DISTRIBUTED ENERGY RESOURCES AND WAVEFORM DISTORTION

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ABSTRACT

This paper addresses the waveform distortion due to increasing penetration of distributed energy resources (DER). Low-frequency distortion, up to 1 kHz is not a major concern. The capacitance at the interface of many DER units may cause harmonic resonances or shift resonances to lower frequencies, but resonances below 1kHz are unlikely. High-frequency distortion, above a few kHz, may become a concern for inverter-based DER and requires further attention.

INTRODUCTION

Increasing levels of distributed generation (DG) and other forms of distributed energy resources (DER) will lead to a change in load composition for distribution networks, where the load becomes a combination of "consuming load" and "generating load". This change will place new and different requirements on the design and operation of the distribution system, which may lead to a deterioration of the performance of the network. This paper addresses the change in current waveform distortion and its impact on the voltage waveform distortion. The work is part of the European project EU-DEEP (www.eu-deep.com) in which quantification and removal of barriers against a widespread DER penetration is an important task.

Distributed energy resources (DER) have both positive and negative impacts on the operation of distribution networks. A large number of papers have been dedicated to this, with main emphasis on the voltage rise due to the injection of active power in the distribution grid. This paper addresses three aspects of waveform distortion in association with DER: low-frequency emission; resonances; and high-frequency emission [1][2].

LOW-FREQUENCY DISTORTION

As an example for low-frequency distortion, one 5MWp photovoltaic power plant has been chosen. The plant is located close to Leipzig in Germany. Big photovoltaic power plants need special permission to be connected to the distribution grid, and utility companies usually perform a lot of calculations (existing distortion and estimated additional distortion) before they sign a contract with these customers.

In this installation, twelve PV-inverters SINVERT solar 400 in Master-Slave-Slave combination feed the produced electricity to the medium voltage grid via two medium voltage transformers, which are connected to the utility company's MV substation. The inverters are equipped with an active harmonic filter, reactive power control, voltage rise control (automatically limiting output power according to the voltage of the medium voltage grid), and automatic disconnection of the medium voltage transformers during the night.

Over a period of four weeks, the total-harmonic distortion (THD) on the low voltage side of one of the inverters was between 0.5% and 0.8% when the inverters were in operation, and between 0.8% and 1.7% when the inverters were not in operation. Three sample days show the effects on voltage harmonics under different operating conditions. Day A was a sunny day, where the measured inverter started operation as Master (Figure 1). Day B was an unsettled day, where the measured inverter started operation as Master (Figure 2). Day C was a first sunny then unsettled day, where the measured inverter started operation as one of the Slaves (Figure 3).

The inverters start operation around 05:00, as soon as there is sunlight. And in the same moment, there is a drop in THD. The drop in power at 08:00 on day A is caused by other inverters taking over part of the load. Every time the power drops (due to weather conditions, especially on day C), the THD rises, as with lower power fed to the grid, the capability for compensation of the harmonics is reduced. These changes in power can be highly dynamical, over 50% in less than 5 minutes (at 12:40 on day C), depending on the speed of the clouds passing the large PV field. You can see the THD rising at 20:00, when the inverters stop operation, but additionally people turn on their TVs that cause additional harmonic distortion. Then, around 22:00, people go to bed. The "television peak" in harmonic distortion is visible on all three days.

A general conclusion from these measurements is that the voltage distortion due to domestic equipment (like televisions) is more than the distortion due to the photovoltaic plant.

