POWER QUALITY AND STABILITY ISSUES IN MODERN DISTRIBUTION GRIDS: IDENTIFICATION AND MITIGATION

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ABSTRACT

Traditionally, the architecture of electrical power systems has always followed design principles that fit to energy generation accomplished by relatively few centralized power stations. However, especially during the last decade the actual situation has changed with increasing speed - there is a clear move towards small, decentralized generation (DG) units being appended mostly to the lower voltage distribution levels. Often drawing on fluctuating renewable energy sources and employing new power conversion technologies, these DG units can introduce power quality and even stability issues into the distribution grid.

In this paper we present a number of case studies supported by measurement data from actual electricity networks in Germany to shed light on some of the most pressing issues. We propose pertinent requirements towards measurement hardware to effectively characterize these phenomena, such as static voltage and frequency band violations, higher order harmonics in excess of 9 kHz but also subharmonic oscillations that are a threat to feed-in stability. We conclude that for mitigation of these issues, novel active distribution level regulation devices will be necessary in the future.

INTRODUCTION

Globally, investments into the expansion of renewable energy production are steadily on the rise. The global average for the rate of change of installed wind and photovoltaic power production capacity exceeds 25% year to year. In Germany, due to state-driven financial incentives, a lot of the photovoltaic and some wind power installations enter into the lower levels of the distribution grids as small-scale distributed generation elements.

With more than 22000 wind power and close to 1,1 Mio. photovoltaic (PV) installations already in 2012 it comes as no surprise that there are today some German regional distribution network operators that have reached a state in which the clear majority of the power sold in their grid is of "green" origin [1].

This conversion of the distribution grid is not without complications. The first consequence is a large range of power quality (PQ) problems and a need for their mitigation, with authors many focusing on issues related to grid connected PV and wind power inverters [2-5]. The list of phenomena can be divided into those of a generic origin - caused by the fluctuating nature of distributed energy sources and their interplay with the rest of the AC grid, such as

- Overvoltages during feed-in,
- Short and long time voltage fluctuations (including Flicker),
- Frequency deviations,
- Voltage dips,
- Unbalance,

as well as other phenomena originating directly from the technical details of the power electronics often used for grid connection, such as

- Harmonic injection,
- Resonance phenomena,
- Capacitative inrush currents,
- Decreased damping character of the grid through the introduction of nonlinearities.

Of these power quality problems, currently the most widely discussed and arguably most important ones are overvoltages and harmonics injection from power inverters. Applicable regulations in Germany are the DIN-EN-50160 standard defining a permissible 10% voltage band at the generator connection point and the DIN-EN-61000-4-7 defining permissible harmonic voltage levels [6,7].

Another aspect of large-scale DG presence that in contrast is not well research nor understood is the field of dynamic effects and grid stability. Considering the increasing penetration of decentralized energy feed-in and its importance for the distribution level, dynamic processes related to fluctuating energy sources should be expected to become more and more important. This a potential source of grid instability should therefore be carefully evaluated, both theoretically and experimentally. The current concerns are two-fold. As large numbers of small power producers (e.g. photovoltaic) are integrated, a totally new situation arises in low to medium voltage networks: the direction of power flow is frequently reversed. Power is pumped up into the higher voltage levels, a process for which today´s power grid is not well prepared. Secondly, the detailed dynamic behavior of the vast variety of DG units currently must still be considered as a largely unknown and of course also unregulated field.

This sharp contrast with the well-established power quality issues: virtually no legally binding national grid codes currently exist regulating dynamic behavior of generation units with the goal of grid stability in mind. Despite that, on the European level, dynamic system behavior monitoring of voltage, frequency and other variables are presently being discussed as mandatory requirements for generators connected to the distribution level [8].

CASE STUDIES

In order to highlight particularly pressing power quality and stability issues that can play a role in distribution grids with a high level of DG units connected, a selection of pertinent case studies is given below.
The first case study addresses the necessity to actively control overvoltages by means of suitable active low voltage regulation systems. The second subchapter addresses harmonics emission of generators and loads. Evidence is shown that nowadays, harmonics of progressively high order (f>10 kHz) are emitted by power electronics devices. Unprecedented high orders of harmonics lead to a situation where despite the fact that harmonic polluters comply with all presently applicable power quality norms, grave power quality problems are still created for other grid connected participants.
The final case study deals with some novel dynamic effects coming from the interplay of distributed generators. Specifically we present evidence that in some conditions, dynamic effects can lead to the tripping of PV inverters and thus to the harmful loss of generation capacity.

