Improvement of Power Quality and Reliability with multifunctional PV-inverters in distributed energy systems

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Improvement of Power Quality and Reliability with Multifunctional PV-Inverters in Distributed Energy Systems

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***Abstract*—The share of distributed generation (DG) within the distribution network increases strongly. A lot of these DG units are driven by Renewable Energy Sources (RES). Up to now, these units only inject active power depending from the availability of their primary source. In future on the one hand DG units have to contribute to grid stability, but on the other hand DG units can provide additional functionalities in order to offer a surplus value for the customer. Therefore especially inverter-coupled systems are well suited. Additional functionality could be improvement of Power Quality and Reliability (PQR), but also peak shaving, provision of control energy or reactive power compensation is conceivable. This paper presents several approaches of such multifunctional inverter systems developed by ISET e.V., SMA and TU Sofia with the focus on PQR.**

Keywords - Active Power Filter; Distributed Energy System; Power Quality; Power Factor; Uninterruptible Power Supply; Renewable Energy Sources

I. INTRODUCTION

Development of RES installation in the past and in the future can be analysed very well regarding the German situation due to its leading role in this sector. Figure 1 shows the aggregated capacity of RES installation in Germany from 1990 until 2008. From 1990 to 1994 mainly hydro power plants existed. Penetration of wind power plants has been increasing since 1994 rapidly. With beginning of 2004 installed capacity of photovoltaic (PV) and biomass power plants has been grown very fast. In 2008 new PV power plants with a capacity of about 1.5 GW_p were installed in Germany alone.

In Bulgaria, total installed RES power in 2008 is 1648.2 MW; whereas installed wind power in 2008 was 112.6 MW and of photovoltaic power only 140 kW in 2009, but 800 kW are under construction: But interest for investments is high. The production of energy from RES in 2008 is 2,891.9 GWh and covers 6.5 % from total production of energy in Bulgaria. In 2007 new feed-in tariffs of wind energy and in 2008 new feed-in tariffs for energy from photovoltaic power plants are salaried.

In opposite to wind power plants, which are mainly connected to the transmission network, PV and biomass power plants are connected to the distribution network. Therefore new challenges appear for the distribution network. For assuring grid stability DG units have to support grid operation in static and transient case now. New grid codes for the interconnection of DG units to the distribution network, for example in France, Germany or Austria [1], define the additional requirements of RES units.

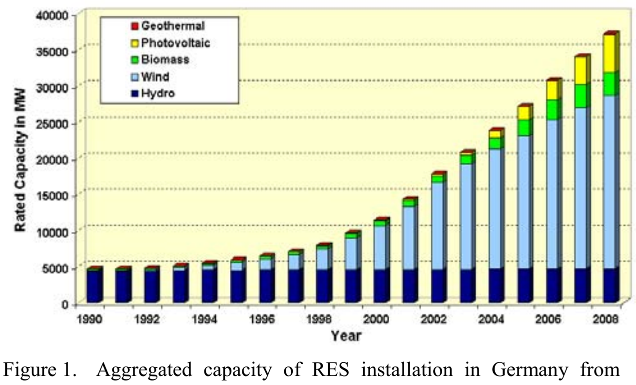

Figure 1. Aggregated capacity of RES installation in Germany from 1990 until 2008 [2], Data: BMU, DEWI, BSW Solar

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The fast growth of PV plants can be lead back to high subsidies given through special feed-in tariffs. For reaching grid parity efforts in cost reduction has to be undertaken. In 2009 in Germany a new renewable energy act came into force. Feed-in tariffs for new PV plants reduce from 8 % to 10 % per year. This has to result in lower prices for PV systems in order to be economical as attractive as today.

Another approach for compensating the decrease of feed-in tariffs is to provide a surplus value through additional functionalities. Within this paper technical behaviour of such multifunctional inverter systems is explained. Here the focus is on improvement of power quality and reliability.

