A Dynamic Equivalent Method for PMSG-WTG Based Wind Farms Considering Wind Speeds and Fault Severities

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Abstract—The dynamic security assessment of power systems needs to scan contingencies in a preselected set through time-domain simulations. With more and more wind power generation integrated into power systems, the complexity of simulation will increase greatly if wind farms are modeled in detail. Thus, it is critical to develop dynamic equivalent methods for wind farms. The dynamic response characteristics of permanent magnet synchronous generator-wind turbine generators (PMSG-WTGs) are not only influenced by their control strategies, but also by the operating wind speeds and the fault severities. Thus, this article proposes a dynamic equivalent method for a PMSG-WTG based wind farm considering the wind speeds and the fault severities. Firstly, we propose a clustering method based on the operating wind speed and the terminal voltage of each PMSG-WTG at the end of the fault. Then, a single-machine equivalent method is introduced for each cluster of PMSG-WTGs. For the cluster of PMSG-WTGs with active power ramp recovery process, an equivalent model with segmented ramp rate limitation for active current is designed. In order to obtain the clustering indicators, a simulation-based iterative method is put forward. Eventually, the efficiency and accuracy of the proposed method are verified by the simulation results.

Index Terms—PMSG-WTG, dynamic security assessment, dynamic equivalent method, transient simulation, power systems.

I. INTRODUCTION

With its safety, cleanliness and high efficiency, wind power has been widely integrated in power systems [1]. However, large-scale wind power integration has great effects on the stable operation of power systems due to the randomness and fluctuation [2]. In order to maintain the reliability of power supply, it is necessary to perform the dynamic security assessment (DSA) of power systems with large-scale wind power integration. The DSA of a power system usually refers to the problem of how well a particular system condition can withstand a set of possible faults, which is always realized by the time domain simulation methods [3]. The set of faults is referred to “expected contingencies” in this article. However, if modeling every wind power generator in detail during simulation, the computational complexity will be increased greatly, even the problem of “dimension disaster” will occur [4]. In addition, the DSA of power systems needs to be applied to the expected contingencies, so that preventive measures can be taken to ensure the system safety even if the expected contingencies occur [5]. Therefore, it is of vital significance to establish a dynamic equivalent model of wind farm which is suitable for analyzing the expected contingencies.

The existing methods for dynamic equivalent modeling are divided into two categories. The first category is the single-machine equivalent method, which can be further classified into one wind turbine with one generator model and multiple wind turbines with one generator model. In the former model, the equivalent wind speed is calculated by the principle of constant active power before and after equivalence [6], [7]. Other parameters of the equivalent model are obtained by the capacity weighting method or some other optimization algorithms, such as genetic learning particle swarm optimization algorithm [8] and recursive least-squares method [9], which make the dynamic response of the equivalent model closer to the reality. In the latter model, the sum of mechanical torques of each wind turbine is set as the input mechanical torque of the equivalent model [10]. The single-machine equivalent method is effective when the wind speeds among wind turbines have no obvious difference. However, with the continuous increase of the scale of wind farms, the operating wind speeds and dynamic characteristics of wind turbines in the same wind farm vary a lot. Thus, the single-machine equivalent method cannot represent the dynamic characteristics of a whole wind farm accurately.

The second category is the multi-machine equivalent method, which is able to represent the different behaviors among wind power generators. In the method, one or a group of features that can characterize the operating state of wind power generators are usually selected as the clustering indicators. These methods sometimes require the post-fault information, such as the
reactive power of wind generator [11], the rotor currents [12] or the stator short-circuit currents [13]. However, these indicators are difficult to obtain before the occurrence of a fault. Thus, these methods cannot analyze the expected contingencies. There are also multi-machine equivalent methods that only use pre-fault information, such as the wind speed [14], [15], [16], [17], the pitch angle [18] and the active power sequence before the fault [19], which are able to analyze the expected contingencies. Nevertheless, wind power generators are clustered without considering the influence of the fault severity in [14], [15], [16], [17], [18], [19]. Considering the reactive power priority control and the active power ramp recovery process, the pre-fault states of wind power generators and the fault severity together determine the dynamic responses of wind power generators. In [20], wind power generators are clustered by the similarity among the measurable output characteristics under a specific fault. After building an equivalent model based on the clustering result, the model is used to analyze different system faults, which also does not consider the influence of the fault severity. In [21], [22], [23], wind power generators are divided into different clusters according to the operation characteristics of crowbars, while the terminal voltages are assumed as constants during a fault. Although these methods consider the effects of faults on the wind power generators, they do not reveal the relationship between the severity of the fault and the output characteristics of the wind power generators.

