9th International Conference.
Electrical Power Quality and Utilisation.
Barcelona, 9-11 October 2007

Inductive Decoupling of Low-Voltage Sub-Networks

Jörg Jahn
Department Engineering and Power Electronics
Institut für Solare Energieversorgungstechnik e. V. (ISET)
Kassel, Germany
Email: jjahn@iset.uni-kassel.de

Dr. Alfred Engler
Department Engineering and Power Electronics
Institut für Solare Energieversorgungstechnik e. V. (ISET)
Kassel, Germany
Email: aengler@iset.uni-kassel.de

Abstract— **Voltage control in networks with predominantly resistive coupling is most efficient when controlling the active power flow. By introducing a series connected inductor for a dedicated part of the network the coupling can be shifted to the inductive type. Hence the voltage in such sub-networks can be influenced by injection of reactive power. Furthermore harmonic distortions present in the main grid are reduced. This paper presents the functional principle of such inductively decoupled sub-networks including both simulation and measurement results. The measurement were performed on a prototype in the power range of 3.3 kVA. The implementation into a 100 kVA prototype is progressing.**

I. INTRODUCTION

In weak low-voltage networks the line impedance is relatively large with respect to the short-circuit power of the point of common coupling (PCC) [1]. Sensitive loads connected to weak networks can be affected by poor power quality in terms of large voltage variations, harmonics, sags/swells introduced by disturbing loads, by grid faults or even by regular switching operations.

Since the grid impedance of the low-voltage grid is predominantly resistive the voltage is mainly depending on the real power flow and can only marginally be influenced by reactive power injection. In order to protect sensitive loads connected to (weak) low-voltage networks from being affected by disturbances uninterruptible power supplies (UPS) can be installed. These devices are usually sized to completely supply the dedicated loads in the range of a few minutes until the grid recovers or a back-up generator has been started.

Sensitive equipment such as computers and electronic control units are usually supplied by switch mode power supplies which will fail within the first few ten milliseconds of an interruption. So the reliability of such devices could significantly be improved by avoiding short-term disturbances and outages caused by, e. g. automatic reclosing after grid faults.

Shunt connected devices are state of the art for grid feeding inverters in the low-voltage grid. Many inverters of renewable energy sources are just moderately utilized. In the federal state of Saxony (Germany) a typical PV inverter is utilized by about 800 full load hours [2]. Looking at the total installed PV power of about 1600 MWp in 2005 [3] large capacities can be used for different additional functions such as power quality improvement.

This paper presents a novel approach using shunt connected inverters in combination with a series connected inductor. This combination is capable of independently controlling the voltage in a dedicated part of the grid during steady-state operation. Furthermore it is able to reduce voltage transients and harmonic distortion.

II. ENERGY TRANSMISSION IN RESISTIVELY AND INDUCTIVELY COUPLED NETWORKS

The power exchange between two sources is determined by the voltage amplitude and angle differences of the sources as well as the parameters of the connecting line (see Figure 1).

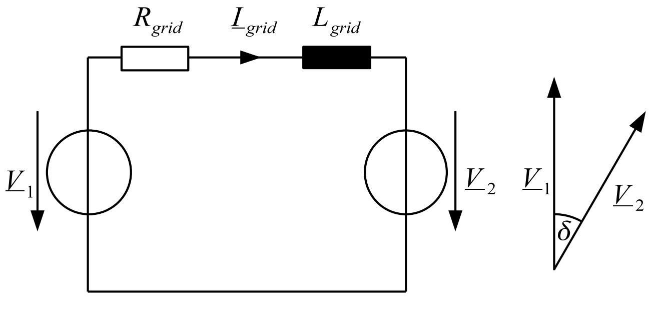


Fig. 1. Simple energy transmission system consisting of two voltage sources and a connecting line

The power exchanged by the sources can either be real or reactive depending on the line characteristics. The equations that describe the power flow in such network are given in the following subsections with respect to purely resistive and inductive coupling. Further details can be found in [4], [5] and [6].

