Increasing Grid Transmission Capacity and Power Quality by new Solar Inverter Concept and Inbuilt Data Communication

Prof. Dr.-Ing. Norbert Grass, Ohm-University Nuremberg,
Institute of Power Electronic Systems, Germany
Dipl.-Ing. Georg Kerber, Prof. Dr.-Ing. Rolf Witzmann, Technische Universität München,
Institute of Power Transmission Systems
Markus Sebeck, iAd GmbH, Grosshabersdorf, Germany
Reinhold Keck, Siemens AG, Fürth, Germany

Summary / Abstract

Increasing regenerative power sources installed in low voltage grids tend to cause overvoltage problems due to the reverse power flow direction. Consequently, regenerative sources need to be turned off temporarily or on the long term, the grid infrastrucutre would have to be extended by the utility company. Additionally, the increasing number of grid connected power electronic systems causes a high level of reactive power flow and harmonics in the grid affecting power quality.
The concept described in this paper uses reactive power which is generated in the solar power inverters to increase power capability of the grid.
By means of additional reactive power consumption, the grid voltage can be decreased to acceptable values and stabilized. Grid extension in many cases can be avoided or, at least it can be delayed. For control of a distributed system of a number of solar inverters installed in a grid segment distributed data collection and central control is required. Data and control parameters are being transmitted over the power lines with inbuilt real time DLC (distribution line carrier) communication.
Additionally, the inverters can be remotely controlled to compensate harmonic distortion and to improve phase voltage balance by feeding unsymmetrical currents into the three phases.

The concept can be applied not to solar power systems only; it is rather a basic technology which can be used in future grids with distributed generation and storage. Even the power consumption in the grid can be optimized accordingly to the generation if remotely controllable appliances will be installed in the future.
With the technology shown in the paper higher reliability, increased and controllable power quality and less problems in low voltage grids can be achieved. Thus, the capability to accept, integrate and transmit higher quantities of decentralised generated power can be improved..

1 Introduction

The approach described in this paper is to implement additional functionality into power electronic equipment which is permanently connected to the grid to improve power quality. Modern power electronic devices provide fast switching and low losses during operation. New communication technologies use power lines for real time data transmission. Main advantages of this technology are in the availability of data communication at any location on the power grid and a high level of reliability because no additional equipment or service provider is required.
The combination of both technologies, power electronics and information and communication technology enables the control of a distributed system as described in this paper.

Limits of Grid Transmission Capacity

Conventional design of a power grid considers a load flow directed from the transformer to the load. Additionally, passive loads with sinusoidal currents have been assumed for the rating of transformers and distribution lines. Figure 1 shows the voltage decreasing with the distance from the transformer. Therefore, the design usually is made to keep the voltage at the transformer above the nominal voltage in order to achieve a voltage drop which is below the minimum specified value. In the last few years the usage of distribution grids has changed heavily as many devices are using uncontrolled bridge rectifiers at the mains input side. In many rural areas large decentralised power generation (e.g. photovoltaic, wind, micro turbines and combined generation) has been installed. In some areas the installed

generation power significantly higher than the consumption and often reaches to the rated grid power.
Therefore, the grid needs to be improved to offer new services and new functionality to deal with the new requirements. Avoiding high installation or operating cost promotes further growth in decentralized power generation.

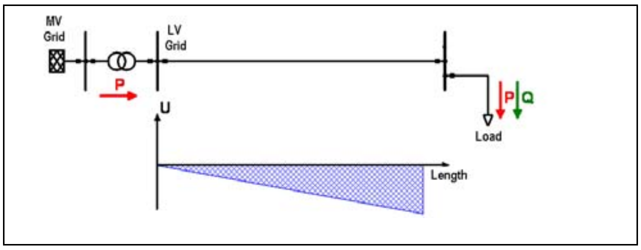

Figure 1 Conventional load with voltage minimum at end of line

1.1 Example Grid Structure

For testing the functionality of the control system a typical sample grid with a high penetration level of solar electricity generation has been selected. According to Figure 2 there are 3 relevant branches and as many as 11 solar generation units connected to that grid segment.

