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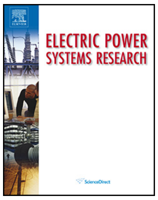

Interharmonic currents from a Type-IV wind energy conversion system

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ABSTRACT

This paper presents, for the first time, the verification of the classic model for the origin of interharmonic emission from a frequency converter, for a Type-IV wind turbine by using long-term measurements. Interharmonic variations in magnitude and in frequency are due to the difference between the generator-side and grid-side frequency of the full-power converter. The model verification consists of three parts: correlation between frequencies; relation between magnitude of interharmonics and active-power production, and relation between magnitudes of different interharmonics. The measurements are in agreement with the model predictions. The paper also introduces a novel graphical correlation method to extract information on interharmonics from long-term measurement series.

1. Introduction

The presence of harmonic emission from wind turbines is well documented in various papers and books. A field measurement of harmonic voltage and current from a wind park with five variable-speed on-shore wind turbines is presented in [1,2]. Characteristics of harmonics and interharmonics from a number of modern on-shore wind turbines are presented in [3,4].

The presence of interharmonics due to the use of power electronics in wind turbines is documented in a lesser number of sources [5–7]. Papers [5,6] present theoretical sources of interharmonics, and paper [7] presents field measurements from a wind turbine. It is shown in [8] that certain interharmonic currents have the general tendency to increase with the active-power production, whereas most others present a varying and complicated tendency.

General explanations for the emission of interharmonic currents from wind turbines with power-electronic converters are given in [5,7,9]. But none of these publications goes into sufficient details. Interharmonics are observed in a number of loads, which include static frequency converters, cycloconverters, subsynchronous converter cascades and loads pulsating non-synchronously with the fundamental frequency [5,11,11]. It is stated in [7] that the interharmonics from a Type-III wind turbine are due to the slot harmonics from the induction machine. However no further detail is given (for example about how these slot harmonics propagate through the converters) and the simulations presented in [7] also do not include the slot harmonics so that the statement cannot be verified. For the same reasons it is not possible to verify if slot harmonics can be the explanation for harmonics from Type-IV wind turbines.

Reference [5] only mentions the presence of interharmonics in wind turbines, but without giving more details. A model of a power conversion system including a six-pulse wind-turbine power converter is presented in [9]. Interharmonics are generated according to this model, because the generator speed is not synchronized with the power-system frequency. As the generator speed varies, the interharmonic frequencies will vary. That model has however not been verified using measurements.

Harmonic distortion from a Type III wind turbine presents a time-varying characteristic; the difference between the average, 90, 95 and 99-percentile levels indicates large variations in time at certain frequency bands [12]. Phenomena also indicate varying emission in frequency. When looking at individual spectra, obtained for example over a 200-ms window, most of them show high emission at narrowband interharmonic frequencies, whereas the emission has shifted to another frequency a few minutes later. When taken over a longer duration, days of weeks, the average or high-percentile spectrum presents a broadband characteristic for interharmonics together with narrowbands for harmonics [8].

In this paper a model for the emission of interharmonics from a Type-IV wind turbine (based on the classical frequency-conversion model) is proposed and verified by measurements in four different ways.

The model explaining the origin of interharmonics from a Type-IV wind-turbine is introduced in Section 2. This section also gives

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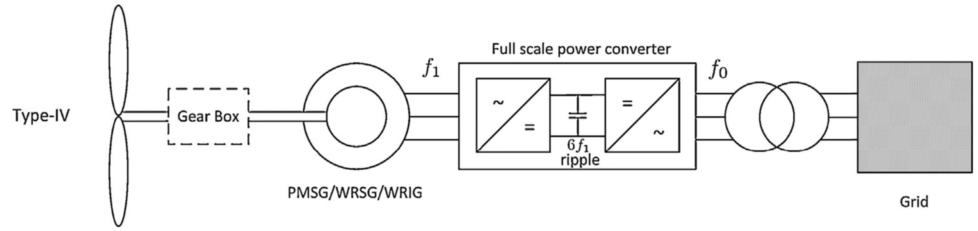

Fig. 1. Type-IV wind turbine with a full-power converter and the generator type permanent magnet synchronous generator (PMSG), wound rotor synchronous generator (WRSG) or wound rotor induction generator (WRIG).

an overview of the four verification methods used. The emission frequencies and their correlations, predicted from the model are presented in Section 3, together with a description of the measurements used to verify the model. The predicted correlation between the emission at different frequencies is presented in Section 4. Further verification is presented in the next two sections. The relation between emission and active-power has been studied in Section 5. The relationship of amplitudes between emission at different frequencies has been studied in Section 6. The conclusions of the work are presented in Section 7.

