Study on the resonance stability problem of the wind power base with the MMC–HVDC system

Facai Xing1,*, Shijia Wang1, Feng Zhang2, Heng Wang2, Zheng Xu1, Huanqing Xiao1
1College of Electrical Engineering, Zhejiang University, Hangzhou, People’s Republic of China
2State Grid Xinjiang Electric Power Co., Ltd, Urumqi, People’s Republic of China
*E-mail: xingfacai@zju.edu.cn

Abstract: Considering the negative resistance effect of power electronic equipment, unstable resonance problems may occur between wind farms and converter stations. This paper focuses on the resonance stability problem of a wind power base coupling with a multi-level converter–high-voltage direct-current transmission (MMC–HVDC) system. Firstly, the s-domain impedance models of the doubly-fed induction wind generator, the permanent magnet synchronous wind generator, and the modular MMC are built, through the theoretical derivation and simulation test. Secondly, based on the s-domain nodal admittance matrix method, the resonance structure of the wind power base coupling with an MMC–HVDC system is analysed, including the resonance mode frequencies, the resonance mode damping factors, the nodal participation factors, and the nodal voltage mode shapes. Thirdly, the main factors influencing the resonance structure are studied, including the topology of the wind power base, the capacity of the wind turbines, and the operation mode of the MMC station. Finally, a brief conclusion ends the paper.

1 Introduction

The renewable energy generation has increasingly attracted attention, in order to deal with the resources shortage and the environment pollution [1]. Due to its intrinsic intermittence and fluctuation, high-voltage direct-current transmission (HVDC) is an appropriate choice to connect the renewable power base to the main ac grid. Especially, modular multi-level converter technology (MMC) is preferred with a flexible control strategy [2]. However, there may exists a resonance problem between the renewable power base and the MMC station, owing to the negative resistance effect of power electronic equipment. For example, the sub-synchronous resonance (SSR) problem has occurred in the wind power base in Hebei China and Xinjiang, China [3], and Texas, America [4]. Therefore, this paper mainly focuses on the resonance problem between the wind power base and the MMC station.

In recent years, a series of relevant research about the resonance problem of wind power base has been executed. For example, the SSR problem involving doubly-fed induction generator (DFIG) is analysed with the state-space method [5, 6], and the impedance-based model [7, 8]. Also, the small-signal stability problem involving a permanent magnetic synchronous generator (PMSG) is studied with the impedance-based model [9–11]. Nevertheless, most of them take one equivalent wind generator to represent the wind power base, ignoring the influence of the connection cables and the collection grid topology. Liu et al. [12] analyses the harmonic resonance problem of an offshore wind farm based on the modal analysis method [13], with the internal structure and components of the wind farm considered, but the resonance stability problem is not considered.

Generally, a wind power base connected to an MMC station is geographically dispersed, in order to exploit the wind energy fully. Thus, the influence of the collection grid topology should be considered. In addition, both the DFIG and the PMSG are generally installed in the same wind power base, although they have different electrical characteristics. Therefore, this paper analyses the influence of the capacity configuration of different wind turbines on the resonance stability. Remarkably, the state-space method and the impedance-based Nyquist criterion are not appropriate for analysing the high-dimension and multi-input multi-output system. So this paper studies the resonance problem between the wind power base and the MMC station based on the s-domain nodal admittance matrix method [14].

The rest of this paper is organised as follows. Firstly, the s-domain nodal admittance matrix method is introduced in Section 2. Then the s-domain model of the DFIG, PMSG, and MMC are built through the theoretical derivation and simulation test in Section 3. In Section 4, this paper analyses the resonance structure of a wind power base with an MMC station. Especially, the topology of the wind power base, the capacity configuration of different wind turbines, and the operation mode of the MMC station are considered. Finally, a brief conclusion ends the paper in Section 5.

2 S-Domain nodal matrix method

The dynamic model of components in a power system have two detailed forms. One is the time-domain differential equations, and the other is the s-domain algebraic equations. The time-domain differential equations describing large-scale power system are difficult to establish and to solve. Therefore, the s-domain algebraic equations are more appropriate for the dynamic behaviour analysis of a large-scale power system. Generally, a large-scale power system can be described in the form of an s-domain nodal admittance matrix, as shown in (1):

\[ Y(s)U_{\text{node}}(s) = I_{\text{node}}(s) \]  

where \( Y(s) \) is the s-domain nodal admittance matrix, and \( U_{\text{node}}(s) \) and \( I_{\text{node}}(s) \) are the node voltage vector and the node injection current vector, respectively.