The active power of wind power generators operating at different wind speeds will restore to their pre-fault value with different recovery time after the fault clearance. If the wind turbine generators with ramp recovery characteristics are equivalently modeled by the traditional single-machine equivalent method, the active power of the equivalent model will restore to its pre-fault active power at a certain ramp rate after the fault clearance, which is inaccurate. Most equivalent methods do not consider the different characteristics between wind turbine generators after the fault clearance. In [15], a four-machine equivalent method is proposed to fit the different recovery characteristics of wind power generators with four different recovery rates. When a large number of wind power generators are under consideration, the active power recovery process is divided into many segments with different recovery rates which is far more than four segments. Thus, the method is still inaccurate when considering large scale wind farms. In [24], [25], the reference active power of each doubly fed induction generator (DFIG) after the fault clearance is calculated analytically by the wind speeds and the terminal voltages. The reference active power of the equivalent model is obtained by the sum of the reference active power of all DFIGs. Nevertheless, as for the permanent magnet synchronous generator-wind turbine generator (PMSG-WTG), the reference value of active current is influenced by the characteristic of the dc-link voltage, which cannot be calculated analytically. Therefore, there is currently no equivalent method to accurately model the ramp recovery part of a PMSG-WTG based wind farm.

In summary, it is difficult to find a dynamic equivalent method that considers both the pre-fault operating state and the severity of fault when takes account of the reactive power priority control and active power ramp recovery process. Therefore, this article try to develop a dynamic equivalent method applicable to expected contingencies for a PMSG-WTG based wind farm, which takes the influence of wind speed, the fault severity, the reactive power priority control and the active power ramp recovery process into account. It is worth mentioning that the method of this article is only applicable to the symmetrical faults. The main contributions are listed as follows:

1) A clustering method is proposed considering pre-fault wind speeds and PMSG-WTG terminal voltages at the end of a fault. All possible dynamic response characteristics of PMSG-WTGs and the corresponding boundary conditions are derived considering the reactive power priority control and the active power ramp recovery process. Moreover, a convenient clustering method is put forward.

2) Single-machine equivalent models are proposed for each cluster of PMSG-WTGs. However, the model is still cannot reflect the differences among PMSG-WTGs with active power ramp recovery process. Thus, an improved single-machine equivalent model with segmented ramp rate limitation for active current is presented.

3) In order to obtain the clustering indicators before the expected contingencies occur, a simulation-based iterative method is introduced to calculate the voltage at point of common connection (PCC) of the wind farm at the end of faults. A terminal voltage calculation method is further designed. Based on the voltage calculation method, the proposed equivalent method can be applied to analyze expected contingencies.

The rest of the article is arranged as follows: the control strategy of PMSG-WTG is introduced in Section II. A clustering method considering wind speeds and terminal voltages is put forward in Section III. Different single-machine equivalent models are designed for each cluster of PMSG-WTGs in Section IV. A terminal voltage calculation method is presented in Section V. The proposed equivalent method is verified with different faults in a modified IEEE 39-bus system in Section VI. Conclusions are drawn in Section VII.

II. CONTROL STRATEGY OF PMSG-WTG

In the PMSG-WTG studied in this article, the machine-side converter (MSC) consists of an uncontrolled diode rectifier bridge and a boost chopper circuit. The grid-side converter (GSC) consists of a controlled inverter bridge composed of insulated gate bipolar transistors (IGBTs). The control strategies of converters are described below. Models of other parts of the PMSG-WTG such as wind turbine, drive train system and synchronous generator are consistent with the conventional models, which can be found in the literature [26].

