HARMONICS - ANOTHER ASPECT OF THE INTERACTION BETWEEN WIND-POWER INSTALLATIONS AND THE GRID

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ABSTRACT

Wind parks are known as sources of harmonic distortion. The emission at the classical harmonic frequencies (low order non-triplen odd harmonics) is however low. Potential problems with connecting individual turbines and wind parks occur at non-standard frequencies, mainly due to harmonic resonances. Next to the harmonic currents driven by the emission from the turbines, studies should also consider the currents driven by the harmonic background distortion.

INTRODUCTION

Modern, MW-size, wind turbines contain power-electronic converters. This can either be a full-power converter or a part-size converter in a double-fed induction generator. The presence of power-electronic converters makes that distorted currents are expected and that there is concern from network operators that distortion levels in the grid will increase with increased penetration of windpower. Harmonic studies are therefore a common requirement as part of the connection agreements for individual turbines as well as wind parks.

The subject is however rarely taken up in general discussions about the impact of wind power on the grid. Also is there almost no research ongoing in this subject. Rather straightforward, often standardized, methods are used to quantify the emission as part of the connection studies, without considering any specific properties of wind power. In this paper some of those specific properties will be discussed.

EMISSION FROM INDIVIDUAL TURBINES

Harmonic spectra

Measurements have been performed [1] of the emission from three turbines of 2 to 2.5 MW size, equipped with power-electronics: two DFIG (Nordex N90 and Vestas V90) and one full-power converter (Enercon E82)..

The emission spectrum of the three turbines is shown in Figure 1. The measurements were performed on the medium-voltage side of the turbine transformer during a period between 8 and 13 days. The harmonic and interharmonics subgroups, as defined in IEC 61000-4-7, were obtained every 10 minutes. Shown in the figure is the 95-percentile of the harmonic subgroups as a percentage of the 95-percentile of the fundamental component (the latter was close to the rated current). The highest of the values for the three phases was chosen.

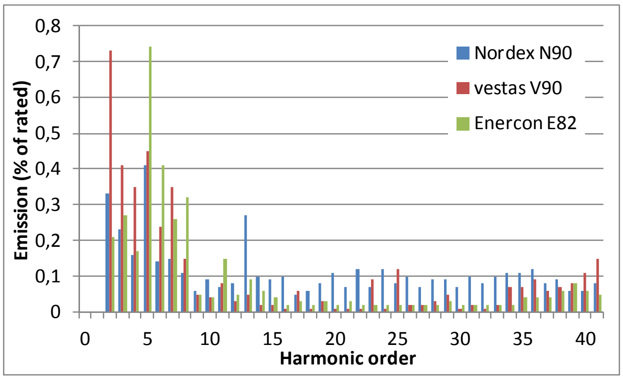

Figure 1. Emission spectrum (harmonic subgroups) from three modern MW-class wind turbines

There are differences as well as similarities between the three spectra. All three turbines show their predominant emission up to about order 10; they also all three show increased emission between harmonic 35 and 40.

Interharmonic spectra

For comparison, the interharmonics spectra, obtained in the same way, are shown in Figure 2. The emission at interharmonic frequencies is similar in magnitude to the emission at harmonic frequencies. The spectra of the three turbines are different also for interharmonics, but a general observation is that all of them emit distortion at interharmonic frequencies.

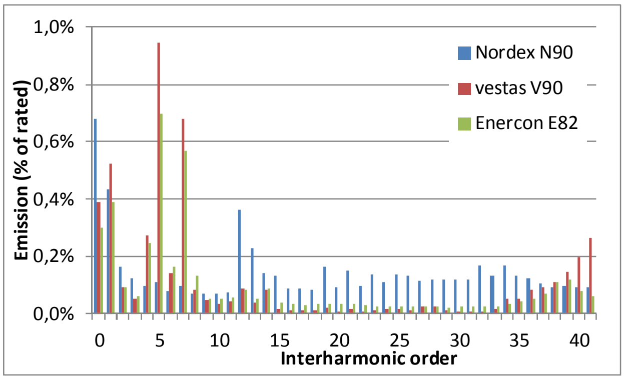

Figure 2. Emission spectrum (interharmonic sub-groups) from three modern MV-class wind turbines

Emission limits

Excessive amounts of harmonic emission from wind-power installations (or from any other installation) impacts the grid in two different ways:

- ✓ Excessive harmonic currents through grid components like transformers;
- ✓ Excessive harmonic voltage distortion for other network users. Limits on this are typically set in international standards (like EN 50160) or in national regulation [2].

