances is to add an extra control loop to the inverter which gives the inverter a resistive behavior for the harmonic frequency range. This will bring extra damping to resonances in the network [Aka 96], [Ryc 05a]. As can be seen in figure 5, implementing both methods can be very effective.

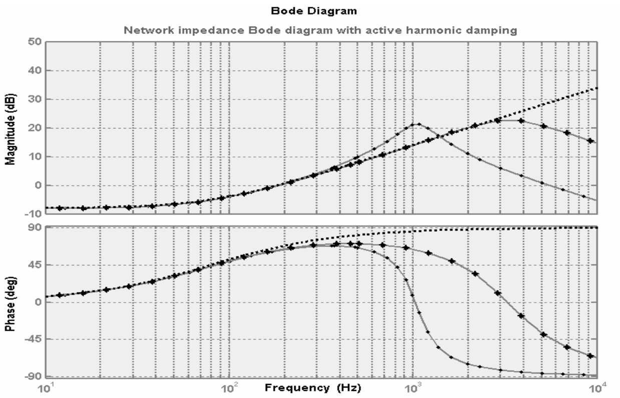

Figure 5, Bode impedance plot with a damped parallel resonance, dotted line: Unloaded network, line with dots: High cap. inverter load, line with asterisk: Low cap. inverter load.

C. Damping of harmonics

Harmonics in an electricity distribution network can come from different origins and should be split-up in two groups that need different measure for reduction, as seen in the survey of figure 1. One group is harmonic currents coming from non-linear loads in the distribution network itself, and the other group is harmonics coming from the next higher network, as so called background harmonics.

1) Harmonics from non-linear loads inside the network

Harmonic currents are transferred into harmonic voltages via network impedances. All cable parts and also the transformer in a distribution network have impedance; the impedance of the distribution transformer is caused by its leakage inductance. For studying the main cause and effect on harmonic interaction, these impedances are lumped together, so that the network model can be simplified to that of figure 6, just for understanding.

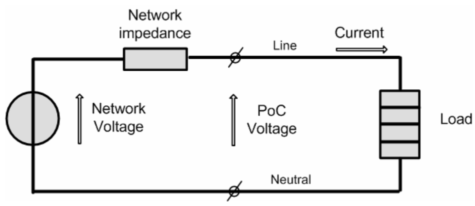

Figure 6, a more simplified network model.

The load in figure 6 can be seen as a single load as well as the lump-sum of a large number of loads.

With this model it easily can be seen that voltage drop over the network impedance will affect the voltage on all the loads connected to the Point of Connection (PoC). This counts for the fundamental as well as for harmonics. Assume that the network is loaded with a nonlinear load, as depicted in figure 7, than harmonic currents from this nonlinear load will distribute itself over all impedances in the network, and the lowest impedance path will get the most share.

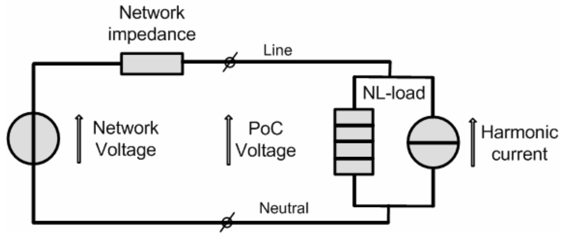

Figure 7, network loaded the with a nonlinear load.

For harmonic frequencies, the lowest impedance path does not have to be the network impedance, i.e. cables or overhead lines and the distribution transformer, because of the inductive character. So the part of the harmonic currents from nonlinear loads in the distribution network, that flows through network impedance towards the next higher network, depends strongly on the type and number of loads in the network. However the parts of the harmonic currents that are flowing through the network impedance will be the main cause for the transfer into harmonic voltages at the PoC, beside this, parallel resonances with capacitive loads could rise up the impedance and with that harmonic voltages [Ens 04].

If extra loads are added in the network, resonances can be damped, and that will reduce harmonic voltages at the PoC. The best type of load for this damping in general is a resistive load [Ryc 02]. Figure 8 shows an added damping resistance in the distribution network model. This damping resistance must only have effect on the harmonic frequency range, to avoid dissipation at the fundamental frequency.