A. Control Strategy of MSC

The active power control strategy of MSC is to achieve the maximum power point trace (MPPT). The optimal reference
rotor speed can be calculated by:

$$\omega_{opt} = \lambda_{opt} V_w / \gamma$$  \hspace{1cm} (1)$$

where $\omega_{opt}$ is the optimal mechanical angular speed of wind turbine; $V_w$ is the wind speed; $\gamma$ is the wind turbine radius; $\lambda_{opt}$ is the optimal tip speed ratio, which is a constant in the MPPT control. The boost IGBT switching signal is generated using the duty ratio, which can be obtained by the PI controller with eliminating the difference between the real dc current and the reference dc current.

B. Control Strategy of GSC

The GSC adopts grid voltage-oriented vector control to stabilize the dc-link voltage and realize the unity power factor control. The $dq$-axis voltage of grid can be derived as:

$$\begin{cases}
u_d = e & \\
u_q = 0 
\end{cases}$$  \hspace{1cm} (2)$$

where $e$ is the magnitude of grid voltage space vector; $u_d$ and $u_q$ are the $d$-axis and $q$-axis voltages of grid, respectively.

The active and reactive output power of GSC are:

$$\begin{cases}
P = \frac{1}{2} e i_d & \\
Q = \frac{1}{2} e i_q 
\end{cases}$$  \hspace{1cm} (3)$$

where $i_d$ and $i_q$ are the $d$-axis and $q$-axis currents of grid side, respectively. It can be found that the active and reactive output power of GSC can be controlled independently by $i_d$ and $i_q$. Thus, $i_d$ and $i_q$ are also called active current and reactive current, respectively.

1) Control Strategy of GSC During Normal Operation: During normal operation, the dc-link voltage is compared with the reference voltage and the error is PI controlled to obtain the reference value of $d$-axis current. The reference value of reactive power is usually set to 0 to achieve the unity power factor control. Thus, the reference value of $q$-axis current is also 0.

2) Control Strategies of GSC During and After a Fault: The GSC is unable to output the active power normally when the grid-side voltage suddenly drops, which will lead to the increase of the dc-link voltage. The chopper circuit connected in parallel with the dc capacitor will operate and consume the excess active power when the dc-link voltage reaches the set threshold. Since the dc-link voltage is always higher than the reference value during a fault, the $d$-axis current will continuously increase until the dc-link voltage returns to its reference value or the $d$-axis current is limited by the converter capacity. At the same time, PMSG-WTGs are required to generate reactive power to support the grid voltage during a fault. According to the grid codes [27], the reference value of output $q$-axis current during low-voltage ride through (LVRT) in this article is:

$$I_{qref} = 1.5 \times (0.9 - U_T) I_N, \hspace{0.1cm} (0.2 \leq U_T \leq 0.9)$$  \hspace{1cm} (4)$$

where $I_{qref}$ is the reference value of $q$-axis current in per unit; $U_T$ is the terminal voltage of PMSG-WTG in per unit; $I_N$ is the rated current of PMSG-WTG in per unit.

The PMSG-WTG adopts the reactive power priority control strategy during faults. The reference value of $d$-axis current is:

$$I_{dref} = \min\{I_{dref1}, I_{dmax}\}$$

$$I_{dmax} = \sqrt{I_{dmax}^2 - I_{qref}^2}$$  \hspace{1cm} (5)$$

where $I_{dref1}$ is obtained by the constant dc-link voltage control, which is the same as the control strategy during normal operation; $I_{dmax}$ is the maximum value of $d$-axis current; $I_{max}$ is the maximum current allowed through the converter.

After the fault clearance, if the active power does not restore to its pre-fault value, it will ramp up to the pre-fault value by limiting the recovering rate of $d$-axis current [28], [29], [30], which can reduce the mechanical stress [31]. The topology of the PMSG-WTG is shown in Fig. 1.