Current emission limits for individual installations are in turn set to prevent such excessive amounts. Emission limits for individual installations can either be set on a case-by-case basis or by using general limits. The former is the case in most European countries, where planning levels on harmonic emission, together with the source impedance as a function of frequency at the point of connection, are used to obtain location-specific emission limits. Whether the emission from an installation is acceptable or not depends strongly on the specific properties of the grid at that location. A case study is needed for each new installation.

A different approach is used in France [2], where the emission limits are dependent on the short-circuit capacity at the connection point. The resulting limits are still location dependent, but no study is needed to obtain the source impedance as a function of frequency. Only the source impedance at the power-system frequency is needed.

The emission limits as recommended by IEEE Std. 519 are location independent. Instead for each harmonic order, the emission limit is set as a percentage of the maximum current.

Comparing with limits

The measured emission has been compared with the limits according to IEEE Std.519 and the limits as used in France. The comparison with IEEE Std.519 is shown in Figure 3. The figure shows the ratio between the measured emission level (as in Figure 1) and the emission limit for voltage levels through 69 kV. A value above 100% means that the emission exceeds the limit. It has been assumed that the harmonic spectrum in a 60-Hz system would be the same as in a 50-Hz system.

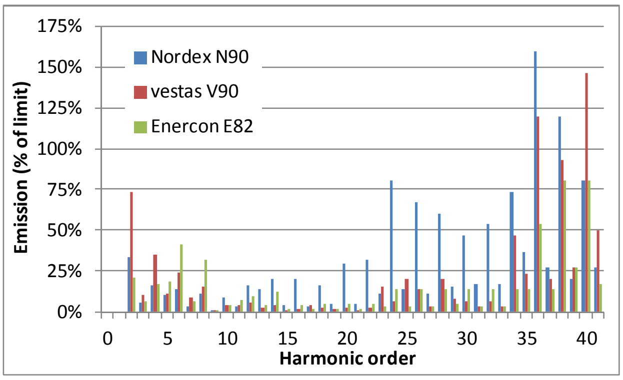

Figure 3. Emission spectra (harmonic subgroups) from three modern MW-class wind turbines as a percentage of the IEEE 519 limits.

The figure shows that the limits are exceeded for harmonics 36, 38 and 40, for the Nordex and Vestas turbines. The emission for all harmonics in this range is relatively high, but the emission limits for even harmonics are only 25% of the limits for odd harmonics. When the limits in IEEE Std. 519 are strictly followed it will not be allowed to connect these turbines to the grid without additional filtering.

The emission from the three turbines is compared with the French emission limits at medium voltage in Figure 4. Like the previous figure, this one shows the ratio of the measured emission and the emission limit. None of the harmonics exceeds 50% of the limit. This means that these turbines can be connected to the French medium-voltage network without any additional measures.

The French regulation only considers frequencies up to order 25, whereas IEEE Std.519 considers frequencies up to order 41.

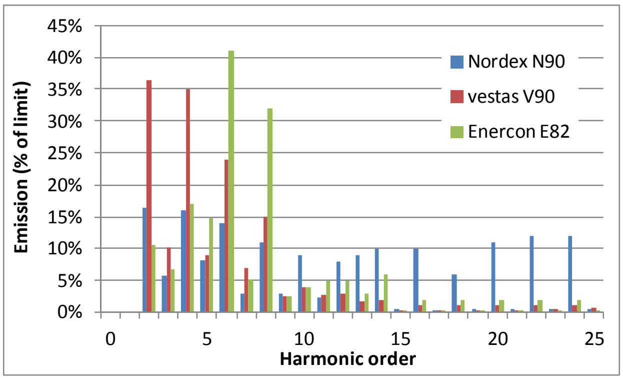

Figure 4. Emission spectra (harmonic subgroups) from three modern MW-class wind turbines as a percentage of the limits for French MV networks.