Based on the \( Y(s) \), the s-domain nodal matrix method takes its determinant as the equivalent characteristic polynomial of small-signal stability analysis, as shown in (2), which is validated in paper [14, 15]:

\[ \det [Y(s_{\text{node}})] = 0 \]  

where \( s_{\text{node}} \) represents the resonance mode of small-signal stability.

In addition, two indices to describe the resonance mode is proposed in paper [14], that is, the nodal voltage mode shape and the nodal participation factor.
### 3.1 S-domain model of a wind generator

The DFIG and PMSG are the most widely used wind generators, with its variable speed constant-frequency characteristic, which makes it tracking the maximal wind energy perfectly. Thus, this paper mainly introduces the s-domain model of the DFIG and PMSG.

#### 3.1.1 S-domain model of the DFIG: The DFIG consists of the induction generator and the back-to-back converter, as shown in Fig. 1.

Ignoring the zero sequence current, the induction generator can be described as follows in the time-domain dq reference frame:

\[
\begin{align*}
\dot{u}_d &= R_d i_d + \frac{d}{dt} i_d - \omega_L i_q + M \frac{d}{dt} i_q - \alpha_d M i_q \\
\dot{u}_q &= R_q i_q + \frac{d}{dt} i_q + \omega_L i_d + M \frac{d}{dt} i_d - \alpha_q M i_q \\
\dot{u}_r &= R_i i_r + \frac{d}{dt} i_r - \omega_L i_n + M \frac{d}{dt} i_n - \alpha_r M i_n
\end{align*}
\]

where \( u \) and \( i \) represent the voltage and the current, respectively; \( R, L, \) and \( M \) represent the resistance, the self-inductance, and the mutual-inductance, respectively; \( \omega \) represents the angular frequency of the \( dq \) reference frame. The subscripts 'd' and 'q' represent the \( d \)-axis variable and \( q \)-axis variables, respectively, the subscripts 'r' and 'n' represent the rotor-side variable and the stator-side variable, respectively.

According to [7], the generator-side converter and grid-side converter can be decoupled to analyse. The controller of the generator-side converter and the grid-side converter can be described as shown in Fig. 2 [16].

To define the positive sequence and the negative sequence space vector as (6) for convenience, based on the transformation of the reference frame [17]. Remarkably, the positive and negative sequences in this paper are different from those in the phasor domain:

\[
\left[ \begin{array}{c}
\dot{x}_p \\
\dot{x}_n
\end{array} \right] = \frac{1}{2} \left[ \begin{array}{c}
[X_d + jX_q] e^{j\omega t} \\
[X_d - jX_q] e^{-j\omega t}
\end{array} \right] + \left[ \begin{array}{c}
X'_d \\
X'_n
\end{array} \right]
\]

\[
\left[ \begin{array}{c}
X'_d \\
X'_n
\end{array} \right] = \frac{1}{2} \left[ \begin{array}{c}
[X_d(s - j\omega)] + j[X_q(s - j\omega)] \\
[X_d(s + j\omega)] - j[X_q(s + j\omega)]
\end{array} \right]
\]

where \( x \) and \( X \) represent the voltage or the current in the time-domain and the s-domain, respectively; the subscript 'p' and 'n' represent the positive sequence variable and the negative sequence variable, respectively; the superscript with '→' represents the space vector. Only the positive frequency space vector is considered.

Assuming that the three-phase is symmetric, the negative sequence space vector can be ignored. Thus, the subscript 'p' is also omitted. The DFIG can be described as shown in (7) in the s-domain. Its equivalent circuit is shown in Fig. 3.

### 3 S-domain model of the DFIG, PMSG, and MMC

The s-domain model of components in a power system is the basis of the s-domain nodal matrix method. In the wind power base, the wind generators and the MMC station are the main components. Therefore, this paper especially introduces the s-domain model of the DFIG, PMSG, and MMC.