III. CLASSIFICATION AND DISCRIMINATION METHOD OF ACTIVE POWER DYNAMIC RESPONSE CHARACTERISTICS

The active power dynamic response characteristics of the PMSG-WTG after a fault can be divided into two parts: the characteristics during the fault and the recovery characteristics after fault cleared, which will be analyzed respectively based on a single PMSG-WTG in the following parts.

A. Active Power Dynamic Response Characteristics During a Fault

The output active power of GSC will instantaneously reduce to $\alpha P$ when the grid-side voltage drops to $\alpha$ due to an external fault. To maintain the dc voltage at the reference value, the steady-state value of $I_{dref1}$ is:

$$I_{dref1} = I_{d0} / \alpha$$  \hspace{1cm} (6)$$

where $I_{d0}$ is the pre-fault $d$-axis current of grid side. Due to the fast response of PMSG-WTGs, it can be assumed that PMSG-WTGs are able to adjust the outputs $dq$-axis currents to the reference value [32]. According to (5) and (6), the reference value of $d$-axis current at the moment before fault clearance can be calculated by:

$$I_{dref1}^f = \frac{I_{d0}}{\alpha}$$

$$I_{dmax}^f = \min\{I_{dref1}^f, I_{dmax}^f\}$$  \hspace{1cm} (7)$$

where the superscript $f$ denotes the moment before the fault clearance; $\alpha$ is the terminal voltage magnitude at the moment before the fault clearance; $I_{dref1}^f$ is the reference value obtained by the constant dc-link voltage control at the moment before the fault clearance; $I_{dmax}^f$ is the reference value and the allowed maximum value of the $d$-axis current of GSC at the moment before the fault clearance.

It can be known whether the output active power can recover to the pre-fault value during a fault by comparing $I_{dref1}^f$ and $I_{dmax}^f$. When $I_{dref1}^f \leq I_{dmax}^f$, we can get $I_{dref}^f = I_{dref1}^f$, which means that the GSC can stabilize the dc-link voltage by increasing the $d$-axis current during the fault. The output power of GSC is equal
to the power input from the MSC during the fault. Thus, the output active power of PMSG-WTG can recover to the pre-fault value during the fault.

When $I_{d_{ref}}^{-} = I_{d_{max}}^{-}$, we can get $I_{d_{ref}}^{-} = I_{d_{max}}^{-}$. It means that the $d$-axis current of GSC is limited by the converter capacity. Thus, the dc-link voltage cannot be stabilized at the reference value and the output power of GSC is lower than the power input from the MSC during the fault.

B. Active Power Dynamic Response Characteristics During Fault Recovery

The main difference of the active power transient response characteristics during fault recovery is the presence or absence of the active power ramp recovery process. Since the recovery rate of $d$-axis current is limited, the existence of active power ramp recovery process depends on whether the active power restores to the pre-fault value at the moment of fault clearance. That is, whether the $I_{d_{ref}}^{-}$ restores to $I_{d_{0}}$. Since $I_{d_{ref}}^{-}$ is always greater than $I_{d_{0}}$, the existence of the ramp recovery process for the PMSG-WTG can be determined by comparing $I_{d_{max}}^{-}$ and $I_{d_{0}}$.

C. Complete Active Power Dynamic Response Characteristics

Considering the active power dynamic response characteristics of PMSG-WTG during the fault and the fault recovery, the active power characteristics of PMSG-WTGs can be classified into the following three categories:

1) When $I_{d_{max}}^{-} < I_{d_{0}}$, we can get $I_{d_{ref}}^{-} = I_{d_{max}}^{-}$. There is a ramp recovery process after the fault clearance.

2) When $I_{d_{0}} < I_{d_{max}}^{-} < I_{d_{ref}^{-}}$, we can get $I_{d_{ref}}^{-} = I_{d_{max}}^{-}$. The output active power of PMSG-WTG is lower than the pre-fault active power during the fault. The output active power rises above the pre-fault value after the fault clearance and will return to the pre-fault value after a short period of oscillation.

3) When $I_{d_{max}}^{-} = I_{d_{ref}^{-}}$, we can get $I_{d_{ref}}^{-} = I_{d_{max}}^{-}$. The output active power of PMSG-WTG has recovered to the pre-fault value during the fault, which can keep the dc-link voltage at the reference value.