The requirements for the French HV networks are formulated in a different way. The maximum current for harmonic n is set as follows:

$$I_{max}(n) = K(n) \times \frac{S}{\sqrt{3}\,U_{nom}}$$

Where $K(n)$ is the maximum relative emission, S the lower of the rated power of the installation and 5% of the short-circuit capacity at the point of connection and U_{nom} the nominal voltage at the point of connection. The limits are thus location independent for small installations (up to 5% of the short-circuit capacity) and dependent on the short-circuit capacity for large installations.

Alternatively, the requirements can be interpreted as a minimum short-circuit ratio for which an installation can be connected without the need for additional filtering. This requirement is obtained by inserting $S = \frac{S_k}{20}$ and rewriting the above expression:

$$\frac{S_k}{S_{nom}} > \frac{20}{K(n)} \times \frac{I_{obs}(n)}{I_{nom}}$$

Where the left-hand side is the minimum short-circuit ratio and the second factor on the right-hand side the observed emission as a fraction of the rated current of the installation. This expression results in a minimum SCR for each harmonic, as shown in Figure 5 and Figure 6 for different voltage levels. When connecting an installation it is the highest value over all harmonics that sets the limits.

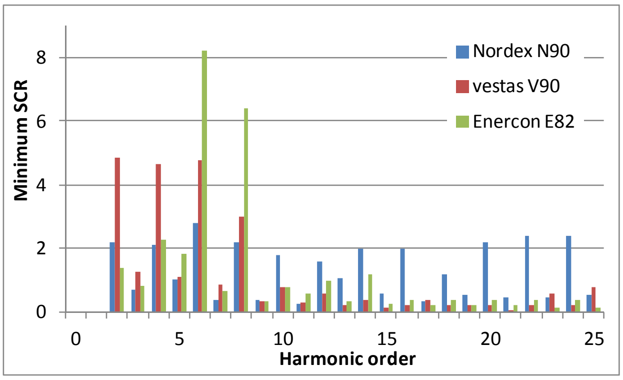

Figure 5. Minimum short-circuit ratio for wind-power installations connected to the French 63 to 225 kV networks.

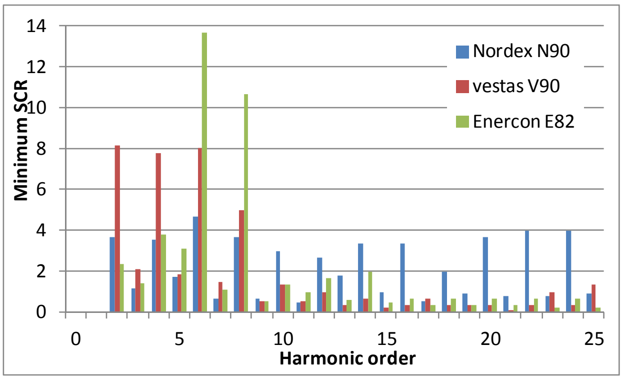

Figure 6. Minimum short-circuit ratio for wind-power installations connected to the French 400kV network

At the voltage levels for which these two figures hold, wind-power installations would always consist of multiple turbines. The limits shown thus only hold under the assumption that the relative emission (harmonic current as a percentage of the rated current) is independent of the size of the park.

Under these assumptions, the Enercon E82 turbine requires a strong grid (SCR above 8 up at 220 kV and above 13 at 400 kV). Also here the minimum SCR is determined by the emission at even harmonics (order 6 and order 8), for which the limits are much lower than for neighbouring odd harmonics. The Nordex N90 can be connected even to weak grids without the need for additional filtering; whereas the Vestas V90 needs a moderately strong grid.

PROPAGATION THROUGH A WIND PARK

With wind farms, the impact of turbines on the grid is not determined by the emission from the individual turbines but by the emission from the park as a whole. The relation between the emissions from individual turbines and from the park as a whole is discussed in a companion paper [3]. There it is concluded that the emission from a park can be higher as well as lower than the emission that would be obtained by adding the harmonic magnitudes of the individual turbine emissions. Two phenomena contribute to this:

- ✓ The aggregation of the emission from individual sources. The 95% value of the total emission from a number of individual sources is in most cases less than the sum of the 95% values. Guidelines for the aggregation from different harmonic sources are given in IEC 61000-3-6, but it is unclear if these rules hold for wind turbines.
- ✓ Due to resonances and damping in the collection grid, the emission from the park can be amplified or damped compared with the aggregation.

