MEASUREMENT OF VOLTAGE INSTABILITIES CAUSED BY INVERTERS IN WEAK GRIDS

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ABSTRACT

The research presented in this paper shows that the stability of pulse-width modulation (PWM) inverters is strongly related to the short-circuit power, and especially to the frequency dependent grid impedance (fGI) at the point of common coupling (PCC). Based on two different cases, it is shown that inverters can lead to unstable behaviour in a weak grid, independent of the nominal voltage level.

With a set of field measurements, it is shown, that the fGI is highly influenced by the number and type of connected inverters. It is discussed that commercial, power-grid simulation tools are not able to predict this kind of instability. Finally, some recommendations are made to ensure a stable operation of distribution grids with a large number of inverter-based grid elements.

INTRODUCTION

Modern PWM-inverters feed the grid with a sinusoidal current curve with a marginal distortion. This is true for most products at most points of common coupling. However, an unfortunate combination of inverter parameter settings and grid impedance can induce high levels of oscillations in the grid voltage. With this oscillation disturbance, weak grids can become unstable.

The Swinging Grids project

With the project, Swinging Grids [1] the generation and propagation of harmonic and sub-synchronous oscillations could be better understood and described, based on theoretical considerations, measurements, simulations as well as field and laboratory tests. Starting with the recognition that modern PWM-inverters and other non-linear loads generate oscillations and electromagnetic interference on the grid, recommend-dations for grid layout, component choices and the control of converters are provided. These recommendations are directed to the attention of electrical utilities and Distribution System Operators (DSOs), in order to meet the power quality requirements defined in the new grid codes. The recommendations will also be relevant to Technical Standards committees and working groups in charge of the maintenance of the national Grid Codes and international EMC standards [2].

In the framework of the project comprehensive measurement campaigns were performed at various locations in Switzerland with six DSO's and one hydro power plant, focusing on grids with a high penetration of inverter-based devices.

Power-quality measurement devices, which were distributed throughout these grids, generated a complete set of information about the voltage quality at the bus bars and current quality in the connection lines. An EMT-simulation showed in turn, how the stability of the grids can be influenced, if the inverter regulation parameters are not adapted to the frequency-dependent grid impedance (fGI). Two illustrative cases for an unfortunate interference of regulation parameters and grid impedance were observed. In the first case, issues occurred when connecting PV-systems over a static serial voltage compensator (SSCV) in a weak, rural distribution grid. The second case occurred during a black-start test in a hydro power station with a full-scale storage pump converter.

FREQUENCY-DEPENDENT GRID IMPEDANCE (FGI)

Inverters have a strong impact on the frequency-dependent grid impedance (fGI). The impact depends on the type, size and number of inverters, as well as on the local short-circuit power at the point of common coupling.

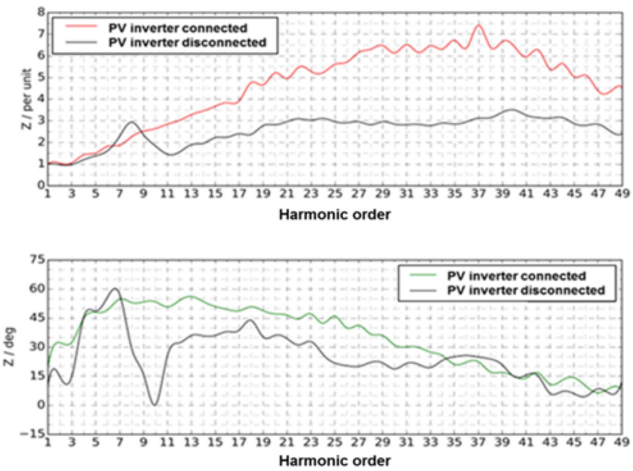

Fig. 1: Influence of three parallel inverters (S_{equ} = 56 kVA) connected to a weak grid (Z@50Hz PV-inverter off = 0.259 ohm, Z@50Hz PV-inverter on = 0.314 ohm) (Upper diagram: Amplitude in per unit, Lower diagram: phase or argument, absolute)

The technical standard EN61000-4-7 [3] proposes an fGI showing an ohmic inductive behaviour and a maximum value of approximately 5 Ω @ 900 Hz.