The schematic diagram of the active power dynamic response curve of each cluster is shown in Fig. 2. In Fig. 2, $t_{0}$ denotes the time of fault start; $t_{c}$ denotes the time of fault clear and $t_{n}$ denotes the time when the PMSG-WTG return to normal.

D. Discrimination Method of Active Power Dynamic Response Characteristics

During the normal operation, the $d$-axis current of PMSG-WTG can be derived by:

$$I_{d_{0}} = \frac{2P_{0}}{3e} \quad (8)$$

where $P_{0}$ is the pre-fault active power of PMSG-WTG. According to (4) and (5), $I_{d_{max}}^{-}$ can be derived by:

$$I_{d_{max}}^{-} = \sqrt{I_{d_{max}}^{2} - 2.25 \times (0.9 - \alpha f^{-})^2 I_{N}^2} \quad (9)$$

When $I_{d_{max}}^{-} = I_{d_{0}}$, the critical pre-fault active power can be calculated by (8) and (9):

$$P_{crit} = \frac{3}{2} \sqrt{I_{d_{max}}^{2} - 2.25 \times (0.9 - \alpha f^{-})^2 I_{N}^2} \quad (10)$$
When \( I_{d_{\text{max}}} = I_{d_{\text{ref}}} \), the second critical pre-fault active power is:

\[
P_{\text{cri}2} = \alpha f^{-1} P_{\text{cri}1}
\]

(11)

\( I_{\text{max}} \) and \( I_N \) can be known when the PMSG-WTG model is determined and the scale value of \( e \) during normal operation is close to 1. The critical power can be calculated at different voltage drop degrees. The critical power can be compared with \( P_0 \) to determine which cluster a PMSG-WTG belongs to. When \( P_0 > P_{\text{cri}1} \), the PMSG-WTG belongs to the cluster I in Fig. 2; when \( P_{\text{cri}2} < P_0 \leq P_{\text{cri}1} \), the PMSG-WTG belongs to the cluster II; when \( P_0 < P_{\text{cri}2} \), the PMSG-WTG belongs to the cluster III.

Moreover, the critical wind speeds of each sub-group can be calculated from the critical power and the wind power curve of the PMSG-WTG. The wind power curve can be divided into three regions: the maximum power tracking region, the constant speed region and the constant power region. These parts can be fitted separately as the function of wind speed. The numerical relationship between wind power and wind speed can be seen in Appendix A. Moreover, the wind power curve is shown in Fig. 3. Thus, the critical wind speeds can be derived by:

\[
V_{\text{cri}1} = f^{-1}(P_{\text{cri}1})
\]

\[
V_{\text{cri}2} = f^{-1}(P_{\text{cri}2})
\]

(12)

Where \( f^{-1} \) is the inverse function of wind power curve.

According to (10)–(12), the wind speed boundary conditions for each cluster under different voltage dips are shown in Fig. 4. Thus, the critical wind speeds can be derived by:

\[
V_{\text{cri}1} = f^{-1}(P_{\text{cri}1})
\]

\[
V_{\text{cri}2} = f^{-1}(P_{\text{cri}2})
\]

(12)

Where \( f^{-1} \) is the inverse function of wind power curve.

According to (10)–(12), the wind speed boundary conditions for each cluster under different voltage dips are shown in Fig. 4. Thus, the critical wind speeds can be derived by:

The three regions in Fig. 4 correspond to the three types of response characteristics in Fig. 2. The classification boundaries only show the part of wind speeds from the cut-in wind speed of 3.5 m/s to the rated wind speed of 11.17 m/s. When the wind speed is below the cut-in wind speed, the output power of PMSG-WTG is 0. When the wind speed is above the rated wind speed, the output power of PMSG-WTG is the same as the active power of PMSG-WTG operating at the rated wind speed due to the pitch angle control.