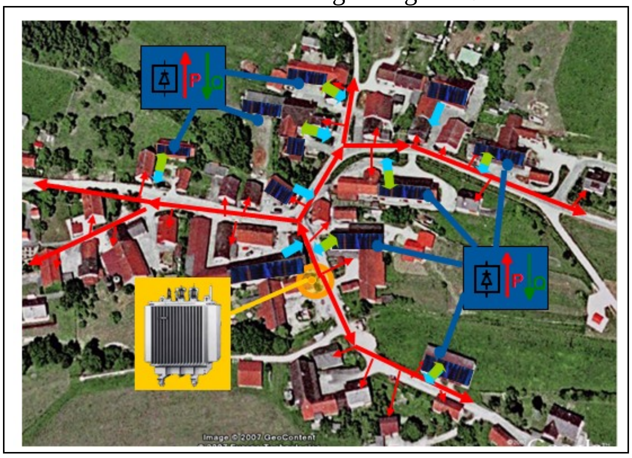

Figure 2: Sample grid

The location of the transformer is given in Figure 2 as well. The power rating of the transformer is 150 kW.
During a trial installation of solar inverters, data acquisition units, data communication and a central control computer the stable operation of the system will be tested and the increased transmission capability will have to be proved.

1.2 Power Consumption Cycles in Rural Areas

Power consumption schedules in rural areas are different to industrial areas. People go to industrial areas or to their offices during the day and due to the reduction in domestic power demand there is only low power consumption during the day in housing areas. The power generation within a grid branch can be significantly higher than the consumption during high solar gain periods such as but not restricted to summer days.
Basically, solar generation fits comparable well to the consumption schedule but the energy is being used in a different location than it is generated. Therefore, power has to be transmitted over the transformer and the medium voltage grid.

1.3 Overvoltages due to Solar plant Generation Cycles

Due to high levels of generated power from decentralized generation stations the load flow may change its direction. Particularly in high solar gain periods when solar plants feed their highest power levels into the grid, while the power consumption can be fairly low in the entire grid branch, reverse power flow may occur. Therefore, solar generated power is fed into the medium voltage grid over the transformer of that branch. If the power is in the range of the nominal power of the branch the voltage at the connection point of the generation plant may significantly increase. If the voltage exceeds the tolerance of usually 10 % above nominal voltage other devices and equipment may be damaged. Figure 3 shows the possible voltage variation with the distance from the transformer for different load and generation conditions. Therefore, the design usually is made to keep the voltage at the transformer above the nominal voltage in order to achieve a voltage drop which is below the minimum specified value.

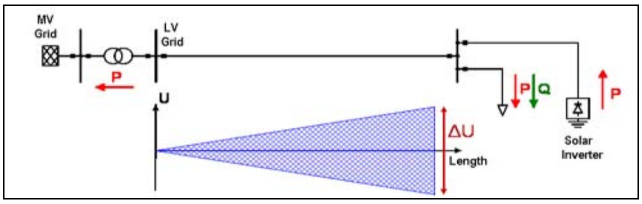

Figure 3: **Voltage maximum or minimum at end of line**

With decentralized generation the voltage may increase at the connection point as shown in Figure 3. With the voltage at the transformer being set above the nominal value it is very likely to exceed the specified maximum voltage (e.g. 10 % above nom. voltage). In case of reverse power flow the maximum permitted voltage will be reached even below nominal power of the grid branch.

1.4. Reactive Power and Harmonics

Many electrical devices require reactive power from the grid for proper operation. Induction motors need it for generating a magnetic field which transmitts torque to the rotor. For other power electronic equipment (e.g. switch mode power supplies for all kind of applications) quite frequently diode rectifier bridges and capacitors are used to generate a DC voltage. Their grid current is not sinusoidal and it's not in phase with the grid voltage. Therefore, reactive power and harmonics are becoming very important

issues. While modern power electronics can be designed to avoid these power quality problems the power factor correction technology is not yet very commonly used due to slightly higher cost.
Reactive power flow and harmonics result in additional grid currents and therefore they cause power losses on power lines and transformers.
Reactive power compensation to this date requires additional equipment and associated installation and commissioning costs which should be recovered in greater efficiencies. So far, compensation is mainly used in large industrial plants.
Therefore, generating decentralized reactive power for compensation lowers significantly the power losses due to short transmission distances of the reactive power. For generating reactive power short term energy storage is required. This can be done with capacitors or inductors. Voltage link based solar inverters usually have capacitors anyway, so the already installed capacity can be used for reactive power.
As the voltage distortion is low on the grid, grid current harmonics do not transmit active power, therefore harmonics are transmitting reactive power only. The vector graph in Figure 4 shows the context.

