An Efficient Stability Criterion for Near-Fundamental-Frequency Oscillation Risk Assessment of Wind Power Integrated Systems via MMC-HVDC

Linlin Wu[1], Wenkai Dong[2(✉)], Yina Ren[1], Xiao Wang[1], and Xiaorong Xie[2]

[1] State Grid Jibei Electric Power Co. Ltd. Research Institute, North China Electric Power Research Institute Co. Ltd., Beijing 100045, China

[2] State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China

dwk@mail.tsinghua.edu.cn

Abstract. Recently, near-fundamental-frequency oscillations (NFFOs) have been observed in practical wind power integrated systems via MMC-HVDC (WISM). However, a practical WISM is often high-order, causing the oscillation risk assessment to be computationally heavy. Therefore, in this paper, an efficient stability criterion is proposed, which gives the critical stability conditions considering the impact of number of generators and network topology. Then NFFO risk of a WISM under different numbers of generators and network topologies can be quickly judged. The stability criterion can be obtained via the Nyquist-based stability analysis on a single generator integrated system via MMC-HVDC and hence is simple in application. In addition, derivations of the stability criterion also give an analytical explanation to the NFFO risk induced by the integration of wind power. Finally, effectiveness of the proposed method and conclusions drawn is verified based on a typical WISM.

Keywords: Near-fundamental-frequency oscillations · Wind power integrated system via MMC-HVDC · Stability criterion · Oscillation risk assessment

1 Introduction

MMC-HVDC transmission has been widely used in the integration of wind power, due to its advantages of high efficiency, scalable structure and so on [1]. However, dynamic interaction between the MMC and wind power generators (WPGs) can adversely affect the stability of the system [2]. Recently, oscillations with a frequency of 40 to 60Hz were observed in a practical wind power integrated system via MMC-HVDC (WISM), which seriously affects the consumption of wind power [3, 4]. This new-type oscillation is called near-fundamental-frequency oscillation (NFFO) as its frequency is close to the fundamental value, i.e., 50Hz [4]. Thus, for the stable operation of the WISM, it is important and necessary to conduct oscillation risk evaluation.

Q. Yang et al. (Eds.): ACCES 2024, LNEE 1310, pp. 208–215, 2025.
https://doi.org/10.1007/978-981-96-1383-0_22

The impedance-based analysis (IA) and the mode analysis (MA) are widely used in the oscillation stability analyses of the WISM. In the IA, a WISM can be divided into two subsystems, i.e., the wind power generation subsystem and the MMC-HVDC subsystem. Then the stability analyses can be conducted based on the generalized Nyquist criterion (GNC) or the Bode diagram [5–7]. Besides, with each equipment modelled as an impedance, a WISM can be seen as an impedance network [7] and the oscillation risk evaluation can be achieved via frequency-domain mode analysis [8, 9]. The MA is carried out based on the linearized state-space model. By calculating the eigenvalues and eigenvectors of the state-space matrix, oscillation modes and the corresponding mode shapes or participation factors can be obtained. Then the WISM is stable if and only if there is no oscillation mode on the right half of complex plane [10–12]. Both the IA and MA can give quantitative analyzing results of the oscillation stability of a WISM. However, in a practical WISM, there can be a large number of WPGs, causing the linearized model to be high-order and the stability analyses to be computational heavy. Besides, since oscillation stability is affected by the operating point (OP) [13], once the OP is changed, the stability analysis should be reconduct, which further increases the computational burden.

Focusing on the gap mentioned above, this paper proposes an efficient criterion for the NFFO risk evaluation of WISM. To do so, the equivalent decoupling is conducted on the impedance model of a WISM at first. And a WISM with N WPGs can be decoupled into N subsystems, each of which is composed of a single grid-connected WPG. Secondly, based on the GNC, critical stability condition for each subsystem is be derived. According to this, an efficient criterion for the quick evaluation of NFFO risk considering various OPs is obtained. Finally, effectiveness of the criterion proposed is validated via case studies.

