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.

Keywords: Wind power generation; harmonic analysis; frequency scan

Nomenclature

N_r, N_c	number of rows and columns of the WP collection grid
R_S, X_S	grid resistance and reactance
R_{TH}, X_{TH}	HV/MV transformer resistance and reactance
R_{TL}, X_{TL}	MV/LV transformer resistance and reactance
R_L, X_L	MV cable longitudinal resistance and reactance
X_C	MV cable transversal reactance
$R_{L,D}$, $X_{L,D}$	MV cable per-unit length longitudinal resistance and reactance
$X_{C,D}$	MV cable per-unit length parallel reactance
X_{CB}	capacitor bank reactance
f_{p1}, f_{p2}	frequencies of the first and second parallel resonances

k_{p1}, k_{p2}	harmonics of the first and second parallel resonances
η_{N_c}, β_{N_c}.	coefficients of the second parallel resonance expression
AF_{kpi}	amplification factor at the resonance frequency
$Z_{E,kpi}, Z_{E,kpi}^{\mathrm{NC}}$	harmonic impedances with and without the WP capacitors at the resonance frequency
R_{f1}, R_f	Resistance values at the fundamental frequency and any frequency
α_c, α_t	MV cable and transformer skin-effect exponents
f_1	fundamental frequency of the grid supply voltage
f	frequency
k	harmonic
pu	per unit

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] – [8]. Several studies have been conducted on these emissions based on actual measurement, [1], [3] – [6], 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 in [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 [7], [8], [10] – [15]. 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 [12], [14]. Studies [7] and [12] also present a summary of the most important WP harmonic and resonance issues. The variables affecting resonances are discussed but their influence is not widely analyzed. 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. Recent works also point out that the WT harmonic model as ideal current source traditionally used to perform frequency scan studies could be inappropriate and provide misleading results because the converter control may affect resonance [??]. According to this, WT frequency-dependent models as Norton equivalent sources are claimed to be used in WP resonance studies. This WT frequency-dependent model would allow considering the influence of WT control on the resonance frequencies and also approaching analytical studies on this issue.

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 [16] of a generic WP considering 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 resonances.

FIGURE 1

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 x N_c collection grid of medium voltage (MV) underground cables from the MV collector bus [7], [8], [10] – [12], [14], [15]. 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. 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 EN 50160 limits [2], [3], [17]. 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., $\underline{Z}_{S,k}$, $\underline{Z}_{TH,k}$, $\underline{Z}_{TL,k}$, $\underline{Z}_{L,k}$, $\underline{Z}_{C,k}$ and $\underline{Z}_{CB,k}$, respectively) are as follows [8], [11]:

$$\begin{aligned}
\underline{Z}_{S,k} &= R_S + jk\cdot X_S = \frac{U_O^2}{S_S}\cdot\left(\frac{U_{N,\mathrm{M}}}{U_{N,\mathrm{H}}}\right)^2 \frac{1}{\sqrt{1+\tan^2\varphi_{Scc}}}(1+j\cdot k\cdot\tan\varphi_{Scc})\\
\underline{Z}_{TH,k} &= R_{TH} + jk\cdot X_{TH} = \varepsilon_{THcc}\cdot\frac{U_{N,\mathrm{M}}^2}{S_{THN}}\frac{1}{\sqrt{1+\tan^2\varphi_{THcc}}}(1+j\cdot k\cdot\tan\varphi_{THcc})\\
\underline{Z}_{TL,k} &= R_{TL} + jk\cdot X_{TL} = \varepsilon_{TLcc}\cdot\frac{U_{N,\mathrm{M}}^2}{S_{TLN}}\frac{1}{\sqrt{1+\tan^2\varphi_{TLcc}}}(1+j\cdot k\cdot\tan\varphi_{TLcc})\\
\underline{Z}_{L,k} &= R_L + j\cdot k\cdot X_L = D\cdot(R_{L,\mathrm{D}} + j\cdot k\cdot X_{L,\mathrm{D}})\\
\underline{Z}_{C,k} &= -j\frac{X_C}{k} = -j\frac{1}{k}\cdot\frac{1}{D}\cdot 2\cdot X_{C,\mathrm{D}}\\
\underline{Z}_{CBk} &= -j\frac{X_{CB}}{k} = -j\frac{1}{k}\cdot\frac{U_{N,\mathrm{M}}^2}{Q_C},
\end{aligned} \tag{1}$$