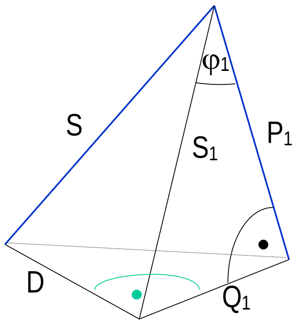

Figure 4: Vector graph for reactive power

S : total apparent power, ➔ grid current (RMS)
S_1: apparent power of base frequency (50 Hz)
P: active power
Q: reactive power base frequency
D: reactive power of harmonics

$$S = \sqrt{P^2 + Q^2 + D^2}$$

2. Conventional Approaches

In the past, grid extension was required to increase the transmission capacity resulting in additional cabling and higher investment cost even if the additional capacity is being used only for a few operating hours per year, usually, on solar gain days, when additional grid capacity is actually needed.
In the short term, additional connection of solar generation systems can often not be permitted until grid extension had been carried out.

3. Increased Transmission Capacity with Reactive Power

The approach given in this paper is based on knowledge and research in grid control, power electronics, decentralized measuring technologies and real time data communication.

3.1. Solar Power Inverter providing Reactive Power

Solar inverters above 8 to 10 kW are usually connected by three phases to the grid. They can operate in all four quadrants thus being able to inject or absorb reactive power while active power is fed into the grid. They are using topologies which can be controlled by the space vector modulation. Their application is very common in the drive technology as well. It is a logical control system based on pulse with modulation (PWM) with time synchronisation of the 3 inverter branches in order to obtain highest possible phase to phase voltage from an inverter. The space vector method generates a three phase voltage system which can easily be phase shifted against the grid voltage. Connecting the inverter through an inductor to the grid results in sinusoidal currents with a phase shift compared to the grid voltage.
Figure 5 shows in a qualitative way the voltage drop at a transmission line. While under normal load conditions the voltage at the end of the line U2 is lower than at the beginning (transformer side) U1, this changes when active power is fed in at the end (left part of Fig. xx). The voltage at the dnf may be significantly higher at the end than at the transformer. By additionally absorbing reactive power (or current) the overvoltage can be decreased (right hand side of Fig. xx). This is also the case in low voltage distribution grids with a relative high R/X ratio especially when taking into consideration the transformer impedance

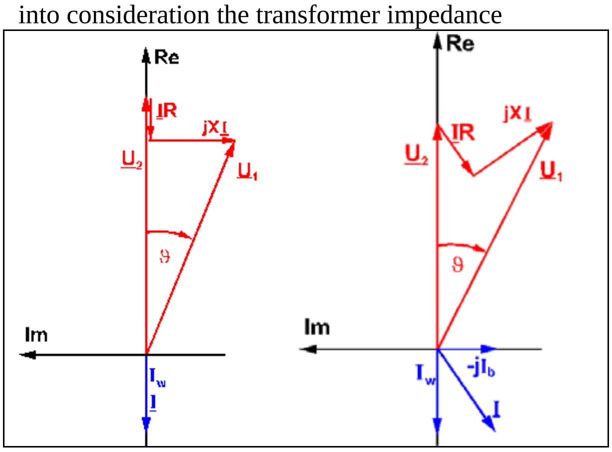

Figure 5: Voltage drop at a line when feeding in actice (left) as well as active and reactive power (right)

The reactive power flow results in an additional current to be driven from the inverter. The following example gives an indication regarding the increased current rating which is required for the solar inverter. A maximum power factor cos φ = 0.9 provides reactive power of 43 % of the active power. This would result in a 10 % higher current of the inverter.

