Inverter performance problems in PV power plants

Power oscillation | In the last few years the power rating of PV power plants has risen very quickly to values reaching several hundred megawatts. This means there are hundreds, or even thousands, of inverters operating in parallel in these plants. Furthermore, these large-scale PV power plants are often built far away from cities and are therefore connected to the grid via long transmission lines. This leads to weak grid conditions in the power plants, and these conditions give rise to the risk of electrical instabilities within the plant, or instabilities of the plant within the grid. Roland Singer of Fraunhofer ISE explains how these electrical instabilities can be detected and counteracted

There are many aspects to consider regarding the performance of inverters in PV power plants. Inverters should be highly efficient at converting PV energy from DC to AC. They have to follow the maximum power point (MPP) of the PV generator very precisely, under various conditions, and all requirements of the local grid codes have to be met during the operation. All these functions must be delivered in a very reliable way over many years of operation, with as little maintenance as possible; often they have to be fulfilled under very harsh environmental conditions, for example very high temperatures and dusty air in desert regions. The requirements for an inverter mainly focus on maximising the power output over its lifetime, thereby minimising the costs and maximising the economic return.

In view of all these factors, inverter manufacturers optimise their products during the development phase and perform tests to establish inverter performance. Often these tests are performed by third-party organisations to convince the customers of the quality of their product through independent test results. All these tests are done with single inverters, and during the design of the inverters the manufacturers focus on the optimisation of a single inverter too.

Undesirable oscillations of the currents and voltages are referred to as *instabilities* in power plants. Often these oscillations are not recognised during the commissioning and the normal operation of the plant; this is because they cannot be measured by typical monitoring systems, as will be explained later in this paper. The instabilities often result in malfunction of the inverters and poor yield from the power plant, or even lead to failure of the inverters or other components of the plant.

During the building of a PV power plant the typical approach can be described as 'build and forget'. After the commissioning of the power plant, apart from some minor maintenance work, the plant should 'run itself'. Instabilities are therefore not recognized until serious problems arise, such as a high failure rate of the inverters or significant deviations in yield compared with expectations. Even after serious problems have been detected, oscillations are usually not recognised directly, because often the failures could also have been caused by other, more common, problems. In general, the instabilities therefore remain undetected for a long time during the troubleshooting.

This paper is based on the article by Dötter, G. et al. [1].

Electrical instabilities

The majority of transmission systems in the world are operated at a rated frequency of 50Hz or 60Hz; however, other frequencies are always present in the voltages and are mainly parasitic and mostly limited by the local grid code. To characterise voltages and currents with different frequencies present, the spectral representation in the frequency domain is used. Each single frequency present in a signal is expressed by a frequency, amplitude and phase angle; the superimposing of frequencies using this method is exploited and illustrated in this paper. When oscillations appear, they are described as *electrical instabilities*; their amplitudes are higher than stability thresholds and therefore endanger the normal operation of the PV power plant or neighbouring systems. The frequencies of these oscillations can be above or below the rated frequency of the system.

For an oscillation to occur in an electrical system, the presence of a resonance point is necessary. The resonance of a system is defined by the energy-storing elements in the system. These elements are inductive and capacitive in nature, and in a PV power plant many such elements are present – they are partly parasitic and therefore their values are not precisely known. Depending on their values, arrangement and number, there may be one or several resonances present in the system.

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In the control algorithms of PV inverters, additional 'virtual' energy storage devices are also present; these are integral to typically used PI (proportional and integral) controllers. The calculation of the system resonances must therefore not only take into account the typical electrical components (such as cables, transformers, filter chokes and capacitances), but also consider the control algorithms of the inverters.

Moreover, whether or not the system will oscillate at the resonance frequency depends also on the excitation and the damping: in electrical systems the ohmic parts or loads attenuate the oscillations, and control algorithms can have a damping, neutral or even exciting action. Oscillations can also be triggered by load steps, switching operations in the grid, nonlinear loads or other events. If the frequency is not damped properly such events can cause long-lasting oscillations.

Typical frequency spectra of grid voltages or inverter currents

In the first step the frequency range can be separated into two parts: 1) the range below the rated frequency (e.g. 50Hz) – frequencies in this range are called *subharmonic oscillations*; 2) the range above the rated frequency – this is the *harmonics* range.