II. Inverter Coupled DG Units with Additional Functionalities

DG units coupled with an inverter to the interconnected grid are capable of providing additional functionalities without extensive design changes. Mainly the inverter control has to be adopted. Especially for PV power plants the full apparent power of the inverter is used least time within a year. Thus existing apparent power reserve is available for additional functionalities. Within this chapter two approaches of inverter coupled RES units are described which have been developed within research projects at ISET e.V., SMA and TU Sofia.

A. Multifunctional PV-Inverter Systems (ISET e.V. and SMA)

This section describes an approach of a Multifunctional PV-inverter system developed within a German research project [3]. The intention is to extend a state of the art PV-inverter with an additional storage system, a fast circuit breaker and a decoupling inductor in order to provide additional functionalities as:

- Improvement of Power Quality for sensitive loads within the local sub-network
- Improvement of Reliability through an UPS functionality for loads in the sub-network
- Peak shaving for reduction of demand charge for industrial customers

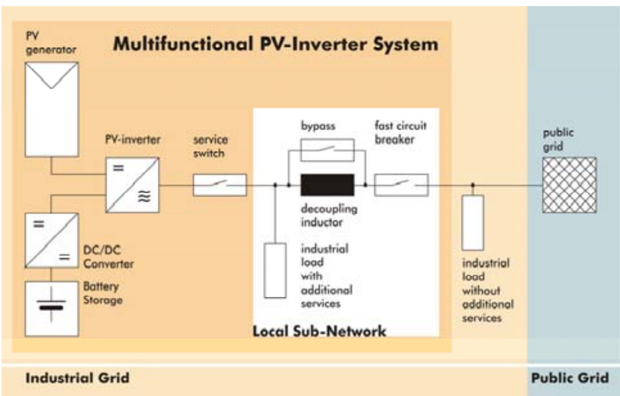

Figure 2. Concept of a Multifunctional PV-Inverter System integrated into an industrial grid

- Ancillary services
- Harmonic compensation
- Reactive power compensation or supply

Figure 2 shows the concept of the proposed Multifunctional PV-inverter integrated into an industrial grid. Within the project duration economic and technical analyses [4, 5] have been made. During the year 2009 a 100 kVA prototype system runs on a real test side, a factory of the Hübner AG in Kassel, for demonstrating the feasibility of this approach.

B. Concept of Active Power Filters (TU Sofia)

The general structural diagram of connecting the system of active power filters is shown in Figure 3. In their traditional use as Unified Power Quality Conditioner (UPQC), the intermediate DC voltage U_{DC} is obtained through transformation from the AC grid. In such a way, the active power consumed by the grid is increased at the expense of the power dissipated in the system of the two active power filters.

As it can be seen in Figure 3, in this case a photovoltaic generator is used for obtaining the intermediate DC voltage U_{DC}. The energy is transformed by a DC/DC Converter and stored in an accumulator battery. Controlling the DC/DC Converter may be performed through a system for Maximum Power Point Tracking (MPPT) for the photovoltaic generator, at an optimal regime of loading the accumulator battery depending on its type. The energy may be also stored in another element intended for that purpose – for instance, a supercapacitor. In such a way, the system of APF's does not consume any active power from the AC grid, its supply being provided by the renewable energy source.

a) Series APF

Its control system is synchronized with the voltage of the public distribution grid; it tracks continuously the instantaneous values of the local-grid voltage U_L, and compares them to those of a reference sinusoid of fixed value [6]. Switching over the filter devices is performed in such a way that at any time the voltage U_F complements the instantaneous values of the voltage U_S from the public distribution grid to those of the reference sinusoidal voltage. As a result, stabilization of the value of the local-grid voltage U_L is achieved for a change in the value of the public-grid voltage. In addition, distortions in the waveform of that voltage depending on the power devices