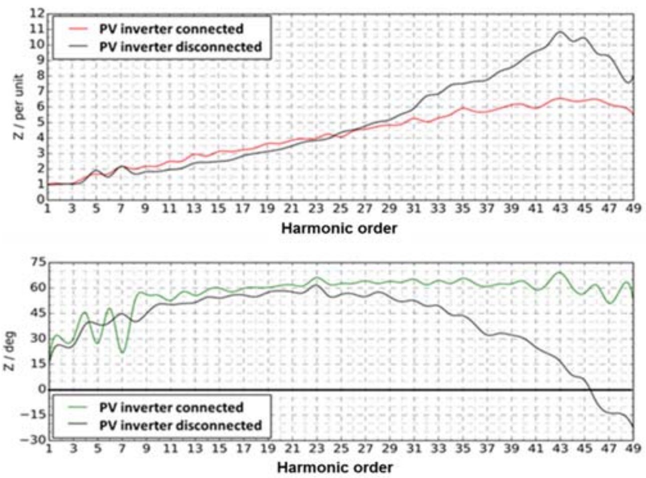

Fig. 2: Influence of 30 parallel, similar inverters (S_{equ}= 930 kVA) connected to a strong grid point (Z@50Hz PV-inverter off = 0.059 ohm, Z@50Hz PV-inverter on = 0.064 ohm) (Upper diagram: Amplitude in per unit, Lower diagram: phase or argument absolute)

In the present study [1], the measured fGI is less than half this maximum value over the total range from 50 Hz to 2.5 kHz. With certain types of inverters, the measured fGI shows an ohmic to capacitive behaviour for higher orders of harmonics. Fig. 1 and Fig. 2 show two sets of measurements at different PCC, where, in addition to customer loads, PV–systems with different inverters are connected. Fig. 1 shows clearly that the installed inverters create a resonance point at approximately the 8th harmonic (400 Hz). On the other hand, the installed inverters in Fig. 2 create a resonance point at approximately the 44th harmonic (2.2 kHz). While the phase or argument of the fGI in goes nearly to zero; in Fig. 2 the inverters create a capacitive fGI after 2.25 kHz (45th harmonic).

A capacitive behaviour can have a negative influence on communication signals in the same frequency range. Especially for signals with a higher frequency, a capacity acts like a sink. In this case, current harmonics in the range of the resonance point will largely pass through the electrical elements of the inverter resulting in additional strain. If a controlled signal (e.g. a ripple-control signal) is sent with a frequency in the range of the resonance, it could be disturbed and the signals may not be detected by the receiver. It is highly recommended to check if the installed inverters, in combination with the local distribution grid, create a resonance point near the ripple-control frequency. If the resonance reduces the signal amplitude critically, modifications will be required.

Fig. 3 shows an analyse of measurements of the fGI at PCC where inverters of different manufacturers had been connected. The conclusion is obvious, that the design of the inverter based on intra-company specifications has a bigger influence on the fGI at the PCC.

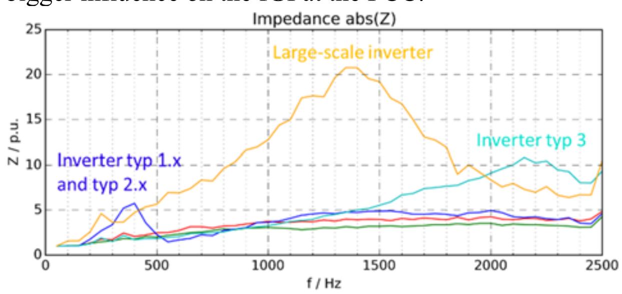

Fig. 3: Grid impedance measurements in inverter dominated girds at different PCC.

3-PHASE PV-INVERTERS IN WEAK DISTRIBUTION GRIDS

In a rural, low-voltage grid, where a feeder line of PV-installations is connected by through a static, serial voltage compensator (SSVC) to the remaining low voltage grid, some devices self-disconnected as soon as the SSVC was activated. The resulting changes in the grid topology influence the fGI at the PCC.