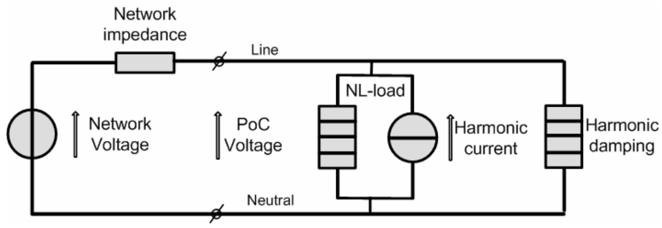

Figure 8, added damping resistance in the distribution network.

This damping can be the same damping that could be used for the damping of parallel resonances, as discussed before. Bringing this damping in the network by means of extra control loops in power electronic converter, has the advantage that the damping resistance is virtual, and most of the damping energy will be stored in the energy buffer capacitor of the power electronic converter, only a small part of the energy will be dissipated due to losses in the power electronic converter.

a) Harmonics coming from outside the network

Harmonics from nonlinear loads outside the network can be modeled as an added voltage source in series with the fundamental voltage [Std 03], see figure 9. The network impedance in this figure is the impedance of the low voltage network plus the impedance of the next higher network where the disturbing load is located; the latter impedance is lower in magnitude. In practice this so called background pollution can be significant with large nonlinear loads like railway rectifiers, or generators like wind turbines[1].

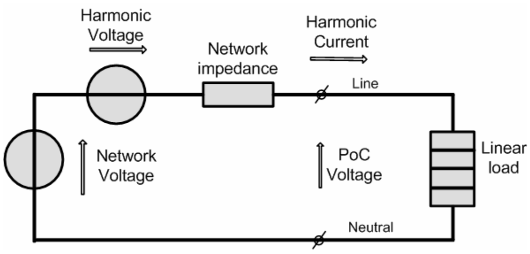

Figure 9, a simplified network model with background pollution.

In case of background voltage pollution on the fundamental, all loads in the low voltage network will draw current from this harmonic voltage source. This current then will flow in total through the network impedance, which can bring a number of unwanted effects in the distribution transformer and cables. Beside this, seen from the medium-voltage network, there is a possibility of series resonances. This series resonance can bring a low impedance path for harmonic currents from a disturbing load or generator in the medium voltage network, which can strongly increase the unwanted effects in the distribution transformer and cables [Std 03].

If an extra harmonic damping is added to the distribution network, then this damping would at one hand reduce possible series resonances, but at the other hand could draw more harmonic current from background nonlinear loads, and with that would not guaranty an optimal effect. Figure 10 gives a drawing of this situation.

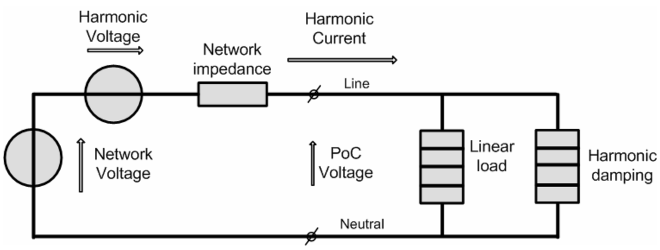

Figure 10, harmonic damping here brings an extra load for the harmonic voltage source and could therefore increase harmonic currents through the network impedance, i.e. the distribution transformer .

So bringing this extra damping loads into the low voltage distribution network, to reduce this series resonance effect, is in contradiction with the effect that this damping draw more harmonic current from background nonlinear loads.

Assume that the discussed damping of figure 10, is replaced by a negative harmonic damping, then this would reduce harmonic currents from background nonlinear loads. This kind of damping could be made virtually by a power electronic converter, however it is not recommended to implement this, because it will reduce damping of series and parallel resonances and reduce damping of effects of nonlinear loads in the distribution network.