A. *Resistive coupling*

The transmission of active power in resistively coupled networks can be described by

$$P = \frac{V_{1,rms}^2}{R_{grid}} - \frac{V_{1,rms} \cdot V_{2,rms}}{R_{grid}} \cdot cos\delta \ , \tag{1}$$

while the reactive power flow is determined by

$$Q = -\frac{V_{1,rms} \cdot V_{2,rms}}{R_{grid}} \cdot sin\delta \ . \tag{2}$$

Assuming small angles δ the real power transmission is determined by the voltage difference between the sources. Thus a voltage drop is even required for transmission of real power. Compensating this voltage drop would result in reduced transmittable real power and could only be achieved by placing a supplying generator next to each load. Such network structures would contradict all ideas of power transmission.

B. *Inductive coupling*

Predominantly inductive coupling is typically found in high-voltage networks and the dependencies are exactly opposite to the previously mentioned dependencies. Now the reactive power flow is depending on the angle between the sources

$$P = \frac{V_{1,rms} \cdot V_{2,rms}}{\omega_{grid} L_{grid}} \cdot sin\delta \ , \tag{3}$$

(using the same assumption as in the previous section) and the reactive power flow

$$Q = \frac{V_{1,rms}^2}{L_{grid}} - \frac{V_{1,rms} V_{2,rms}}{\omega_{grid} L_{grid}} \cdot cos\delta \tag{4}$$

is determined by the voltage difference [5].

Regarding this kind of energy transmission control of load voltage could be done by reactive power injection according to the FACTS (Flexible AC Transmission Systems) technology [7].

III. STRUCTURE OF INDUCTIVELY DECOUPLED SUB-NETWORKS

As mentioned in the previous section inductive coupling is required for voltage control by reactive power injection. A suitable way of changing the line parameters is to introduce a serial inductor. A voltage source such as an inverter is now able to influence the voltage profile by reactive power injection into the sub-network (see Figure 2).

Since the voltage is only controlled by reactive power injection the real power flow can be controlled independently and the real power for the loads in the sub-networks can be further on drawn from the main grid. For this reason even inverter systems without energy source (comparable to e.g. STATCOM devices) can be used for this task.

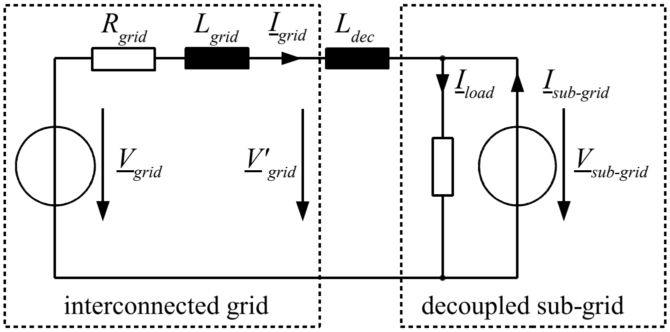


Fig. 2. Functional principle of inductively decoupled sub-grids for local improvement of the voltage quality.

A. *Reactive power flow*

To explain the dependencies on the reactive power flow caused by the sub-network Figure 3 is showing the phasor diagram of the equivalent network shown in Figure 2. The voltage $\underline{V}'_{grid}$ represents a distorted grid voltage profile caused by non linear loads.

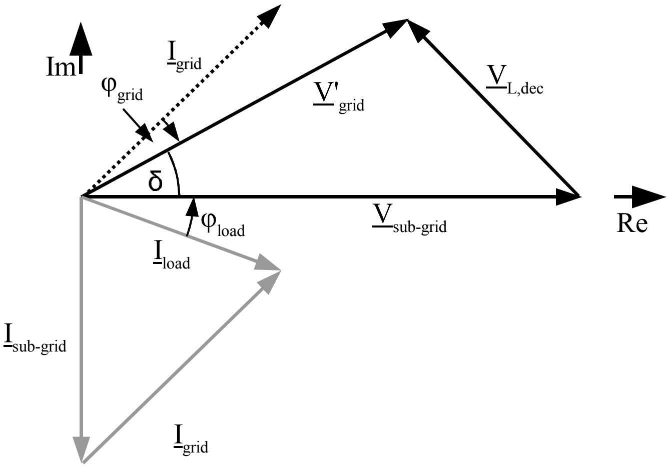


Fig. 3. Phasor diagram of equivalent circuit according to Figure 2.

