Wind power plant resonances
风力发电厂的共振

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Abstract - **Onshore and offshore wind power plants comprising wind turbines equipped with power converters are increasing in number worldwide. Harmonic emissions in power converters distort currents and voltages, leading to power quality problems. Low order resonances in the collector grid can increase the impact of wind turbine emissions. These resonances may also produce electrical instabilities in poorly damped wind power plants. The paper performs frequency scan with Matlab/Simulink simulations and compares low order frequencies of parallel resonances in onshore and offshore wind power plants. It also investigates the influence of wind power plant variables on resonance. Finally, simplified equivalent circuits of wind power plants are proposed to study low order parallel resonances.**

Keywords - **Wind power generation, resonance, frequency scan.**

I. INTRODUCTION

The presence of wind power plants (WPPs) with wind turbines (WTs) equipped with power electronics is currently increasing in traditional power systems [1]. Several power quality concerns related to harmonic emissions of these WTs are present in WPPs [1] – [6]. These concerns increase with parallel resonances in the WPP collector grid at frequencies close to harmonic emissions. These resonances are due to the interaction between inductors and capacitors of the WPP network, [1], [4] – [9]. Several works study WPP resonance to address harmonic concerns [4] – [9]. The most important WPP harmonic and resonance issues are illustrated in [4], [6], [8]. Recent works also study resonance influence on stability of WT converters [10] – [12]. Low order resonances are the most worrisome because they can be close to low order harmonic emissions of power converters and to the poorly damped frequency range. Resonance studies are mainly based on frequency scan analysis, which establishes the frequency range and peak impedance values of resonances. A few works include analytical expressions to determine low order parallel resonance frequency [8], [13], [14]. The influence of WPP parameters on resonances is also discussed in most of the

above studies. In order to investigate this influence further, it is necessary to examine WPP resonance frequencies in depth from frequency scan or analytical expressions which characterize resonance frequencies as a function of WPP parameters [14].

The present work analyzes WPP parallel resonance from frequency scan with Matlab/Simulink simulations. It compares low order parallel resonance frequencies in onshore and offshore WPPs. The impact of WPP parameters on resonance is also investigated. Approximated equivalent circuits for analyzing WPP parallel resonance are proposed from the above studies.

II. WIND POWER PLANTS

The configuration of a generic WPP layout is shown in Fig. 1. Type 4 WTs are supplied from the strings of the N_r x N_c
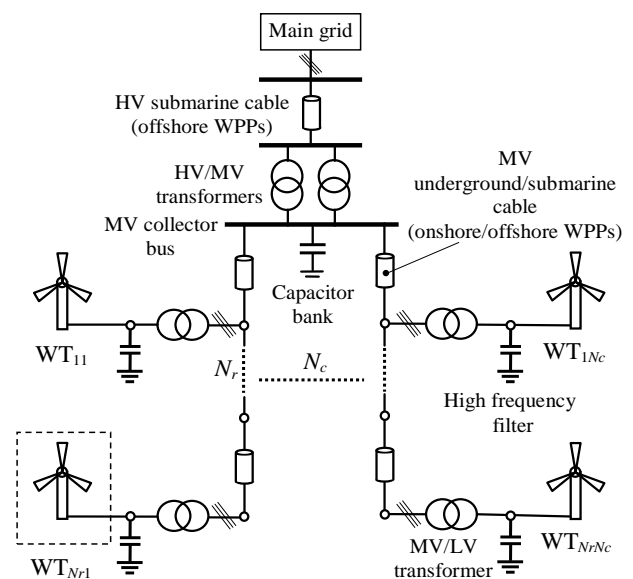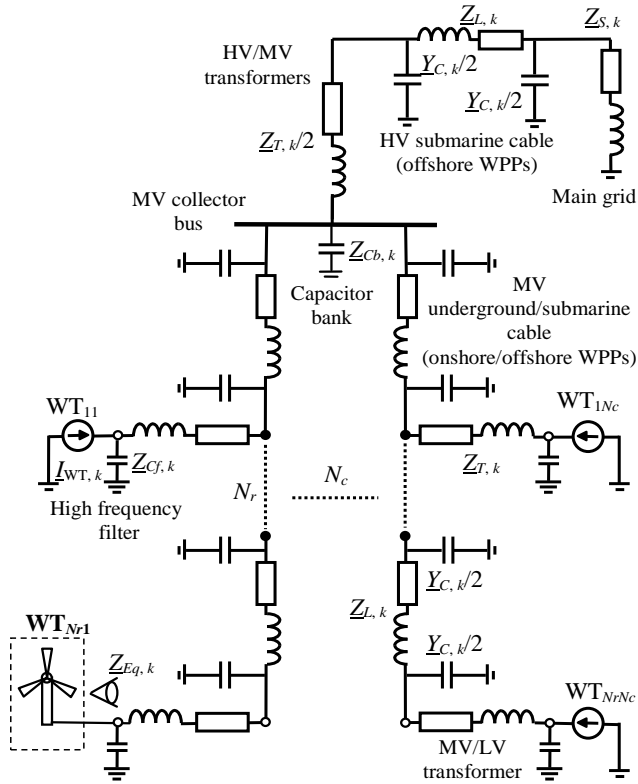

Fig.1. Wind power plant layout

Fig.2. Wind power plant equivalent circuit

collector grid through step-down medium to low voltage (MV/LV) transformers. High frequency filter capacitors are usually installed on the grid-side of WT converters to mitigate frequency switching harmonics [4], [5]. The strings are interconnected with medium voltage (MV) underground cables in onshore WPPs and MV submarine cables in offshore WPPs. These cables are clustered at the MV collector bus [4], [5], [6] – [10], [13]. In onshore WPPs, capacitor banks can also be connected to this bus in order to compensate reactive power. The MV collector bus is connected to the main grid with two step-down high to medium voltage (HV/MV) transformers in parallel. In onshore WPPs, the transformers are directly connected to the main grid while, in offshore WPPs, high voltage (HV) submarine cables are used to link the transformers to the main grid on shore.

Voltage distortion of the WPP collector grid usually remains below standard limits because WT converter harmonic emissions are generally low [2], [3], [15], [16]. However, parallel resonances may increase distortion above these limits and affect WT operation if the resonance frequency is close to WT converter emission harmonics [4], [5]. These resonances may also affect stability of WT converters [10] – [12]. The frequency scan method is commonly used in the literature to characterize the resonance problem at WT terminals and approach harmonic penetration and WT stability studies.

II. WIND POWER PLANT HARMONIC MODEL

In order to perform frequency scan, the WPPs are characterized by the equivalent circuit in Fig. 2, and the equivalent harmonic impedance $\underline{Z}_{\mathrm{Eq},\,k}$ at the WTs must be determined to identify resonance frequencies. To do that, the harmonic impedances of the main grid, $\underline{Z}_{S,\,k}$, HV/MV and MV/LV transformers, $\underline{Z}_{T,\,k}$, HV and MV underground/submarine cables, $\underline{Z}_{L,\,k}$, capacitor bank, $\underline{Z}_{Cb,\,k}$, and high frequency filters, $\underline{Z}_{Cf,\,k}$, are modeled as follows [4], [5], [7]:

$$\underline{Z}_{S,k} = \frac{U_O^2}{S_S} \frac{1}{\sqrt{1+\tan^2\varphi_S}}\left(1 + jk\tan\varphi_S\right)$$

$$\underline{Z}_{T,k} = \varepsilon_{cc}\frac{U_{N,\mathrm{s}}^2}{S_N}\frac{1}{\sqrt{1+\tan^2\varphi_{cc}}}\left(1 + jk\tan\varphi_{cc}\right) \quad (1)$$

$$\underline{Z}_{L,k} = \underline{Z}_{Lx,k}\frac{\sinh\left(\underline{\gamma}_{x,k}D\right)}{\underline{\gamma}_{x,k}} \qquad \underline{Y}_{C,k} = \underline{Y}_{Cx,k}\frac{\tanh\left(D\underline{\gamma}_{x,k}/2\right)}{\underline{\gamma}_{x,k}/2}$$

$$\underline{Z}_{Cb,k} = -j\frac{1}{k}\frac{U_{Nb}^2}{Q_{Cb}} \qquad \underline{Z}_{Cf,k} = -j\frac{1}{C_f k\omega_1},$$

where $k = f_k/f_1$ (with f_k and f_1 being the analyzed harmonic frequency and the main grid fundamental frequency, respectively), $\omega_1 = 2\pi \cdot f_1$ and,