**Fig. 1** Structure diagram of the DFIG

**Fig. 2** Controller of the converter
(a) The generator side, (b) The grid side

**Fig. 3** Equivalent circuit of the DFIG

The nodal voltage mode shape index describes the relative magnitude and phase of each node voltage under the resonance mode, which can be calculated by

\[
\{R \{Y_{(s_{mod})} \} \} = 0, R^T R = 1
\]

The nodal participation factor index describes the contribution of the one node injection current to the other node voltage when the resonance mode is excited. It corresponds to the extent of the participation of each node under the resonance mode, which can be calculated by

\[
\{F \{Y_{(s_{mod})} \} \} = 0, F^T F = 1
\]

\[
P = RL
\]
Since the synchronous generator and the main ac grid are decoupled, only the grid-side converter is considered. The controller of the grid-side converter is shown in Fig. 5.

Similar to the modelling process of the DFIG, the PMSG can be described as follows in the s-domain, ignoring the effect of the phase-locked loop (PLL):

\[
\begin{align*}
\Delta U_g & = H_s(s - j\omega_l)(I_{g,\text{ref}} - I_{g,\text{mean}}) + jK_g I_{g,\text{mean}} + U_{\text{sys,mean}} \\
U_{g,\text{ref}} - U_{\text{sys}} & = sL_g I_g \\
\Delta I_g & \approx U_{d,\text{dc}} U_{g,\text{ref}} \\
I_{g,\text{mean}} & \approx G I_g \\
U_{\text{sys,mean}} & \approx G I_g U_g
\end{align*}
\]

In some cases, the dynamic behaviour of PLL needs to be considered. The control block diagram of synchronous-reference-frame PLL (SRF-PLL) is shown in Fig. 6, which is the most practised PLL [18].

The small-signal dynamic behaviour of SRF-PLL can be described as follows:

\[
\Delta \theta(s) = \frac{G_s H_{\text{PLL}}(1/s)}{1 + sH_{\text{PLL}}(1/s)} \Delta U_q
\]

The effect of PLL is shown in the transformation of the reference frame, such as the measurement of the voltage and current, the signal modulating, which is described as follows in the s-domain: (see (10) and (11)) where the subscript ‘ideal’ represents variables under the ideal transformation of the reference frame. The second term on the right side of (10) represents the effect of PLL, which makes the positive sequence variable and negative sequence variable coupled, as follows in the s-domain: (see (11)) Remarkably, the coupling term can be ignored if the disturbance is three-phase symmetric.

\[ \Delta \theta(s) = \frac{G_s H_{\text{PLL}}(1/s)}{1 + sH_{\text{PLL}}(1/s)} \Delta U_q \]

3.2 S-domain model of the MMC station

The structure of the MMC station is shown in Fig. 7.

Since each submodule of the MMC has an energy-storage capacitor, its dynamic behaviour is difficult to be described. Harnefors et al. and Lyu et al. [19, 20] approximately consider its effect in the form of the total capacitor voltage and the imbalance capacitor voltage. For more accuracy, this paper builds the s-domain model of MMC by the test-signal method, as shown in Fig. 8.

The positive sequence impedance and the negative sequence impedance of MMC can be calculated with (12), ignoring the asynchronous frequency-coupled effect, which can be achieved by the imposed test signal:

\[
Z_p(f) = \frac{\Delta U_p(f)}{\Delta I_p(f)} = \frac{\Delta U_{q}\text{PLL}(f)}{\Delta I_{q}\text{PLL}(f)} = \frac{\Delta U_{q0}\text{PLL}(f)}{\Delta I_{q0}\text{PLL}(f)}
\]

\[
Z_n(f) = \frac{\Delta U_n(f)}{\Delta I_n(f)} = \frac{\Delta U_{q}\text{PLL}(f)}{\Delta I_{q}\text{PLL}(f)} = \frac{\Delta U_{q0}\text{PLL}(f)}{\Delta I_{q0}\text{PLL}(f)}
\]

3.1.2 S-domain model of the PMSG: The PMSG consists of the permanent magnetic synchronous generator and the back-to-back converter, as shown in Fig. 4.