where $k = f_k/f_1$ (being f_k and f_1 the harmonic and the fundamental frequencies, respectively) and, according to Fig. 1(a),

- U_O, S_S and $\tan\varphi_{Scc}$ 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}, ε_{THcc} and $\tan\varphi_{THcc}$ are the HV/MV transformer rated voltages and

power, per-unit short-circuit impedance and X_{TH}/R_{TH} ratio.

- $U_{N,M}$ / $U_{N,L}$, S_{TLN}, ε_{TLcc} and $\tan\varphi_{TLcc}$ are the MV/LV transformer rated voltages and power, per-unit short-circuit impedance and X_{TL}/R_{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 [1], [8], [10] – [13], [15].
- A distributed parameter model of the cables could be required for more accurate WP resonance analysis [7], [15], but a concentrated parameter model is assumed because it provides an acceptable problem insight and is commonly used in WP resonance studies [1], [7], [8], [12], [14].
- 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).
- The LV underground cables are omitted because their length is short, and therefore the capacitance values are very small and their longitudinal impedance can be included in the impedance of the MV/LV transformer.
- The 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 will shift the natural resonance of the WP [7]. Nevertheless, their influence on resonance frequencies is discussed in Section 6.3.

FIGURE 2 and Table 1

Frequency scan analysis makes it possible to numerically determine resonances observed from any wind turbine. As an example, Fig. 2 shows the frequency response of the system equivalent impedance without capacitor banks (i.e., $Q_C = 0$, and therefore $X_{CB} = \infty$) at bus N_r1 (i.e., from WT_{Nr1}) for four different WP layouts (labelled as Examples #1). This response was numerically obtained by Matlab/Simulink simulation [16] considering the WP parameters in Table 1 (data #1 [6]) and it is referred to the MV level. Fig. 2 illustrates that two parallel resonances, $k_{p1} \approx 28$, 34, 49, 56, 72 and 106 (i.e., $f_{p1} = k_{p1} \cdot f_1 = k_{p1} \cdot 50 \approx 1.4$, 1.7, 2.45, 2.8, 3.6 and 5.3 kHz) and $k_{p2} \approx 110$ and 165 (i.e., $f_{p2} = k_{p2} \cdot f_1 = k_{p2} \cdot 50 \approx 5.5$ and 8.25 kHz), can appear close to harmonic emission frequencies of WT converters, and therefore they should be analyzed in order to prevent harmonic power quality problems [7] – [9], [12]. It must be noted that these resonances depend not only on WP electrical parameters, but also on WP configuration (i.e., number of rows N_r and columns N_c of the WP collection grid in Fig. 1(a)). Two additional frequency scan simulations are also shown in Fig. 2 in order to check the assumptions made about WP resistances and MV/LV transformers in the study,

- Examples #2: The system frequency response with WP resistances fifty times higher is shown in gray lines to illustrate that they damp the system harmonic response but do not affect resonance frequency identification significantly; hence, they can be neglected [8]. This damping phenomenon, which is discussed in Section 6, is mainly produced by the frequency-dependent resistance of the WP cables and transformers due to the skin effect [8].

- Examples #3: The system frequency response without the MV/LV transformers is shown in dashed black lines to illustrate that these transformers can be omitted in the study of the parallel resonance observed from wind turbines because they do not affect significantly these resonances. The MV/LV transformers influence series resonance and the equivalent impedance values of frequencies beyond the parallel resonance point.