- U_O, S_S and $\tan\varphi_S$ are the main grid open-circuit voltage,

TABLE 1. WPP PARAMETERS (WTs OF $P_{WT} = 5$ MW)

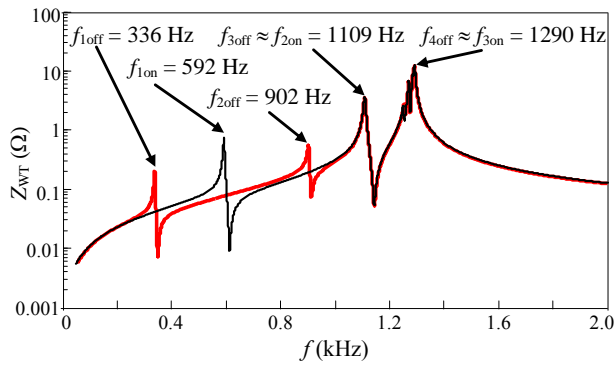|		
Main grid	U_0 (f_1)	150 kV (50 Hz)
	S_S	$(10\ldots100)\cdot N_rN_cP_{WT}$
	$\tan\varphi_S$	20 pu
HV/MV transformers	$U_{N,\,H}/U_{N,\,M}$	150/33 kV
	S_N	125 MVA
	ε_{cc} $(\tan\varphi_{cc})$	0.1 pu (12 pu)
MV/LV transformer	$U_{N,\,M}/U_{N,\,L}$	33/0.69 kV
	S_N	5 MVA
	ε_{cc} $(\tan\varphi_{cc})$	0.05 pu (12 pu)
HV submarine cable (offshore WPPs)	R_x	0.032 Ω/km
	L_x	0.401 mH/km
	C_x	0.21 μF/km
	D_{HV}	1 to 50 km
MV underground /submarine cable (onshore/offshore WPPs)	R_x	0.041 Ω/km
	L_x	0.38 mH/km
	C_x	0.23 μF/km
	D_{MV}	0.5 to 1 km
Compensation and filter equipment	Q_{Cb}	0 … 50 Mvar
	C_f	1000 μF

Fig. 3. Frequency scan of 8x5 onshore (black line) and offshore (red line) WPPs (data in Table 1, with S_S = 2500 MVA, D_{HV} = 25 km, D_{MV} = 1 km and Q_{Cb} = 0 Mvar)

short-circuit power and X_S/R_S ratio at the point of coupling.

- $U_{N,p}/U_{N,s}$, S_N, ε_{cc} and $\tan\varphi_{cc}$ are the HV/MV and MV/LV transformer rated primary/secondary voltages and power, per-unit short-circuit impedance and X_{cc}/R_{cc} ratio.

- $\underline{\gamma}_{x,k} = (Z_{Lx,k}\cdot\underline{Y}_{Cx,k})^{1/2}$ is the propagation constant of the cable, $Z_{Lx,k} = R_x + jL_x k\omega_1$ and $Y_{Lx,k} = jC_x k\omega_1$ are the cable distributed parameters and D is the cable length.

- U_{Nb} and Q_{Cb} are the capacitor bank rated voltage and reactive power consumption (i.e., the capacitor bank size).

- C_f is the WT high frequency filter capacitor.

The transformers are modeled as RL equivalent circuits and the WTs are modeled as ideal current sources. These models are accurate enough to analyze the influence of WPP parameters on low order resonances. The WT current source model is commonly chosen to perform frequency scan studies because it offers a useful insight into low order parallel resonance analysis [1], [4], [5] [8], [13]. Table 1 shows usual WPP parameter values.

II. ONSHORE AND OFFSHORE WPP RESONANCES

The frequency response of an 8x5 onshore and an 8x5 offshore WPP (data in Table 1) is determined to compare their low order parallel resonances. Both WPPs consist of 40 type 4 WTs (i.e., full-scale VSC WTs), each with a rated capacity of 5 MW, arranged in five strings of 33 kV underground/submarine cables. These strings collect eight WTs (separated 1 km from each other) at the collector substation. This substation is directly connected to the main grid in the onshore WPP and by a 25 km submarine cable in the offshore WPP. The short circuit power of the main grid is 2500 MVA and capacitor banks are not connected to the collector bus of the onshore WPP (i.e., Q_{Cb} = 0 Mvar). The results of the equivalent harmonic impedance $\underline{Z}_{Eq,k}$ at WT_{Nr1} (see Fig. 2) are illustrated in Fig. 3. From these results, it can be noted that
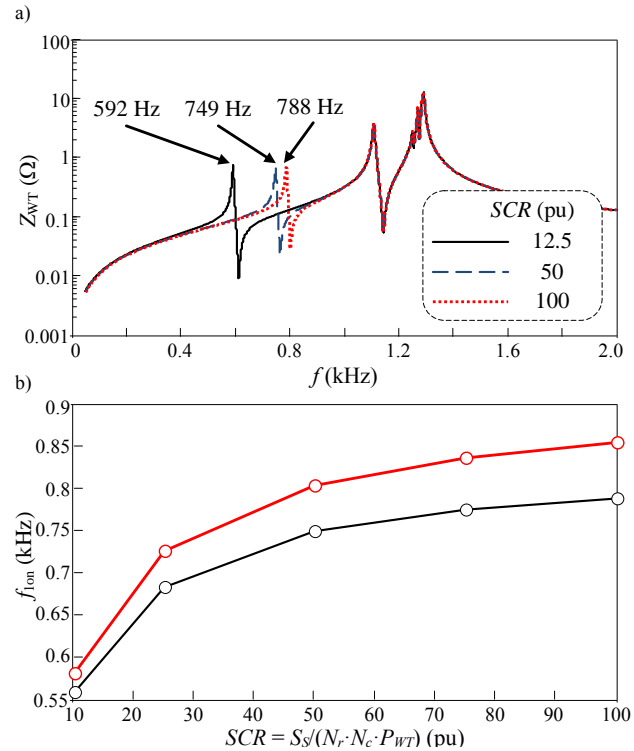

Fig. 4. Influence of the short circuit ratio, SCR, of the main grid on 8x5 onshore WPP resonance (data in Table 1, with D_{MV} = 1 km and Q_{Cb} = 0 Mvar): a) Frequency scan. b) Frequency of first parallel resonance vs Short circuit ratio (black lines: Equivalent circuit in Fig. 2; red lines: Equivalent circuit in Fig. 19)

- WPP connection to shore by the HV submarine cable is the only difference between the onshore and offshore WPPs. The difference between the first parallel resonances of the onshore WPP (at f_{1on} = 592 Hz) and offshore WPP (at f_{1off} = 336 Hz) is due to the transversal capacitors of the cable. These capacitors shift the parallel resonance to low order frequencies, which are close to WT harmonic emissions.

