HARMONIC ASPECTS OF WIND-POWER INSTALLATIONS

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Abstract: With increasing amounts of wind power connected, the power system is impacted in a number of ways. In this paper, the emphasis has been on one of those impacts: the harmonic emission from wind-power installations. The harmonic emission of individual wind turbines as well as from a wind park has been studied. For four modern wind turbines estimations have been done on the impact on the grid per harmonic and interharmonic group. The primary emission from complete windpark due to the emission from the turbines has been analyzed.

Keywords: Emission, Harmonic distortion, Harmonic spectrum, Power quality, Wind power.

INTRODUCTION

The electric power system can accept only a certain amount of windpower before additional investments in the grid are needed. This is not a specific problem with windpower, but it also holds for any other type of production and also for additional consumption of electricity.

This so-called "hosting capacity" varies a lot between different locations in the grid. At some locations, the grid can accept almost no windpower, whereas it can accept large amounts at other locations. The hosting capacity is impacted by a number of electrical phenomena; an overview of these is given in several books, e.g. [1, 2, 3].

One of these phenomena is the fact that the current waveform is not a perfect sine wave at the point of connection between the grid and a wind-power installation (an individual wind turbine or wind park). This is called "waveform distortion" or also "harmonic distortion".

Other phenomena that limit the amount of wind power that can be accepted by the grid receive a lot of attention in the technical literature and in nontechnical discussions; examples are overload, overvoltage, prediction errors, and intermittency. The amount of attention given to harmonic distortion in relation to windpower is much smaller and the phenomenon appears to be sometime completely forgotten in the discussion on wind-power integration.

This is partly because other phenomena often put more strict limits on the hosting capacity, but also because of the lack of knowledge on harmonic distortion and the fact that it is a rather complicated phenomenon.

This lack of knowledge on harmonic distortion in relation to windpower has been an important driving force behind this paper. Two issues have been studied in detail: the emission from individual turbines and the emission from a complete windpark.

WAVEFORM DISTORTION – TERMINOLOGY AND STANDARDS

The term waveform distortion or harmonic distortion is used when the voltage or current waveform in the power system deviates from a sine wave. The waveform in reality is never exactly a sine wave so that there is always a certain level of distortion present.

Basic sources of this disturbance include arcing loads, variable-load electric drives, static converters, in particular direct and indirect frequency converters. Many new types of production and consumption are equipped with a power-electronics converter. Modern power electronic equipment is not only sensitive to voltage disturbances, it also causes disturbances for other customers [4]. For example, the power-electronics converters produce a non-sinusoidal current waveform. In power quality terms: they inject harmonics into the grid. These harmonics are caused by the switching pattern of the converters.

An example of a distorted current waveform containing harmonics is shown in Fig. 1.

There are a number of concerns with high levels of distortion of the current, which in turn results in limits on the maximum level of distortion.

I. There are maximum-permissible levels for the distortion of the voltage waveform. These limits are set in national or international standards (EN 50160 sets minimum requirements for Europe) or in national regulation (EIFS 2011:2 for Sweden). These limits are chosen such that equipment connected to the grid (including home equipment like energy-saving lamps, televisions and washing machines) does function correctly. It is the task of the network operator to ensure that the actual levels do not exceed these limits. To ensure this, without excessive costs for the other customers, the network operator sets limits on the emission from large installations, like wind-power installations. The

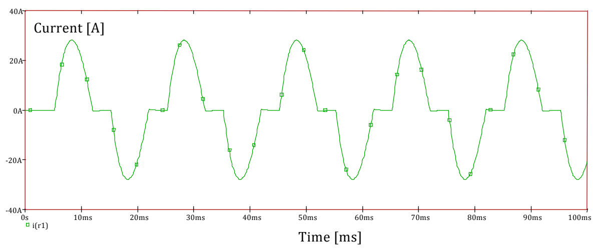

Fig.1 - *Example of a distorted current waveform*

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term emission is used to refer to waveform distortion of the current taken by a device or an installation connected to the grid i.e. the electromagnetic pollution produced by a device.

II. High current distortion gives increased heating of components in the grid (especially transformers are sensitive to this) resulting in a reduced lifetime of these components. High current distortion also increases the risk of the protection operating incorrectly, which in turn results in more interruptions of the electricity supply. Telecommunication interference is another risk from high current distortion.

Risks from high waveform distortion can be mitigated by limiting the emission of the loads; harmonic filters; strengthening the network i.e. increasing the short-circuit capacity.