2 Modelling of the WISM

Typical topology of a WISM is shown in Fig. 1. In oscillation stability studies, a WPG can be represented by an admittance [5–12], and hence, it can have

$$\Delta \boldsymbol{I}_{\mathrm{w}i} = \boldsymbol{G}_{\mathrm{w}i}(s)\Delta \boldsymbol{V}_{\mathrm{w}i} \tag{1}$$

where $\boldsymbol{I}_{\mathrm{w}i} = [I_{\mathrm{w}ix}\ I_{\mathrm{w}iy}]^{\mathrm{T}}$ and $\boldsymbol{V}_{\mathrm{w}i} = [V_{\mathrm{w}ix}\ V_{\mathrm{w}iy}]^{\mathrm{T}}$ are respectively the output current vector and terminal voltage vector of the i^{th} WPG; $\boldsymbol{G}_{\mathrm{w}i}(s)$ is the admittance model of the i^{th} WPG; $i = 1, 2, \ldots, N$, N is the total number of WPGs.

Similarly, for the MMC-HVDC part, there is

$$\Delta \boldsymbol{V}_{\mathrm{mmc}} = \boldsymbol{Z}_{\mathrm{mmc}}(s)\Delta \boldsymbol{I}_{\mathrm{mmc}} \tag{2}$$

where $\boldsymbol{I}_{\mathrm{mmc}} = [I_{\mathrm{mmc}x}\ I_{\mathrm{mmc}y}]^{\mathrm{T}}$, $\boldsymbol{V}_{\mathrm{mmc}} = [V_{\mathrm{mmc}x}\ V_{\mathrm{mmc}y}]^{\mathrm{T}}$ and $\boldsymbol{Z}_{\mathrm{mmc}}(s)$ are respectively the output current vector, terminal voltage vector and impedance model of the MMC.

By using the node impedance matrix, network equation for the WISM is

$$\Delta \boldsymbol{V} = \boldsymbol{Z}_{\mathrm{net}}(s)\Delta \boldsymbol{I} + \Delta \boldsymbol{V}_{\mathrm{Mm}} \tag{3}$$

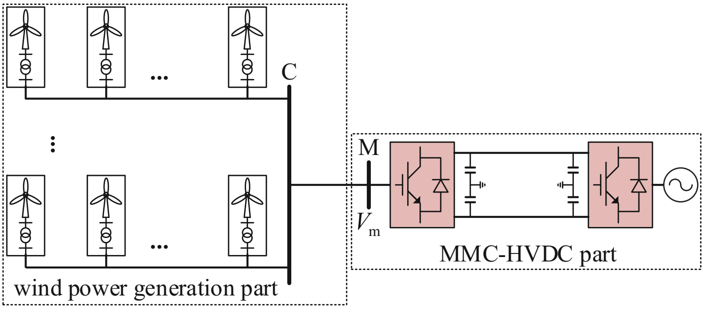


Fig. 1. A typical WISM

where $\boldsymbol{V} = [\boldsymbol{V}_1{}^{\mathrm{T}}\ \boldsymbol{V}_2{}^{\mathrm{T}}\ \ldots\ \boldsymbol{V}_N{}^{\mathrm{T}}]^{\mathrm{T}}$, $\boldsymbol{I} = [\boldsymbol{I}_1{}^{\mathrm{T}}\ \boldsymbol{I}_2{}^{\mathrm{T}}\ \ldots\ \boldsymbol{I}_N{}^{\mathrm{T}}]^{\mathrm{T}}$, $\boldsymbol{V}_{\mathrm{Mm}} = [\boldsymbol{V}_{\mathrm{mmc}}{}^{\mathrm{T}}\ \boldsymbol{V}_{\mathrm{mmc}}{}^{\mathrm{T}}\ \ldots\ \boldsymbol{V}_{\mathrm{mmc}}{}^{\mathrm{T}}]^{\mathrm{T}}$; $\boldsymbol{Z}_{\mathrm{net}}(s) = [z_{ij}(s)]|_{i,j=1,2,\ldots,N}$ is the node impedance matrix, $[z_{ij}(s)]|_{i,j=1,2,\ldots,N}$ denotes a block matrix with the element on the i^{th} row and j^{th} column to be $z_{ij}(s)$, $z_{ij}(s)$ is a 2×2 polynomial matrix.