4. Harmonic resonance without capacitor banks

As pointed out in the previous Section, the harmonic of the parallel resonances observed from any WT mainly depends on the WP reactances (resistances are neglected) and rows N_r and columns N_c of the collection grid. To study the identification of the first and second parallel resonances, Matlab/Simulink extensive simulations were made by varying the WP rows and columns from 1 to 20 (i.e., $N_r = 1$ to 20 and $N_c = 1$ to 20) and considering data #1 in Table 1 without capacitor banks (i.e., $Q_C = 0$, and therefore $X_{CB} = \infty$).

FIGURE 3 and 4

The harmonics of the parallel resonances observed from bus N_r1 for all the row and column combinations were numerically identified by simulation. Fig. 3(a) shows harmonics k_{p1} and k_{p2} of the first and second parallel resonances as a function of the collection grid rows N_r and for different values of the collection grid columns N_c. The harmonics of the parallel resonances in Fig. 2 are labeled with black dots in Fig. 3(a). From these results, it must be noted that

- Harmonic k_{p1} of the first parallel resonance depends on the WP electrical parameters and the N_r x N_c layout. The expression to determine k_{p1} can be deduced by considering that $k_{p1}\cdot X_L$ is much lower than $k_{p1}\cdot(X_S + X_{TH})$ and X_C / k_{p1}. From this assumption, the equivalent circuit without capacitor banks in Fig. 1(b) can be simplified to the circuit in Fig. 4(a) with $X_{CB} = \infty$, and the expression of the harmonic of the first parallel resonance observed from any WT is

$$k_{p1}\cdot(X_S + X_{TH}) = \frac{X_C}{2}\frac{1}{N_r\cdot N_c}\frac{1}{k_{p1}} \quad \Rightarrow \quad k_{p1} = \frac{1}{\sqrt{2}}\cdot(N_r\cdot N_c)^{-0.5}\cdot\sqrt{\frac{X_C}{X_S + X_{TH}}}. \qquad (2)$$

To validate (2), the harmonic k_{p1} calculated with the above expression and data #1 in Table 1 is compared with the simulation results in Fig. 3(a). It is numerically verified that the error with respect to the frequency scan results is below 10%.

- Harmonic k_{p2} of the second parallel resonance depends on the WP electrical parameters and the N_r x N_c layout. However, this resonance is independent of the collection grid columns for $N_c \neq 1$. The expression to determine k_{p2} is deduced by considering that $k_{p2}\cdot(X_S + X_{TH})$ is much higher than $k_{p2}\cdot X_L$ and X_C / k_{p2}. From this assumption, the equivalent circuit without capacitor banks in Fig. 1(b) can be simplified to the circuit in Fig. 4(b) and the expression of k_{p2} is a function of the MV underground cable ratio X_C/X_L and the collection grid layout. This expression could be deduced from the study of the equivalent circuit in Fig. 4(b) but it is no easy task. For this reason, it is determined with an empirical formula which is a function of the MV underground cable ratio X_C/X_L and the number of rows N_r and columns N_c of the collection grid. To deduce this formula, harmonic k_{p2} in Fig.3(a) is divided by the ratio $(X_C/X_L)^{1/2}$, and the obtained curves in Fig. 3(a) are fitted with a power function of N_r:

$$k_{p2} = \eta_{N_c}\cdot N_r^{-\beta_{N_c}}\cdot\sqrt{\frac{X_C}{X_L}} \qquad (3)$$
$$\eta_{N_c=1} = 1.979 \quad \beta_{N_c=1} = 0.929 \qquad \eta_{N_c\neq 1} = 1.087 \quad \beta_{N_c\neq 1} = 0.992.$$

To validate (3), the harmonic k_{p2} calculated with this expression and data #1 in Table 1 is compared with the simulation results in Fig. 3(a). It is numerically verified that the error with respect to the frequency scan results is below 5%.