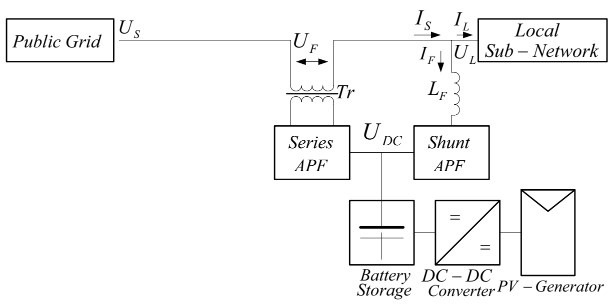

Figure 3. General structure diagram

used and the algorithm of control system realization are compensated for. It is also possible to compensate for short-duration overvoltages or drops in the curve of the public-grid voltage. This is the main function of the Series APF. In addition to that, it is possible to perform one more function – realization of supply to the local grid if the public-grid voltage has disappeared. In such a case the connection to the public distribution grid can be interrupted by means of a circuit breaker, and the winding of transformer T_r for connection to the public grid can be switched over to supplying the local grid. Here again, the control system follows the reference sinusoid, but in this case the filter generates the entire voltage, and not only the complementary voltage to the sinusoidal waveform as it was in the first case described.

b) Shunt APF

Its control system tracks the instantaneous values of the current IL consumed by the local grid. It controls the power devices in such a manner that at any time the filter current IF complements the current of the local grid in such a way that the current IS being consumed from the public distribution grid is of sinusoidal waveform and in phase with the voltage UL [7]. As a result, the Shunt APF compensates for the reactive power Q of the local grid and eliminates the higher harmonics of its current, i. e. it compensates for the distortion power D as well. This allows maintaining the value of the power factor K_P close to 1. In case of disappearance of the voltage of the public distribution grid and if supplying of the local grid is conducted by the Series APF, the operation of the Shunt APF is disabled as it would consume additional active power from the storage element. It should be noted that due to the power circuit configuration of the Shunt APF it is possible that it also provides the power supplying of the local grid. At the same time, the connection to the public distribution grid should be interrupted, without switching over the transformer Tr. In this case, the operation of the Series APF is disabled, and the system for controlling the Shunt APF performs the control of its devices for synthesizing a sinusoidal voltage to the local grid, for instance, in accordance with any of the known methods used in voltage invertors.

III. Improvement of Power Quality

Inverter coupled DG units with the functionality of an active power filter (APF) for improving Power Quality can be implemented as a shunt or series APF as described before. Within this chapter measurement results of the prototypes of ISET e.V., SMA and TU Sofia are shown and described.

A. DG units with a Shunt APF functionality

Oscillograms characterizing the performance of a Shunt APF, for a non-linear load, are shown in Figures 4 and 5. The harmonic composition of the current without and with a Shunt APF is presented in Figures 6 and 7.

As it can be seen from the comparison between Figure 6 and Figure 7, the Total Harmonic Distortion (THD) is diminished from 32.8 % for operation without a Shunt APF to 10.2 % after connecting the filter. In this case, an index for correcting the waveform of consumed current towards the sinusoid one is the so called crest factor (K), which has diminished from 10.1

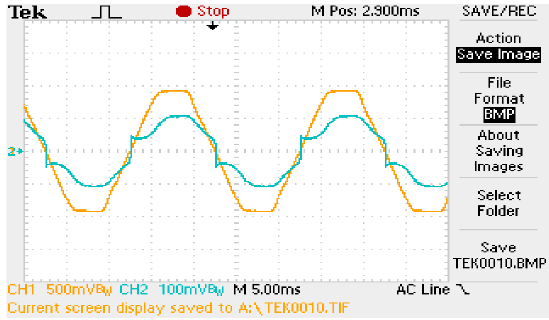

Figure 4. Voltage of the public grid (CH1) and current of the non-linear local consumer (CH2) without a Shunt APF.