With charging capacitances of the lines ignored, there is

$$\Delta \boldsymbol{I}_{\mathrm{mmc}} = -\sum\nolimits_{i=1}^{N} \Delta \boldsymbol{I}_i \tag{4}$$

By combining (1), (3) and (4), admittance model of the wind power generation part can be obtained as $\Delta \boldsymbol{I}_{\mathrm{mmc}} = \boldsymbol{G}_{\mathrm{w}}(s)\Delta \boldsymbol{V}_{\mathrm{mmc}}$. Then the NFFO stability analysis can be carried out based on the GNC. However, since there can be a large number of WPGs in the WISM, establishment of the admittance model $\boldsymbol{G}_{\mathrm{w}}(s)$ can be computationally heavy, especially when various OPs are considered. To reduce the computation burden of the risk evaluation, an efficient criterion for the NFFO will be proposed.

3 A Stability Criterion for NFFO Risk Evaluation

3.1 Derivation of the Stability Criterion

According to [14, 15], with the resistances of the lines ignored, the node impedance matrix in (3) can be expressed as $\boldsymbol{Z}_{\mathrm{net}}(s) = \boldsymbol{X}_{\mathrm{net}} \otimes \mathrm{E}(s)$, with $\boldsymbol{E}(s) = \begin{bmatrix} \frac{s}{\omega_0} & -1 \\ 1 & \frac{s}{\omega_0} \end{bmatrix}$. Then under the assumption that admittance models of the WPGs are approximately identical, the wind power generation part can be decoupled into N subsystem as,

$$\Delta \boldsymbol{I}_{\mathrm{y}i} = \boldsymbol{G}_{\mathrm{w}}(s)\Delta \boldsymbol{V}_{\mathrm{y}i}\ \ \Delta \boldsymbol{V}_{\mathrm{y}i} = \lambda_i \boldsymbol{E}(s)\Delta \boldsymbol{I}_{\mathrm{y}i} + u_{\mathrm{s}i}\Delta \boldsymbol{V}_{\mathrm{mmc}} \tag{5}$$

where λ_i are the eigenvalues of the matrix $\boldsymbol{X}_{\mathrm{net}}$; $u_{\mathrm{s}i} = \sum_{j=1}^{n} u_{ji}$, $\boldsymbol{u}_i = [u_{1i}\ u_{2i}\ \ldots\ u_{Ni}]^{\mathrm{T}}$ are the eigenvectors of $\boldsymbol{X}_{\mathrm{net}}$; $\boldsymbol{I}_{\mathrm{Y}} = [\boldsymbol{I}_{\mathrm{y}1}{}^{\mathrm{T}}\ \boldsymbol{I}_{\mathrm{y}2}{}^{\mathrm{T}}\ \ldots\ \boldsymbol{I}_{\mathrm{y}N}{}^{\mathrm{T}}]^{\mathrm{T}}$ and $\boldsymbol{V}_{\mathrm{Y}} = [\boldsymbol{V}_{\mathrm{y}1}{}^{\mathrm{T}}\ \boldsymbol{V}_{\mathrm{y}2}{}^{\mathrm{T}}\ \ldots\ \boldsymbol{V}_{\mathrm{y}N}{}^{\mathrm{T}}]^{\mathrm{T}}$ are the newly induced variable vectors to describe the dynamics of the WISM; $\boldsymbol{I}_{\mathrm{y}} = \boldsymbol{U}_2{}^{\mathrm{T}}\boldsymbol{I}$, $\boldsymbol{V}_{\mathrm{y}} = \boldsymbol{U}_2{}^{\mathrm{T}}\boldsymbol{V}$, $\boldsymbol{U}_2 = \boldsymbol{U} \otimes \boldsymbol{E}_2$, $\boldsymbol{U} = [\boldsymbol{u}_1\ \boldsymbol{u}_2\ \ldots\ \boldsymbol{u}_N]$, $\boldsymbol{E}_2$ is a 2×2 unity matrix; $i = 1, 2, \ldots, N$.

Since models of the WPGs are approximately identical, the subscript i in the admittance model $\boldsymbol{G}_{\mathrm{w}i}(s)$ is ignored. Besides, since the dynamics of the WPGs are nearly identical, all the WPGs can participate in the oscillation, which is the worst circumstance. In addition, with the equivalent decomposition in (5) induced, dynamic response of the wind power generation part can be expressed as [16],

$$\Delta \boldsymbol{I}_{\mathrm{mmc}} = -u_{\mathrm{s}N}\Delta \boldsymbol{I}_{\mathrm{y}N} \tag{6}$$