If reactive power is used for limiting the grid voltage additional power losses are generated in the inverter and in the grid lines due to the higher grid current. But the benefit is that higher active power can be transmitted and the surplus solar generated electrical power can be fed in to the grid.

If the inverter is used for local compensation of reactive power required by other loads power losses in the grid lines are decreased because the reactive power does not need to be transmitted over large distances. This operating mode will be required more often in limiting the voltage.

If considering additional losses against avoided losses the system in total enhances the energy efficiency of the grid.

Additionally, voltage fluctuations due to fast load and generation changes e.g. moving clouds, can be compensated and damped by injecting and absorbing reactive power through the solar inverters.

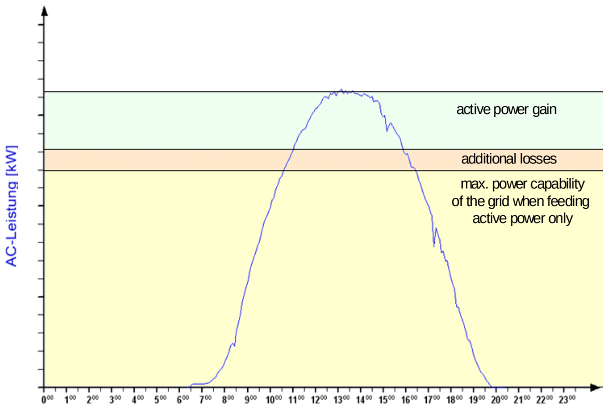

Figure 6: solar power generation during a cloudless day

3.2 Distributed Solar Inverters in a Grid Segment

If there are a number of inverters operating in a grid branch, the reactive power setting for each inverter has to be calculated in order to keep the voltage within the permissible limits and to minimize transmission distances for the reactive power. Inverters have to be coordinated to minimize power losses and to achieve stable operation.

4 Additional Power Quality Improvements

4.1 Compensation of Harmonics

Harmonic currents cause a number of problems in electrical grids and they are responsible for a decrease in power quality. Typical effects of harmonics are:

- Additional losses due to eddy currents in motors
- Torque losses in motors
- Noise
- Additional losses in capacitors of power supplies due to high frequencies
- High currents in static compensation
- Skin effect on power lines, higher losses
- Stress of insulation
- Distortion of other electronic equipment

Using an extended space vector modulation method the inverter will be enhanced to compensate harmonic currents by delivering harmonics in phase opposition to the grid. Focus will be on the low order harmonics as 3rd, 5th and 7thorder.

5 Control structure

The operational status of the grid has to be measured continuously at connection points of large loads and decentralized generation. Solar inverters are equipped with data acquisition capabilities because they need to synchronize their voltage and frequency to the grid voltage. For load connection points measuring technology is to be installed. As shown in Figure 7 a main computer is networked to a number of data acquisition devices and solar inverters. Data acquisition devices and solar inverters monitor voltage, current and power flow at their locations on the grid. Data acquisition devices are located at large loads (e.g. industrial plants) and grid nodes. The main computer receives the grid status data and then calculates the values for the required reactive power for the individual solar inverters which will be sent over the data network to the inverters.

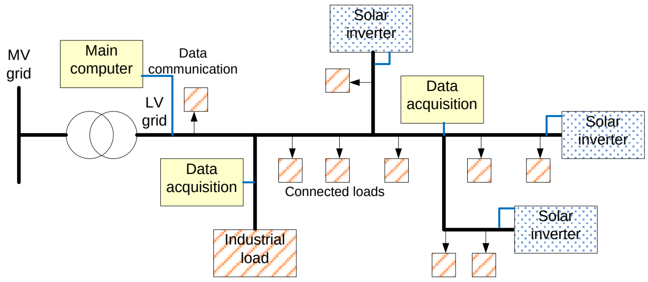

Figure 7: Data acquisition and control structure

6 Real Time Data Transmission over Power Lines

Reliable operation of safety critical applications requires high level communication technology and data transmission regarding short response times, time synchronisation and robustness against electromagnetic distortion. Thus, efficient pre-processing and data compression with use of encryption algorithm is required. Besides, for this application a high number of distributed components have to be monitored, coordinated and controlled, whereas a lot of plants in the energy sector are not connected to a communication network. Therefore, the use of an economic communication technology is required. The proposed power line carrier technology (DLC) with high data rates will be proved in critical environment to be appropriate for the proposed application.