\[
\begin{align*}
\begin{bmatrix} \Delta X_d,\text{ideal} \\ \Delta X_q,\text{ideal} \end{bmatrix} & = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta X_d,\text{ideal} \\ \Delta X_q,\text{ideal} \end{bmatrix} + \begin{bmatrix} 0 \\ -s \end{bmatrix} X_{\text{d,ideal}} G_s H_{\text{PLL}} \frac{U_{d,\text{PLL}} H_{\text{PLL}}}{s + U_{d,\text{PLL}} H_{\text{PLL}}} \begin{bmatrix} \Delta U_d,\text{PLL} \\ \Delta U_q,\text{PLL} \end{bmatrix} \\
\begin{bmatrix} \Delta X_d \\ \Delta X_q \end{bmatrix} & = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta X_d,\text{ideal} \\ \Delta X_q,\text{ideal} \end{bmatrix} + \begin{bmatrix} 0 \\ -s \end{bmatrix} X_{\text{d,ideal}} G_s H_{\text{PLL}} \frac{U_{d,\text{PLL}} H_{\text{PLL}}}{s + U_{d,\text{PLL}} H_{\text{PLL}}} \begin{bmatrix} \Delta U_d,\text{PLL} \\ \Delta U_q,\text{PLL} \end{bmatrix}
\end{align*}
\]
Generally, the MMC station connected to the wind power base is in the passive control mode. The ac system voltage and frequency can be controlled. Its controller block diagram is shown in Fig. 9.

Based on the test-signal method, the positive sequence impedance of the MMC station is shown in Fig. 10.

4.1 Structure of the wind power base

The structure of the wind power base in this paper is shown in Fig. 11. There are four wind farms equipped with the PMSG and the DFIG, and no synchronous generators in the wind power base. All the power is transmitted to the main ac system by the MMC–HVDC system. The parameters of the wind power base and the MMC station are listed in Tables 1–3. The detailed parameters of the 2-MW wind generator is from [7, 9, 16].

4.2 Resonance structure analysis

Based on the s-domain nodal admittance matrix, this paper analyses the resonance structure of the wind power base in scheme 1, mainly in the sub-synchronous frequency range. There is only a resonance mode in this range, of which the resonance frequency is 42.7 Hz. Its damping factor is $-0.0601 \, \text{s}^{-1}$, which indicates that this resonance mode is unstable. For further studying this resonance mode, its nodal participation factors and its nodal voltage mode shapes are also analysed, as shown in Table 4 and Fig. 12.

Table 4 indicates Bus 6, i.e. the MMC station node, is most likely to lead to this resonance mode. Fig. 12 indicates that all the nodal voltage phase is almost similar when this resonance mode occurs. Bus 6 is the most appropriate node to observe this resonance mode.

4.3 Influence of the topology structure

For eliminating this unstable resonance mode, this paper analyses the influence of the topology structure on the resonance structure. The new topology structure is shown in Fig. 11.

The resonance structure analysis of the new topology structure indicates that there is still only one resonance mode, whose resonance frequency is still 42.7 Hz. But the damping factor changes to $-0.1132 \, \text{s}^{-1}$, which means this resonance mode is more unstable. From the view of qualitative analysis, the total network resistance in the new topology structure is decreased; thus, the resonance mode becomes more unstable. The nodal voltage mode shapes of this resonance mode are shown in Fig. 13.

\[
\begin{align*}
U_d &= \frac{Z_{dd} \, Z_{dq}}{Z_{dd} \, Z_{dq} + Z_{qd} \, Z_{qq}} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \\
\bar{U}_p &= \frac{1}{2} \begin{bmatrix} U_d(s - j\omega_0) + jU_q(s - j\omega_0) \\ U_d(s + j\omega_0) - jU_q(s + j\omega_0) \end{bmatrix} \\
\bar{U}_n &= \frac{1}{2} \begin{bmatrix} I_d(s + j\omega_0) \\ I_d(s - j\omega_0) \end{bmatrix} \\
\begin{bmatrix} I_d \\ I_q \end{bmatrix} &= \frac{1}{j} \begin{bmatrix} I_n(s + j\omega_0) \\ I_n(s - j\omega_0) \end{bmatrix} \\
Z_n &= \frac{Z_{dd}(s - j\omega_0) + Z_{qq}(s - j\omega_0) + jZ_{qd}(s - j\omega_0) - Z_{dq}(s - j\omega_0)}{2} \\
Z_{mp} &= \frac{Z_{dd}(s - j\omega_0) - Z_{qq}(s - j\omega_0) + jZ_{qd}(s - j\omega_0) + Z_{dq}(s - j\omega_0)}{2} \\
\bar{U}_n &= \begin{bmatrix} Z_{np} & Z_n \end{bmatrix} \begin{bmatrix} I_p(s + j2\omega_0) \\ I_n(s - j2\omega_0) \end{bmatrix} \\
Z_{np} &= \frac{Z_{dd}(s + j\omega_0) - Z_{qd}(s + j\omega_0) + jZ_{qd}(s + j\omega_0) + Z_{dq}(s + j\omega_0)}{2} \\
Z_n &= \frac{Z_{dd}(s + j\omega_0) + Z_{qq}(s + j\omega_0) + jZ_{qd}(s + j\omega_0) - Z_{dq}(s + j\omega_0)}{2}
\end{align*}
\]
Compared with Fig. 12, there is nearly no changes in Fig. 13, which indicates the topology structure has no influence on the nodal voltage mode shape of the 42.7 Hz resonance mode.

