INCREASING GRID TRANSMISSION CAPACITY AND POWER QUALITY BY A NEW SOLAR INVERTER CONCEPT IN LOW VOLTAGE GRIDS WITH A HIGH PROPORTION OF DISTRIBUTED POWER PLANTS

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ABSTRACT

The proportion of renewable energies in power generation has increased according to the political aims in recent years. In low-voltage grids, these are mostly decentralized renewable energy systems such as photovoltaic (PV) that are connected through inverters to the grid. The temporary reversal of the power flow causes overvoltage problems. Consequently, regenerative sources need to be turned off temporarily or on the long term the grid infrastructure has to be extended by the utility company.

The concept described in this paper uses reactive power which is generated by the solar power inverters to increase power capability and quality of the grid. Thus grid extension can be avoided in many cases or at least can be delayed. Voltage fluctuations due to varying power input, e.g. caused by passing clouds, can be reduced. Distributed data collection and central control is required for control of a distributed system of multiple solar inverters installed in a grid segment.

The concept can be applied not only to PV systems; it is rather a basic technology which can be used in future grids with distributed generation and storage.

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.

The combination power electronics and information and communication technology enables the control of a distributed system as described in this paper.

LIMITS OF GRID TRAMSMISSION CAPACITY

Conventional design of a power grid considers a load flow directed from the transformer to the load. 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.
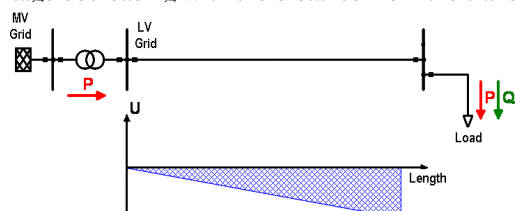

Figure 1: Conventional load with voltage minimum at end of line

Therefore, the design is usually 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 is significantly higher than the consumption and often reaches the rated grid power.

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, 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 might be damaged.

Figure 2 shows the possible voltage variation with the distance from the transformer for different load and generation conditions. Therefore, the design is usually made to keep the voltage at the transformer above the nominal voltage in order to reduce voltage drops below the minimum specified value.
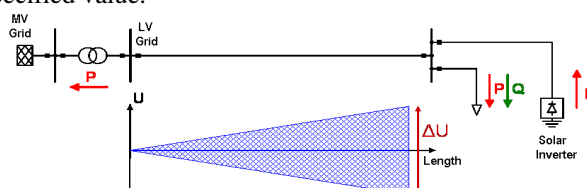

Figure 2: Voltage maximum or minimum at the end of line

With decentralized generation the voltage may increase at the connection point as shown in Figure 2. With the voltage at the transformer being set above the nominal value it is very likely to exceed the specified maximum voltage. In Germany a maximal voltage increase of 2 % [1] or 3 % in the future [3] caused by distributed power plants in low voltage grids is recommended. In case of reverse power flow the maximum permitted voltage will be reached even below nominal power of the grid branch [2].

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 costs promotes further growth in decentralized power generation.

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 only being used 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.

INCREASING VOLTAGE QUALITY AND GRID CAPACITY BY REACTIVE POWER

While the grid capacity and grid quality have primarily been provided by network expansion so far, this project aims to use the installations which are distributed in the grids effectively. This is done by the use of distributed measurement technology, intelligent control of power electronics, new information and communication technology and the possibilities of the grid control.

The concept is developed and tested on the example of distributed PV systems. However the use is not restricted to this application. In all networks with controllable feed-in installations and loads network efficiency can be increased by distributed network services.

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 3 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.
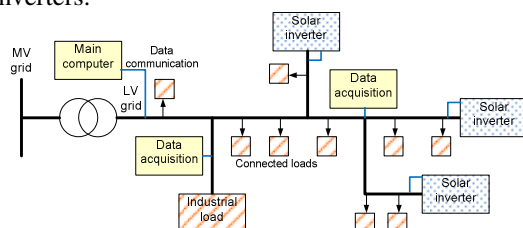

Figure 3: Data acquisition and control structure

The control structure consists of three different controls. The first part is the limitation of the grid voltage by reactive power absorption of the inverters. To avoid unnecessary losses only as many inverters as needed have to absorb only as much reactive power as needed to limit the grid voltage. Thus the main computer only activates the inverters with the highest voltage levels in the grid.