- The HV submarine cable of the offshore WPP also produces a parallel resonance at f_{2off} = 902 Hz which does not appear in the onshore WPP. The frequency of this parallel resonance depends on the cable length, as is analyzed in Subsection 4.3.

- Parallel resonances above 1 kHz (i.e., $f_{3off} \approx f_{2on}$ and $f_{4off} \approx f_{3on}$) are not affected by the capacitors of the HV submarine cable, thus being similar in both WPPs.

III. ONSHORE WPP RESONANCE STUDY

The frequency response of the 8x5 onshore WPP in Section II (data in Table 1) is analyzed to study the influence of the main grid short circuit ratio, $SCR = S_S/(N_r\cdot N_c\cdot P_{WT})$, WPP layout (i.e., number of WTs and strings N_r, and N_c), MV underground cable length, D_{MV}, and capacitor bank size, Q_{Cb}, on low order parallel resonances. To study the influence of these parameters, Matlab/Simulink simulations are made by varying their values. In these simulations, frequency scan is
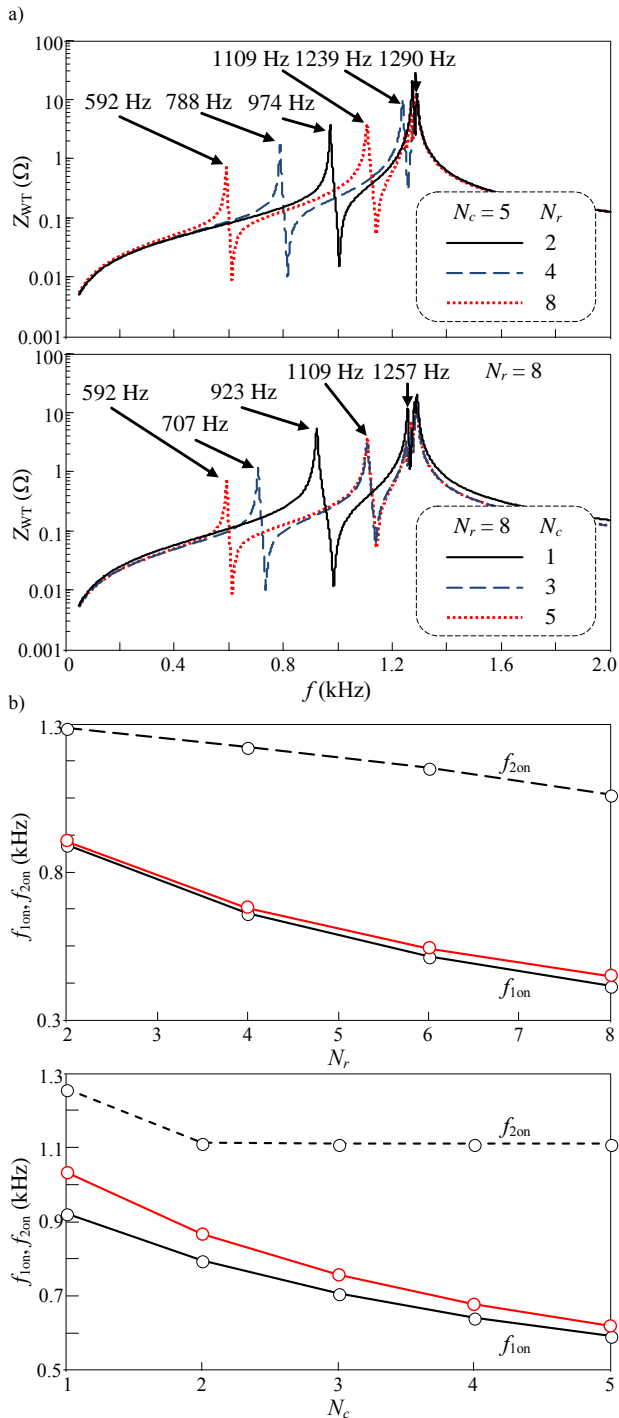
a)

a)

b)

Fig. 6. Influence of MV underground cable length, D_{MV}, on 8x5 onshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu and $Q_{Cb} = 0$ Mvar): a) Frequency scan. b) Frequency of first and second parallel resonances vs MV underground cable length (black lines: Equivalent circuit in Fig. 2; red lines: Equivalent circuit in Fig. 19)

In order to study the influence of the short circuit ratio, SCR, of the main grid on parallel resonance, Matlab/Simulink simulations are made by varying the short circuit ratio value from 10 to 100 (i.e., $S_S = 2000$ MVA to 20000 MVA considering the 8x5 WPP with 5 MW WTs in the study). As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq,k}$ at WT_{Nr1} for three values of the short circuit ratio ($SCR = 12.5$, 50 and 100) is shown in Fig. 4(a). From these results, it can be noted that

- Small values of the short circuit ratio (i.e., grids that tend to be weak) lead to high values of the main grid inductances (1), which shift the first parallel resonance, f_{1on}, to low frequencies.

- The other parallel resonances are not affected by the main grid inductance, and therefore they are not affected by the short circuit ratio.

The influence of short circuit ratio on the first parallel resonance, f_{1on}, is illustrated with black lines in Fig. 4(b). It can be observed that grids that tend to be weak (i.e. grids with low short circuit ratios) can shift the first parallel resonance to the low frequency range because of the large values of the main grid inductances. Thus, weak grids can produce onshore WPP resonances close to WT harmonic emissions.

3.2. INFLUENCE OF WIND POWER PLANT LAYOUT

In order to study the influence of the number of WTs, N_r, and strings, N_c, on parallel resonance, Matlab/Simulink

b)

Fig. 5. Influence of WPP layout on onshore N_rxN_c WPP resonance (data in Table 1, with $SCR = 12.5$ pu, $D_{MV} = 1$ km and $Q_{Cb} = 0$ Mvar): a) Frequency scan. b) Frequency of first and second parallel resonances vs N_r and N_c (black lines: Equivalent circuit in Fig. 2; red lines: Equivalent circuit in Fig. 19)

performed at WT_{Nr1} (see Fig. 2) and the equivalent harmonic impedance $\underline{Z}_{Eq,k}$ is obtained. Subsequently, the frequency of the parallel resonances is numerically identified from the frequency scan.