Simulations have been performed on a simplified model of a 3-turbine, 10-turbine and 100-turbine park to estimate the combined impact of these two phenomena. For the 3-turbine park, the amplification reaches its maximum between 6 and 9 kHz and the emission from the park was, in that frequency range, up to 5 times the emission from one individual turbine, expressed in percent of the rated current. When expressed in Ampere, the emission of the park is 15 times the emission of the individual turbine, but as the rated current of the park equals three times the rated current of one turbine, the total emission is amplified up to five times as a percentage of rated.
For the 10-turbine park, the maximum was reached at 1.85 kHz, with a maximum equal to 3.4 times the emission from one individual turbine, in percent of rated. For the 100-turbine park the emission was at most twice the emission from the sum of the individual turbines, at 1.56 kHz.
At frequencies below the resonance frequency, the emission of the park, in percent of rated, is less than the emission from an individual turbine. How much less depends on the aggregation (the first phenomenon mentioned above). The square-root law is commonly used in studies, where the relative emission decreases with the square-root of the number of turbines. It is unclear if this holds for wind-power installations at all frequencies, but a reduction in relative emission is expected for all frequencies. The short-circuit requirements at lower harmonic orders will thus be less than according to Figure 5 and Figure 6.
The large parks, with amplification of emission below 2 kHz, will be connected to higher voltage levels. When considering the French situation, this is where the limits in Figure 5 and Figure 6 are valid. For the lower

frequencies, the relative emission of the park will be less than of the individual turbines. The requirements on short-circuit ratio will thus also be less. For higher frequencies, the relative emission could be amplified by up to a factor of three. When this amplification takes place at frequencies below order 25, the minimum short-circuit ratio for a park consisting of Nordex turbines could be as high as 6 at 63 to 225 kV and as high as 12 for 400-kV. For connections at weaker locations additional filtering may be needed. The requirements on SCR are also here set by even harmonics where the emission limits are low.

Considering the limits in IEEE Std.519, these are already exceeded for two of the three turbines at higher-order even harmonics. Amplification at these frequencies will result in further exceeding of the limits at harmonic orders 35 to 40. The emission at odd harmonics in this range remains below the limits.

EMISSION FROM A WIND PARK

Studies of the emission from a wind park as a whole are even more complicated then might be concluded from the earlier discussions. 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 should thereby be 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, albeit 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.

Studies on secondary emission from wind parks are rare, as the grid code normally does not require this. A study of secondary emission with an off-shore wind park is presented in [4]. The conclusion from that study was that the primary emission is small but that the secondary emission can be several orders of magnitude bigger than the primary emission. The secondary emission is not a concern to the network operator; in fact it has a reducing effect on the voltage distortion from other sources. The secondary emission makes it however difficult to verify if an installation complies with the connection requirements. Secondary emission may also result in high harmonic voltage distortion in the collection grid.

CONCLUSIONS

The measured emission from individual wind turbines and the estimated emission from wind parks have been compared with emission limits. The French regulations and IEEE Std.519 have been used as a reference. It is concluded that the emission from individual turbines is below the emission limits in almost all cases. Only higher-order even harmonics exceed the IEEE limits.

For small wind parks the situation is probably even somewhat better because of aggregation effects between the individual turbines. Further study of the aggregation effect is needed.

For large wind parks amplification due to resonances should be considered. Such resonances could occur at frequencies as low as 1 kHz. Transmission cables could even further reduce this resonance frequency. This amplification could result in the need for additional filtering when connecting such parks to relatively-weak parts of the grid.

A discussion should be started on what are acceptable levels of voltage distortion for even harmonic and for interharmonics. The need for filtering is, in the examples shown here, determined by the even harmonics. Limits for these have been set long time ago based on equipment available in those days.

It is important to distinguish between primary emission (driven by the turbines) and secondary emission (driven by sources outside of the park). For large parks the latter might easily exceed the former because of the small emission from individual wind turbines.

The various uncertainties discussed in this paper makes that harmonic studies are needed before the connection of wind parks, and that these studies should be broader than only comparing the primary emission with the voltage or current limits. The emission from individual turbines is small, but takes place at unfamiliar frequencies. Resonances may strongly amplify the emission. Secondary emission may be much bigger than primary emission.

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