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Study of resonance in wind parks

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ABSTRACT

Wind turbine harmonic current emissions are a well-known power quality problem. These emissions flow through wind park impedances, leading to grid voltage distortion. Parallel resonance may worsen the problem because it increases voltage distortion around the resonance frequency. Hence, it is interesting to analyze the parallel resonance phenomenon. The paper explores this phenomenon in wind parks and provides analytical expressions to determine parallel resonances.

1. Introduction

Wind parks (WPs) comprising high power wind turbines (WTs) are increasing in number worldwide [1]. This leads to power quality problems such as WP and main grid current and voltage waveform distortion due to harmonic emissions of WTs equipped with power electronics [1–10]. Several studies have been conducted on these emissions based on actual measurement [1,3–6,8], and probabilistic procedures because WT behavior varies stochastically with time [1–3]. They conclude that dominant WT emissions belong to low-order harmonics (below 1 kHz). Moreover, a high-order harmonic pattern is recognized in the current spectrum between 1.0 and 7.5 kHz due to WT power electronic converter switching frequencies [7]. Recent studies show that WT harmonic emissions are also rich in interharmonics, which are measured and statistically characterized [8,9].

The impact of WT voltage and current emissions on WPs and the main grid can be increased by series and parallel resonances in the collection grid, respectively. Most research works model converters as harmonic current sources and analyze the influence of WP parameters on parallel resonance [1,7,8,11–18]. These studies are mainly based on frequency scan simulations which allow the frequency range and peak impedance values of parallel resonances to be established. Some studies point out analytical expressions to determine the frequency of the first parallel resonance, which can be close to low- and high-order harmonic emissions of WT power electronic converters [13,15]. Studies [7,13] also present a summary of the most important WP harmonic and resonance issues. Recent studies analyze resonance influence on stability of WT power converter control [17,18]. The variables affecting resonances are discussed in most of the previous studies but their influence is not analyzed in depth. In order to investigate this influence further, it is necessary to examine WP resonance frequencies in depth and provide analytical expressions for determining resonance frequencies close to the WT harmonic emission spectrum as a function of WP parameters. Some works also point out that the WT harmonic model as an ideal current source traditionally used to perform frequency scan studies could be inappropriate and provide misleading results because of the possible impact of converter control on resonance [7,17,18]. According to this, WT frequency-dependent models such as Norton equivalent sources are claimed to be used in WP resonance studies. These models would allow considering the influence of WT control on resonance frequencies.

This paper presents analytical expressions to calculate parallel resonance frequencies in onshore WPs and offshore WPs close to shore and thus detect power quality concerns due to WT current emissions. These expressions are obtained from Matlab/Simulink simulations [19] of a generic WP modeling WT behavior as ideal current sources. They are validated by several WP studies where parallel resonances are numerically and analytically identified. These studies also analyze WP parameter influence on resonance.

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Nomenclature

f_1	fundamental frequency of the grid supply voltage
f, k	frequency and harmonic
f_{p1}, f_{p2}, k_{p1}, k_{p2}	frequencies and harmonics of the first and second parallel resonances
R_{Tx}, X_{Tx}	HV/LV ($x=H$) and MV/LV ($x=L$) transformer impedances
R_L, X_L, X_C	MV cable longitudinal and transversal impedances
$R_{L,D}$, $X_{L,D}$, $X_{C,D}$	MV cable per-unit length longitudinal and transversal impedances
X_{CB}	capacitor bank reactance
η_{N_c}, β_{N_c}	coefficients of the second parallel resonance expression
AF_{kpi}	amplification factor at the resonance frequency
$Z_{E,\,kpi}$, $Z^{NC}_{E,\,kpi}$	impedances with and without capacitors at the resonance frequency
R_{f1}, R_f	Resistance values at the fundamental and other frequencies
α_c, α_t	MV cable and transformer skin-effect exponents

2. Wind parks

Fig. 1(a) shows a generic WP layout where WTs are supplied through low voltage (LV) underground cables and medium to low voltage (MV/LV) transformers and are interconnected with an $N_r \times N_c$ collection grid of medium voltage (MV) underground cables from the MV collector bus [7,8,11–13,15–17]. Capacitor banks in onshore WPs can also be connected to this bus and harmonic filters are usually installed on the line side of WT converters to mitigate frequency switching harmonics [7,8]. The MV collector bus is connected to the main grid with a high to medium voltage (HV/MV) transformer and a high voltage (HV) overhead line or underground cable in onshore or offshore WPs, respectively.

The harmonic current emissions of WT converters are generally low, and therefore voltage distortion usually remains below standard limits [2,3,10,20,21]. However, the presence of parallel resonance in the WP collection grid may increase voltage distortion above these limits and also affect WP harmonic emissions to the main grid [7,8]. Several works analyze the resonance problem at WT terminals by the frequency scan method and a few points out expressions to calculate the first parallel resonance. In the next Sections, WP harmonic behavior is studied to find analytical expressions for identifying the parallel resonance frequencies closest to the WT harmonic emission spectrum. Although a frequency scan provides more accurate results, it requires high computational effort to simulate different WP configurations with system modeling software and plotting of results obtained [7]. On the other hand, analytical expressions can be a fast, simple and useful engineering tool to analyze resonance frequencies prior to WP design.