In conclusion, the resonance frequency and the nodal voltage shape of this resonance mode do not depend on the topology structure, but the damping factor is influenced by the topology structure.

4.4 Influence of the capacity configuration

The DFIG and the PMSG have different electrical characteristics, of which the capacity configuration may have an influence on the resonance structure of the wind power base. To study the extent of this influence, the capacity configuration of wind farms changes to scheme 2, as shown in Table 1.

The resonance structure analysis shows that there is still only one resonance mode, whose resonance frequency is unchanged. However, the damping factor changes to 0.0425 s$^{-1}$, which indicates that this resonance mode is stable. It means that the capacity configuration can adjust the damping of this resonance mode so that this resonance mode becomes stable. The nodal voltage mode shape of this resonance mode is shown in Fig. 14.

Fig. 14 shows that all the nodal voltage phase is still almost similar when this resonance mode occurs and Bus 6 is still the most appropriate node to observe this resonance mode. Due to the nodal voltage phase is the relative phase, it is influenced by the reference phase. Essentially, the mode shape in Fig. 14 is similar to the mode shape in Figs. 12 and 13. Therefore, the nodal voltage mode shape of this resonance mode is not influenced by the capacity configuration.

4.5 Influence of the MMC operation mode

From Sections 4.3 and 4.4, it concludes that the resonance frequency of the 42.7 Hz resonance mode is not influenced by the topology structure and the capacity configuration. It means that this resonance mode depends on the MMC station. Therefore, this paper analyses the influence of the MMC operation mode on the resonance structure. Due to the MMC station in the passive control mode, the dc operation voltage has an influence on the electrical characteristics of the MMC. This paper builds the s-domain model of MMC when the dc voltage is 510 kV by the test-signal method, as shown in Fig. 15.

Based on the s-domain admittance matrix method, when the MMC station operates in the 510 kV dc voltage, the resonance structure of the wind power base is analysed. Results show that there is still only one 42.7 Hz resonance mode in the sub-synchronous frequency range, of which the damping factor is $-0.0184$ s$^{-1}$. It indicates that this resonance mode is still unstable, but has an improving tendency. The nodal voltage mode shape under 510 kV dc operation voltage is shown in Fig. 16. It indicates that the dc operation voltage has nearly no influence on the nodal voltage mode shape of this resonance mode.

5 Conclusions

This paper builds the s-domain model of the DFIG, PMSG and MMC through the theoretical derivation and simulation test. Based on the s-domain admittance matrix method, this paper studies the resonance stability of the wind power base with an MMC–HVDC system, especially considering the influence of the topology structure, the capacity configuration, and the MMC operation mode. With the test system, some conclusions are drawn as follows:

(i) There may exist unstable resonance mode in the sub-synchronous frequency range when the wind power base is connected to the grid through an MMC–HVDC system. Therefore, it is necessary to analyse the resonance structure of the wind power base in the planning stage.

(ii) The resonance frequency and the nodal voltage shape of the unstable resonance mode may not depend on the topology structure, but the damping factor is influenced by the topology configuration.