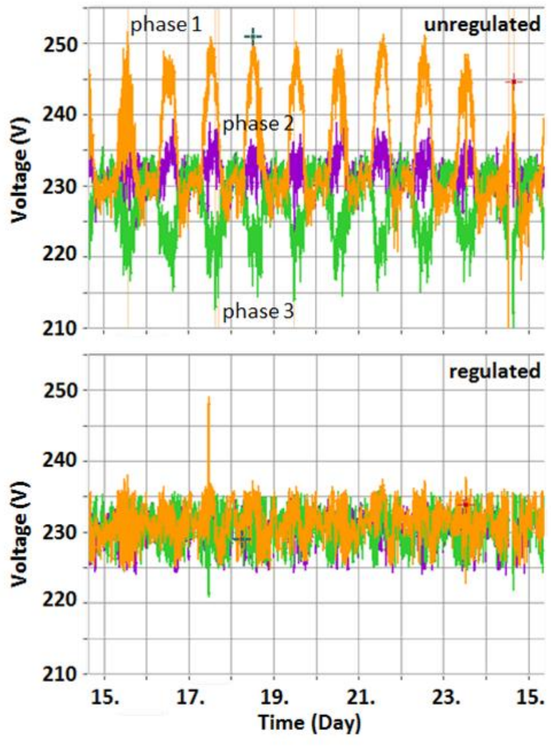

Figure 1 Daily voltage profiles in a rural distribution grid with a large portion of connected PV. Unregulated voltage (upper panel) and conditioned voltage obtained with the connection of a LVRSys device (lower panel).

Decentral voltage regulation for DG integration

According to the European norm EN 50160, the distribution-level voltage is globally allowed to deviate no more than 10% from the rated value over an extended period of time. In Germany, VDE-AR-N 4105 additionally forbids DG units to raise grid voltage locally by more than 3%. These regulations represent severe restrictions for DG practical operation and feed-in. Distribution grid operators can feel this pressure quite dramatically even when only a comparably small amount of DG Units (e.g. photovoltaics) are connected to "regular" voltage cables. A simple calculation demonstrates this: when only about 45 kW of generation is connected to an average low voltage cable (150 mm^2, 500m length), the voltage level is already raised by 3%. This amount of generation can be reached already with only one or two independent PV sites.

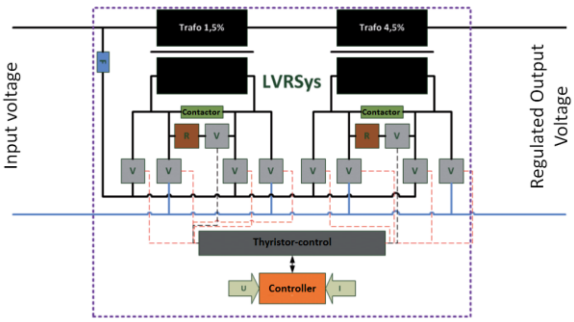

Figure 2 Schematic circuit diagram of a single phase of thyristor-based low voltage regulation system LVRSys

What a real-life voltage profile can look like when a number of DG units are present is shown in the upper panel of Figure 1. It can be seen that connected PV generation clearly dominates the phase voltages in the sense that around mid-day (large amount of generation), the phase voltage closely approaches the allowable limit of +10%. In this case, a number of single phase power inverters feed into the grid, leading to the asymmetries seen in the three phases. Even though most modern PV generators now feature symmetric three phase inverters, many old single phase installations will continue to operate in our distribution grids. In any case - the 3% / 10% deviations are not to be exceeded in the grid. The traditional remedy consisted of network expansion measures, aiming at lowering grid impedance and thus also the voltage excursions. The disadvantage of this is however two-fold: network expansions are costly to build and time-consuming. Once finished, larger cables would by definition only work if utilization was restricted to very low values - again at economically prohibitive costs. Secondly, network expansions would not adequately address the observed asymmetry.
Due to this, we propose that in future distribution grids, mitigation of these problems from the utility side should approached using active voltage regulation and conditioning devices. As pointed out in [5], a plethora of power quality mitigation devices ranging from ultrafast energy storage based devices (super-caps, flywheels,…) three-phase-steppable low voltage

transformers exists.
However in order to fix all voltage issues shown in the upper panel of Figure 1, symmetric three-phase devices such as step-up transformers are not enough.
We therefore propose the more flexible solution that is schematically shown in Figure 2. The idea behind this device - called "low voltage regulation system" (LVRSys) - is that at high levels of DG penetration in a distribution grid, there is a large variety of influences, with a large spatial distribution on one hand and possible phase asymmetries similar to Figure 1 on the other hand. Thus, a truly adequate active voltage conditioning device should be flexible with respect to the deployment location in the grid as well as provide independent power quality conditioning for all three phases. LVRSys meets these requirements by being an active device than can also operate independently of existing low voltage transformers, at many locations deep inside the grid, close to critical DG installations if necessary. As seen in the schematic of Figure 2, the device is able to regulate power quality problems actively by means of one independent thyristor controller per voltage phase. The result can be seen in the lower panel of Figure one: LVRSys voltage control restricts static voltage variation to an absolute minimum and at the same time removes voltage asymmetry, a feat not possible with symmetric three-phase devices.