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

The inverters can also be used for local compensation of reactive power required by other loads in order to minimize power losses in the grid.

Voltage limitation by reactive power consumption

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.

Figure 4 shows in a qualitative way the voltage drop at a transmission line. While the voltage at the end of the line U_2 is lower than the voltage U_1 at the beginning (transformer side) in case of normal load conditions, this changes when active power is fed in at the end of the line (left part of Figure 4). The voltage may be significantly higher at the end of the line than at the transformer. By additionally absorbing reactive power (or current) the overvoltage can be decreased (right hand side of Figure 4). This is also the case in low voltage distribution grids with a relative high R/X ratio especially when taking the transformer impedance into consideration.
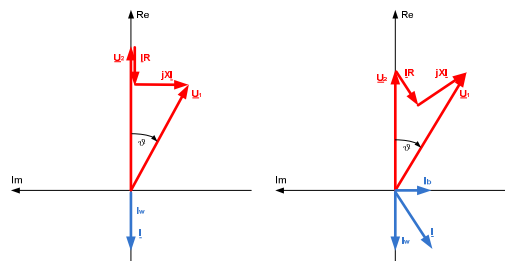

Figure 4: Voltage drop at a line when feeding in active (left) as well as active and reactive power (right)

The reactive power flow results in an additional current that has to be driven from the inverter. Studies on the reactive power have shown that a minimum power factor of $\cos \varphi = 0.9$ in typical low voltage grids is sufficient to keep the voltage within the permissible limits. A power factor $\cos \varphi = 0.9$ provides reactive power of 43 % of the active power. This causes a 10 % higher current of the inverter. If the reactive power is only absorbed at increased voltage levels, the higher rating of the solar inverter may be lower or it may even not be necessary.

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. Therefore it is appropriate to provide the reactive power not by a static characteristic of the inverters, but to minimize the reactive power absorption by individually activating those inverters which have the most significant effect to the grid voltage. The communication of each inverter with a central computer ensures the optimization of the reactive power absorption.

Smoothing of voltage fluctuations

Fluctuating power input to PV systems due to passing clouds or highly fluctuating loads cause voltage fluctuations in the low voltage grid. Reactive power consumption (capacitive) at negative voltage peaks and reactive power

absorption (inductive) at positive voltage peaks by the distributed solar inverters can smooth voltage fluctuations in the grid. The risk of flickers can be reduced by such an additional control that is implemented locally in the inverters. The smoothing does not need any communication of the inverters with a central computer.

Reactive power compensation

Reactive power compensation to this date requires additional equipment and associated installation and commissioning costs which should be recovered by greater efficiencies. So far, compensation is mainly used in large industrial plants.

Therefore, generating decentralized reactive power for compensation significantly lowers 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, so the already installed capacity can be used for reactive power.

The existing reactive power reserves which are inherently present by the distributed inverters can be used to provide reactive power to the overlaid middle voltage grid or to reduce the reactive power consumption of the low voltage grid to minimize the losses.

FIELD TEST

The field testing is done in a real low-voltage grid with a high penetration of PV power plants.