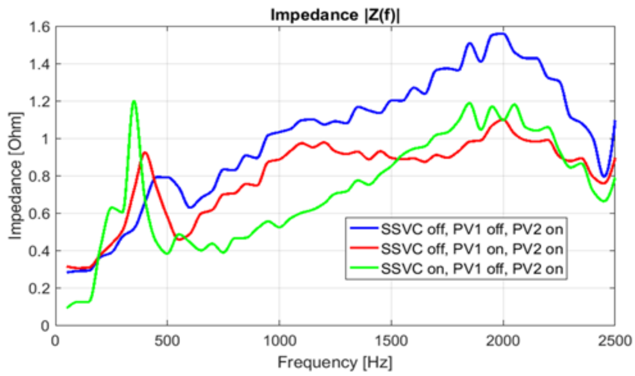

Fig. 4: Change of the frequency dependent grid impedance related to the amount of connected PV systems and the upstream (SSVC).

Fig. 4 shows the measured fGI for three different states with various combinations of components activated. The resonance in the fGI given by the PV inverters at approximately 400 Hz (blue and red lines) is much higher in amplitude and shifted to 350Hz (green line) when the SSVC is connected upstream of the PV systems.

Fig. 5 shows the instantaneous values of the voltage and current on the PV-side of SSVC. It can clearly be seen that the converters produce harmonic currents, depending on the fGI at the corresponding PCC.

If this type of coupling is strong enough, the distortion of the system can reach such a level that the inverters switch off. Due to the weak grid, with a low short-circuit capacity at the PCC of the PV-inverters, a higher level of current harmonics than expected was measured even when the SSVC was bypassed. The converter current (i_o) has a feedback on the voltage at the PCC, which is strongly related to the fGI (Fig. 6). A change in the grid impedance (Z_g), like the green line in Fig. 4, can intensify the feedback of the grid, thus influencing the current curve form through the current controller. This voltage feedforward (Fig. 6, blue line) can induce a current distortion which can end in unstable inverter behaviour, like in Fig. 5. In this case, if the SSVC tries to actively control the voltage level. The change of the fGI causes the PV-inverters to fall into an unstable operation mode.