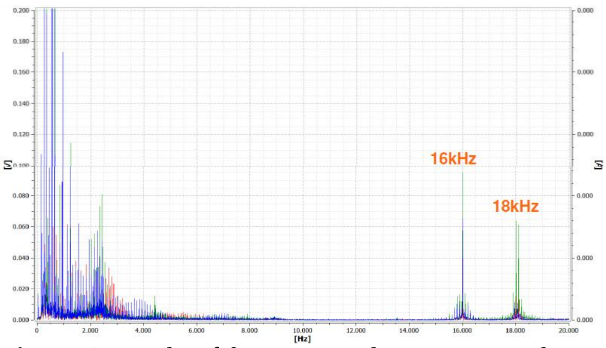

Figure 3 Levels of harmonic voltages measured in a rural grid with two single-phase PV inverters.

Higher order harmonics emission

Of course even when slow voltage variations remain within permissible bounds, especially power inverters can create other types of serious disturbances on the distribution level. It is well known that harmonics in the electricity supply can disrupt the operation of a diverse range of connected loads such as electric motors or high precision industrial machinery equipment. The current range of harmonics whose emission is under normative restrictions extends to a maximum frequency of 9 kHz (governed by IEC 61000-2-2 and -2-4). Above this frequency, no binding regulations presently exist.
However, as is seen from the measurement in Figure 3, there are cases in which significant harmonics levels are also seen at much higher frequencies. This data was measured in a rural low voltage grid with a mix of large farms and multiple photovoltaic generation sites. The cause for these power quality investigations were problems with a mechanical milking machine on one of the farms. Without obvious reasons the machine "randomly" stopped to work shortly after the installation of some PV generators. The harmonics data gives two insights: (1) the lower frequency harmonics (<9 kHz) - even though clearly visible in the graph - are well in the permissible range allowed by IEC 61000. (2) There are two clear harmonics peaks at frequencies of 16 kHz and 18 kHz, both of which could be identified as the chopping frequencies of two nearby PV power inverters.

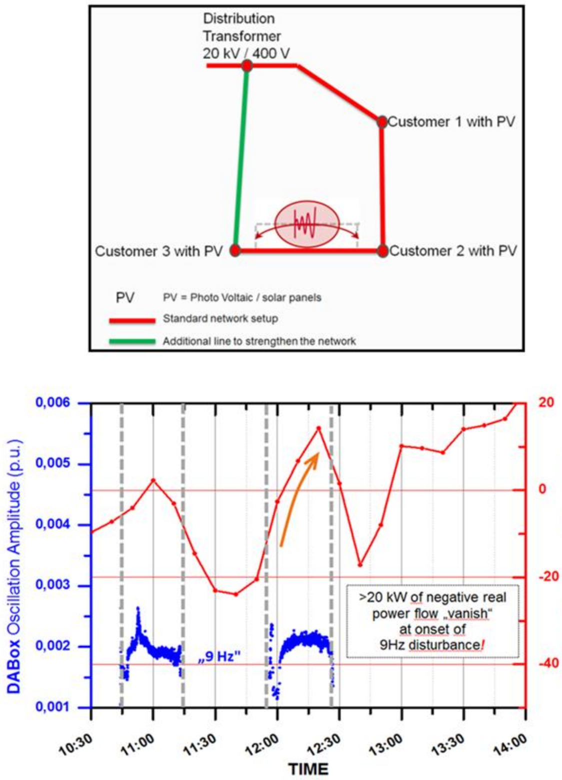

Figure 4 Sketch of a LV network setup with distributed photovoltaic power generation (upper panel). Low frequency oscillations and reactive power vs time at customer site 2 (lower panel).

Further measurements revealed that the milking machine stopped working whenever these "solar inverter" frequencies were present in the grid.
It is obvious to conclude that an easy way for inverter manufacturers to comply with sub-9kHz harmonics regulations is to simply move inverter frequencies well into the presently unregulated higher order harmonic range. However the downside of this are previously unknown electromagnetic interference problems with sensitive equipment such as the milking machine.
This problem is generic enough so that upcoming technologies such as inverter-based battery loading

devices for electric vehicles should be expected to lead to similar effects, over wide-spread areas in the grid. Again this is especially problematic in high impedance branches where harmonic currents cause the highest harmonic voltage levels. Hence in the future it is clearly necessary to extend the normative range of power quality standards considerably above the currently used 9 kHz. An effective way to mitigate such harmonics problems is to introduce active filters at the location of the disturbed network element or at the location of harmful harmonic emission. Another possibility would be an active voltage condition system such as LVRSys, however with fast-acting power inverter logic that is capable to do harmonic compensation.