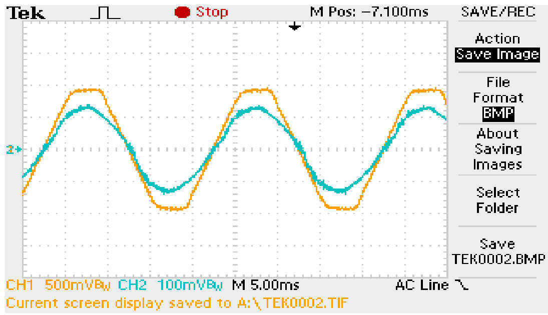

Figure 5. Voltage of the public grid (CH1) and current of the non-linear local consumer (CH2) with a Shunt APF

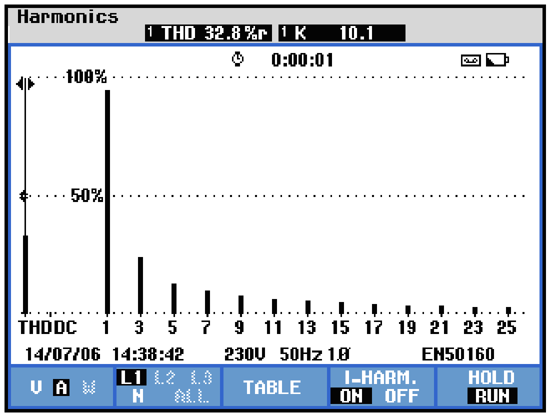

Figure 6. Harmonic composition of the current without a Shunt APF

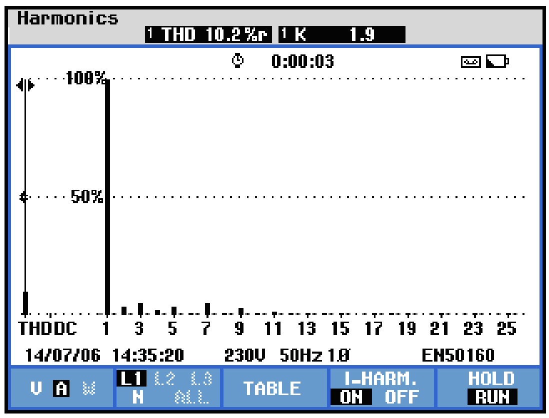

Figure 7. Harmonic composition of the current with a Shunt APF

to 1.9 after connecting a Shunt APF. An increase in the total power factor K_P from 0.93 to 0.99 is found out after connecting a Shunt APF.

B. *Series APF*

1) Voltage Quality Improvement for sensitive loads in the sub-network: With the principle of inductive decoupling, presented in [8], it is possible to improve Power Quality within a sub-network. Depending on the size of the decoupling inductor, the improvement capability varies. Figure 10 shows measurement results with the prototype of the Multifunctional PV-inverter system. In the superior grid several harmonics (3rd, 5th, 7th, 11th, 13th and 17th) with different amplitudes are simulated. These typical odd harmonics appear mostly in industrial grids. In total a THD-value of almost 9.5 % is achieved. According to the norm EN 61000 2-4 this industrial grid would range in class 3. With the smallest decoupling inductor (0.3 mH) a THD-value for sensitive loads in the sub-network of 7.11 % is possible; using 1.8 mH only 2.83% is feasible what results in an improvement into class 1 concerning the THD-value. All other tested inductor sizes lead to an enhancement from class 3 to class 2.

2) Series APF for non-linear loads: Oscillograms characterizing the performance of a Series APF for a non-linear load are shown in Figures 8 and 9. It is possible to observe the improvement of the voltage waveform around its maximal value.

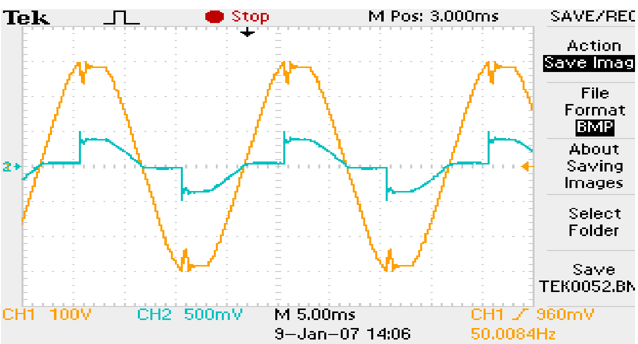

Figure 8. Voltage for the non-linear local consumer (CH1) and current of the consumer (CH2) without a Series APF.