According to (5) and (6),

$$\Delta \boldsymbol{I}_{\mathrm{mmc}} = -u_{\mathrm{s}N}\boldsymbol{G}_{\mathrm{w}}(s)\Delta \boldsymbol{V}_{\mathrm{y}N} \quad \Delta \boldsymbol{V}_{\mathrm{y}N} = u_{\mathrm{s}N}\left[-\frac{\lambda_N}{u_{\mathrm{s}N}^2}\vec{E}(s)\Delta \boldsymbol{I}_{\mathrm{mmc}} + \Delta \boldsymbol{V}_{\mathrm{mmc}}\right] \tag{7}$$

Besides, from [14-15], $u_{\mathrm{s}N} = \sqrt{N}$ and $\frac{\lambda_N}{u_{\mathrm{s}N}^2} = x_{\mathrm{L}} + \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} x_{ij}}{N}$, where x_{L} is the reactance of the transmission line and x_{ij} is the self or mutual reactance of the WPGs considering the power collecting network [15]. Thus, let $X_{\mathrm{t}} = \frac{\lambda_N}{u_{\mathrm{s}N}^2}$, which can quantify the average electrical distance between the WPGs and the MMC-HVDC.

Then based on (2) and (7), with the equivalent decoupling induced, the WISM can be represented by a feedback system as shown by Fig. 2, where $\boldsymbol{Z}_{\mathrm{mmcL}}(s) = \boldsymbol{Z}_{\mathrm{mmc}}(s) - X_{\mathrm{t}}\boldsymbol{E}(s)$. According to the GNC, stability of the system can be analysis based on the impedance ratio matrix $N\boldsymbol{G}_{\mathrm{w}}(s)\boldsymbol{Z}_{\mathrm{mmcL}}(s)$. Thus, if cross point of the Nyquist curves of the impedance ratio matrix $\boldsymbol{G}_{\mathrm{w}}(s)\boldsymbol{Z}_{\mathrm{mmcL}}(s)$ with the negative real axis is (-a, 0) with $a > 0$. The feedback system in Fig. 2 is stable if and only if $Na < 1$. Thus, a criterion for the oscillation stability of the WISM can be obtained as,

$$N < \frac{1}{a} \tag{8}$$

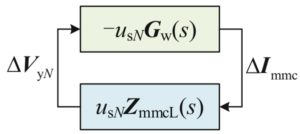


Fig. 2. Configuration of the feedback system1.

The criterion given in (8) can judge the oscillation stability of the WISM under considering the impact of the number of generators. Besides, in line with (2) and (7), the WISM can also be expressed as a feedback system as shown by Fig. 3, where $\boldsymbol{G}_{\mathrm{wm}}(s) = [\frac{1}{N}\boldsymbol{Z}_{\mathrm{w}}(s) + \boldsymbol{Z}_{\mathrm{mmc}}(s)]^{-1}$, $\boldsymbol{Z}_{\mathrm{w}}(s) = \boldsymbol{G}_{\mathrm{w}}{}^{-1}(s)$ and $\boldsymbol{V}_{\mathrm{tY}}$ is a newly induced voltage to describe the dynamics of the system. Similarly, if cross point of the Nyquist curves of the impedance ratio matrix -$\boldsymbol{G}_{\mathrm{wm}}(s)\boldsymbol{E}(s)$ with the negative real axis is (-b, 0) with $b > 0$, then the system is stable if and only if,

$$X_{\mathrm{t}} < \frac{1}{b} \tag{9}$$

Based on the stability criterion in (8) and (9), with the increase of the number of WPGs or reactance of the network, NFFO stability of a WISM deteriorates.

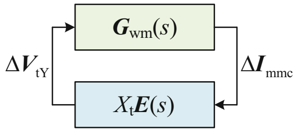


Fig. 3. Configuration of the feedback system2.