The best solution for the reduction of background harmonics is to tackle the problem at the source, for example a harmonic compensator nearby the disturbing load. But assume that compensating the disturbing load locally, i.e. with harmonic shunt filters, cannot be performed; a possible solution could be the implementation of a series active filter on substation level. This kind of filter compensates harmonic voltages by adding compensation voltages to the network voltage; as a result no harmonic currents from the disturbing load will flow through the network [Aka 05].

b) Location for harmonic damping

The best location for harmonic damping is the end terminal of a power distribution line or cable, acting as a harmonic termination resistor, however when the network situation is not known and loads can vary, a good choice for a location is somewhere between the middle and the end of the line or cable [Wad 02], [Aka 99], [Aka 97], [Ryc 04].

2) Compensation of harmonics

Modern active harmonic filters can have several functions on harmonic reduction, like: harmonic filtering, damping, isolation and termination. Beside this also other functions, like: reactive-power control, voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations [Aka 05].

a) Passive filters

Passive filters in general are shunt filters. Shunt passive filters compensate harmonic currents by creating a conductive path for these currents. These filters can be a single-tuned series resonator with a high quality-factor for one harmonic or a band-pass filter for a whole frequency band. The best location is nearby a polluting load. One disadvantage of passive filters is that beside the wanted resonance also unwanted resonances can show up as interaction with other network components, i.e. other passive harmonic filters.

b) Active filters

Series active filters are connected in series with the network and compensate harmonic voltages by adding voltages to the network as a counter measure, see the survey in figure 1. This kind of filter is often placed at a central point to isolate two areas, this means that the network voltage at one side of the filter can be of a different pollution then the other side. However this can only work well if the non-linear loads in the network find a current path nearby. As explained before, non-linear loads can be modeled as linear loads with a parallel current source for each harmonic. If there is no path provided for these harmonic currents in the surrounding area, the current will propagate through the series filter to a wider area. For a

[1] Personal conversation with J.F.G. Cobben, (Continuon, The Netherlands), at the Eindhoven University of Technology (TUE) , March 2007.

good control of harmonics therefore, series active filters can be best combined with shunt active or passive filters.

Shunt active filters are connected in parallel with the network and compensate harmonic currents by injecting currents to the network as a counter-measure, see the survey in figure 1. For this function, the best location of the shunt active filter is nearby a polluting load.

c) Combination of reduction techniques

The combination of a series active filter on substation level, together with a number of shunt active filters in the distribution network can bring a total package of mitigation: At one hand side the compensation of background harmonics by the series active filtering and at the other hand side the damping of harmonic propagation and harmonic current compensation by the shunt active filtering [Fuj 98a], [Fuj 98b], [Aka 96], [Jin 03]. The last item, harmonic current compensation can also be done with passive shunt filters. The shunt active filter can be integrated in DG or loads, with a power electronic converter inside [Ryc 05b].

Table 1 gives a survey of the cause of harmonic problems in the distribution network and a possible measure.

Table 1

Problem	Measure
nonlinear loads inside the distribution network	resistive harmonic damping
nonlinear loads outside the distribution network	central series active harmonic filter
high impedance due to parallel resonances	resistive harmonic damping
low impedance due to series resonances	central series active harmonic filter and/or limited resistive harmonic damping

III. CONCLUSIONS

The great advantage of harmonic damping by a resistive harmonic behavior of a power electronic converter is that it can have effect on a total range of harmonics and that there is no need for estimating the actual level of harmonics in the network. Beside this, there is no fear for instabilities involved with this system [Ryc 05a]. Because the damping resistance is virtual, the energy involved is limited to losses in the power electronic converter. Another advantage to this damping being virtual is, that the only effort to be taken, to implement this kind of ancillary service, is an extension in the control system of the power electronic converter, therefore costs can be kept minimal. However, the performance can be limited in this situation, depending on the operation mode of the power electronic converter.

Harmonic compensation is difficult to achieve, but can reduce harmonics to zero. If a rest distortion is allowed, total compensation may not be needed and harmonic current compensation could be replaced for only harmonic damping, which has the above mentioned advantages.

A disadvantage with harmonic reduction is, that there is a contradiction in the needed measure for background harmonics, therefore the harmonic reduction must be limited to avoid wrong compensation for these background harmonics, resulting in excessive currents through the distribution transformer, cables and/or lines. However the combination with a series active filter on substation level, can solve this problem.

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