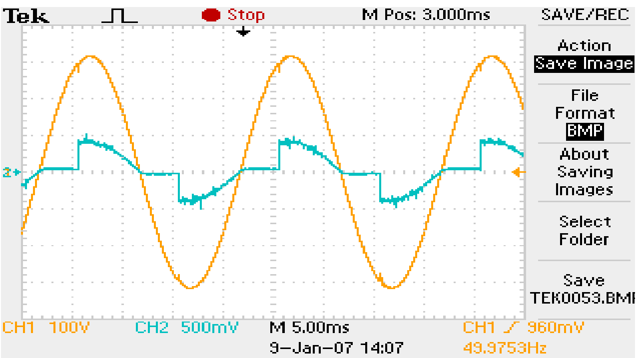

Figure 9. Voltage for the non-linear local consumer (CH1) and current of the consumer (CH2) with a Series APF.

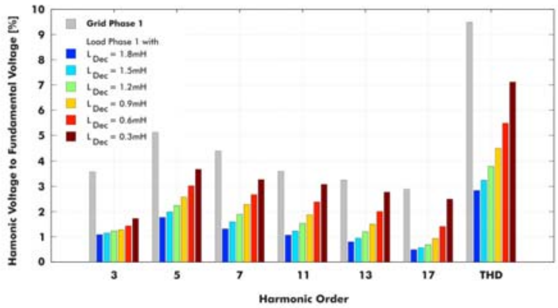

Figure 10. Harmonic reduction for various decoupling inductors for P_{MPV} = 50 kW and P_{load} = 100 kW

IV. Improvement of Reliability

PV-inverters and UPS units are composed of power electronic devices and therefore have a common ground. However different priorities for PV and UPS applications exist. While PV-inverters try to reach a preferable high efficiency, UPS units have to fulfil strict requirements of power quality and reliability stated in IEC EN 60240-3 at first. Using both functionalities at the same time imply considerable challenges [9]. The Multifunctional PV-inverter introduced within this paper is not qualified to substitute a conventional UPS unit, but it provides the possibility having a more reliable network for customers with the primary aim using PV energy. This is valuable especially for regions with the combination of high solar radiation and weak networks.

The Multifunctional PV-inverter is able to supply a voltage between 230 V±10 % for sensitive loads within the sub-network for small voltage dips down to a remaining voltage of at least 80% of the nominal voltage. For voltage dips with a lower remaining voltage, the Multifunctional PV-inverter disconnect instantaneously from the grid by opening the fast circuit breaker. Depending from the configuration of the Multifunctional PV-inverter – operation with or without the decoupling inductor – different behaviour of the sub-network voltage during the transition between interconnected and island operation is achieved. During the island operation the loads of the sub-network are powered by the battery storage. Additional PV energy extend the time duration of an island operation normally limited by the capacity of the storage system.

A. *Voltage dips without diconnection from interconnected grid*

Occurring voltage dips within the network voltage can be damped for sensitive loads in the local sub-network. The control of the inverter tries to hold the voltage in the sub-network constant at a given set-point value. During a voltage dip the Multifunctional PV-inverter injects an additional reactive current for reducing the impact of the voltage dip in the sub-network. Depending from several parameters, e.g. the size of the decoupling inductor, the damping factor capability varies. For a detailed evaluation voltage dips with a remaining voltage of 85% of the nominal voltage are analysed. Therefore several duration times (70 ms and 100 ms) and phase angles (0° and 90°) are considered. The phase angles are related to the

