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Decompositions of harmonic propagation in wind power plant

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ABSTRACT

This paper presents harmonic propagation in a wind power plant. The two groups of propagation are distinguished based on the harmonic sources: propagation from one individual wind turbine to other turbines and to the public grid; and propagation from the public grid to the collection grid and to individual wind turbines. The paper studies the characteristics of the different harmonic propagation paths. A case with emission from all turbines, at different production levels, and from the public grid is presented as well. Also the impact of a turbine filter on the propagation is studied. The study indicates that, resonances of a wind power plant have a significant impact on the propagation. It is also shown that harmonic studies should consider both emission originating from turbines and emission originating from the public grid. It is also shown that the filter with the turbine has a significant impact on the harmonic propagation.

1. Introduction

The environmental advantages of using wind to produce electric power are well known and broadly documented. Wind power does however have adverse impacts on the electric power system. These need to be addressed to prevent that the electric power system becomes a barrier against the introduction of wind power. One of such adverse impacts concerns the distortion of the voltage and current waveforms. Harmonic distortion of wind power installations, has attracted significant interests [1–4]. Such installations emit apparent non-characteristic and interharmonics, which are different from conventional devices and installations [5,6]. A new type of distortion has been observed for wind energy conversion system using power electronics [3,7]. Problems caused by harmonics, include shortened lifetime of components such as generators, transformers, cables, and filter capacitors by overheating, extra losses of the components; mechanical vibration of filter inductor; undesired trigging of grid and inverter; and even shutdown of the wind power plant (WPP) [8,9].

Harmonic distortion from wind power installations shows significant levels of interharmonics, and even harmonics [4,10]. The origin of apparent interharmonics has been addressed in [7]. The emission of individual turbines is however low as a percentage of the rating at the low-order odd harmonics [1,3,10].

The use of underground cables in a WPP significantly impacts the emission of the WPP as a whole. Those cables introduce resonances in the collection grid at relatively low frequencies [11,12] because of combination of the cable capacitance and the source inductance (dominated by the grid transformer). These resonance problems have been widely studied [13–15]. The harmonic currents emitted by a wind turbine are amplified by the resonance, which results in a risk of exceeding the harmonic voltage limits set by the grid operator.

Additionally, the harmonic distortion behaves stochastically with certain types of probability distribution in the complex plane [16–19]. The result of the stochastic behaviour is that the magnitude of the total emission is lower than the sum of magnitudes of the emission from the individual turbines; this effect is called "harmonic aggregation".

The standard IEC 61000-3-6 recommends the use of an aggregation model based on an "alpha exponent" for each harmonic and interharmonic order. The aggregation depends on the distribution of the complex harmonics and interharmonics [17,18].

The interaction between a turbine and the grid determinate the distortion level into and from the grid, in addition to the interaction with other turbines [20]. The background voltage distortion also contributes to the harmonic currents at the point of connection (POC) and in the collection grid. This is not commonly considered in harmonic studies. Ref. [14] mentions the importance of this and in

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Table 1
Values of the aggregation exponent in Standard IEC 61000-3-6.

Order	Value of alpha exponent
Harmonic order < 5	1
5 ≤ harmonic order ≤ 10	1.4
10 < harmonic order ≤ 999	2
Interharmonic order < 999	2

[21] a case is shown where the contribution of the background distortion at the POC if bigger than the contribution from the turbines. The spread of the emission, either from the background distortion or from the turbines, inside of the WPP is however not studied.

This paper considers both phenomena: the harmonic emission originating from a turbine and spreading to other locations in a WPP or to the public grid; and the harmonic emission driven by external sources connected elsewhere to the public grid.

Based on the harmonic aggregation in Section 2, a case study is performed for a nine-turbine WPP in Section 3. Results of harmonic penetrations from a wind turbine and from the external grid, emission with combined power bins and the impact of a turbine filter are presented in Section 4. The study is discussed in Section 5 and main conclusions are summarised in Section 6.

2. Harmonic aggregation

The study is based on the traditional frequency-domain analysis. The calculated voltage and current are valid in the complex plane where the contributions from the different sources add. The magnitude of the harmonic distortion at a certain location is less than the sum of the magnitudes from different contributions. This is because of the different phase-angles of the different vectors. Next to that the variations in emission do not occur at the same time for the individual turbines. Because of this the maximum of the sum of total emission is less than the sum of the maxima of the individual contributions.