3.2 NFFO Risk Assessment Based on the Stability Criterion

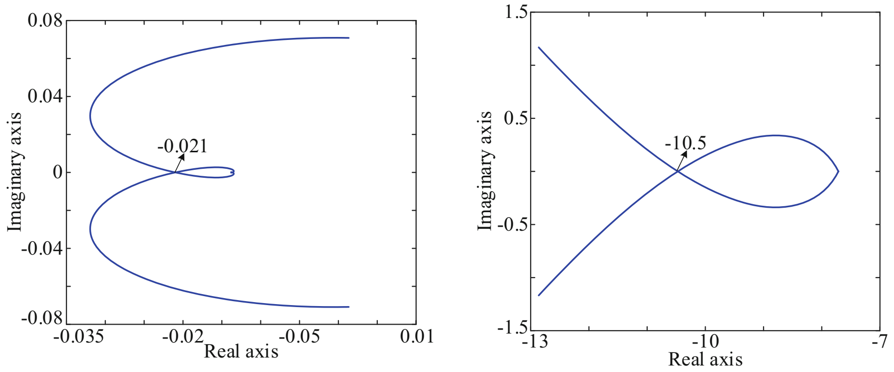
In Sect. 3.1, a stability criterion is derived for the oscillation risk assessment. As for the NFFO, in line with the actual events, the oscillation generally occurs when the active power output of the WPGs increases to a certain level and hence, the delivery capacity of the MMC-HVDC is limited. The stability criterion in (8) and (9) can be used for the oscillation risk assessment considering different number of WPGs and network topologies. Since the NFFO is closely related to the high active power transmission, in the oscillation risk assessment, we can assume that all the WPGs operate at rated state, which is the worst condition. Then via power flow calculation, steady-state operating points for WPG and the MMC-HVDC can be obtained and the impedance/admittance model $\boldsymbol{G}_{\mathrm{w}}(s)$ and $\boldsymbol{Z}_{\mathrm{mmc}}(s)$ can be established. Therefore, based on (8) and (9), the stability limit $1/a$ or $1/b$ can be obtained. Besides, the stability criterion can also be used for the oscillation risk assessment under other power transmission levels, for example, when the power outputs of the WPGs are 90% of the rated value. The procedure for the risk assessment is the same as that under the rated state and will not be repeated here.

4 Case Studies

In this section, effectiveness of the criterion proposed in Sect. 3 was verified based on an example WISM as shown by Fig. 1. At initial state, there are forty DFIGs in the example system and $X_{\mathrm{t}} = 0.1p.u.$. Rated capacity of the DFIG is $0.1p.u.$ with the base value to be 100 MVA.

First, impact of the number of DFIGs was analyzed. Impedance/admittance models of the DFIG and the MMC-HVDC were built under the condition that the WPGs were operating at the rated state. Then Nyquist curves of the eigenvalues of the impedance ratio matrix $-\boldsymbol{G}_{\mathrm{w}}(s)\boldsymbol{Z}_{\mathrm{mmcL}}(s)$ were plotted, and the results are shown in Fig. 4(a). Then from (8), when number of the DFIGs (N) exceeds forty-seven, the example system will losses oscillation stability.

Second, oscillation stability of the example WISM was studied considering the impact of network topology. To do so, Nyquist curves of the eigenvalues of the impedance ratio matrix $\boldsymbol{G}_{\mathrm{wm}}(s)\boldsymbol{E}(s)$ were plotted when there were fifty DIFGs, and the results are shown in Fig. 4(b). Then from (9), when X_{t} is lower than 0.095 $p.u.$, the example WISM is stable.



(a) Impact of N (b) Impact of X_t

Fig. 4. The Nyquist curves, (a) Impact of N, (b) Impact of X_t.

Finally, effectiveness of the results of oscillation stability based on the criterion shown in (8) and (9) was verified via nonlinear simulation. At 0.5s of the simulation, the AC-side terminal voltage of the MMC decreased by 5% and recovered at 0.6 s. The results are shown in Fig. 5. It can be seen that, the results of the nonlinear simulation are consistent with that obtained via the stability criterion and hence, effectiveness of the stability criterion is verified. Besides, with the increase of the number of generators or reactance of the network, NFFO stability of the system deteriorates.

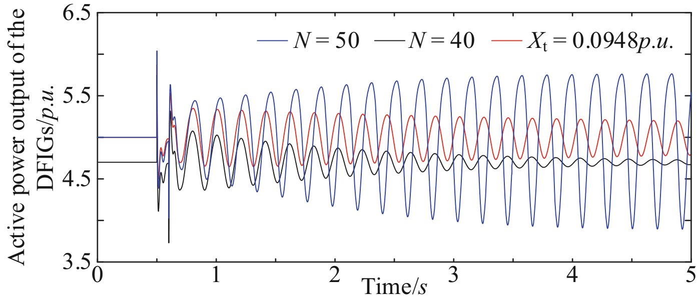


Fig. 5. Nonlinear simulation results.