In this case the sub-grid source is providing reactive power only and the decoupling inductor is assumed lossless. While the load current I_{grid} is determining both magnitude and phase in relation to $V_{sub-grid}$ the magnitude and phase of the voltage drop across the decoupling inductor $V_{L,dec}$ is depending on the load's real power demand and the voltage difference between the two sources. The current drawn from the main grid can be calculated since it has to be perpendicular to the voltage drop and Kirchhoff law for nodes

$$\underline{I}_{load} = \underline{I}_{grid} + \underline{I}_{sub-grid} \tag{5}$$

has to be fulfilled. As a result of the phase shift between V_{grid} and I_{grid} and $V_{sub-grid}$ and I_{load} respectively both voltage sources have to deliver a certain amount of reactive power. Assuming constant voltages, e. g. $U_{grid} = 240\,\text{V}, U_{sub-grid} = 230\,volt$, and load conditions, e. g. $P_{load} = 1.1\,\text{kW}@pf =$

$0.9(ind.)$, the reactive power to be provided by the two sources Q_{grid} and $Q_{sub-grid}$ can be calculated as a function of the decoupling inductance (see Figure 4 for details).

The total amount of provided reactive power

$$Q_{total}(L_{dec}) = Q_{grid}(L_{dec}) + Q_{sub-grid}(L_{dec}) \quad (6)$$

can now be calculated (see Figure 5).

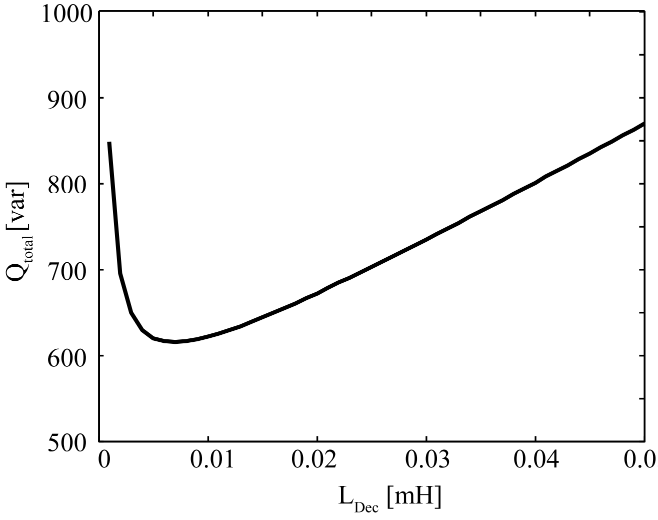


Fig. 5. Total reactive power flow vs. size of decoupling inductor. $U_{grid} = 240\,\mathrm{V}, U_{sub-grid} = 230\,\mathrm{V}, P_{load} = 1.1\,\mathrm{kW}@pf = 0.9(ind.)$

The trend shows large total reactive power demands at small and large decoupling inductances. While at small inductances the coupling is still predominantly resistive large amounts of reactive power are necessary to control the voltage. Large inductances increase the angle δ according to Equation 3 resulting in steadily increasing reactive power demand. The value of the inductance which causes minimum total reactive power demand will be different in different voltage combinations and load demands. Intensive load flow calculations performed in [6] have shown that inductances in the range of 5 mH to 10 mH will be most effective.

B. Transient behavior

The sub-grid source runs in voltage controlled mode. So it is able to supply loads without the presence of the grid source. For this reason the dynamic performance of the sub-grid during faults of the main grid was investigated. Two typical faults, interruption and short-circuit close to the sub-grid (compare Figure 6), were analyzed. For all simulations the active power set value of the sub-grid source was set to zero so the load is fully supplied by the main grid.

During a high-impedance fault the sub-grid source seamlessly takes over the supply of the load (see Figure 7) although the active power set-point equals zero. Since the voltage control ensures the desired voltage profile the current supplied by the sub-grid source is driven by this voltage.

During a low-impedance fault the decoupling inductor appears as an additional parallel load for the sub-grid source. Assuming a lossless inductor large power oscillations will occur during this type of fault since the load flow through the inductor abruptly changes (compare Figure 8).