Table 1 Parameters of wind farms

| Name     | Power, MW | Scheme 1 (DFIG proportion), % | Scheme 2 (DFIG proportion), % |
|----------|-----------|-------------------------------|-------------------------------|
| wind farm I | 400       | 0                             | 50                           |
| wind farm II | 100       | 100                           | 50                           |
| wind farm III | 300       | 0                             | 50                           |
| wind farm IV | 400       | 100                           | 50                           |
Table 2  Parameters of transmission lines

| Node 1 | Node 2 |  R, Ω  | X, Ω  | B, 10⁻⁶ S |
|--------|--------|--------|--------|-----------|
| bus 1  | bus 5  | 3.703  | 21.4774| 2.5331    |
| bus 2  | bus 5  | 10.58  | 61.364 | 7.2590    |
| bus 3  | bus 5  | 10.58  | 61.364 | 7.2590    |
| bus 4  | bus 5  | 3.703  | 21.4774| 2.5331    |
| bus 5  | bus 6  | 5.29   | 30.682 | 3.6295    |
| bus 2  | bus 1  | 6.877  | 41.4207| 4.8960    |
| bus 3  | bus 4  | 6.877  | 41.4207| 4.8960    |

Table 3  Parameters of the MMC station

| Parameter                        | Value  |
|----------------------------------|--------|
| capacity, MVA                    | 1500   |
| DC voltage, kV                   | 500    |
| AC voltage, kV                   | 220    |
| sub-modules                      | 200    |
| module capacitor, μF             | 7895   |
| arm inductance, mH               | 32     |
| arm resistor, Ω                  | 0      |

Table 4  Nodal participation factors (>0.1) of the 42.7 Hz resonance mode

| Node 1 | Node 2 | Value   |
|--------|--------|---------|
| bus 6  | bus 6  | 0.1974<5.46° |
| bus 3  | bus 6  | 0.1840<5.38° |
| bus 1  | bus 6  | 0.1837<3.75° |
| bus 5  | bus 6  | 0.1835<2.88° |
| bus 2  | bus 6  | 0.1726<0.69° |
| bus 3  | bus 3  | 0.1714<5.29° |
| bus 1  | bus 3  | 0.1711<3.67° |
| bus 3  | bus 5  | 0.1710<2.79° |
| bus 1  | bus 5  | 0.1709<2.04° |
| bus 1  | bus 5  | 0.1707<1.17° |
| bus 5  | bus 5  | 0.1705<0.29° |
| bus 4  | bus 6  | 0.1683<1.99° |
| bus 2  | bus 3  | 0.1609<0.78° |
| bus 1  | bus 2  | 0.1606<2.40° |
| bus 2  | bus 5  | 0.1604<3.28° |
| bus 3  | bus 4  | 0.1569<2.08° |
| bus 1  | bus 4  | 0.1566<3.70° |
| bus 4  | bus 5  | 0.1565<4.58° |
| bus 2  | bus 2  | 0.1510<6.85° |
| bus 2  | bus 4  | 0.1472<8.15° |
| bus 4  | bus 4  | 0.1436<9.44° |

Fig. 12 Nodal voltage mode shape of 42.7 Hz resonance mode

Fig. 13 Nodal voltage mode shape of 42.7 Hz resonance mode under the new topology structure

Fig. 14 Nodal voltage mode shape of 42.7 Hz resonance mode with scheme 2 capacity configuration

Fig. 15 Positive sequence impedance of the MMC station under 510 kV dc operation voltage

(a) 1–100 Hz, (b) 100–1000 Hz
structure. Thus, the design of the topology structure needs to consider the influence of the resonance stability in the wind power base.

(iii) The capacity configuration in wind farms can adjust the damping of the unstable resonance mode so that the resonance mode becomes stable. Therefore, the appropriate capacity configuration can be chosen to avoid the unstable resonance mode.

(iv) When the MMC station operates in the passive control mode, the dc operation voltage may have no influence on the resonance frequency and the nodal voltage mode shape, but the damping factor is influenced by it. Thus, the dc voltage operation range of the MMC station is limited by the resonance stability.

6 Acknowledgments

Project Supported by Headquarters Research Projects of State Grid Corporation of China (Estimating and supressing as well as preventing control technologies for sub-synchronous or super-synchronous oscillations from new energy base under complex network conditions, SGXJ0000TKJS1800238).