The spectrum of the waveform from Fig. 1 is shown in Fig. 2.

The fundamental 50-Hz supply frequency component is the dominant component. The current spectrum contains *harmonics* with a frequency that is an integral multiple of the fundamental supply frequency. The non-integral multiple of the fundamental supply frequency are referred as *interharmonics*.

In close relation with the waveform distortion, besides emission the terms immunity and compatibility are used. The immunity is the device's ability to withstand electromagnetic pollution. Compatibility levels are reference values for coordinating emission and immunity requirements of equipment. For a given disturbance, the compatibility level is in between the emission level and the immunity level [4]. Immunity limits for waveform distortion are given in IEC 61000-4-13. The compatibility limits are given in IEC 61000-2-2. At this moment, no voltage distortion limits for interharmonics exist in any international standard. The values used in the calculations are indicative values given in an informative annex with IEC 61000-2-2.

EMISSION FROM INDIVIDUAL TURBINES

Measurements have been performed of the emission from four turbines of 1.8 to 2.5 MW size, equipped with power-electronics [5, 6, 7]. The first turbine Nordex 90 is a type-3 wind turbine with a rated power 2.5MW. It is equipped with a gearbox of multi-stage planetary plus one stage spur gear, a six-pole doubly-fed asynchronous generator (DFIG). A partial rated converter is installed between the rotor and line connection. It is designed as a DC voltage link converter with IGBT technology. The rotor outputs a pulse-width modulation (PWM) modulated voltage, while

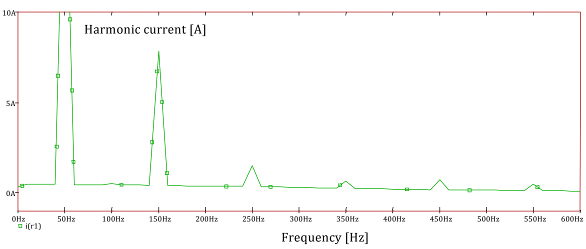

Fig.2 - *Spectrum of a distorted current. The value for 50 Hz is about 20 A, beyond the vertical scale of the figure.*

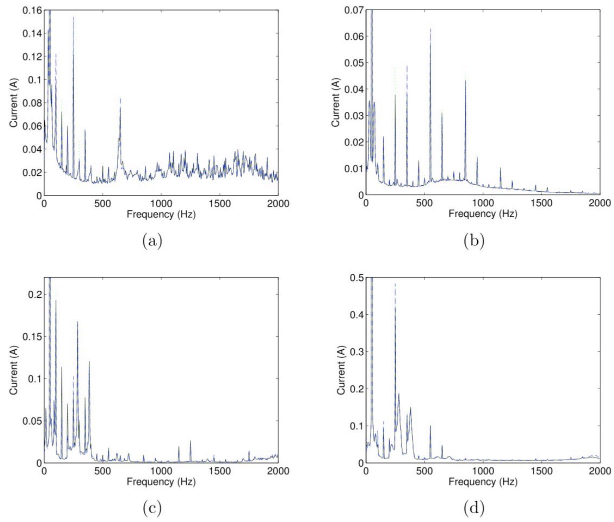

Fig.3 - *Emission spectrum from four individual turbines*

the stator outputs 3*660V/50Hz voltage. The wind turbine is connected to the collection grid through one medium-voltage (MV) transformer, which is housed in a separate transformer station beside the turbine foundation.

The other 3 turbines are Vestas V90 - type-3 wind turbine with a rated power of 2 MW, Enercon E82 - type-4 wind turbine with a rated power of 2 MW and Enercon E 40 with rated power of 3x600 kW.

The average spectra for these turbines, obtained over a period of one to four weeks, are shown in Fig. 3.

Measurements have shown that the emission of wind-power installations is relatively small for the characteristic harmonics (5, 7, 11, 13, etc) but relatively large for non-characteristic harmonics. The latter especially in the form of a broadband spectrum but some spectra even contain narrowband interharmonics. The emission of the turbines at harmonic frequencies is much smaller than for other industrial installations or other loads at medium-voltage levels; however the emission at interharmonic frequencies is not present with most other installations. Although all four spectra show this combination of harmonics and interharmonics, they are further all four different.