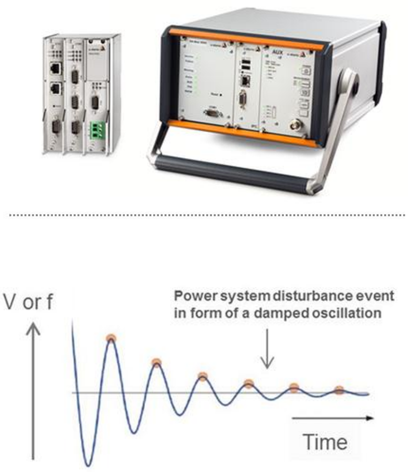

Figure 5 Mobile grid dynamics analysing system for power system oscillation monitoring (upper panel). Damped sinusoid model of dynamic power system disturbances (lower panel).

Grid dynamics and unstable PV generation

Large numbers of power inverters can however also exhibit some unexpected dynamic effects leading to new kinds of stability problems in the distribution grid as is described in the following case: A schematic of a rural 400V grid with three integrated photovoltaic generation sites is shown in the upper panel of Figure 4. In this grid there are three nodes with customer-operated PV generators.

Customers repeatedly experienced generator instabilities and multiple complaints about bad feed-in performance were submitted to the utility owning the distribution grid. The employed PV inverters regularly dropped off the grid for unknown reasons, terminating energy feed-in and causing lost financial returns. Standard power quality measurements alone were not able to clarify the problem as harmonic emission was absolutely unproblematic. Further insight into the nature of the underlying disturbance was only reached by utilizing a mobile grid dynamics analysing device (GDASys, [9]) as shown in the upper part of Figure 5. This device is able to extract low frequency oscillation modes and their damping in the grid by way of spectral Wavelet analysis. Such a low frequency oscillation mode is schematically depicted in the lower panel of Figure 5. With a mobile GDASys measurement device located at the transformer station, substantial low frequency oscillations with a frequency of 9 Hz were discovered. These 9Hz oscillations were only present during daylight hours, establishing a plausible causal link to photovoltaics.

Of course the mere existence of low frequency oscillations during the day does not prove that these disturbances are indeed responsible for the observed disruption of photovoltaics feed-in. However, a comparison of the grid dynamics measurements with power flow measurements obtained with a power quality measurement device located in the same substation established a revealing correlation.

The combined measurement results are shown in the lower panel of Figure 4. The blue data points measured with a mobile GDASys device called DA-Box 2000 indicate two instances around noon on a day where the 9 Hz disturbance is observed in strength. The red data points are real power flow measurements from a PQ-analyzer called PQ Box 100 taken at the same time, at the same substation.

A negative sign of the power flow indicates that energy flows from the PV generator into the electrical grid, i.e. that generation is undisturbed. It is interesting to see that as soon as the 9 Hz disturbance is measured, power flow reverses its sign and turns positive. In other words, during the disturbance, feed-in of energy by photovoltaics is interrupted. The low frequency disturbance seems to be responsible for this.

An attempt by the grid operator to simply strengthen the network with an additional line - depicted in green in Figure 4 - did not cause the 9 Hz disturbance to stop. In other words, a simple improvement of the short circuit impedance of the system did not help. Additional measurements however showed that an opening of the ring between customer 2 and customer 3 reliably extinguished the harmful 9 Hz oscillation. This is a strong indication that an unwanted interaction between two photovoltaic inverters over a short grid connection is behind the network disturbance. One specific candidate is a controller loop interference between the two neighboring power inverters. While in this case the mitigation was a modification of grid topology, it is conceivable that also and active voltage regulation between customer 2 and 3 could have helped to dampen out the observed low voltage oscillations and restore a stable feed-in situation.

SUMMARY

In summary, three case studies representing power quality and stability challenges for modern distribution grids with a high level of DG units were presented. According to our observations, long term overvoltages that can already be caused even by comparably moderate levels of energy feed-in into typical distribution cables and increasingly higher order harmonic injections from power inverter technologies are among the largest power quality challenges in the distribution level. Wide-spread identification of higher harmonics will require the introduction of suitable measurement devices with measurement capabilities well above the conventionally seen 9 kHz as well as the development of updated international power quality regulations. Furthermore it was pointed out that also low frequency oscillations can sometimes lead to detrimental effects such as unstable dynamic behaviour of DG units. Measuring such dynamic disturbances in distribution networks could therefore prove to be an important future tool in the analysis of feed-in problems, should the effect prove to be of high prevalence. To mitigate all of the above effects we propose the wide spread introduction of active low voltage regulation and conditioning devices, based on active thyristor or power inverter control. Such voltage conditioning devices have the potential to dynamically compensate voltage oscillations ranging from the low frequency grid dynamic / stability regime all the way to the highest harmonics defined in the power quality field.

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