7 References

[1] Lacal Arantegui, R., Jäger-Waldau, A.: ‘Photovoltaics and wind status in the European Union after the Paris Agreement’, Renew. Sust. Energy Rev., 2018, 81, (P2), pp. 2460–2471

[2] Xu, Z.: ‘Flexible DC transmission system’ (China Machine Press, Beijing, 2016, 2nd edn.)

[3] Mingjie, L., Zhao, Y., Tao, X., et al.: ‘Study of complex oscillation caused by renewable energy integration and its solution’, Power Syst. Technol., 2017, 41, (4), pp. 1035–1042

[4] Adams, J., Pappu, V.A., Dixit, A.: ‘ERCOT experience screening for sub-synchronous control interaction in the vicinity of series capacitor banks’, Power and Energy Society General Meeting, San Diego, CA, USA, July 2012, pp. 1–5

[5] Ostadi, A., Yardani, A., Varma, R.K.: ‘Modelling and stability analysis of a DFIG-based wind-power generator interfaced with a series-compensated line’, IEEE Trans. Power Deliv., 2009, 24, (3), pp. 1504–1514

[6] Fan, L., Kavasseri, R., Miao, Z.L., et al.: ‘Modelling of DFIG-based wind farms for SSR analysis’, IEEE Trans. Power Deliv., 2010, 25, (4), pp. 2073–2082

[7] Fan, L., Zhu, C., Miao, Z., et al.: ‘Modulation of a DFIG-based wind farm interfaced with a series compensated network’, IEEE Trans. Energy Convers., 2011, 26, (4), pp. 1010–1020

[8] Fan, L., Miao, Z.: ‘Nyquist-stability-criterion-based SSR explanation for type-3 wind generators’, IEEE Trans. Energy Convers., 2012, 27, (3), pp. 807–809

[9] Liu, H., Sun, J.: ‘Voltage stability and control of offshore wind farms with AC collection and HVDC transmission’, IEEE J. Emerg. Sel. Topics Power Electron, 2014, 2, (4), pp. 1181–1189

[10] Cheah-Mane, M., Sainz, L., Liang, J., et al.: ‘Criterion for the electrical resonance stability of offshore wind power plants connected through HVDC links’, IEEE Trans. Power Syst., 2017, 32, (6), pp. 4579–4589

[11] Liu, J., Cai, X., Molinas, M.: ‘Frequency domain stability analysis of MMC-based HVDC for wind farm integration’, IEEE J. Emerg. Sel. Topics Power Electron, 2016, 4, (1), pp. 141–151

[12] Liu, Z., Rong, J., Zhao, G., et al.: ‘Harmonic assessment for wind parks based on sensitivity analysis’, IEEE Trans. Sustain. Energy, 2017, 8, (4), pp. 1373–1382

[13] Xu, W., Huang, Z., Cui, Y., et al.: ‘Harmonic resonance mode analysis’, IEEE Trans. Power Deliv., 2005, 20, (2), pp. 1182–1190

[14] Xu, Z., Wang, S., Xing, F., et al.: ‘Qualitative analysis method of electric network resonance stability’, Electr. Power Constr., 2017, 38, (11), pp. 1–8

[15] Varricchio, S.L., Gomes, S.: ‘Electrical network dynamic models with application to modal analysis of harmonics’, Electr. Power Syst. Res., 2018, 154, pp. 433–443

[16] Bin, W., Yongjia, L., Navid, Z., et al.: ‘Power conversion and control of wind energy systems’ (China Machine Press, Beijing, 2012, 1st edn.)

[17] Ma, Z.: ‘Electric machine transient analysis’ (China Electric Power Press, Beijing, 1998, 1st edn.)

[18] Golnestan, S., Guerrero, J.M., Vasquez, J.C.: ‘Three-phase PLLs: a review of recent advances’, IEEE Trans. Power Electron., 2017, 32, (3), pp. 1894–1907

[19] Harnefors, L., Antonopoulos, A., Norga, S., et al.: ‘Dynamic analysis of modular multilevel converters’, IEEE Trans. Ind. Electron., 2013, 60, (7), pp. 2526–2537

[20] Liu, J., Cai, X., Molinas, M.: ‘Impedance modelling of modular multilevel converters’, IECEN 2015-41st Annual Conf., Yokohama, Japan, November 2015, pp. 180–185