A qualitative example of a typical frequency spectrum of the output currents of a central inverter is shown in Fig. 1. The indistinctness in the colours of the spectral lines represents the typical range of the specified oscillation frequencies. In the following discussion the sources and behaviour of the different frequency components are explained, and possible problems are highlighted.

Switching frequency

Central inverters on the market currently use switching frequencies in the range 2kHz to 5kHz. The power electronic switches of an inverter are controlled with this frequency, so this frequency and its multiples are always present in the spectrum of the output current. When multiple inverters of the same type (same switching frequency) are operated in parallel, these frequencies often superimpose in a destructive manner as a result of the changing phase angle between the inverters [2].

The changing phase angle is caused by small differences in the switching frequencies between the inverters, for example because of tolerances in the frequency sources inside the inverters. This gives rise to a slowly changing amplitude of the switching frequency in the overall current of the power plant. The main problem caused by the switching frequency is the violation of emission thresholds. However, there have been no reports of problems in PV power plants as a result of this 'beating' of the switching frequency, or any reports of instability problems due to frequencies above the switching frequency.

System resonance

The system resonance is typically within the range of the harmonics; during the design of an inverter the value is usually set in the range of one-half to two-thirds of the switching frequency for systems with single inverters under normal operation conditions. In PV power plants, because of multiple inverters operating in parallel and weak grid conditions, the system resonance is lower [3], taking a value of around 1kHz. The system resonance is formed from all elements in the electrical system of the PV plant, including the grid impedance, the transformers and cables in the plant, the filter elements in the inverter, and the behaviour of the inverter's control system.

The system resonance can occur at any arbitrary frequency; the frequency of oscillation that can be measured thus often occurs at a harmonic frequency. Harmonics are multiples of the rated grid frequency, and these frequencies then act as the excitation of the oscillation. Harmonics are often present in the grid voltage and are introduced by, for example, nonlinear loads.

If the system resonance lies in a frequency range within which the phase margin of the control system is very low, then the control of the inverter can excite the oscillation too. Oscillations at the system resonance cause increased losses in the inductive components of the power plant (chokes, transformers), which in turn lead to a decrease in conversion efficiency. These increased losses can also result in higher temperatures of these elements and therefore accelerated ageing. The ageing of capacitive elements can also be accelerated by higher currents. In extreme cases, even inverter failures can be caused by the oscillations, because of over-voltages or over-currents. Another problem can be excessive harmonic emissions of the power plant and hence problems with the grid operators.

Subsynchronous resonance

The reasons for this phenomenon in inverters have not been investigated to the same extent as the above-described harmonic effects. Some inverter manufacturers have reported that changes in control parameters could result in damping of subsynchronous oscillations in PV power plants. These oscillations cause the output power of the inverter to vary over a wide range, so the MPP tracker may no longer operate, causing a reduction in the harvested energy of the power plant. Another problem can be violation of flicker limits in the grid.

Measurements of instabilities in PV power plants

Oscillations in large PV power plants have been measured by Fraunhofer ISE on several occasions. There have also been several reports by inverter manufacturers and park operators of oscillations in large power plants. These measurements and reports again show that such oscillation problems can be distinguished by oscillations in the frequency ranges above (harmonic) and below (subsynchronous) the grid frequency.

Harmonic oscillations

For the measurement of the oscillations, illustrated in Fig. 2, the grid impedance for the power plant was artificially increased by adding a grid choke of a low-voltage ride-through (LVRT) test container. The oscillation in the voltages and currents can be seen in the figure. The frequency of this oscillation is 850Hz, which is the 17th harmonic component. This was also present in the voltage outside the PV power plant but had a much smaller amplitude; however, because the system resonance was only a few hertz below this harmonic component, the oscillation was excited at 850Hz.