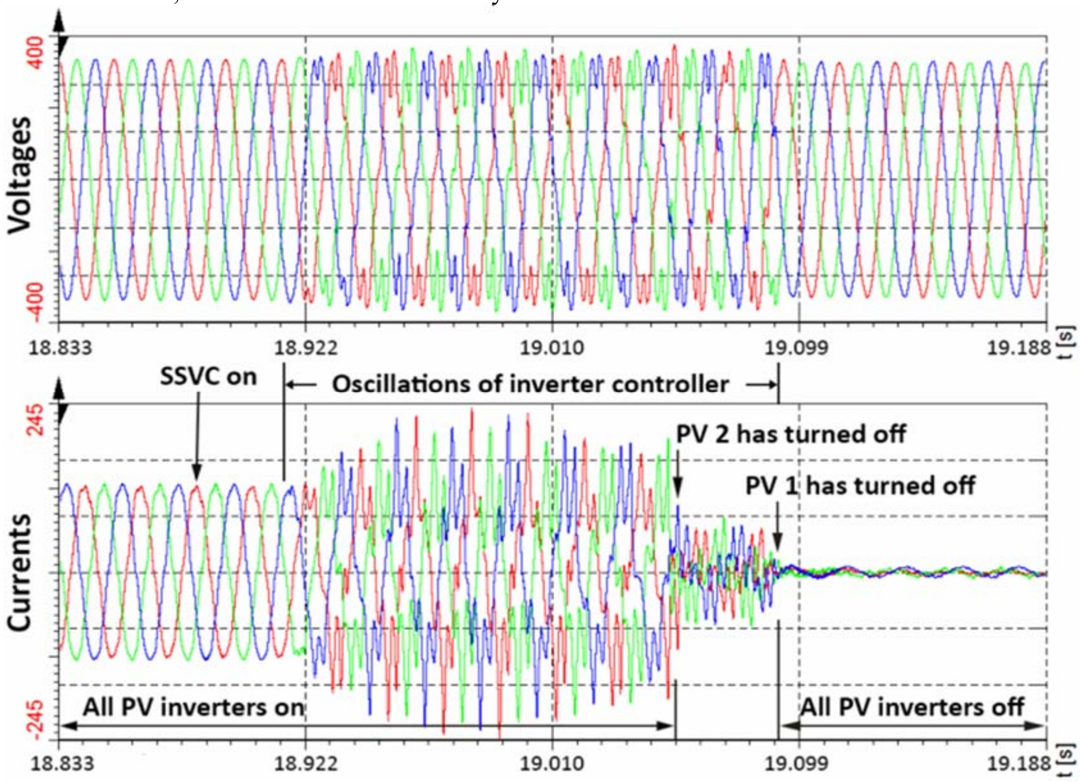

Fig. 5: Voltage and current on the output of the SSVC when the SSVC is connected

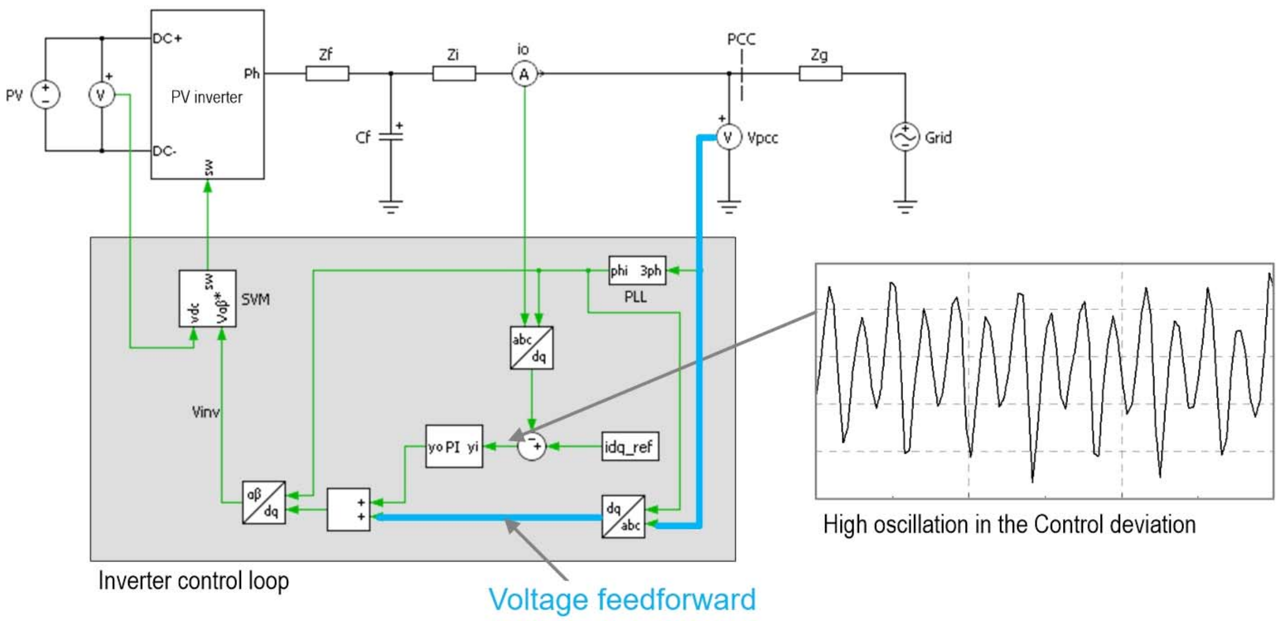

Fig. 6: PV inverter control loop with the voltage feedforward

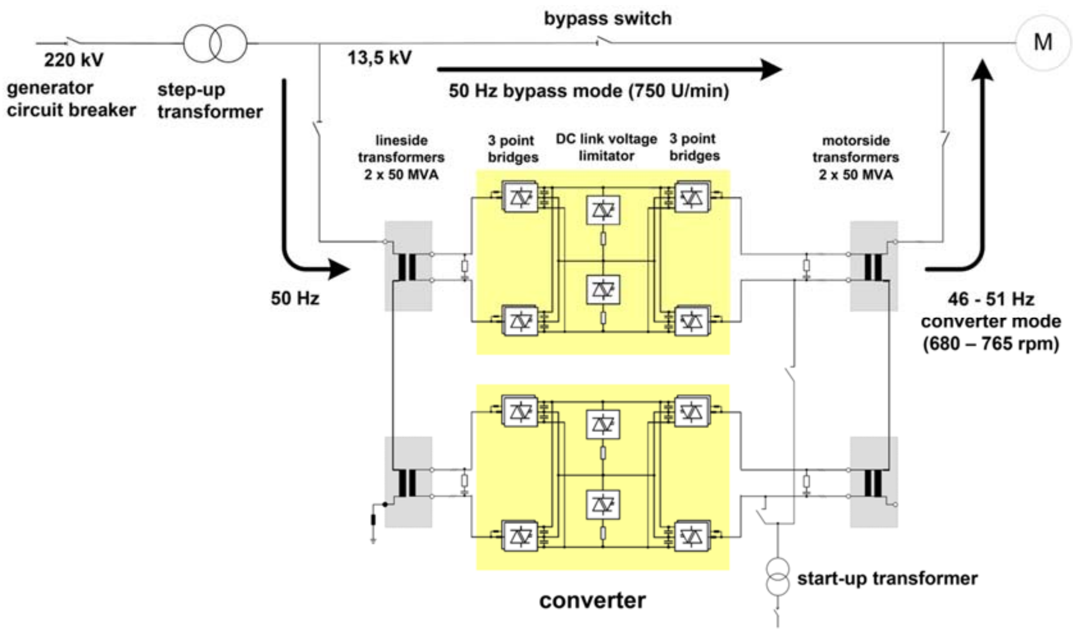

Fig. 7: Single line diagram of the converter Grimsel 2 [4]

FULL-SCALE STORAGE PUMP CONVERTER IN ISLANDING OPERATION

A second case was investigated during black-start and islanding operation tests in one of the largest Swiss hydro power stations. The nine hydro power plants of the Kraftwerke Oberhasli (KWO) have a total generating capacity of about 1.4 GW at a nominal voltage level of up to 220 kV. The pumped storage plant Grimsel 2 consists of four units with a pumping capacity of 90 MW each. One unit can be operated with a 100 MVA full-scale PWM converter so that pump speed and