A previous study [1] indicates that, low-order harmonics tend to be synchronised to the fundamental voltage waveform with small difference in phase angle, whereas the phase angles for high frequencies vary randomly. Further studies have shown that characteristic harmonics and non-characteristic harmonics at low-orders behave differently. Especially interharmonics and high frequencies show uniformly distributed phase angles [22].

The aggregation at certain harmonic order deviates between different turbine types or WPP locations. The harmonic aggregation is chosen in this paper according to the standard IEC 61000-3-6, which describes a "second summation law" (applicable to both voltage and current) as:

$$U_h = \sqrt[\alpha]{\sum_{m=0}^{N} {U_{h,m}}^{\alpha}} \quad (1)$$

where U_h is the resulting voltage magnitude due to the aggregation of N sources at order h, and α is the "aggregation exponent". The values for the aggregation exponent according to IEC 61000-3-6, are given in Table 1.

3. Simulation

A case study has been performed using the commercially-available software package DIgSILENT PowerFactory. The case study involved a WPP with nine wind turbines connected to the public power grid.

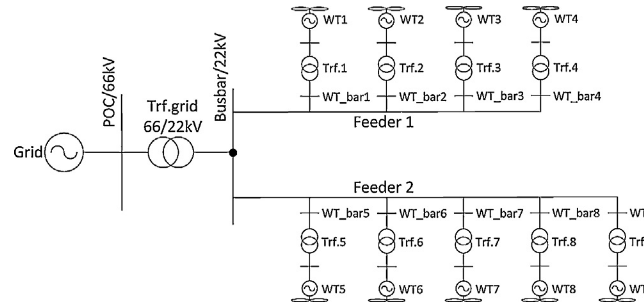

Fig. 1. The topology of the studied wind power plant with nine identical wind turbines spread over two feeders.

3.1. Wind power plant topology

Nine identical variable-speed wind turbines are connected to two underground cable feeders, as depicted in Fig. 1; four turbines to one feeder, five to the other. The distance between neighbouring turbines on each feeder and the distance from the WPP substation to the nearest turbine is 1 km.

The power produced by the nine wind turbines is sent through the turbine transformers at the voltage level of 22 kV and further to the public grid through a single substation transformer at 66 kV.

3.2. Cable model

The cable feeders are modelled as distributed parameters. The frequency dependency of the cable resistance is modelled as follows:

$$\frac{R_f}{R_1} = (1-a) + a \times \left(\frac{f}{f_{nom}}\right)^b \quad (2)$$

where R_f is the resistance at the frequency f and R_1 the resistance at power-system frequency f_{nom}.

The choice of coefficients a and b, strongly impacts the impedance resulting from the frequency scan analysis around resonance frequencies. A sensitivity study has been performed with $a = 1$ and with b equal to 0.6, 0.8 and 1.0 respectively.

The differences show in the frequency scan near the resonance frequency. For frequencies beyond the resonance frequency, the impedances are not much impacted by the use of different parameters. The study in the remainder of the paper uses the coefficients $a = 1$ and $b = 0.8$.

3.3. Transformer model

Both turbine and substation transformers are modelled as a T-equivalent circuit, with leakage reactance and resistance equally distributed between HV and LV sides, and magnetising impedance. The resistance is assumed to be constant with frequency.

3.4. Wind turbine model

The Type-III (Doubly-Fed Induction Generator) wind turbine has a rated power of 3 MW and is connected at LV side of turbine transformer (690 V). The turbine is modelled as an ideal current source in parallel with an induction machine (through T-equivalent with rotor resistance 0.0389 pu, reactance 0.085 pu; and stator resistance 0.005 pu, reactance 0.179 pu and magnetising reactance 7.089 pu). The stator resistance of turbine generator is modelled as frequency-dependent parameters, (2), $a = 1$ and $b = 0.8$.

Harmonic measurements, in accordance with IEC 61400-21, were performed at the terminals of the turbine. Current spectra were obtained for the different active power bins (PB), e.g., PB 10