2. Turbine model and verification

2.1. Model of Type-IV turbine

A Type-IV wind turbine (with a full-power converter, as defined by Institute of Electrical and Electronics Engineers) is studied, for the purpose of this work, as an AC–DC–AC converter connecting the turbine generator to the grid, as shown in Fig. 1.

The frequency of the voltage on the generator-side of the converter, f_1, is typically different from the power system frequency on the grid-side of the converter, f_0. The former varies with wind speed and thus with active-power production, whereas the latter is independent of wind speed and active-power production. The power-system frequency varies in a small range, and throughout this work the power-system frequency will be considered as constant.

The AC–DC part of the converter on the generator side is a six-pulse rectifier resulting in a DC-bus voltage, which consists of a DC component and a voltage ripple of frequency $6f_1$.

The DC–AC part is a voltage-source converter (VSC) using pulse-width modulation (PWM) to create a close-to-sinusoidal voltage behind impedance. The slight distortion of the voltage source is partly due to imperfections in the converter and its control algorithm, and partly due to the DC-bus voltage not being a perfect DC voltage. In this work the latter contribution will be considered. The PWM pattern will also result in waveform distortion, starting at frequencies close to the switching frequency used. This distortion takes place at higher frequencies than the ones discussed here and they will not be considered in this paper.

The voltage generated by the VSC drives a current through the impedance connecting the VSC with the grid, including the source impedance of the grid at the point of connection. It is this current that is referred to as the “emission from the wind turbine”. That impedance consists of the converter reactor, the turbine transformer, the grid-impedance on medium-voltage side of the turbine transformer, and in many cases a harmonic filter. In this work, specifically in Section 3, it is assumed that this impedance is purely inductive for the frequencies of interest.

2.2. Model verification

The model for the origin of interharmonic emission that is described in Section 3, has been used to make a number of prediction that can be verified using measurements. A series of measurements used for this purpose are presented in Sections 3.2–6.2. The predictions, the ways of verification and their limitations are listed as follows:

- The dominant time-varying broadband interharmonics in the average, 90-, 95- and 99-percentile spectra are within the expected frequency ranges. The frequencies are calculated in Section 3.1 and the average spectrum is studied in Section 3.2. However the frequency-varying emission cannot be tracked and visualized in the above statistical spectra.
- A very important part of the verification concerns the correlation between interharmonic frequencies. Those correlations are predicted in Section 4.1 and verified by means of a graphical correlation diagram in Section 4.2. The varying frequency pairs, due to the frequency change of the generator-side, are visualized and the relations between interharmonics are present. The track of the varying frequency is clearly visible even in the relatively-low 5 Hz resolution.
- The model used predicts that the magnitude of the interharmonics is correlated with the active-power production. The predicted relation is derived in Section 5.1 and the measurement results are shown in Section 5.2. The main predicted trend is visible in the measurements, however the measurement results are impacted, among others by noise and spectral leakage.
- The model used also predicts a constant ratio between the emission at related interharmonic frequencies. The ratio is derived in Section 6.1 and the measurement results are shown in Section 6.2. In this case, there is less impact of noise and spectral leakage since the emission of studied frequency pairs are related to each other and simultaneously impacted.

3. Interharmonic origin and frequencies

3.1. Model of frequency conversion

The frequency on the generator side of the converter is equal to f_1. For a six-pulse rectifier this results in a voltage ripple with frequency $6f_1$ superimposed on the DC-bus voltage. The DC-bus voltage will contain, next to the DC component, components with frequencies $6f_1$, $12f_1$, $18f_1$, etc. The first frequency component is the dominant one. The amplitude of the ripple and the relation between the different frequency components depend among others on the size of the DC-bus capacitor.

The DC component is inverted into the power system frequency through the grid-side inverter, by modulation with a PWM switching pattern [13,14]. The resulting waveform on the grid side is regenerated mathematically by multiplication with $\cos(\omega_0 t)$ where $\omega_0 = 2\pi f_0$ and f_0 represents the power system frequency.

At the AC output of a converter, the current is the ratio of output voltage of the VSC and the grid-side impedance, assuming there is no background voltage distortion.