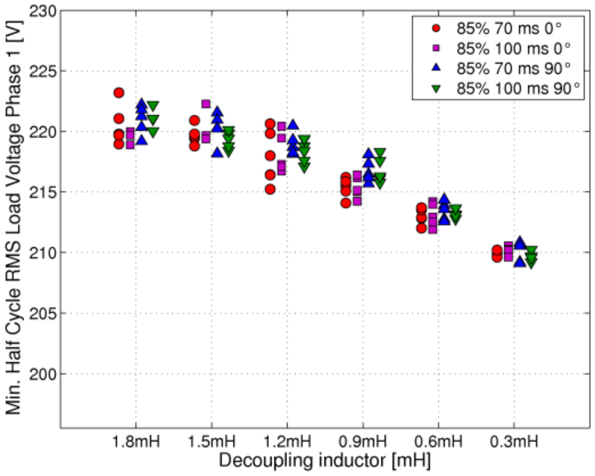

Figure 11. Measurements of sub-network voltage phase 1 for single phase voltage dips with 85% remaining nominal voltage

phase 1. Voltage dips for one, two and three phases variations are performed. In Figure 11 measurements of the sub-network voltage during several single phase voltage dips are shown. The minimal half cycle RMS voltage value is given.

The conclusions of the measurements are that using smaller values of the decoupling inductor result in deeper voltage dips for sensitive loads in the sub-network. A minimal voltage dip of 205 V_{RMS} for a decoupling inductor of 0.3 mH has been measured. The differences between values of the decoupling inductor for 1.8 mH, 1.5 mH and 1.2 mH are slight, 215 V_{RMS} can be achieved for these inductors at minimum, which reduce the voltage dip about 57 %.

Allowing a voltage deviation of ± 10% at most, a decoupling inductor of 0.6 mH is sufficient for the considered voltage dips. If deeper voltage dips in the network voltage occur and the operating mode is switched to an UPS service it has to be tested whether the chosen value of the decoupling inductor desire the classification according to EN 62040-3.

B. Voltage dips with disconnection from the interconnected gird

The Multifunctional PV-inverter will disconnect from the interconnected grid for voltage dips deeper than 80 % of the nominal voltage. Depending from the control of the inverter, whether in current or voltage control mode, the voltage behaviour during the transition time significantly is influenced. The kind of control mainly depends whether the decoupling inductor is used (voltage control) or bypassed (current control).

1) In Voltage Control Mode with decoupling inductor

If the decoupling inductor is used, the Multifunctional PV-inverter is voltage controlled. The behaviour of the Multifunctional PV-inverter has been tested using a decoupling inductor with 0.6 mH. In order to determine the voltage decrease in the sub-network for grid faults, a three phase failure with 0% remaining network voltage has been performed in laboratory. Transient recording can be seen in Figure 12. The fault was generated by a Spitzenberger & Spies AC-simulator

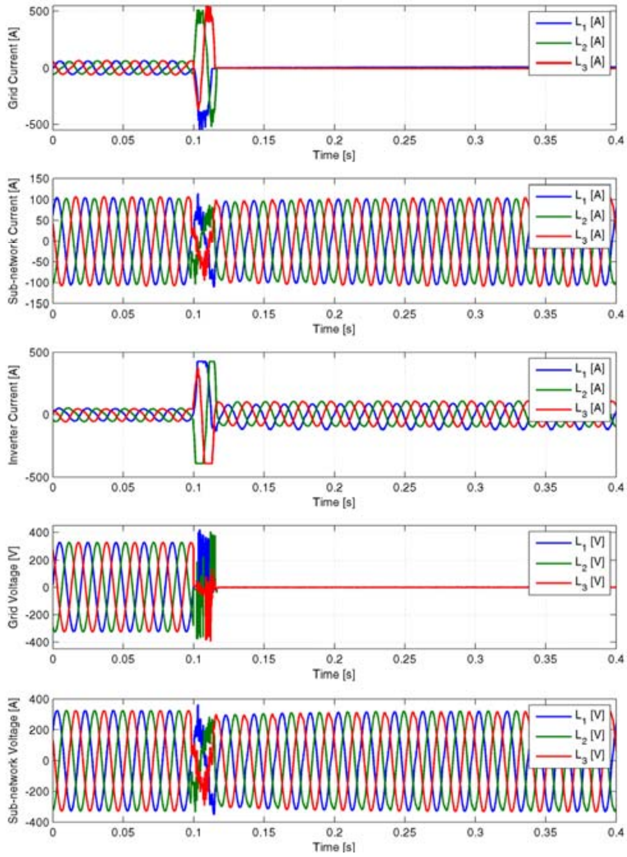

Figure 12. Measurements of the laboratory sample with a decoupling inductor of 0.6 mH