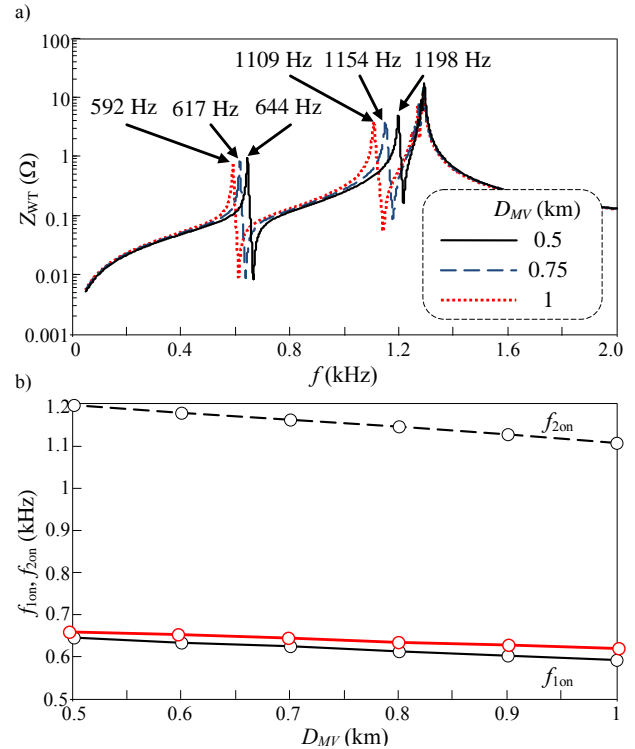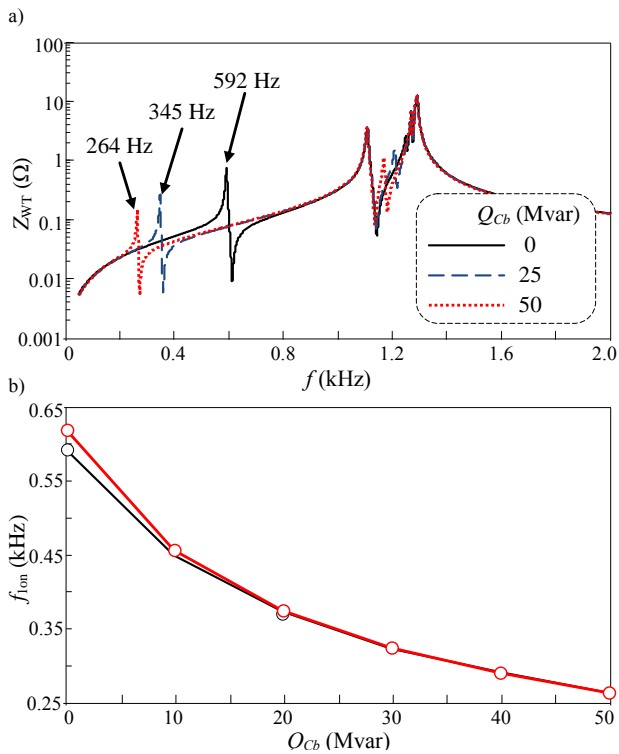3.1. INFLUENCE OF SHORT CIRCUIT RATIO

a)

b)

Fig. 7. Influence of capacitor bank size, Q_{Cb}, on 8x5 onshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu and $D_{MV} = 1$ km): a) Frequency scan. b) Frequency of first parallel resonance vs Capacitor bank size (black lines: Equivalent circuit in Fig. 2; red lines: Equivalent circuit in Fig. 19)

simulations are made by varying the N_r value from 2 to 8 and the N_c value from 1 to 5. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq,\,k}$ at WT$_{Nr1}$ for three values of N_r ($N_r = 2$, 4 and 8) and for three values of N_c ($N_c = 1$, 3 and 5) is shown in Fig. 5(a). From these results, it can be noted that

- High number of the WTs and strings shift the first and second parallel resonances, f_{1on} and f_{2on}, to low frequencies.

The influence of WPP layout on the first and second parallel resonances f_{1on} and f_{2on} is illustrated with black lines in Fig. 5(b). It can be observed that parallel resonances are closer to low order harmonics in large onshore WPPs than in small onshore WPPs because parallel resonance frequencies move to lower order harmonics with increasing the number of WTs and strings. An exhaustive study of this influence is presented in [14].

3.3. INFLUENCE OF MV UNDERGROUND CABLE LENGTH

In order to study the influence of MV underground cable length, D_{MV}, on parallel resonance, Matlab/Simulink simulations are made by varying the cable length value from 0.5 km to 1 km. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq,\,k}$ at WT$_{Nr1}$ for three values of the cable length ($D_{MV} = 0.5$, 0.75 and 1 km) is shown in Fig. 6(a). From these results, it can be noted that

- High values of the MV cable length shift the first and second parallel resonances, f_{1on} and f_{2on}, to low
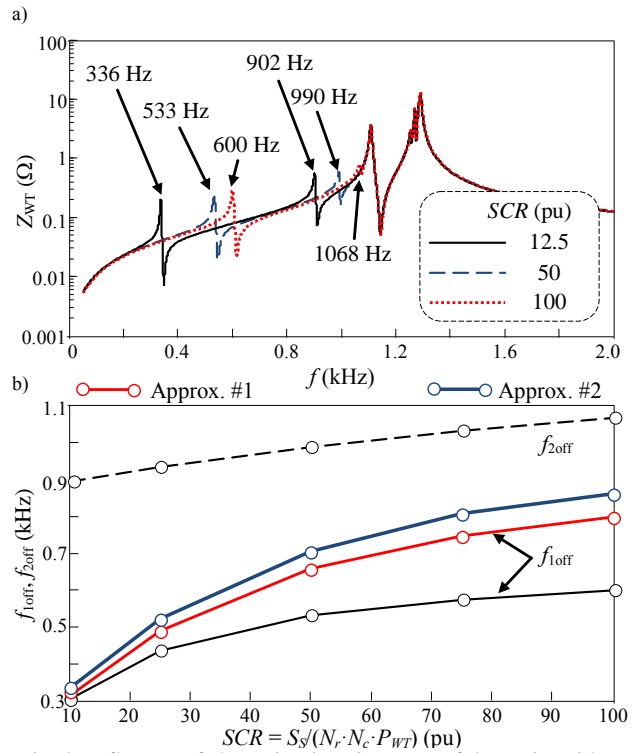
a)

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Fig. 8. Influence of short circuit ratio, SCR, of the main grid on 8x5 offshore WPP resonance (data in Table 1, with $D_{HV} = 25$ km and $D_{MV} = 1$ km): a) Frequency scan. b) Frequency of first and second parallel resonances vs Short circuit ratio (black lines: Equivalent circuit in Fig. 2; red and blue lines: Equivalent circuit in Fig. 19)

frequencies because of the higher value of transversal capacitors of the cable. However, these resonance frequencies exhibit a low sensitivity to MV cable length.

- The other parallel resonance is not affected by cable length.

The influence of MV cable length on the first and second parallel resonances f_{1on} and f_{2on} is illustrated with black lines in Fig. 6(b). It can be observed that, although the frequency of the parallel resonances is only slightly affected by cable length, it decreases with long MV underground cables. Thus, WPPs with WTs far away from each other can produce onshore WPP resonances close to WT harmonic emissions.

3.4. INFLUENCE OF CAPACITOR BANK SIZE

In order to study the influence of capacitor bank size, Q_{Cb}, on parallel resonance, Matlab/Simulink simulations are made by varying the reactive power consumption value of the capacitor bank from 0 Mvar to 50 Mvar. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq,\,k}$ at WT$_{Nr1}$ for three values of the capacitor bank size ($Q_{Cb} = 0$, 25 and 50 Mvar) is shown in Fig. 7(a). From these results, it can be noted that

- High values of capacitor bank size shift the first parallel resonance, f_{1on}, to low frequencies because of the increase in capacitors connected to the collector bus.