Overview of the test grid

Figure 5 shows the structure of the test grid. The grid is fed by two transformers (rated power 630 kVA) and operated meshed. The installed PV system capacity is 400 kW$_p$ and is already higher than the average network load. On sunny days, active power is fed back regularly in the medium voltage grid. There are numerous relatively large PV power plants in the grid due to the high number of agricultural buildings with large roof areas.
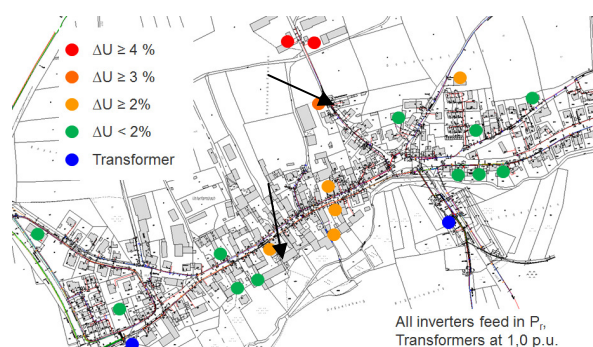

Figure 5: Voltage increase due to PV power plants

The voltage distribution and the loadings of cables and transformers were calculated by a commercial power system analysis software. Figure 5 also shows the voltage distribution in the grid area as a result of PV power plants. According to the VDEW recommendations, the voltages are calculated without loads and with the inverters feeding in

their rated power.

It is evident that in this grid a voltage increase ≤ 2 % is observed only near the transformers. The increase is above 2 % between the transformers and over 3 % or 4 % at the critical network extensions. Despite the voltage increase the transformers and cables in the grid are loaded at 40 %.

Premeasurements in the test grid

Data from both transformers have been available in 10 minute averages over a period of a year from March 2008 till March 2009. Figure 6 shows the number of measured 10 minute averages depending on the reactive power flow of the grid. On sunny days the power generated by the PV power plants in the grid exceeds the load. Thus there is an active power flow from the test grid to the overlaid middle voltage grid.
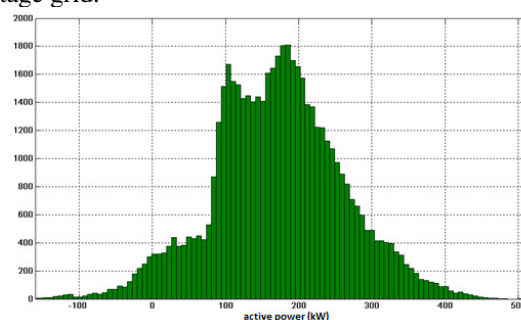

Figure 6: Number of 10-minute averages depending on the active power flow of the test grid

Two measurement points at the inverters of PV power plants (marked with arrows in Figure 5) were available to evaluate the state of the test grid in advance. One is at a PV power plant which is at the end of a critical long line and the other is located between the transformers.
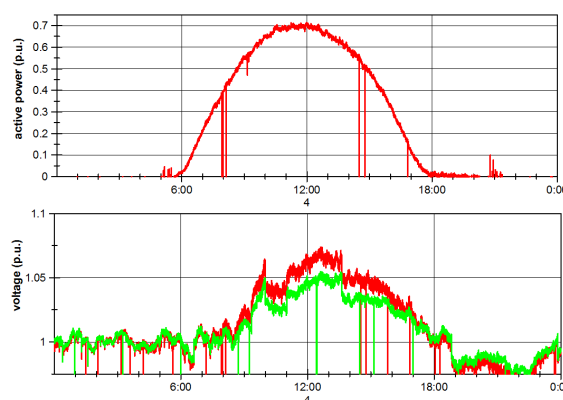

Figure 7: PV feed-in and voltage on 2010-06-04

The upper chart of Figure 7 shows the developing of the PV-feed-in in p.u. based on the rated power of the inverter on 2010-06-04, which was a sunny summer day. The rated power is not achieved because of the strong heating of the PV modules. The lower chart of Figure 7 also shows the corresponding voltages at both measurements points (green: measuring point at the critical grid extension, red: measurement point between the two transformers). The zero values of voltage and power are the result of short-term transmission errors in the measurement. The voltage profile

follows the PV feed-in very well. The left transformer in Figure 5 was out of service due to maintenance on this day. That is the reason why there are high voltage increases. These values correspond well with the results of the grid calculation.