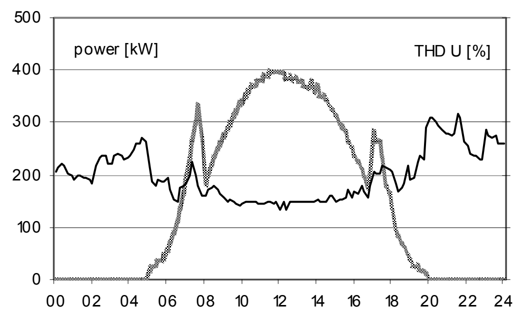

Figure 1 - voltage harmonics, day A

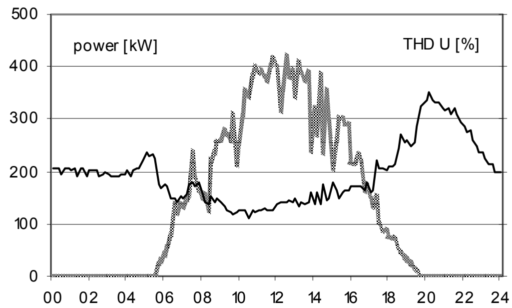

Figure 2 - voltage harmonics, day B

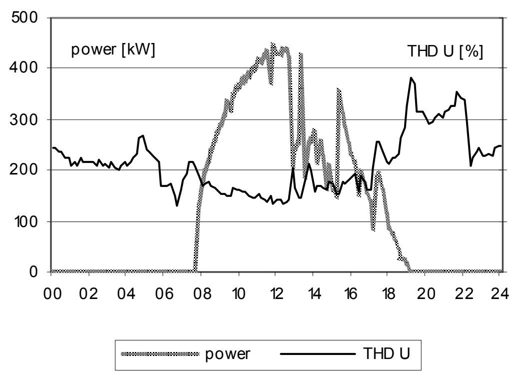

Figure 3 - voltage harmonics, day C

Effects of DER units especially for large inverter-connected PV plants are analysed with help of measurements. Depending on the capabilities of the power conditioning equipment installed, there can be positive or negative effects on power quality of the distribution grid. If the inverters are designed appropriately, staying within the limits of the given standards is not a problem for large scale PV power plants using central inverters, neither on the medium voltage side (which is easier due to the impedance of the medium voltage transformer) nor on the low voltage side (which usually is within the plant operators premises and not subjected to utility companies regulations).

Therefore, concerning low frequency harmonics there is no limit for the size of distributed energy resources - when use the appropriate equipment.

HARMONIC RESONANCE

Parallel resonance occurs between the network capacitance (including also the capacitance of the cable and the inverter) and the leakage inductance of the power transformer (generally: the supply inductance). The high impedance results in high voltage distortion at the PCC (or where the inverter is connected to) due to the harmonic currents injected from the inverter. The resonance is initiated by the inverter current harmonics. These high-resonance voltages are damped only by the resistances of the connected network and load. The high harmonic level can cause operational problems both for the inverter and the equipment connected to the PCC. When the power network is weak.

Series resonance occurs between the supply inductance and the network capacitance. At series resonance the impedance is low resulting in high current distortion through the PCC due to the voltage distortion, i.e. the generating reason is the presence of voltage harmonics close to the resonance frequency.

However, for VSC based FACTS controllers the series resonance may occur also between the power transformer, the VSC transformer and a relatively long cable laid between these transformers [5]. In this case the resonance circuit is composed of the parallel connected leakage inductance of the power transformer's tertiary winding and the leakage inductance of the VSC transformer, as well as the capacitance of the cable. The leakage inductance of the VSC transformer is much higher than that of the power transformer. Therefore, not only serial but also parallel high order resonance can occur in this circuit in a very narrow frequency band. By changing the length of the cable, the resonance frequency can be moved to a frequency band with small generated harmonics. Another mitigation method can be the installation of a harmonic filter on the primary side of the converter transformer.