Subsynchronous oscillations

The measurements seen in Fig. 3 were taken in a PV power plant with more than 100 central inverters operating in parallel; a high-precision measurement system which was distributed in the power plant was used. The sampling of the measurement system was synchronised via a GPS signal. In Fig. 3 the AC voltages and currents of an inverter with a subsynchronous oscillation of 25Hz can be seen. Fig. 4 shows the

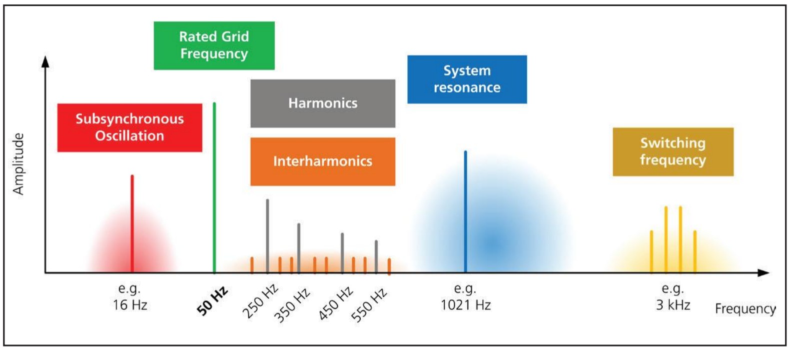

Figure 1. Classification of oscillation frequencies.

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simultaneously measured DC voltages of 10 inverters at a plant consisting of more than 100 inverters. It can be seen that all inverters are oscillating at the same frequency, and that they are also no longer operating at the MPP.

Summary of all measured and reported oscillations in PV power plants

To illustrate that this problem is not associated with just a few low-quality manufacturers, all the problems known by the author with oscillations in PV power plants are illustrated diagrammatically in Fig. 5; the colour scheme is similar to that used in Fig. 1. Two accumulations of oscillation phenomena are observed: at system resonance and in the subsynchronous range. In this diagram a distinction is made between reliable external sources, external sources without detailed reports, and measurements taken by Fraunhofer ISE. It can be seen that problems with electrical instability are not focused on a specific power range of the plant or on a specific manufacturer; with the rising number of power electronic generators, instability is a widespread phenomenon.

Accounts of electrical instability in other technologically related areas have also increased in recent years. For example, oscillation has been known to occur in railway technology, where more and more generators and loads are being replaced by power electronics. Moreover, oscillations were reported during the commissioning of the offshore wind farm BARD Offshore 1 in Germany [4,5].

Detection and counteraction of instabilities in PV power plants

Monitoring systems are typically installed in PV power plants to monitor the correct functioning of all components in the plant and sound the alarm if a fault occurs. In order to reduce the amount of data, averaging intervals of more than one minute are typically used for these measurements. The oscillations described above, however, cannot be detected in these average measurement values, because of the filtering effect of the averaging process. Although any differences in performance might be observed from a comparison of these values with the results from other PV plants, the detection of oscillation is not possible.

If the oscillation leads to a temporary stoppage of an inverter, the monitoring system will signal the alarm; however, inverter error messages do not usually

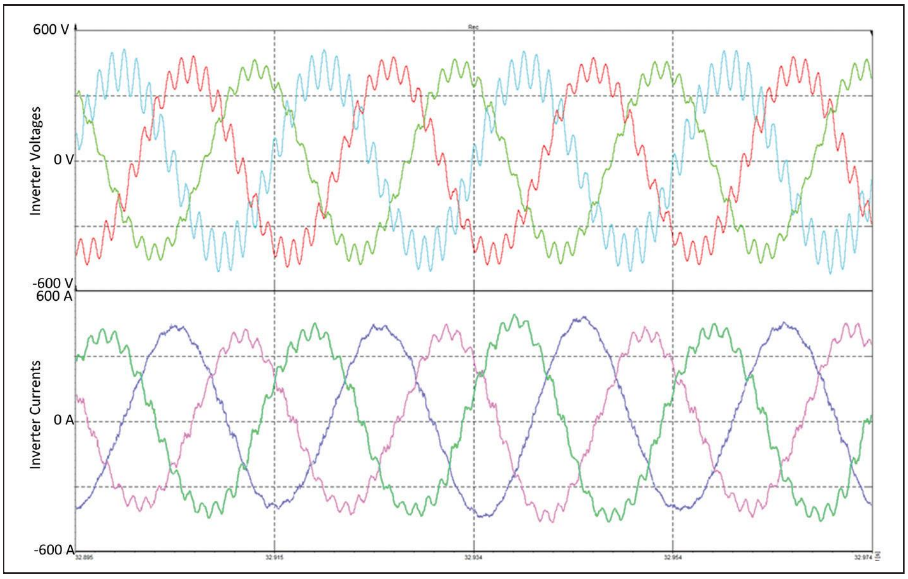

Figure 2. Harmonic oscillation at a frequency of 850Hz: instantaneous values of the inverter voltages (top) and currents (bottom).