3. Wind park harmonic analysis

For harmonic steady-state studies, WPs are modeled by their equivalent circuit (Fig. 1(b)), and the harmonic behavior of the passive set observed from the WTs is studied to identify resonance frequencies. The models of the main grid, HV/MV transformer, MV/LV transformer, MV underground cables and capacitor bank harmonic impedances in Fig. 1(b) (i.e., $\underline{Z}_{S,k}$, $\underline{Z}_{\mathrm{TH},k}$, $\underline{Z}_{\mathrm{TL},k}$, $\underline{Z}_{L,k}$, $\underline{Z}_{C,k}$ and $\underline{Z}_{\mathrm{CB},k}$, respectively) are as follows [8,12,18]:

$$\underline{Z}_{S,k} = R_S + jk \times X_S = \frac{U_O^2}{S_S} \times \left(\frac{U_{N,M}}{U_{N,H}}\right)^2 \frac{1}{\sqrt{1+\tan^2\varphi_{\mathrm{Scc}}}}(1 + j \times k \times \tan\varphi_{\mathrm{Scc}})$$

$$\underline{Z}_{\mathrm{TH},k} = R_{\mathrm{TH}} + jk \times X_{\mathrm{TH}} = \varepsilon_{\mathrm{THcc}} \times \frac{U_{N,M}^2}{S_{\mathrm{THN}}} \frac{1}{\sqrt{1+\tan^2\varphi_{\mathrm{THcc}}}}(1 + j \times k \times \tan\varphi_{\mathrm{THcc}})$$

$$\underline{Z}_{\mathrm{TL},k} = R_{\mathrm{TL}} + jk \times X_{\mathrm{TL}} = \varepsilon_{\mathrm{TLcc}} \times \frac{U_{N,\mathrm{M}}^2}{S_{\mathrm{TLN}}} \frac{1}{\sqrt{1+\tan^2\varphi_{\mathrm{TLcc}}}}(1 + j \times k \times \tan\varphi_{\mathrm{TLcc}})$$

$$\underline{Z}_{L,k} = R_L + j \times k \times X_L = D \times (R_{L,D} + j \times k \times X_{L,D}) \quad \underline{Z}_{C,k} = -j\frac{X_C}{k} = -j\frac{1}{k} \times \frac{1}{D} \times 2 \times X_{C,D}$$

$$\underline{Z}_{\mathrm{CB}k} = -j\frac{X_{\mathrm{CB}}}{k} = -j\frac{1}{k} \times \frac{U_{N,M}^2}{Q_C}, \tag{1}$$

where $k = f_k/f_1$ (with f_k and f_1 being the harmonic and fundamental frequencies, respectively) and, according to Fig. 1(a), U_O, S_S and $\tan\varphi_{\mathrm{Scc}}$ are the main grid open-circuit voltage, short-circuit power and X_S/R_S ratio at the point of coupling.

- $U_{N,H}/U_{N,M}$, S_{THN}, $\varepsilon_{\mathrm{THcc}}$ and $\tan\varphi_{\mathrm{THcc}}$ are the HV/MV transformer rated voltages and power, per-unit short-circuit impedance and $X_{\mathrm{TH}}/R_{\mathrm{TH}}$ ratio.
- $U_{N,M}/U_{N,L}$, S_{TLN}, $\varepsilon_{\mathrm{TLcc}}$ and $\tan\varphi_{\mathrm{TLcc}}$ are the MV/LV transformer rated voltages and power, per-unit short-circuit impedance and $X_{\mathrm{TL}}/R_{\mathrm{TL}}$ ratio.
- $R_{L,D}$, $X_{L,D}$ and $X_{C,D}$ are the MV cable per-unit-length longitudinal and parallel impedances and D is the MV cable length.
- Q_C is the capacitor bank reactive power consumption (i.e., the capacitor bank size).

Note that the following assumptions are made to develop the study from Fig. 1(b):

- Although, in order to consider the influence of WT control on consumed harmonic currents, WTs are better characterized as Norton equivalent sources [7], the typical WT harmonic model as ideal current source is used in the study because it is commonly chosen to perform frequency scan studies and it offers a useful insight into parallel resonance analysis [1,8,11–14,16]. However, further research is required to analyze the impact of WT control on this resonance.
- A distributed parameter model of the cables could be required for more accurate WP resonance analysis [7,16,17], but a concentrated parameter model is assumed because it provides good insights into the resonance problem and is commonly used in WP resonance studies [1,7,8,13,15].
- Only onshore WPs and offshore WPs close to shore (i.e., connected to the main grid through a short length underground cable of a few kilometers [1]) are considered in the study because the transversal impedance of the HV overhead line and underground cable is not considered (the longitudinal impedance is included in the impedances of the main grid and HV/MV transformer).
- LV underground cables are omitted because they are short, and therefore the capacitance values are very small and their longitudinal impedance can be included in the impedance of the MV/LV transformer.
- WT harmonic filters are not considered because they are only rated about 50 kvar per WT, and therefore only aggregation of filters for many WTs would shift the natural resonance of the WP [7]. Nevertheless, their possible influence on resonance frequencies is discussed in Section 6.3.

  Frequency scan analysis makes it possible to numerically determine resonances observed from any wind turbine [7]. As an example, Fig. 2(a) shows, labeled as Simulation no. 1, the frequency response of the system equivalent impedance without capacitor banks (i.e., $Q_C = 0$, and therefore $X_{\mathrm{CB}} = \infty$) at bus