5 Conclusions

A stability criterion for the study of NFFO is derived in this paper based on the equivalent decoupling and GNC. Main contributions of this paper can be summarized as follows.

The stability criterion proposed gives the critical condition for the NFFO stability of a WISM considering the impact of the number of WPGs and the network topology. Based on this, NFFO risk under different number of WPGs and network topologies can be efficiently assessed.

The stability criterion gives an analytical explanation to the NFFO induced by the integration of WPGs. With the increase of the number of WPGs or reactance of the network, NFFO stability of a WISM deteriorates.

Acknowledgment. This work is supported by the State Grid Corporation of China (5108-202218280A-2–312-XG).

References

1. Lyu, J., Zhang, X., Cai, X., et al.: Harmonic state-space based small-signal impedance modeling of a modular multilevel converter with consideration of internal harmonic dynamics. IEEE Trans. Power Electron. **34**(3), 2134–2148 (2019)
2. Xu, Z., Li, B., Han, L., et al.: A complete HSS-based impedance model of MMC considering grid impedance coupling. IEEE Trans. Power Electron. **34**(12), 12929–12948 (2019)
3. Zeng, Q., Zhu, J., Hu, J., et al.: Analysis of 6Hz SSO caused by the interaction between wind turbines and MMC-HVDC. In: 2023 IEEE 6th International Electrical and Energy Conference (CIEEC), pp. 1321–1326. Hefei, China (2023)
4. Liu, H., Dong, W., Wang, X., et al.: Characteristic analysis of quasi-power-frequency sequence oscillations in DFIG wind farms integrated via MMC- HVDC. In: ACCES 2023, pp. 1–8. Nanchang, China (2023)
5. Sun, J.: Impedance-based stability criterion for grid-connected inverters. IEEE Trans. Power Electron. **26**(11), 3075–3078 (2011)
6. Wu, X., Wang, W., Xiao, H., et al.: Overall sequence impedance model of grid-connected inverter and its stability analysis. Proceedings of the CSEE **44**(9), 3645–3656 (2024)
7. Liu, H., Xie, X., Liu, W.: An oscillatory stability criterion based on the unified dq-frame impedance network model for power systems with high-penetration renewables. IEEE Trans. Power Syst. **33**(3), 3472–3485 (2018)
8. Liu, H., Xie, X., Gao, X., et al.: Stability analysis of SSR in multiple wind farms connected to series-compensated systems using impedance network model. IEEE Trans. Power Syst. **33**(3), 3118–3128 (2018)
9. Zhan, Y., Xie, X., Wang, Y., et al.: Impedance network model based modal observability and controllability analysis for renewable power systems. IEEE Trans. Power Delivery **36**(4), 2025–2034 (2021)
10. Du, W., Wang, Y., Wang, H., et al.: Reduced-order method for detecting the risk and tracing the sources of small-signal oscillatory instability in a power system with a large number of wind farms. IEEE Transactions on Power System **36**(2), 1563–1582 (2021)
11. Du, W., Dong, W., Wang, H.: A method of reduced-order modal computation for planning grid connection of a large-scale wind farm. IEEE Transactions on Sustainable Energy **11**(3), 1185–1198 (2020)
12. Du, W., Wang, H., Bu, S.: Small-signal stability analysis of power systems integrated with variable speed wind generators. Springer, Berlin, Germany (2018)
13. Liu, W., Xie, X., Zhang, X., et al.: Frequency-coupling admittance modeling of converter-based wind turbine generators and the control-hardware-in-the-loop validation. IEEE Trans. Energy Convers. **35**(1), 425–433 (2017)
14. Dong, W., Xin, H., Wu, D., et al.: Small signal stability analysis of multi-infeed power electronic systems based on grid strength assessment. IEEE Trans. Power Syst. **34**(2), 1393–1403 (2019)

15. Du, W., Dong, W., Wang, H.: Small-signal stability limit of a grid-connected PMSG wind farm dominated by the dynamics of PLLs. IEEE Trans. Power Syst. **35**(3), 2093–2107 (2020)
16. Dong, W., Du, W., Xie, X., et al.: An approximate aggregated impedance model of a grid-connected wind farm for the study of small-signal stability. IEEE Trans. Power Syst. **37**(5), 3847–3861 (2022)