Consider a situation where an MV/LV transformer supplies an LV bus to which a certain amount of DER is connected. The rating of the transformer is S_k and the short-circuit voltage ratio is ε. The amount of DER connected to the LV bus is P_{DER} with capacitance C_1 per unit power.
The transformer inductance is equal to:

$$L_{tr} = \varepsilon \frac{U_{nom}^{\;2}}{\omega S_k} \tag{1}$$

The capacitance connected to the LV bus is equal to:

$$C_{LV} = P_{DER} C_1 \quad (2)$$

This results in the following expression for the resonance frequency (for simplicity by neglecting the already existing LV capacitance, as well as the capacitance of the lines/cables to DER):

$$f_{res} = \frac{1}{2\pi\sqrt{L_{tr} C_{LV}}} = \frac{1}{2\pi U_{nom}\sqrt{\frac{\varepsilon C_1}{\omega}\Pi_{DER}}} \quad (3)$$

with $\Pi_{DER} = P_{DER} / S_k$ the fraction DER with respect to the rating of the distribution transformer. High harmonic distortion occurs for $f_{res} = n f_0$ with n = 5, 7, 11 or 13, and the power system frequency f_0. This corresponds to the following amount of DER:

$$\Pi_{DER} = \frac{1}{2\pi f_0 n^2 \varepsilon C_1 U_{nom}^2} \quad (4)$$

The capacitance of DER units in the 1-3 kW power range varies between 0.5 and 10 µF per converter [6]. Assuming that the nominal power of the converter is 1 kW, results in C_1 = 0.5 ... 10 nF/W. The capacitance of a LV cable varies from 0.5 µF/km to 2 µF/km (MV cables: 0.14 µF/km - 1.1 µF/km). By supposing a cable length of maximum 500 m for a 1 kW converter, the cable contribution is at most 1 nF/W. The equivalent capacitance of a home connection at 0.4 kV (household capacitance) ranges between 0.6 and 6 µF [6]. For a 1kW converter per household this gives at most 6 nF/W.

The values n=7, U_0=230 V, ε=0.05, and C_1=17 nF/W (the upper limit of the capacitance ranges given) result in Π_{DER} = 1.44 for the hosting capacity. Thus the amount of DER that can be connected to the LV bus before a harmonic resonance at the 7th harmonic order occurs, is 1.44 times the rating of the transformer. The already existing (but not yet considered) capacitance connected to the LV bus, for example in form of additional cables, power electronic equipment and lighting, can further reduce the hosting capacity.

Resonance at the 11th or 13th harmonic order occurs when the amount of DER connected to the LV bus is 59% or 42% of the rating of the transformer. Note however, that this is the worst-case capacitor value. The conclusion to be drawn is that resonances below 1 kHz are unlikely.

A study of a network with large amounts of photovoltaics showed resonances close to the 21st and 23rd harmonic [6].

HIGH-FREQUENCY DISTORTION

DER units with power-electronic interface emit high-frequency components, among others related to the switching-frequency in the active converter. It is shown that small levels of DER penetration may already lead to unacceptable levels of voltage distortion. Part of this work has been to set acceptable limits for the voltage distortion for frequencies above 2 kHz, from information found in different international standards.

To determine the hosting capacity for DER units against high-frequency distortion, the following information is required:

- The current emission of individual DER units in the frequency range of interest.
- The summation law relating the emission of individual units with the emission of a (large) number of units.
- The source impedance at the point-of-common coupling with other customers.
- The acceptable voltage distortion in the frequency range of interest.

In this study the hosting capacity was estimated in the frequency band between 2 and 9 kHz. From a number of sources, see [3] for details, the emission was obtained for DER units per 200-Hz band. The choice of a 200-Hz band was based on IEC 61000-4-7. From the comparison of a number of sources it was decided that reasonable emission levels would be between 1 and 3% for small units and between 0.5 and 1.5% for large units. A square-root summation law was used where the emission due to N units is √N times the emission of 1 unit. The source impedance was taken from the measurement results presented in [4]. The 90-95% values of the source impedance were shown to increase linearly from 3 Ω at 2 kHz through 10 Ω at 9 kHz. Consider as an example a 1-kW, 230-V, single-phase unit (Inom = 4.34 A). The resulting hosting capacity is shown in Figure 4 as a function of the frequency that gives the highest voltage distortion. The current distortion at the critical frequency was assumed to be between 1% and 3% for individual units. The decrease in hosting capacity with frequency is due to the linear increase in source impedance with frequency.