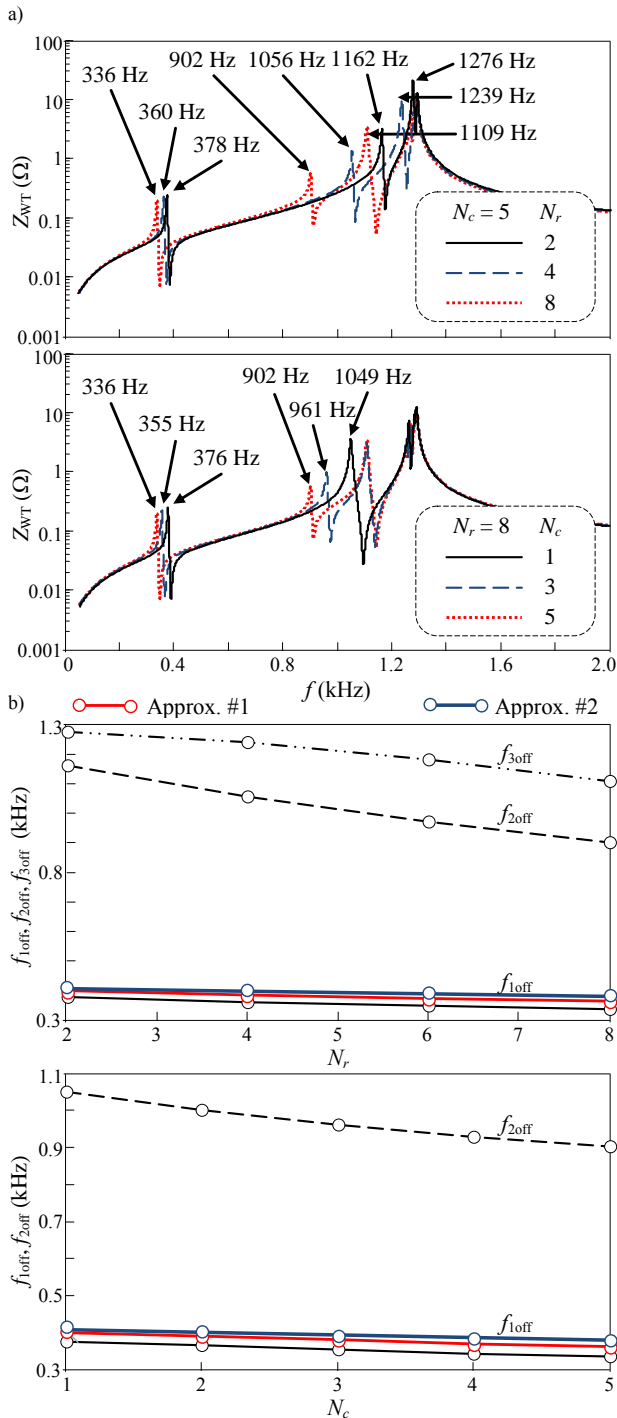- The other parallel resonances are slightly affected by capacitor bank size.

Fig. 10. Influence of HV submarine cable length D_{HV} on 8x5 offshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu and $D_{MV} = 1$ km): a) Frequency scan. b) Frequency of first and second parallel resonances vs MV submarine cable length (black lines: Equivalent circuit in Fig. 2; red and blue lines: Equivalent circuit in Fig. 19)

exhaustive study of capacitor size influence is presented in [14].

IV. OFFSHORE WPP RESONANCE STUDY

The frequency response of the 8x5 offshore WPP in Section II (data in Table 1) is analyzed to study the influence of the main grid short circuit ratio, $SCR = S_S/(N_r \cdot N_c \cdot P_{WT})$, WPP layout (i.e., number of WTs and strings, N_r and N_c), HV submarine cable length, D_{HV}, and MV submarine cable length, D_{MV}, on low order parallel resonances. To do this, Matlab/Simulink simulations are made by varying their values. A frequency scan at WT_{Nr1} (see Fig. 2) is performed in these simulations and the equivalent harmonic impedance $\underline{Z}_{Eq, k}$ is obtained. Subsequently, the frequency of the parallel resonance is numerically identified from the frequency scan.

4.1. INFLUENCE OF SHORT CIRCUIT RATIO

In order to study the influence of short circuit ratio, SCR, of the main grid on parallel resonance, Matlab/Simulink simulations are made by varying the short circuit ratio value from 10 to 100 (i.e., $S_S = 2000$ MVA to 20000 MVA considering the 8x5 WPP with 5 MW WTs in the study). As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq, k}$ at WT_{Nr1} for three values of the short circuit ratio ($SCR = 12.5$, 50 and 100 pu) is shown in Fig. 8(a). From these results, it can be noted that

Fig. 9. Influence of WPP layout on N_rxN_c offshore WPP resonance (data in Table 1, $SCR = 12.5$ pu, $D_{HV} = 25$ km and $D_{MV} = 1$ km): a) Frequency scan. b) Frequencies of first, second and third parallel resonances vs N_r and N_c (black lines: Equivalent circuit in Fig. 2; red and blue lines: Equivalent circuit in Fig. 19)

The influence of capacitor bank size on the first parallel resonance, f_{1on}, is illustrated with black lines in Fig. 7(b). It can be observed that larger capacitor bank sizes lead to lower frequency values of the first parallel resonance. Thus, reactive power compensation at the collector bus can produce onshore WPP resonances close to WT harmonic emissions. An
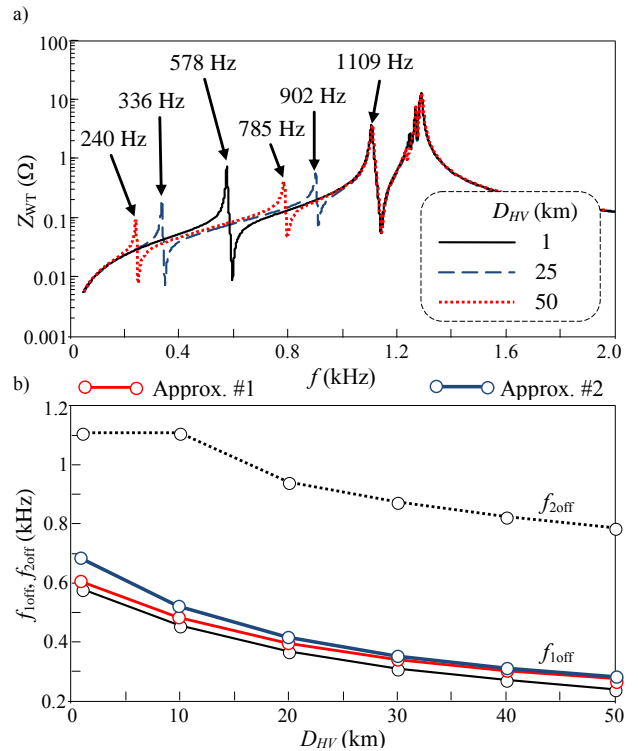
- Similarly to onshore WPPs, small values of the short circuit ratio (i.e., grids that tend to be weak) lead to high values of the main grid inductances (1), which shift the first and second parallel resonances to low frequencies, f_{1off} and f_{2off}.

- The other parallel resonances are not affected by the main grid impedance, and therefore they are not affected by the short circuit ratio.

The influence of short circuit power on the first and second parallel resonances f_{1off} and f_{2off} is illustrated with black lines in Fig. 8(b). It can be observed that grids that tend to be weak (i.e., grids with small short circuit ratios) can shift the first and second parallel resonances to a low frequency range because of the large values of the main grid inductances. Thus, weak grids can produce offshore WPP resonances close to WT harmonic emissions.

4.2. INFLUENCE OF WIND POWER PLANT LAYOUT

In order to study the influence of the number of WTs, N_r, and strings, N_c, on parallel resonance, Matlab/Simulink simulations are made by varying the N_r value from 2 to 8 and the N_c value from 1 to 5. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq, k}$ at WT_{Nr1} for three values of N_r ($N_r = 2$, 4 and 8) and for three values of N_c ($N_c = 1$, 3 and 5) is shown in Fig. 9(a). From these results, it can be noted that

- High number of the WTs and strings shift the first and second parallel resonances, f_{1off} and f_{2off}, to low frequencies.

The influence of WPP layout on the first and second parallel resonances, f_{1off} and f_{2off}, is illustrated with black lines in Fig. 9(b). It can be observed that parallel resonances are closer to low order harmonics in large offshore WPPs than in small offshore WPPs because parallel resonance frequencies move to lower order harmonics with increasing the number of WTs and strings.

4.3. INFLUENCE OF HV SUBMARINE CABLE LENGTH

In order to study the influence of HV submarine cable length, D_{HV}, on parallel resonance, Matlab/Simulink simulations are made by varying the cable length value from 1 km to 50 km. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq, k}$ at WT_{Nr1} for three values of the cable length ($D_{HV} = 1$, 25 and 50 km) is shown in Fig. 10(a). From these results, it can be noted that

- High values of HV cable length shift the first and second parallel resonances, f_{1off} and f_{2off}, to low frequencies because of the higher value of transversal capacitors of the cable.