In addition to the frequency, parallel resonance is also characterized by its impedance amplification factor which determines the severity of the resonance consequences. For this reason, the amplification factors of the parallel resonances observed from bus N_r1 for all the row and column combinations were numerically determined by simulation. These factors were defined as the ratio between the value of the harmonic impedance with and without the WP capacitors ($Z_{E,kpi}$ and $Z_{E,kpi}^{\mathrm{NC}}$, respectively) at the resonance frequency $f_{pi} = k_{pi} \cdot f_1$ (i = 1, 2 …), i.e.

$$AF_{kpi} = \frac{Z_{E,kpi}}{Z_{E,kpi}^{\mathrm{NC}}} \qquad (i = 1, 2). \tag{4}$$

Fig. 3(a)!!!! shows the attenuation factors of the first and second parallel resonances (i.e., AF_{kp1} and AF_{kp2}) as a function of the collection grid rows N_r and for different values of the collection grid columns N_c. It can be observed that …!!

5. Harmonic resonance with capacitor banks

The connection of capacitor banks to the MV collection bus affects parallel resonances. To study the identification of these resonance frequencies, extensive Matlab/Simulink simulations were made varying the WP rows N_r and columns N_c from 1 to 20 for ten steps of the capacitor bank size Q_C (i.e., $0.1 \cdot Q_C$ to Q_C) and considering data #1 in Table 1.

The first and second harmonics of the parallel resonances observed from bus N_r1 for all the row and column combinations were numerically identified by simulations. Fig. 3(b) shows harmonic k_{p1} of the first parallel resonance as a function of the collection grid rows N_r and for two different values of the collection grid columns N_c and three capacitor bank sizes. Fig. 3(b) shows harmonic k_{p2} of the second parallel resonance as a function of the collection grid rows N_r and for any number of WP columns and capacitor bank size (resonances are approximately independent of both variables). From these results, it must be noted that

- Harmonic k_{p1} of the first parallel resonance depends on the WP electrical parameters, the capacitor bank reactance and the N_r x N_c layout, with the capacitor bank reactance being the most influential variable. The expression to determine k_{p1} can be deduced by considering that $k_{p1} \cdot X_L$ is much lower than $k_{p1} \cdot (X_S + X_{TH})$, X_C / k_{p1} and X_{CB} / k_{p1}. From this assumption, the equivalent circuit with capacitor banks in Fig. 1(b) can be simplified to the circuit in Fig. 4(a), and the expression of the harmonic of the first resonance observed from any WT is

$$k_{p1} \cdot (X_S + X_{TH}) = \frac{X_{\mathrm{CEq}}}{k_{p1}} \quad \Rightarrow \quad k_{p1} = \sqrt{\frac{X_{\mathrm{CEq}}}{X_S + X_{TH}}}$$
$$X_{\mathrm{CEq}} = \frac{X_{CB} \cdot \frac{X_C}{2} \frac{1}{N_r \cdot N_c}}{X_{CB} + \frac{X_C}{2} \frac{1}{N_r \cdot N_c}}. \tag{5}$$

  To validate (5), the harmonic k_{p1} calculated with this expression and data #1 in Table 1 is compared with the simulation results in Fig. 3(b). It is numerically verified that the error with respect to the simulations of the frequency scan results is below 2%.

- Harmonic k_{p2} of the second parallel resonance only depends on the WP electrical parameters and the collection grid rows N_r. Beyond this, it can be observed that this resonance in Fig. 3(b) is produced at the same harmonic values as the second parallel resonance without capacitor banks and $N_c \neq 1$ in Fig. 3(a). Thereby, harmonic k_{p2} can be determined by the empirical formula in (3) with $N_c \neq 1$. To validate this, the harmonic k_{p2} calculated with this expression and data #1 in Table 1 is compared with the simulation results in Fig. 3(b). It is numerically verified that the error with respect to the frequency scan results is below 6.5%. The expression of k_{p2} can be analyzed by consider that X_{CB}/k_{p2} is much lower than $k_{p2}\cdot(X_S + X_{TH})$, X_C/k_{p2}. From this assumption, the equivalent circuit with capacitor banks in Fig. 1(b) can be simplified to the circuit in Fig. 4(c), and the expressions of k_{p2} only depend on the MV underground cable ratio X_C/X_L and the collection grid rows N_r. Actually, the circuit in Fig. 4(c) is the same as that derived from Fig. 4(b) if the case $N_c \neq 1$ is analyzed.