For a 1% current distortion (per 200-Hz group) the hosting capacity is more than 50 around 2 kHz but decreases to less than 10 around 9 kHz. For higher current distortion the hosting capacity becomes close to unity, implying that even one single unit would result in voltage distortion close to or exceeding the acceptable limit. The decrease in hosting capacity with frequency makes that especially the distortion at higher frequencies should be limited to obtain an appropriate hosting capacity.

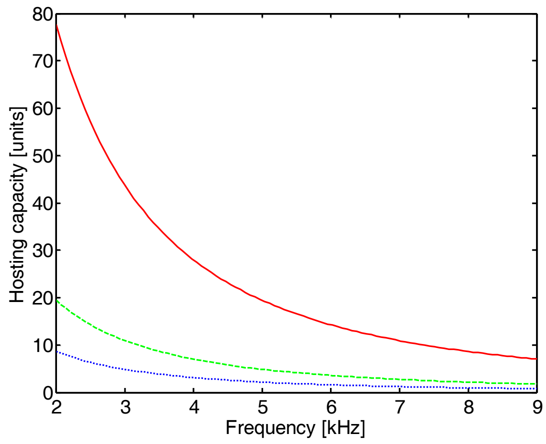

Figure 4 Hosting capacity (number of DER units) for 1-kW single-phase units with current distortion of 1% (red, solid), 2% (green, dashed) and 3% (blue, dotted).

The calculations have been repeated for a 10-kW three-phase unit (Inom = 25 A) connected to the same LV supply. The current distortion for such a unit is assumed to be between 0.5% and 1.5%. It appears reasonable that for a larger unit more investment in filtering and switching technology is economically feasible in order to reduce the distortion. The results are shown in Figure 5. Even for those reduced distortion values, the connection of two DER units close together is not always possible.

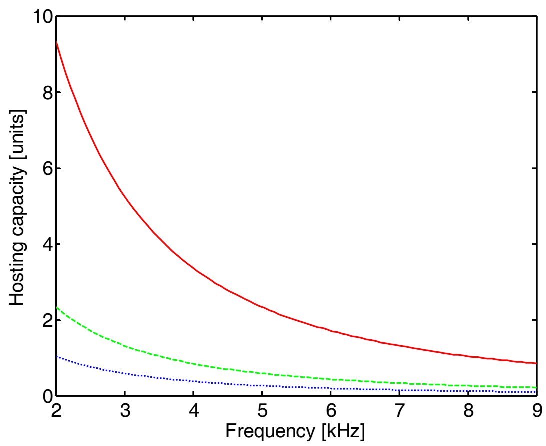

Figure 5 –Hosting capacity (number of DER units) for 10-kW three-phase units with current distortion of 0.5% (red, solid), 1% (green, dashed) and 1.5% (blue, dotted).

A number of assumptions had to be made, some of which were rather uncertain, so that the resulting hosting capacity is merely an estimation of the order of magnitude. Still the conclusion remains valid that a further assessment is needed of emission limits and planning levels in the frequency range between 2 and 9 kHz.

CONCLUSIONS

Low-frequency distortion, up to 1 kHz, due to DER equipment, is not a major concern for the performance of the network. The harmonic distortion caused by DER equipment is less than that of existing equipment like computers and televisions.

The capacitance at the interface to many DER units may cause harmonic resonances or shift resonance frequencies to lower values where the emission is higher. Resonance at frequencies below 1 kHz is unlikely. Attention should be given to the capacitance of DER units and potential resonances at higher frequencies.

High-frequency distortion, above a few kHz, is a concern for inverter-based DER. Serious attention has to be given to the potential problems in this frequency range. This includes the setting of appropriate planning levels and emission limits for equipment.

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