the power consumption can be controlled (Fig. 7). The islanding test series in November 2015 showed that the island grid of KWO becomes unstable, if the converter is operated near nominal power. With only a few synchronous machines, a low short-circuit capacity of approximately 1 GVA could be provided.

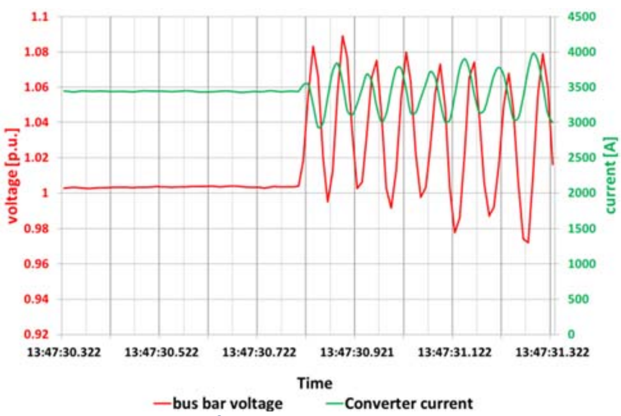

Fig. 8: RMS values of grid voltage and converter current while switching in islanding operation

Fig. 8 shows the behaviour of the system represented by the measured voltage at the PCC of the converter Grimsel 2 and its current as the connection to the Swiss transmission grid is made. The changeover from grid-connected to islanding operation leads to an extreme change of the fGI.

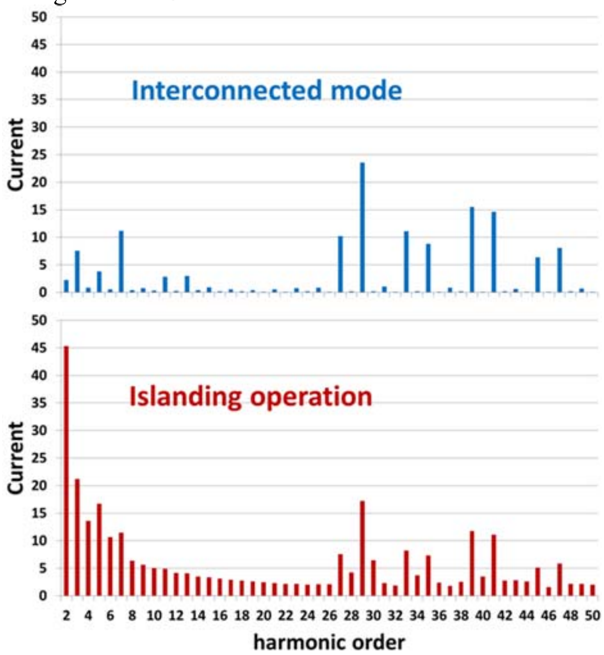

Fig. 9: Harmonics of the converter current in interconnected and islanding operation