In addition to the resonance frequencies, Fig. 3(b)!!! shows the impedance amplification factor (4) of the parallel resonances observed from bus N_r1 as a function of the collection grid rows N_r and for different values of the collection grid columns N_c and capacitor bank sizes Q_C. It can be observed that …!!

6. Impact of WP characteristics on resonance

Previous studies are performed for symmetrical N_r x N_c WPs (i.e., WPs with the same number of WTs, N_r, for each of their N_c columns) and without considering the resistances and the MV/LV transformers. In the following subsections, the influence of these assumptions is analyzed.

6.1. Deviations from the WP row and column symmetry

It is checked from simulations that, according to Fig. 4(b), the expressions of the first parallel resonance in (2) and (5) can be generalized for any deviation from the WP symmetry (i.e., for any number of WTs for each column) as follows

$$k_{p1}=\sqrt{\frac{X_{CEq}}{X_S+X_{TH}}}$$

$$X_{CEq}=\frac{X_{CB}\cdot\sum_{n=1}^{N_c}X_{C,n}}{X_{CB}+\sum_{n=1}^{N_c}X_{C,n}}\qquad X_{C,n}=\frac{X_C}{2}\frac{1}{N_{r,n}},\tag{6}$$

where $X_{C,n}$ is the equivalent capacitor of the n^{th} column (n = 1 to N_c) and $N_{r,n}$ is the number of WTs (or rows) for each of the n^{th} columns. It can be observed that (2) and (5) can be derived from (6) if $N_{r,n} = N_r$ (n = 1 to N_c) and there is not connected any capacitor bank (i.e., $Q_C = 0$, and therefore $X_{CB} = \infty$) and if $N_{r,n} = N_r$ (n = 1 to N_c), respectively.

On the other hand, it is also numerically verified that the expressions of the second parallel resonance in (3) cannot be generalized for any deviation from the WP symmetry because it mainly depends on the MV cable parameters (see Fig. 4(b)) and it is difficult obtaining a general analytical expression of these resonance for any WP configuration.

6.2. Frequency-dependent resistances

According to Fig. 2, WP resistances damp the system harmonic response but do not affect resonance frequency. The damping phenomenon, mainly produced by the frequency-dependent resistance of the WP cables and transformers due to the skin effect, is analyzed in this Section. This effect is modeled as [8]

$$R_f=R_{f_1}\cdot\left(\frac{f}{f_1}\right)^{\alpha_d}\qquad (d=c,t),\tag{7}$$

where R_{f1} and R_f are the resistances at the fundamental frequency f_1 and the analyzed frequency f and α_d with $d = c$ and t are the cable and transformer skin-effect exponents which usually range between 0 to 0.4 and 0 to 0.8, respectively.

Considering (7) in the resistances of the MV underground cables and WP transformers (1), Fig. 5 shows the influence of the skin-effect on the frequency response of the 15x5 system equivalent impedance in Fig. 3. It is observed that the frequency-dependent resistance has no impact on the resonance frequencies, but damps the equivalent impedance at these frequencies (for frequency beyond the resonance point, impedances are not much affected), and the higher the resonance frequency, the higher the damping phenomenon is [8].