To quantify the effect of the measured emission (shown in Fig. 3), allowed voltage distortion limits are used to quantify the required grid strength to meet these limit. For harmonics, the standard EN 50160 is applied. For interharmonics, the standard IEC 61000-2-2 is applied. Notable is that the allowed voltage distortion for harmonics is in the range of 0.5 to 6% with the larger values for the characteristic harmonics 5 and 7. For interharmonics, the standard 61000-2-2 stipulates a limit of only 0.3%. The requirements are thus tougher for interharmonics. The effect of this is clearly visible when the required grid strength is calculated.

Figure 4 shows the required short-circuit ratio, SCR, (grid strength) that is needed to maintain voltage distortion below the limits set in the standards. When harmonic distortion is setting the hosting capacity, a higher value of this SCR implies more impact on the grid and a lower hosting capacity. When the SCR is below five it is unlikely that distortion will set the hosting capacity. We can see that the SCR is less than five for most frequency components, with

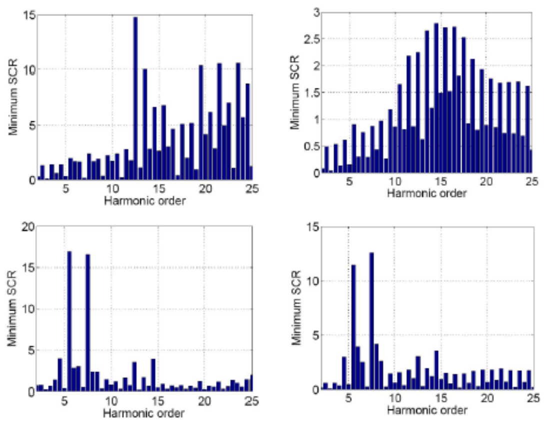

Fig.4 - *Estimated impact on the grid per harmonic and interharmonic group for four modern wind turbines.*

the exception of interharmonics and some high-order harmonics. The impact on the grid is especially big for three interharmonics with three of the turbines.

As the requirements on grid strength are mainly set by the interharmonics, a discussion has started about the need for low limits for interharmonic voltages. The existing approach to ensure electromagnetic compatibility between equipment and the grid consists among others on setting compatibility levels for harmonics. These compatibility levels and the related planning levels, together with the source impedance at the point of connection, result in emission limits for harmonic currents from, for example, windpower installations. The compatibility levels are based on existing levels with the reasoning that maintaining those levels is the best way of ensuring that no unexpected compatibility issues will appear.

There are no voltage-distortion limits in place for interharmonics, so the interharmonic emission is not seen as a concern. Compatibility levels for interharmonics are proposed in an informative annex with IEC 61000-2-2. These levels are very low as these harmonics were not present in the grid at the time when the compatibility levels were set and can easily be exceeded when larger amounts of wind turbines are connected.

That there is no apparent need for such low levels follows also from the comparison in Fig. 5 of the immunity limits (IEC 61000-4-13) and the compatibility levels (IEC 61000-2-2).

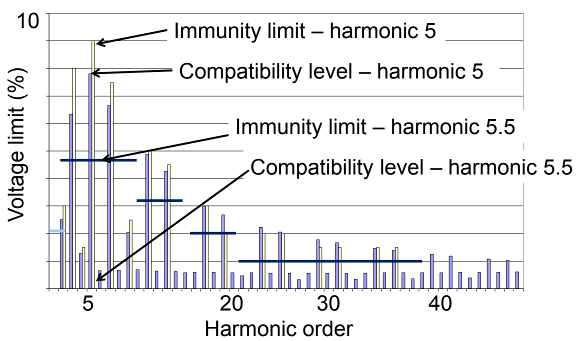

Fig.5 - *Compatibility levels (blue bars) and immunity limits (yellow bars and horizontal lines) for harmonics and interharmonics.*

For the familiar harmonics (2, 3, 5, 7, etc), the immunity limits are somewhat above the compatibility levels. The margin ensures that the probability of electromagnetic interference is sufficiently small, while at the same time the emission requirements are not excessive. For even harmonics and interharmonics the situation is completely different however. The immunity requirements for these components are shown as horizontal lines in the figure. For example for harmonic 5.5 the immunity limit is about 4.5% of the nominal voltage, whereas the compatibility level is only 0.2%.

Instead of setting strict emission requirements on new production and consumption installations and equipment, an increase of the compatibility levels for non-characteristic harmonics could be considered. This would remove a possible barrier against the connection of new equipment probably without noticeably increasing the probability of electromagnetic interference with end-user equipment [8].