Immediately after the switch-over, a system oscillation appears. The whole islanding grid began to oscillate with a frequency of 12 Hz. The bus bar voltage and converter current were swinging around their stationary operating points. The active power consumption oscillated with a

variation of 20% to 30% around 80 MW, the reactive power around zero. The unstable state lasted around 1 1/2 minutes. Due to a disconnection of sensitive auxiliary components, which had been fed by the unstable grid, the island operation collapsed.
The harmonic analysis of converter currents (Fig. 9) during the test phase shows that, in islanding operation, the harmonic distortion rises and especially currents with a lower order appear supplementary.

OPTIMISATION OF THE CONVERTER PARAMETER

The converter control, as used for the full-scale storage pump converter in Grimsel 2, is tested and optimised on a hardware in the Loop (HIL) simulator. The HIL simulator emulates the power part of the converter with the entire environment (grid, transformer, filter, etc.) as close to reality as possible. The Model is verified during commissioning.
Based on calculations and experience the various controllers (current, power, speed, DC-Link voltage, parallel balancing, etc.) are initially parametrised and afterwards optimised during the HIL tests.
Optimisation is done considering two aspects. Firstly, the converter shall accurately follow its set points and shall show smooth transitions when changing from one operation mode to another. Secondly, the converter shall be able to handle pre-defined transients such as voltage dips, harmonics, grid frequency changes, load steps and others, without operational interruption and with as little influence to the machine on the inverter side as possible.
The optimization process depends on the entire controlled system. By changing one of the involved parts significantly, for example grid impedance or short circuit power, the system needs to be optimized again, considering old and new requirements, to avoid stability issues.

DYNAMIC MODELLING AND SIMULATION

Although the grids described above are completely different in terms of their purpose and challenges that they face; the reason for the problems observed were the same: a very high power of inverter-based connection related to the grid impedance. Commercial, grid-simulation tools provide a means for the dynamic simulation of power grids. Usually, appropriate dynamic models of grid elements are already implemented. The level of detail is normally oriented to simulate transient system performance. For the analysis of the voltage and frequency behaviour, standard regulators for generating units can be added to the grid elements. For the simulation of the described instabilities, the given dynamic models of elements such as inverters in commercial grid-simulation tools are normally not detailed enough. As a result, it is not yet possible to simulate oscillation effects, based on the interaction between inverters and the grid impedance. Adequate modelling is possible, based on simulation tools designed for electric circuits, offering detailed elements of the internal converter components such as transistors. The disadvantage is that these tools do not provide options to model the complexity of power grids with a reasonable effort.

SUMMARY

Two important conclusions can be derived from this work. The parameters of the control circuit for the current curve form should be optimized using the real frequency-dependent grid impedance at the foreseen connection points. Inverters should be tested and qualified not only by using a proper voltage source but also with a disturbed voltage. For this, the limits for EN50160 might be a good approach for a voltage distortion in the test lab.
Future grids will combine more and more inverter-based generation and loads and, due to cost pressures, without increasing their capacity. While the short-circuit capacity and its 50 Hz impedance will not change, its run over frequency will get more complex and the prediction of the grid feedback from the connected devices will be challenging. The integration of this aspect in the planning phase will be one of the challenges for grid companies in the coming years.
Summarising the measurements of the Swinging Grids project, the project team recommends to treat with caution every inverter system with an S_{sc}/S_{equ}-ratio < 50 and that supplies < 300 kVA short-circuit power per inverter. Such inverter systems should only be connected to the grid with an additional ex post analysis by monitoring of the current and voltage harmonics. Alternatively, if possible, a smaller number of inverters with a higher power should be installed.

ACKNOWLRDGMENTS

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