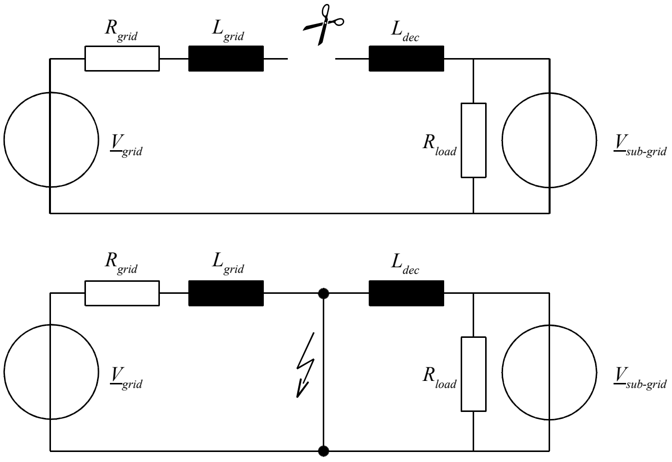


Fig. 6. Typical grid faults. Interruption (top) and short-circuit (bottom)

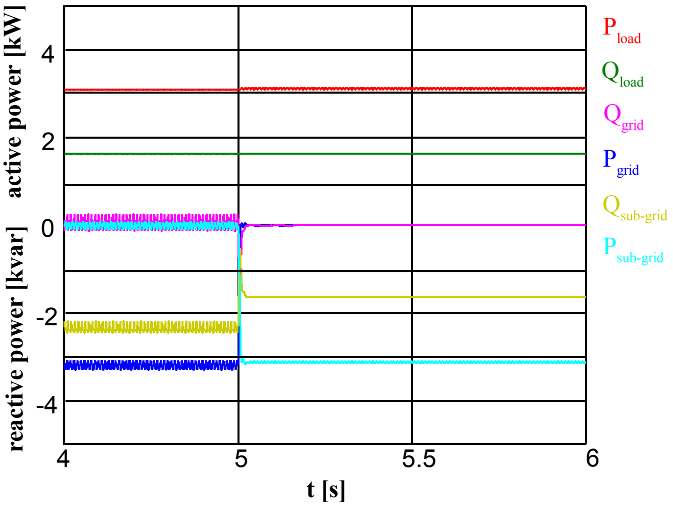


Fig. 7. Load flow during an interruption according to Figure 6, top

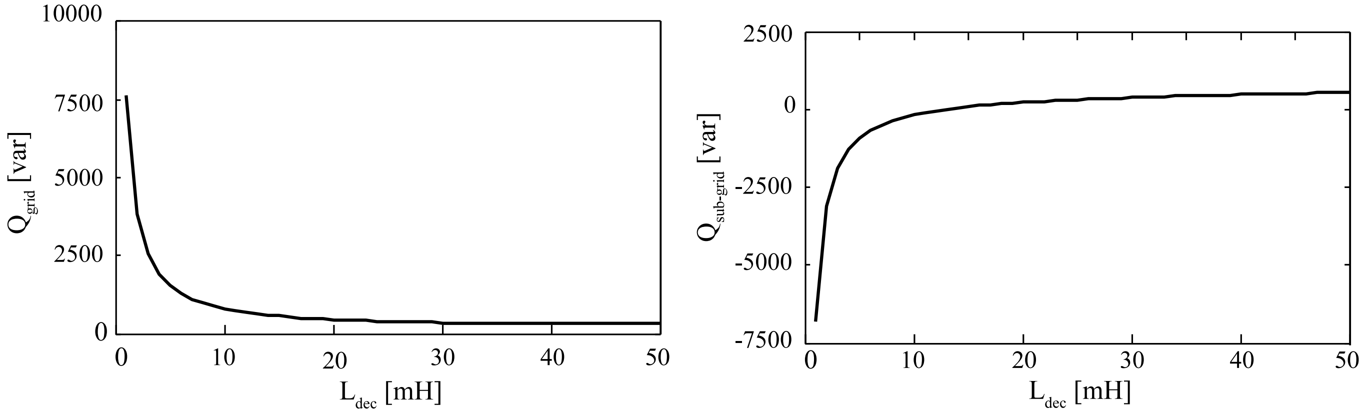
C. Voltage waveform improvement

Assuming an ideal sub-grid voltage source the equivalent circuit in Figure 2 can by analyzed using the principle of superposition for all harmonic orders besides the fundamental wave. In this case the sub-grid source can be bypassed resulting in an inductive voltage divider. The harmonic current supplied by the grid source

$$I_{grid,\nu} = \frac{V_{grid,\nu}}{Z_{grid}(\nu) + Z_{dec}(\nu)} \quad (7)$$

will be decreased by the additional impedance of the decoupling inductor. So the presence of an inductively decoupled sub-grid will tend to reduce even the harmonic voltage drop across the grid impedance.