6.3. Passive harmonic filters

Shunt filters are installed at the WT bus (between the WT and the MV/LV transformer) as harmonic mitigation technique of large WTs. In order to observe the influence of these filters on the frequency response of the WP equivalent impedance, three examples with different filters connected at all the WT buses are performed in the 15x5 system in Fig. 3:

- Filter #1: Notch filters tuned at the 7^{th} harmonic order.
- Filter #2: Notch filters tuned at the 25^{th} harmonic order.
- Filter #3: Second-order high-pass filters tuned at the 13^{th} harmonic order.

Fig. 5 shows the results (the 15x5 system without filters is labelled as Filter #0). Notch filters produce a valley around the tuned frequency and it can shift or damp the natural parallel resonance of WPs if this frequency is far or close from the resonance point, respectively. However, a significant peak still appears in the equivalent impedance which is basically provoked by the filter and the WP impedances. Second-order high-pass filters damp resonance above the tuned frequency.

It must be noted that, the study has been performed for a particular cases and further research should be made in order to understand the WT influence on WP resonance.

FIGURE 5

7. Application of harmonic resonance identification

The parallel resonances of a 4x6 WP with data #2 in Table 1 (called Case #1) are numerically and analytically obtained from Matlab/Simulink simulations and the expressions in the paper, respectively. The cable and transformer skin-effect (7) is also considered in the simulations with skin factors α_c = 0.2 and α_c = 0.4, respectively. The resonances of the following four cases are also studied to illustrate the influence of the main grid short-circuit power, MV cable length, WP size and capacitor bank connection on resonance:

- Case #2: A weak grid with a short-circuit power of 2500 MVA (i.e., with S_S/S_N = 20) is considered.
- Case #3: WTs are up to 1 km away from each other.
- Case #4: WP size is reduced to a 2x2 layout.
- Case #5: A capacitor bank of 40 MVA is connected.

FIGURE 6

Fig. 6 plots the frequency response of all cases studied and Table 2 shows the numerical (N) and analytical (A) results of the parallel resonances. The accuracy of the analytical expressions with a maximum error of 2% is worth noting. The following conclusions can be drawn:

- Case #2: Weak grids with low short-circuit power can shift the first resonance to the 1.0 to 2.0 kHz frequency range of the WT high-order harmonic emission pattern due to the large values of the grid reactance X_S (see $Z_{S,k}$ expression in (1)) and lead to low k_{p1} resonance values in (2), (5) and (6). According to (3), the second resonance is not affected by the main grid short-circuit power.
- Case #3: WTs far away from each other can also shift resonances to the 1.0 to

2.0 kHz frequency range of the WT high-order harmonic emission pattern in WPs without capacitor banks because the first parallel resonance (2) is inversely proportional to the square root of the cable length:

$$k_{p1} = (N_r \cdot N_c)^{-0.5} \sqrt{\frac{1}{D}} \cdot \sqrt{\frac{X_{C,D}}{X_S + X_{TH}}}. \qquad (7)$$

and the second parallel resonance (3) is inversely proportional to the cable length:

$$k_{p2} = \frac{1}{\sqrt{2} \cdot D} \cdot \eta_{N_c} \cdot N_r^{-\alpha_i} \cdot \sqrt{\frac{X_{C,D}}{X_{L,D}}}. \qquad (8)$$

According to the above comments, it can be verified in the examples that $51 \cdot (0.5/1)^{1/2} = 36.1$ and $260 \cdot (0.5/1) = 130$ which approximately matches with the simulation results in Case #1 and #3.

- Case #4: From the analytical expressions of the parallel resonances, it can be observed that these resonances are closer to low-order harmonics in large WPs than in small WPs because parallel resonance frequencies move to lower order harmonics when the columns and rows of WPs increase.
- Case #5: In WPs with capacitor banks, these banks modify parallel resonances but only the first is directly affected (the larger the capacitor size, the lower the harmonic order of the first parallel resonance). This resonance mainly depends on the main grid and HV/MV transformer reactance and the capacitor bank size (5). Thus, in these WPs, only parallel resonance k_{p2} is affected by cable length and is inversely proportional to this length, as in WPs without capacitor banks (8).