- The second parallel resonance, f_{2off}, matches with the third parallel resonance, f_{3off}, for small values of HV cable length and is no longer affected by this parameter.

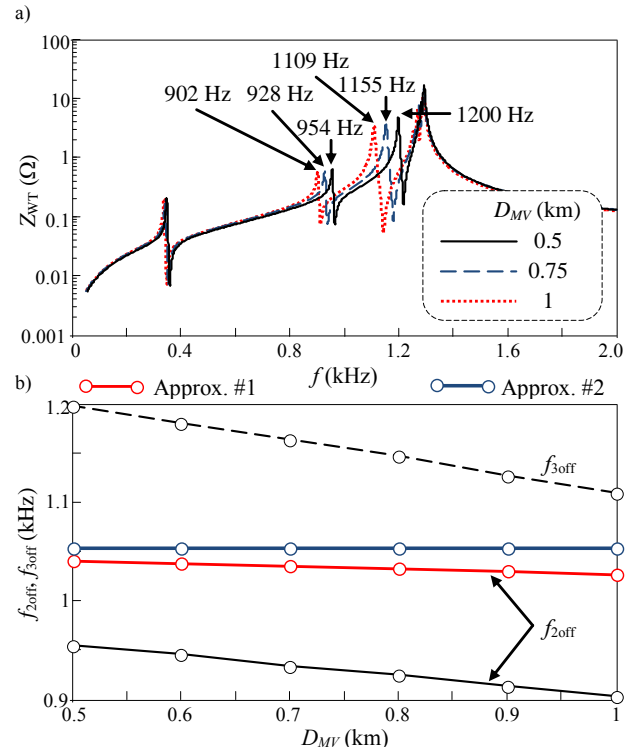- The other parallel resonances are not affected by the cable length.

Fig. 11. Influence of MV submarine cable length, D_{MV}, on 8x5 offshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu, and $D_{HV} = 25$ km): a) Frequency scan. b) Frequency of second and third parallel resonance vs MV submarine cable length (black lines: Equivalent circuit in Fig. 2; red and blue lines: Equivalent circuit in Fig. 19)

The influence of HV cable length on the first and second parallel resonances, f_{1off} and f_{2off}, is illustrated with black lines in Fig. 10(b). It can be observed that greater cable lengths lead to lower frequencies of the parallel resonances. Thus, offshore WPPs far from shore can produce resonances close to WT harmonic emissions.

4.4. INFLUENCE OF MV SUBMARINE CABLE LENGTH

In order to study the influence of MV underground cable length, D_{MV}, on parallel resonance, Matlab/Simulink simulations are made by varying the cable length value from 0.5 km to 1 km. As an example, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq, k}$ at WT_{Nr1} for three values of the cable length ($D_{MV} = 0.5$, 0.75 and 1 km) is shown in Fig. 11(a). From these results, it can be noted that

- High values of MV cable length shift the second and third parallel resonances, f_{2off} and f_{3off}, to low frequencies because of the higher value of transversal capacitors of the cable.

- The low sensitivity of the parallel resonances to MV cable length is similar to that observed in onshore WPPs.

- The other parallel resonances (in particular, the first parallel resonance, f_{1off}) are not affected by the cable length.

The influence of MV cable length on the second and third parallel resonances, f_{2off} and f_{3off}, is illustrated with black lines in Fig. 11(b). It can be observed that, although the frequency
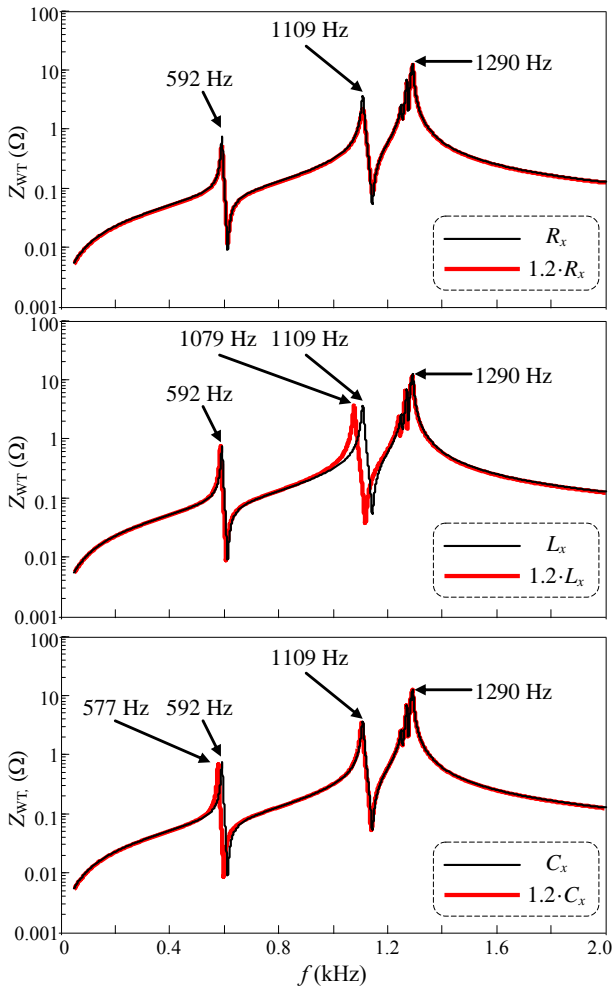
Fig. 12. Influence of MV underground cable electrical parameters on 8x5 onshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu, $D_{MV} = 1$ km and $Q_{Cb} = 0$ Mvar)

of the parallel resonances is only slightly affected by cable length, it decreases with long MV submarine cables. Thus, WPPs with WTs far away from each other can produce resonances close to WT harmonic emissions.

V. INFLUENCE OF WPP ELECTRICAL PARAMETERS

In order to study the influence of WPP electrical parameters on parallel resonance, the frequency scan of the equivalent harmonic impedance $\underline{Z}_{Eq,k}$ at WT_{Nr1} with the parameter values in Table 1 and with the parameter values increased by 20% is compared for onshore and offshore WPPs.

5.1. ONSHORE WIND POWER PLANTS

The influence of the following electrical parameters is analyzed:

- Electrical parameters of the MV underground cable (Fig. 12). It must be noted that

  o The cable resistance does not affect resonance frequencies. It only damps the frequency response of the WPP.
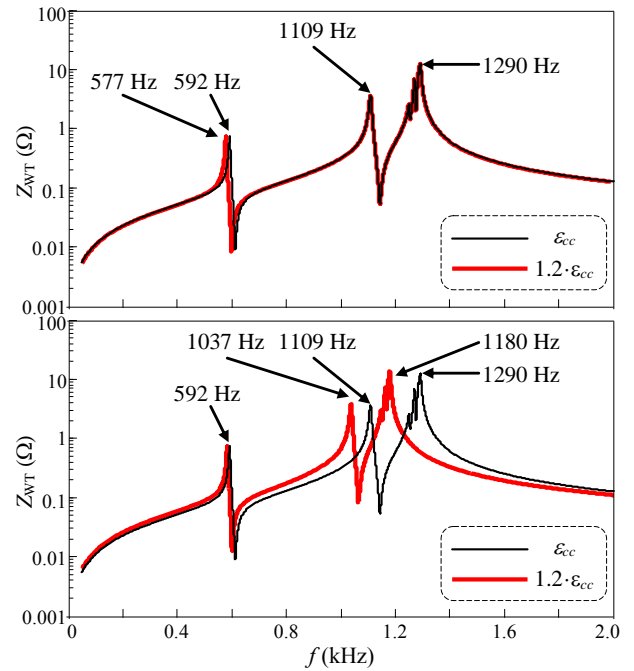

Fig. 13. Influence of HV/MV (top) and MV/LV (bottom) transformer electrical parameters on 8x5 onshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu, $D_{MV} = 1$ km and $Q_{Cb} = 0$ Mvar)

  o The cable inductance slightly affects the second parallel resonance, f_{2on}, because this inductance is negligible compared to the equivalent inductance of transformers. Higher inductances result in lower parallel resonance frequencies.

  o The cable capacitor slightly affects the first parallel resonance, f_{1on}. Higher capacitor values result in lower parallel resonance frequencies.