The simulation result shown in Figure 9 clearly states the improved voltage profile. Although it is not the typical case



(a) Reactive power provided by the grid

(b) Reactive power provided by the sub-grid

Fig. 4. Reactive power distribution between the sources as a function of the value of the decoupling inductance. Calculation result using $U_{grid} = 240\,\text{V}, U_{sub-grid} = 230\,\text{V}, P_{load} = 1.1\,\text{kW}@pf = 0.9(ind.)$

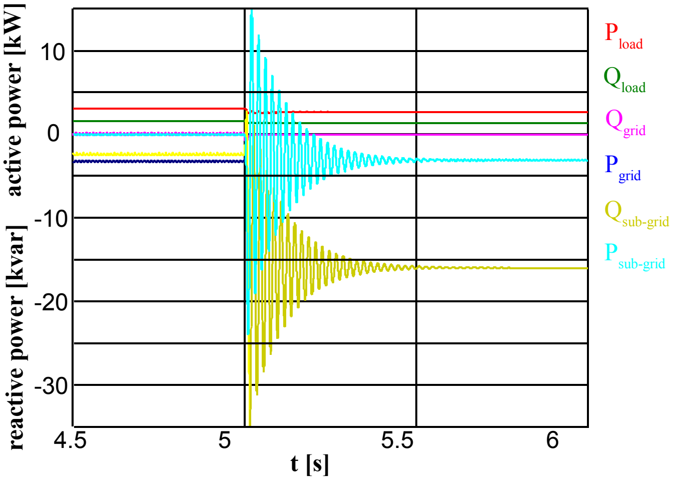


Fig. 8. Load flow during a short-circuit according to Figure 6, bottom

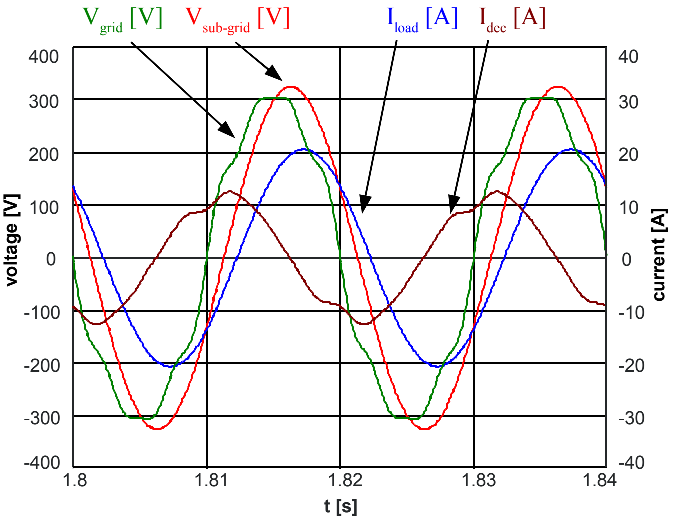


Fig. 9. Reduction of harmonic distortions by inductively decoupled sub-grids

a linear load was assumed for this simulation since voltage distortions will directly result in a distorted current profile. Even if the current through the decoupling inductor is distorted the main grid will not be negatively affected by it.

IV. MEASUREMENT RESULTS

The measurements were performed on a single-phase inverter prototype with a nominal power of 3.3 kVA. The power electronic part is commercially available while the control is done by a dSPACE DS1103 rapid prototyping system. The inverter is not connected to a power source so the DC link was enlarged to 23 mH in order to supply up to 470 $watts$ during short-term disturbances and/or interruptions. 10 mH of decoupling inductance were introduced. During the measurement a programmable voltage source in combination with a line impedance replacement was used as grid substitute.