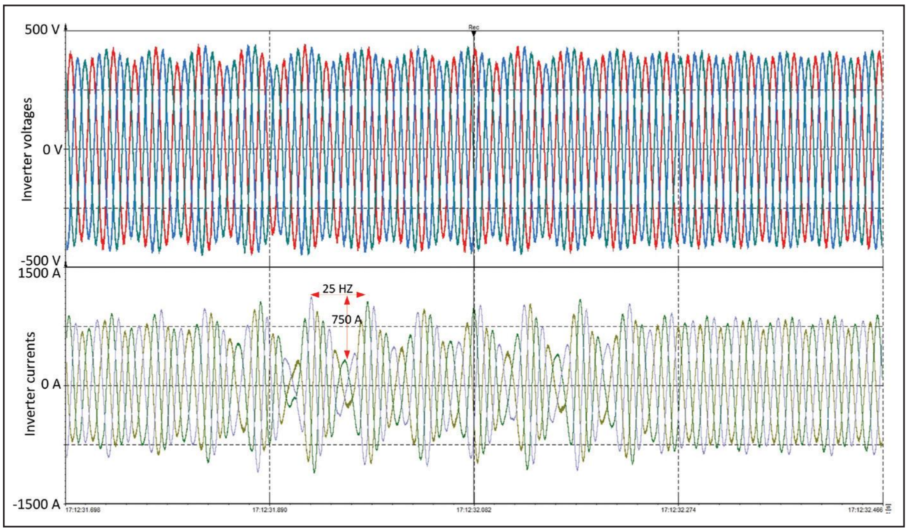

Figure 3. Subsynchronous oscillation at a frequency of 25Hz in a PV power plant with more than 100 parallel central inverters: inverter voltages (top) and currents (bottom).

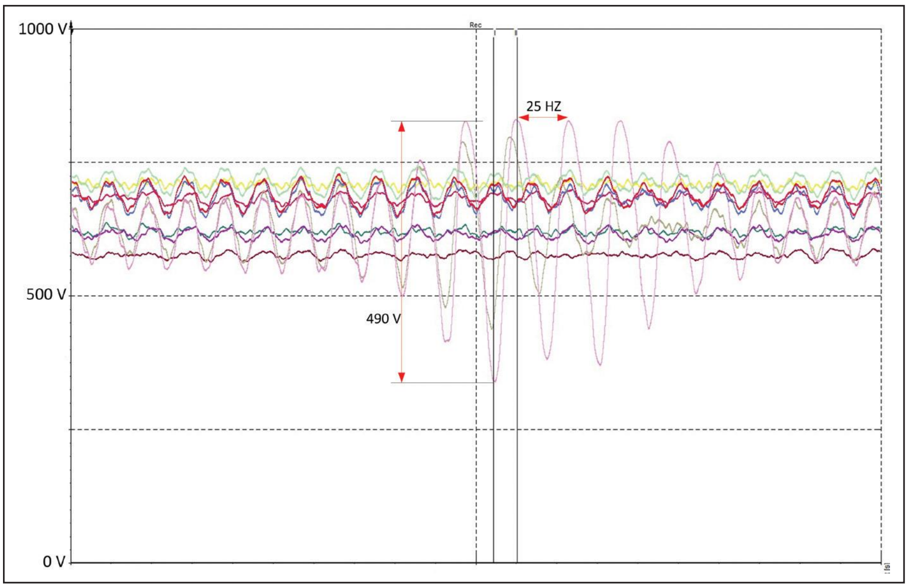

Figure 4. DC voltages of 10 inverters in a power plant with more than 100 central inverters, with the presence of a subsynchronous oscillation of 25Hz.