Note that the expressions in the paper are useful to determine that, in the studied cases, the frequency of resonance k_{p2} is greater than WT harmonic emissions.

The voltage distortions at bus N_r1 (i.e., at WT_{Nr1} terminals where the resonance is analysed) and at collector bus are also numerically obtained from Matlab/Simulink simulations considering WT harmonic current emissions (magnitude and phase angle). The harmonic limits in the German Electricity Association (VDEW) Standard for generators connected to a medium voltage networks are set as the WT current emission magnitudes [A]. Although the standard is for medium voltage networks, it provides specific magnitude values of the generator (or WT) harmonic limits based on the grid short-circuit ratio *SCR* which can be easily included in the simulation program and they are quite similar (in particular harmonics below 1.5 kHz), for a short-circuit ratio of 20 (pu grid impedance of 5%), to the distortion limit requirements in IEEE Standard 15471 [B]. Regard to the harmonic current phase angles, there is a lack of data about them but it is commonly accepted that they are considered uniformly distributed over the $[0, 2\cdot\pi)$ interval (in particular the high-order harmonics). Thus, the harmonic voltage distortions are obtained from the 95% percentile value of 10000-shot Monte Carlo Matlab simulations where the harmonic phase angles of each WT are randomly set with the distribution $U(0, 2\cdot\pi)$. Fig. 7(a) plots the VDEW current emission requirements used in the simulations and Fig. 7(b) plots the voltage distortion results for Cases #1, 3 ad 5. It must be noted that the voltage distortion pattern obtained in both buses matches with the parallel resonances although the distortions at the collector bus are slightly lower (or even much lower as in Case #3) because parallel resonance is more damped at this bus. Comparing Case #1 and #3, it can be observed the consequence of an exact (kp1 = 51) and a close (kp1 = 7.3) resonance to some frequencies of the WT harmonic current emissions. Higher and more dangerous harmonic voltage distortions can be raised when the resonance matches exactly with these frequencies. The performed study is a particular example and further research should be made for accurately evaluating the impact of resonance on WP power quality because WP data (e.g., magnitudes and phase angles of WT harmonic current emissions or cable and transformer skin-effect exponents) can significantly affect the value of these distortions.

8. Conclusions

This paper presents analytical expressions to determine parallel resonance frequencies in onshore WPs and offshore WPs close to shore with and without capacitor banks. These expressions are useful to detect power quality problems due to WT harmonic current emissions and to analyze the influence of grid short-circuit power and WP parameters on resonance. The analytical expressions are validated by analyzing the frequency response of several WP simulations. Although WT behavior as ideal current source is considered in the study, they offer a useful insight about parallel resonances. However, further studies should be conducted in order to analyze the influence of WT control on these resonances. Offshore WPs far from shore could also be investigated in future works to study the influence of long-length HV underground cables on parallel resonance based on the proposed resonance study framework. Moreover, other WP layouts could be analyzed to determine the impact of WT distribution on resonance.

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Table Captions

Table 1. Wind park parameters.

Table 2. Application results.

Figure Captions

Fig. 1. Wind park: a) Typical wind park layout. b) Wind park equivalent circuit.

Fig. 2. Wind park harmonic response.

Fig. 3. Wind park parallel resonances (data #1 in Table 1): a) Parallel resonance without capacitor banks. b) Parallel resonance with capacitor banks.

Fig. 4. Wind park equivalent circuits: a) Equivalent circuit at harmonic k_{p1} with and without capacitor banks (i.e., $X_{CB} \neq \infty$ and $X_{CB} = \infty$, respectively). b) Equivalent circuit at harmonic k_{p2} without capacitor banks. c) Equivalent circuit at harmonic k_{p2} with capacitor banks.

Fig. 5. 15x5 wind park harmonic response: (a) Influence of the skin effect. (b) Influence of the wind turbine harmonic filters.

Fig. 6. Wind park harmonic response.

Fig. 7. Wind park harmonic distortions.