EMISSION FROM A WIND PARK

As a next step studies have been done of the emission from a wind park as a whole. The emission is in this case defined as a distorted current at the point of connection between the public grid and the park. A distinction is thereby made between "primary emission" and "secondary emission". This distinction is made based on what causes the currents to flow.

Primary emission is caused by the distorted current coming from sources inside of the wind park. This are in most cases the wind turbines, but also power-electronic devices to control reactive power. Even the turbine and grid transformers are sources of distortion, although minor ones in most cases. This primary emission is the one that is normally considered first and often it is the only one considered, thereby neglecting the secondary emission. The secondary emission is due to all other sources of harmonics, outside of the wind park. It is the distorted part of the current that would flow in case there would be no sources of harmonics inside of the wind park.

In this study, only the turbines have been considered. The primary emission from the park is in that case due to the emission from the turbines. But it is not simply the sum of the emissions from the individual turbines. To calculate the primary emission from the park, two phenomena have to be considered: cancellation of harmonic currents from individual turbines; and the propagation from the turbines to the grid. Both phenomena have been considered in a general model of a wind park and applied to 3-turbine, 10-turbine and 100-turbine parks [9, 10]. In [9] a number of expressions for the transfer function are derived using a general model of a wind park. The relations between the emission from one turbine and the emission from the wind park as a whole are derived for a 10-turbine park. These results are shown in Fig. 6, where a distinction is made between "individual transfer function" and "overall transfer function. The individual transfer function gives the relation between a frequency component emitted by an individual turbine and the same frequency component at the point of connection to the grid. All other emission sources are neglected in this case. The individual transfer function is strongly frequency

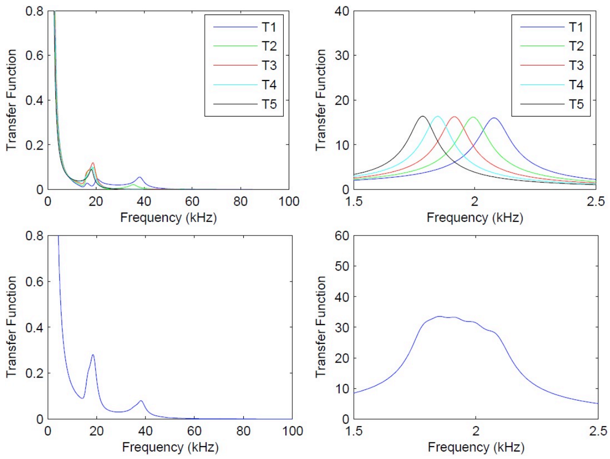

Fig.6. - *Individual transfer functions (top) and overall transfer function (bottom) for the 10-turbine windpark*

dependent and somewhat different for each turbine location. The overall transfer function relates the emission from a windpark into the public grid to the emission from an individual turbine. The overall transfer function is calculated from the individual transfer functions using the square-root aggregation law for random sources of emission as in [9]. For the example in Fig. 6, the highest value occurs somewhere around 2 kHz, where the emission into the grid is almost 20 times the emission from the turbine: this amplification is due to resonances in the collection grid.

For higher frequencies, the individual transfer function reduces in magnitude quickly: the collection grid actually damps these frequencies. The emission into the grid is smaller, and for most frequencies a lot smaller, than the emission from the individual turbine.

The overall transfer function considers all turbines in the park and the cancellation between harmonics from the different turbines. Its value is the ratio between the primary emission from the park and the emission from one turbine. For the calculation it is assumed that all turbines are emitting harmonic distortion. Also for the overall transfer function we see a maximum around 2 kHz and a fast drop for higher frequencies.

Studies on secondary emission have been performed outside of this project [11]. It was shown that secondary emission can reach high values and should not be neglected.

CONCLUSION

Measurements have been performed on four modern wind turbines equipped with power-electronic converters. The emission from such turbines is moderate: at harmonic frequencies their emission is much smaller than the emission from industrial, commercial or domestic installations. However at interharmonic frequencies their emission is larger than for other installations.

Although the levels are still small they could result in interharmonic voltages in the grid increasing. A discussion has been started on what are acceptable levels of interharmonic voltages.

It is important to distinguish between primary emission (driven by the turbines) and secondary emission (driven by sources outside of the park). The primary emission from the park is amplified at a frequency of one to several kHz, depending on the size of the park. For higher frequencies the primary emission quickly drops.

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