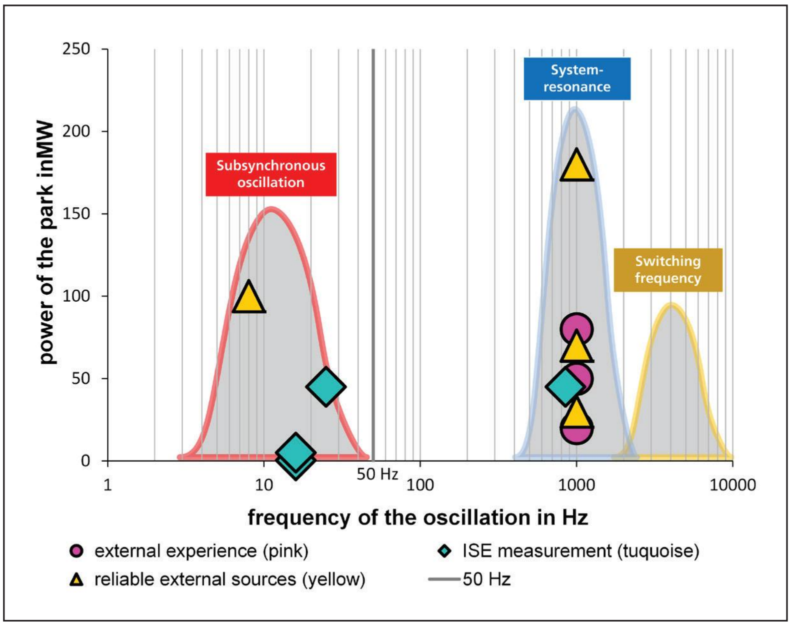

Figure 5. Overview of electrical instabilities in PV power plants.

indicate that the cause of the problem was oscillation. Generally, the disconnections of inverters cannot therefore be linked to oscillations in the plant.

One possible way of detecting instabilities is to install a power-quality measurement system at the plant; this system will recognise increased harmonic content in the grid voltage if an oscillation occurs at a high frequency, such as the system resonance. In the case of oscillations in the subsynchronous range, the flicker values will be increased. The flicker measurement evaluates voltage variations in the low frequency range between 0.05Hz and 35Hz (for 50Hz systems), with a weighting filter that has its maximum sensitivity at 8.8Hz [6].

If oscillations are detected in a PV power plant, several methods for damping are possible. For example, the oscillation can often be damped by changing the control parameters or the control algorithm of the inverters. This method, however, frequently presents problems regarding the certification of the inverters in compliance with the local grid code, because of the fact that as a rule the certification is only valid for one set of control parameters. Moreover, this method is also sometimes restricted as a result of the lack of processing power of the processor used in the inverter. In addition, restrictions of the hardware can limit the effectiveness of changing the control parameters or algorithm; for example, the sinusoidal filter or the switching frequency can limit the effect on the oscillation in the PV power plant. Nevertheless, an advantage of this method is that no additional components have to be installed at the PV plant, which saves time and money.

If it is not possible to damp the oscillation by changing the control parameters or algorithm of the inverter, additional passive filter elements can be installed at the power plant [7]. After instabilities are detected, these filters are specially designed for this specific oscillation problem. Another possibility is the use of active damping elements, which can be adjusted in a fast and flexible manner for all kinds of oscillation. The disadvantage of both of these methods, however, is the need for additional components, which add to the cost and require time to set up.

An expansion of the grid could also be a possible solution to the problem: the system resonance would increase to higher values and, therefore, typically uncritical ones. This solution is very costly, though, and needs a long time to put into action.

All the solutions described above are methods for combating instability after it has already occurred in the PV power plant. In the future, the goal should be to establish policies during the actual planning of the PV power plant to prevent these problems from happening in the first place. For large power plants in particular, during the planning one should anticipate these issues and consider possible actions to address them. There are, for example, ways of determining the system resonance of a planned power plant [8], which can give an idea of whether or not there is an increased risk of instability. However, detailed information about the structure of the power plant, and especially of the control system of the inverters, is necessary, which cannot always be provided by the manufacturers because of know-how protection.

Summary

In this paper, some problems with often-undetected instability problems in PV power plants have been described. The different oscillation phenomena observed in PV power plants have been classified and their possible effects on the performance of the plant discussed; moreover, possible reasons for the oscillations have been given.

Measurements of oscillation phenomena in real PV power plants have been presented. An overview of oscillation problems in PV power plants (depicted in Fig. 5) indicates that it is a widespread problem in power-electronic-dominated grids. The reasons why oscillations are often undetected are explained, as well as how it might be possible to increase the likelihood of detecting these oscillations more quickly. Possible countermeasures which can solve oscillation problems in existing PV power plants have been proposed.

To save time and money in implementing countermeasures in commissioned power plants, however, in the future the potential for electrical instability problems should be taken into account during the planning and construction phases of a power plant. ■

Author

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