with a nominal power of 90 kVA. The minimal half cycle RMS voltage value of the sub-network load during the fault is 60 % of the nominal voltage. The sub-network voltage has reached a RMS value within 230 ±10 % after 50 ms at the latest. For a faster return an optimisation of the control parameters has to be done.

2) In Current Control Mode without decoupling inductor

If the decoupling inductor is not used in order to minimise losses for the injected power from PV, the inverter hardware has a special hardware electronic circuit for current limitation. This prevents the inverter, especially for near short circuits, to shut down due to an over-current. Additional there is a signal generated which can be used for a fast release of network disconnection. This approach was developed by the project partner the SMA Solar Technology AG for the prototype system.

Figure 13 shows the behaviour of a near short circuit within the interconnected network without using the decoupling inductor. Although a low switching frequency of 3 kHz, which allow a very good efficiency of the system, is used the additional circuit limits the current of the inverter reliable at 420 A_{RMS}. The release time of about 17 ms mostly result from the pre-stressed, mechanical circuit breaker. Using faster switches the transition time could be lowered. Here power electronic switches would provide an advantage, which has to

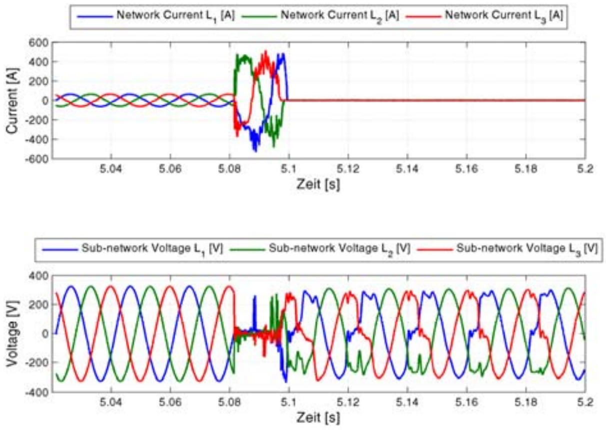

Figure 13. UPS functionality without using the decoupling inductor. Measurements with the Multi-PV prototype of the SMA Technology AG

be bought dearly with additional losses in the PV power injection operation mode.

The initially not sinusoidal voltage after the network disconnection is caused through the saturation of the transformer. This transformer is borrowed from a Sunny Central 100 and for island inverters it has not enough saturation reserve for extreme situations as short circuits, but is able to provide an excellent peak efficiency of 97.6 %. An adaption of the transformer for the special requirements of island operation should lead to better saturation behaviour

V. Conclusions

Distributed generation, especially from renewable sources, will increase within the next years strongly. A high number of decentralised generation units have to be integrated in the distribution network. Most of these units are coupled with an inverter to the interconnected grid. This paper demonstrates additional possibilities of such inverter-systems in terms of improvement of Power Quality and Reliability. Measurements for active power filters (series and shunt) as well as measurements of the behaviour of inverter systems with UPS functionality during grid faults are shown and discussed. The feasibility of a combination of these functionalities with common state of the art inverters could successfully been proofed. Implementation of these functionalities in real series products will strongly depend on the additional economic benefit. Reduced subsidies on renewable energy sources raise the possibilities for a high deployment of such systems.

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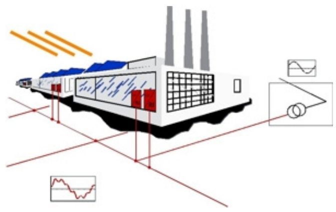

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