These results agree with the influence of MV underground cable length on parallel resonance (see Fig. 6).

- Transformer electrical parameters (Fig. 13). It must be noted that

  o The short-circuit impedance of the HV/MV transformer slightly affects the first parallel resonance, f_{1on}.
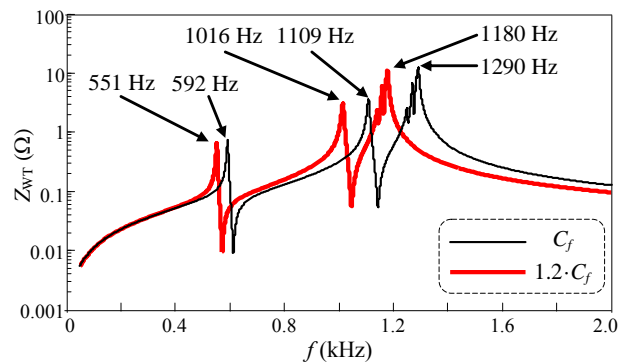

Fig. 14. Influence of WT capacitor filter on 8x5 onshore WPP resonance (data in Table 1, with $SCR = 12.5$ pu, $D_{MV} = 1$ km and $Q_{Cb} = 0$ Mvar)
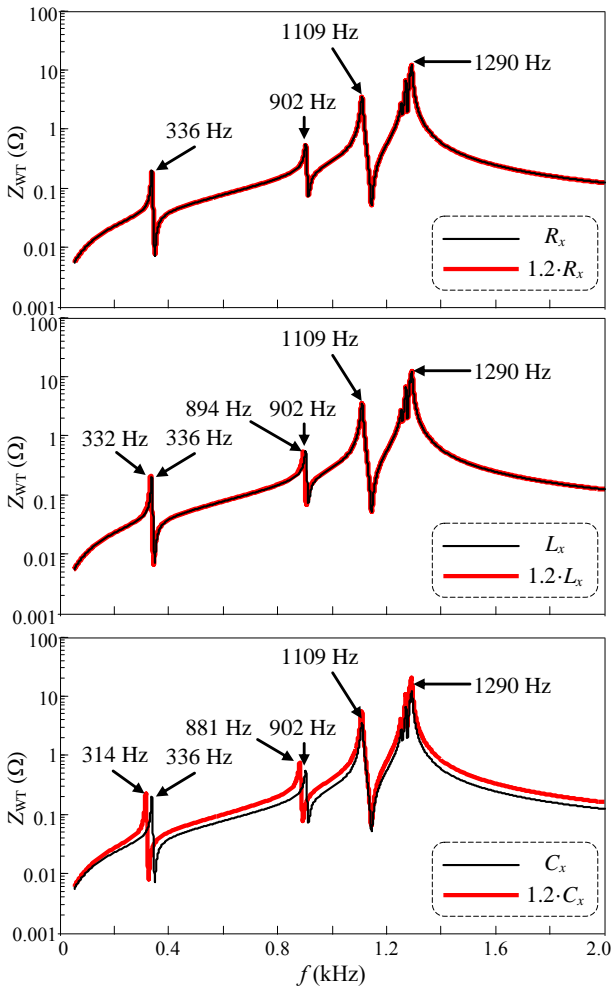
Fig. 15. Influence of HV submarine cable electrical parameters on 8x5 offshore WPP resonance (data in Table 1, with *SCR* = 12.5 pu, D_{HV} = 25 km and D_{MV} = 1 km)
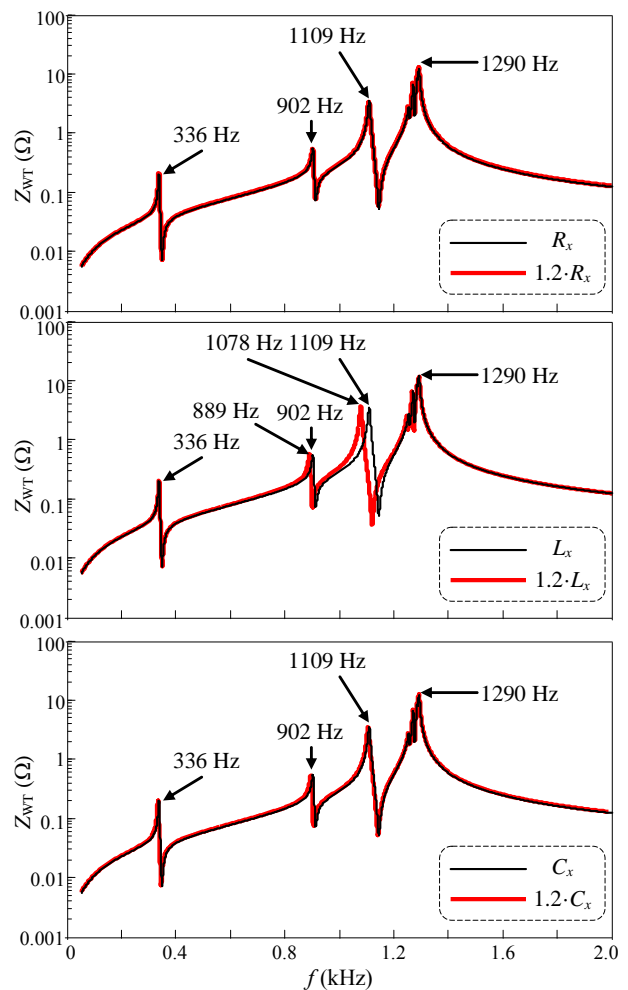

Fig. 16. Influence of MV submarine cable electrical parameters on 8x5 offshore WPP resonance (data in Table 1, with *SCR* = 12.5 pu, D_{HV} = 25 km and D_{MV} = 1 km)

o The short-circuit impedance of the MV/LV transformer significantly affects the second parallel resonance, f_{2on}.

- WT filter capacitor (Fig. 14). The presence of this capacitor must be considered in onshore WPP resonance studies because it significantly affects all the parallel resonances.

5.2. OFFSHORE WIND POWER PLANTS

The influence of the following electrical parameters is analyzed:

- Electrical parameters of the HV submarine cable (Fig. 15). It must be noted that

  o The cable resistance and inductance do not affect resonance frequencies. The resistance only damps the frequency response of the WPP. They could be neglected compared to the equivalent impedance of transformers for low frequency parallel resonance studies.

o The cable capacitor affects the first and second parallel resonance f_{1off} and f_{2off}. Higher capacitor values lead to lower parallel resonance frequencies.

These results agree with the influence of HV submarine cable length on parallel resonance (see Fig. 10).

- Electrical parameters of the MV submarine cable (Fig. 16).

  o The cable resistance does not affect resonance frequencies. It only damps the frequency response of the WPP.

  o The cable inductance slightly affects the second parallel resonance, f_{2off}, and it significantly affects the third parallel resonance, f_{3off}. Higher inductances lead to lower parallel resonance frequencies.

  o The cable capacitor does not affect parallel resonance.