Figure 8 shows a close-up of the PV feed-in and the corresponding voltages on 2010-06-07, an unsettled day (green: measuring point at the critical network extensions, red: measurement point between the two transformers). The figure shows that the voltage also follows the PV feed-in.
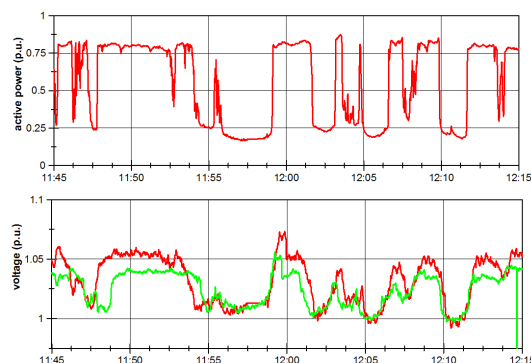

Figure 8: Detail of PV feed-in and voltage on 2010-06-07

On this day the left transformer was also out of service due to maintenance on this day. The gradients of the voltage peaks or drops are usually smaller than the gradients of power peaks or drops. This is due to the distribution of the PV systems in the test grid. Thus the power drops caused by passing clouds are staggered. These staggered power drops cause staggered voltage drops.

The largest power gradient measured so far is 0.07 p.u./s relative to the rated power. The largest voltage gradient measured is so far 0.002 p.u./s relative to the rated voltage.

Simulation of the control concept

The developed control concept was simulated and further optimized with a commercial network calculation software using the knowledge gained from the premeasurements. Therefore simulations with the measured PV feed-in have been carried out.
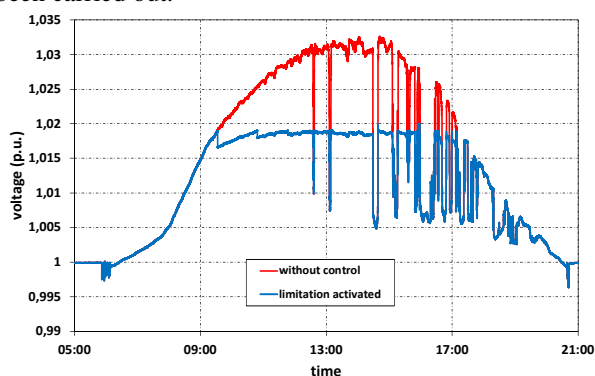

Figure 9: Simulated voltage on 2010-07-19

Figure 9 shows as an example the simulated voltage (red) at the end of the critical line on 2010-07-19, neglecting the load. In addition, Figure 9 shows the simulated voltage when the control for voltage limitation is activated (blue). In

this case a target of a maximal voltage increase of 2 % was set. Eight suitable inverters have to consume reactive power to meet this target. A target of a maximal voltage increase of 3 % would be already possible if only two inverters consume reactive power.

Furthermore the influence of the voltage smoothing on the voltage limitation was investigated. Figure 10 shows a close-up of Figure 9. In addition, it illustrates the voltage (green) when both voltage limitation and voltage smoothing is activated. The smoothed voltage is clearly visible
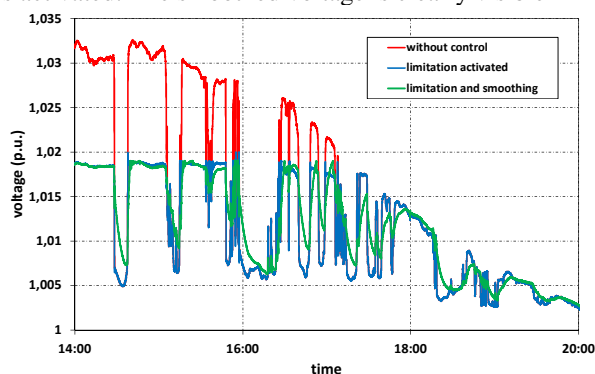

Figure 10: Close-up of simulated voltage on 2010-07-19

CONCLUSION

The concept described in this paper provides an improved voltage quality and higher transmission capacities in low voltage grids with a high penetration of PV power plants. 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.

ACKNOWLEGDEMENTS

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