7 Further Applications

During the entire research project the technology described above is currently under development and being tested with solar inverters on the low voltage grid. Generally speaking, the technology can be applied to any power electronic inverter which is either permanently or temporarily connected to the grid. Due to the inbuilt data communication and data acquisition facilities the system can be automatically configured after connecting a new inverter to the grid. Example components are inverters for drives, switched mode power supplies for telecommunication and internet infrastructure, uninterruptible power supplies as well as wind power, combined heat and electricity generators and small hydro power generators

Further research is already planed to extend the technology to the integration of energy storage devices as they will be provided by future electric cars. Therefore, the technology has the potential to contribute to the integration of the mobility into the electric grid.#

8 Project Partners

iAd GmbH 90613 Großhabersdorf	Measurement, data acquisition, smart metering and power line communication
Siemens AG **Dep. I IA SE DE**	Measurement data acquisition and processing, solar inverters
Technische Universität München (TUM) **Institute of Power Transmission Systems**	Grid simulation, modelling and control, stability
Georg-Simon-Ohm University Nuremberg Institute for Power Electronic Systems (ELSYS)	Control of solar inverters, power quality, Laboratory load emulation

9 Literature

[1] Bendra, Michael; Christ, Thomas;
Beitrag zur Optimierung der Spannungsqualität in Niederspannungsnetzen mit dezentraler Einspeisung Fachkongress Zukunftsenergien am 15.03.2005

[2] BRÜNDLINGER,Roland; BLETTERIE, Benoît.; Mayr,Christoph;
PV-Wechselrichter als aktive Filter zur Verbesserung der Netzqualität - Was können moderne Geräte leisten?; 22. Symposium Photovoltaische Solarenergie, vom 7. bis 9. März 2007 in Kloster Banz, Bad Staffelstein

[3] Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich (EEG)

[4] Hormann, Walter; Just, Wolfgang; Schlabbach, Jürgen;
Netzrückwirkungen; VWEW, Energieverlag; 2005

[5] Kerber, G.; Witzmann, R.
Aufnahmefähigkeit der Verteilnetze für Strom aus Photovoltaik
EW Jg. 106 (2007), pp.50-54, VWEW-Verlag

[6] Potentiale der Leistungselektronik und politische Rahmenbedingungen zur Verbesserung der Energieeffizienz von elektrischen Verbrauchern, ECPE, Nürnberg, Juli 2007

[7] Quadflieg, Dieter,
EN 50160 (Artikel), VDN – Nachrichten 2007

[8] Sakulin, Manfred; Fickert, Lothar; Hipp, Walter; Stranner, Bernhard; Renner;
Der Einfluss dezentraler Erzeugung auf die Verteilnetze; VEÖ 2005

[9] Schmitt, S.; Kremer, P.;
Power Quality of grid connected power conditioner SINVERT solar operation results 2005 of the 5 MWp power plant Espenhain-Leipzig;

[10] Schubert, H., Dinges, R.,
Heutige und zukünftige Kommunikationsstandards. In: FGH (Hrsg.): FGH/VDEW-Fachtagung Kommunikationsnormung in der Stationsleittechnik - Ergebnisse, Erfahrungen, Realisierungsansätze, Perspektiven. FGH/VDEW Tagungsunterlagen. 2000.

[11] Scheffler, Jörg;
Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten; Dissertation Technische Universität Chemnitz 2002

[12] Tietze, Ernst-Günther
Netzleittechnik Teil 2: Systemtechnik; VWEW, Energieverlag; 2006

[13] ZVEI, Energieeffizienz-Steigerung durch Blindleistungskompensation,
Positionspapier zum Grünbuch über Energieeffizienz, Frankfurt, März 2006

[14] Norbert Grass: “Fuzzy-Logic-Based Power Control System for Multifield Electrostatic Precipitators” IEEE Transactions on Industry Applications, Vol. 38, No 5, 2002