These results agree with the influence of MV submarine cable length on parallel resonance (see Fig. 11). Thus, electrical parameters of MV submarine cables of offshore WPPs could be neglected because their equivalent impedance
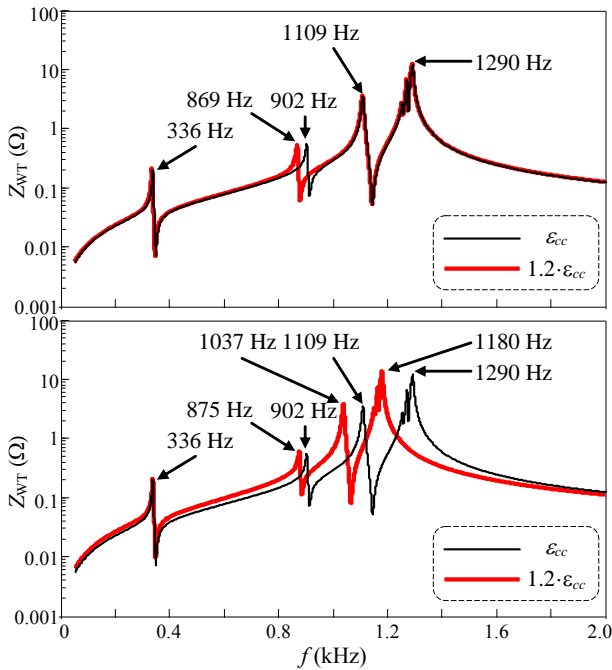
Fig. 17. Influence of HV/MV (top) and MV/LV (bottom) transformer electrical parameters on 8x5 offshore WPP resonance (data in Table 1, with *SCR* = 12.5 pu, D_{HV} = 25 km and D_{MV} = 1 km)

is small and only affects the high frequency parallel resonances.

- Transformer electrical parameters (Fig. 17). It must be noted that

  o The short-circuit impedance of the HV/MV transformer slightly affects the second parallel resonance, f_{2off}.

  o The short-circuit impedance of the MV/LV transformer significantly affects the second and third parallel resonance, f_{2off} and f_{3off}.

- WT filter capacitor (Fig. 18). The presence of this capacitor must be considered in offshore WPP resonance studies because it significantly affects all parallel resonances (in particular, the second and third parallel resonances, f_{2off} and f_{3off}).
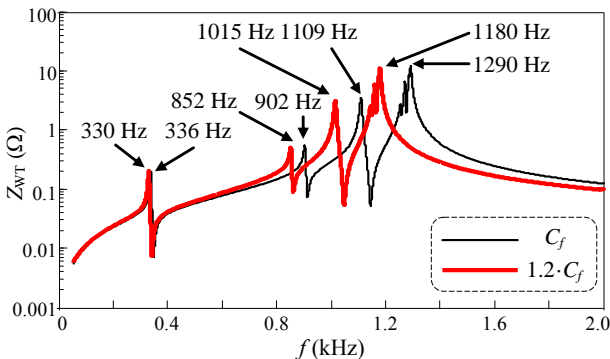

Fig. 18. Influence of WT capacitor filter on 8x5 offshore WPP resonance (data in Table 1, with *SCR* = 12.5 pu, D_{HV} = 25 km and D_{MV} = 1 km)
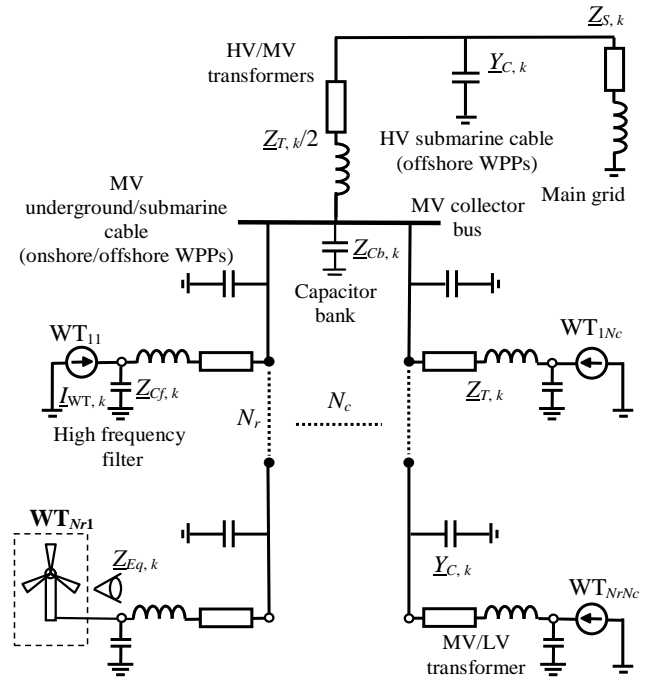

Fig.19. Wind power plant approximated equivalent circuit

VI. WIND POWER PLANT APPROXIMATED EQUIVALENT CIRCUIT

From the above studies, it can be concluded that the transversal impedances of the WPP cables could be removed from the WPP equivalent circuit in Fig. 2 to easily determine the low order parallel resonances. Thus, the approximated circuit of Fig. 19 is proposed to characterize the low order frequencies of WPP resonances. Moreover, considering the small influence of MV submarine cable capacitors on offshore WPP parallel resonance (see Subsection 5.2), these capacitors could also be neglected in offshore WPP resonance studies. These circuits (circuit in Fig. 19 with and without MV underground/submarine cable capacitors, called approximations #1 and #2, respectively) can be used to study the parallel resonance problem analytically, and thus obtain expressions of the resonance frequencies. The studies in Sections III and IV are performed considering the above approximations (results plotted with red lines from Fig. 4(b) to Fig. 11(b)). The accuracy of the proposed approximations can be checked in these plots. It can be noted that,

- The approximations are valid for small values of the main grid short circuit ratio, which lead to high values of the main grid inductances (see Fig. 4(b) and Fig. 8(b)).

- The approximations are valid to study only the first parallel resonance in onshore and offshore WPPs, f_{1on} and f_{1off}, whereas they do not offer good accuracy for the other parallel resonances (see Fig. 11(b)).

- Approximation #2 is accurate for offshore WPP parallel resonance studies.

VII. Conclusion

This paper studied parallel resonance in onshore and offshore WPPs from frequency scan. Extensive Matlab/Simulink simulations were performed to determine the equivalent impedance at WT terminals. The frequency of the parallel resonance was numerically identified from this impedance. The paper compared low order frequencies of parallel resonances in onshore and offshore WPPs and investigated the impact of WPP parameters on resonance. The following conclusions were drawn:

- WT filter capacitors and cables are the factors most and least affecting WPP parallel resonance, respectively.

- Offshore WPPs have parallel resonances at lower order frequencies than onshore WPPs because of the transversal capacitors of the HV submarine cable which connects the WPPs with shore. Moreover, this cable produces a parallel resonance around 1 kHz which does not appear in onshore WPPs.

- Weaker grids lead to parallel resonances closer to low frequencies. This is because grids with low short circuit ratios can produce onshore and offshore WPP resonances close to WT harmonic emissions due to large main grid inductance values.

- Large WPPs have parallel resonance at lower frequencies than small WPPs because of the influence of the number of WTs and strings on resonance.

- Onshore and offshore WPPs with WTs far away from each other have parallel resonances at low order frequencies because of the transversal capacitors of the MV underground cables.

- Reactive power compensation at the onshore WPP collector bus can produce parallel resonances close to WT harmonic emissions.

- Offshore WPPs far from shore have parallel resonances close to low order harmonics.

Based on these conclusions, the paper also proposed approximated equivalent circuits to study low order parallel resonance in onshore and offshore WPPs.

Acknowledgments

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