A. Steady-state operation

In order to prove the functional principle the grid voltage slowly ramped within the limits of EN 61000-3-2 (230 V±10%). The sub-grid voltage was set to 230 V. Figure 10 shows that the sub-grid voltage during the complete ramp is almost kept constant.

B. Transient behavior

The transient behavior of the decoupled sub-grid was tested by exemplarily applying a voltage sag of 15% depth and duration of 70 ms. Even if this sag is not far from the EN 61000-3-2 limits, Figure 11 shows that the voltage sag is not totally compensated but at least mildened significantly. The sag was initiated exactly at the peak value which turned out to be the worst case for the inverter control. So at deeper sags the overcurrent protection tripped the prototype.

C. Voltage waveform improvement

For testing the voltage waveform improvement the grid voltage source was programmed to be distorted to the limits of EN 61000-3-2 regarding the 3rd, 5th and 7th harmonic while

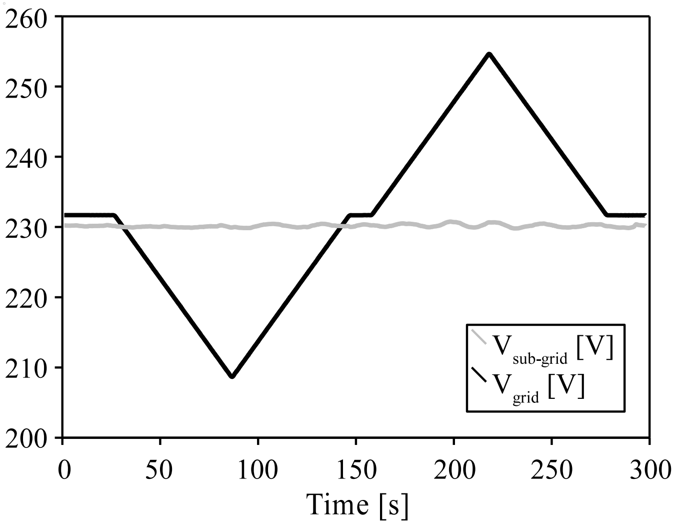


Fig. 10. RMS voltage of the sub-grid (controlled to 230 V) during an applied grid voltage ramp of 230 V ±10%

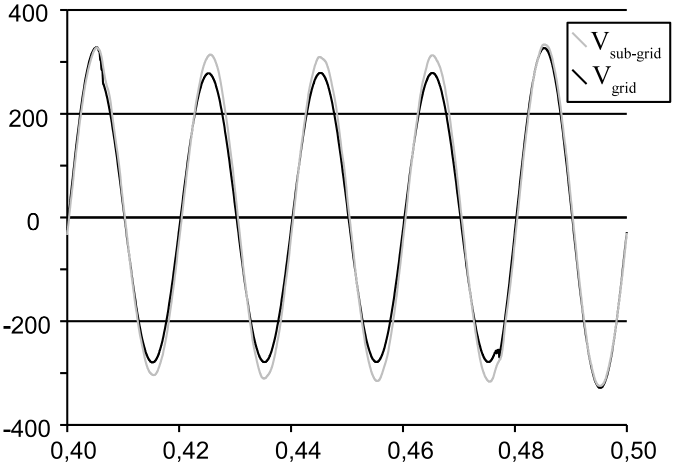


Fig. 11. Grid and sub-grid voltage during a voltage sag of 15% depth an 70 ms duration. Point on wave of initiation positive peak value.

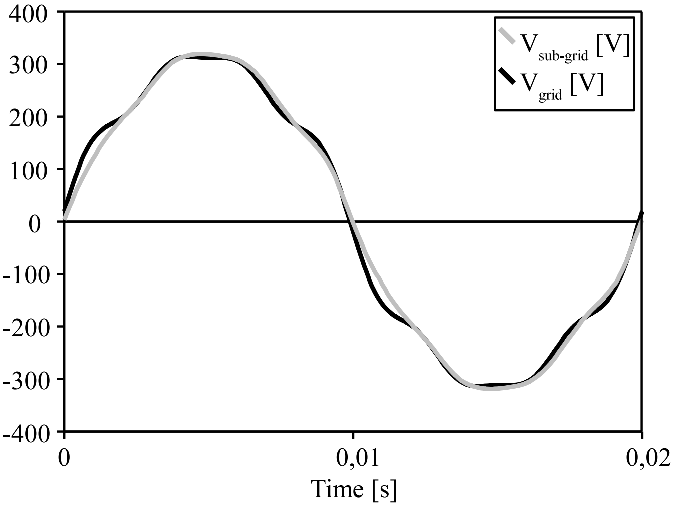


Fig. 12. Voltage waveform improvement by inductive decoupling. Grid voltage 230 V, 3rd in the distorted public network (black) and the improved sub-network (red)

TABLE I

HARMONIC CONTENTS OF V_{grid} AND $V_{sub-grid}$

Harmonic order	$V_{grid}[V]$	$V_{sub-grid}[V]$	$\frac{V_{sub-grid}}{V_{grid}}$
1	230.7	230.3	1.00
3	11.5	5.1	0.45
5	13.8	6.2	0.45
7	11.5	6.0	0.52

the fundamental wave was kept constant at 230 V. Figure 12 shows the result which states a significant improvement of the sub-grid sine wave.

Table I presents the comparison of the harmonic contents of the grid and the sub-grid voltage. The 3rd and the 5th harmonic are damped to about 45% of their original values while the 7th harmonic remains at about 52%.

V. CONCLUSION

This paper presented an approach which allows to control the voltage in dedicated parts of low-voltage networks by reactive power injection in combination with a series connected inductor. Simulations showed that such installation can eliminate voltage variations and reduce voltage harmonics in this sub-grid. It could be shown that the grid current which in most cases will be non-sinusoidal even tends to reduce voltage harmonics present in the main grid. During both high- and low-impedance grid faults the load was continuously supplied but large power oscillations occurred during the low-impedance fault. Measurements were performed on a single-phase inverter prototype to prove the simulation results. During steady-state operation the inverter was able to keep the sub-grid voltage almost constant even at large deviations of the grid voltage. However, during transient processes like voltage sags the inverter was not able to completely eliminate the sag but reduced the effects on the sub-grid voltage. Although the tests were performed on a single-phase system the control principle can be included in the space vector control of a three phase system. The control of the sub-grid source can easily be enabled to feed active power, e. g. produced by PV modules, to the grid in order to improve the utilization of the system by additional functionality.

ACKNOWLEDGMENT

The authors would like to thank the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety for funding the project *Multi-PV - Multifunktionale Photovoltaik-Stromrichter - Optimierung von Industrienetzen und öffentlichen Netzen*, project number 0329943 and the European Commission for funding the projects *DISPOWER - Distributed Generation with High Penetration of Renewable*

Energy Sources, contract number ENK5-CT-2001-00522 and *DGFACTS - Improvement of the Quality of Supply in Distributed Generation Networks through the Integrated Application of Power Electronic Techniques* contract number ENK5-CT-2002-00658.

REFERENCES

[1] G. Orglmeister, *Symmetrierkompensator für Hochspannungsleitungen*, Dissertation, ETH Zürich, Switzerland, 2002.

[2] U. Rindelhardt, *Stromerzeugung aus erneuerbaren Energien in Ostdeutschland*, ew Dossier Regenerative Energien, Jg. 100, 2001.

[3] EnergieAgentur.NRW, *Photovoltaik - installierte Leistung*, Internet source: http://www.energieagentur.nrw.de/.

[4] E. Spring, *Elektrische Energienetze, Energieübertragung und -verteilung*, VDE Verlag GmbH, Berlin und Offenbach, Germany, 2002, p. 35.

[5] A. Engler, *Regelung von Batteriestromrichter in modularen und erweiterbaren Inselnetzen*, Dissertation, Kassel University, Kassel, Germany, 2001.

[6] J. Jahn, *Energiekonditionierung in Niederspannungsnetzen*, Dissertation, Kassel University, Kassel, Germany, 2007.

[7] X. H. Song, A. T. Johns (Editors), *Flexible AC Transmission Systems (FACTS)*, The Institution of Electrical Engineers, London, United Kingdom, 1999.