PMSGs can be divided into three clusters based on the clustering boundaries shown in Fig. 4. The active currents of PMSG-WTGs in Cluster I will recover with a certain rate after the fault clearance. The active currents of PMSG-WTGs in cluster II are limited by the converter capacity during the fault, while the active currents of PMSG-WTGs in cluster III depend on the pre-fault active power during the fault. As a result, the proposed clustering method is able to classify the PMSG-WTGs with the same active response characteristics into a group when deriving the dynamic equivalent.

IV. A DYNAMIC EQUIVALENT MODEL FOR WIND FARM

Based on the proposed clustering method in Section III, single-machine equivalent models are performed for each cluster of PMSG-WTGs separately. Firstly, single-machine equivalent models are proposed for the PMSG-WTGs in cluster II and cluster III. In addition, for the PMSG-WTGs in cluster I, a single-machine equivalent model with segmented ramp rate limitation for active current is introduced. The wind farm will be equivalently modeled as a three-machine equivalent model. Finally, a collector line equivalent method is presented.

A. Single-Machine Equivalent Models for PMSG-WTGs in Cluster II and III

Unlike the conventional capacity weighted method, the article uses a controlled current source to implement a single-machine multiplication model. When we build a equivalent model for \( N \) PMSG-WTGs, the output current of a single equivalent model is multiplied by \( (N-1) \) as the output current of the controlled current source. The grid-side resistance and inductance need to be divided by the number of PMSG-WTGs \( (N) \), as shown in Fig. 5.
The equivalent parameters of the aggregated PMSG-WTG can be calculated by:

\[
\begin{align*}
S_{eq} &= \frac{1}{N} \sum_{i=1}^{N} S_i \\
P_{eq} &= \frac{1}{N} \sum_{i=1}^{N} P_i \\
X_{eq} &= \frac{1}{N} \sum_{i=1}^{N} X_i, \quad R_{eq} = \frac{1}{N} \sum_{i=1}^{N} R_i \\
H_{t,eq} &= \frac{1}{N} \sum_{i=1}^{N} H_{t,i}, \quad H_{g,eq} = \frac{1}{N} \sum_{i=1}^{N} H_{g,i}
\end{align*}
\] (13)

where $N$ is the number of PMSG-WTGs in the same cluster; $S$ is the capacity of PMSG-WTG; $P$ is the active power of PMSG-WTG; $X$ and $R$ are the reactance and resistance of stator; $H_t$ is the turbine inertia time constant; $H_g$ is the generator inertia time constant; the subscript $eq$ denotes the equivalent value; the subscript $i$ denotes the parameter of the $i$th PMSG-WTG.

In order to output the same active power in the steady state before and after the equivalence, the equivalent wind speed of the equivalent model should be derived by:

\[
V_{weq} = f^{-1} \left( \frac{1}{N} \sum_{i=1}^{N} f(V_{wi}) \right)
\] (14)

For the PMSG-WTGs in cluster II and cluster III, their active power response characteristics are still basically the same as the active power of a single PMSG-WTG after accumulating. Therefore, the proposed single-machine equivalent model can be used to perform a proper equivalence for these two clusters of PMSG-WTGs. However, for the PMSG-WTGs in cluster I, the time duration of their ramp recovery process varies due to the different initial operating wind speeds and voltage dips. Traditional single-machine equivalent model cannot model the fault recovery part accurately. As a result, there is still a need to further propose an equivalent model for the PMSG-WTGs in cluster I that can accurately represent the response characteristics during the fault recovery.

### B. Single-Machine Equivalent Model With Multi-Segment Slope Limitation for PMSG-WTGs in Cluster I

By summing the active power of PMSG-WTGs in cluster I during recovery process, the equivalent response curve will restore to pre-fault value with multiple different rates, which cannot be represented in the single-machine equivalent model mentioned above, as shown in Fig. 6.

In order to reflect the differences in recovery characteristics of each PMSG-WTG in cluster I, a single-machine equivalent model with multi-segment slope limitation is proposed. Ignoring the overshoot of active power during constant dc voltage control, it can be assumed that the ramp recovery process ends when the active power rises to the pre-fault value as shown in Fig. 7. The calculation method for the time duration of the ramp recovery process is introduced below.

The pre-fault active power and pre-fault $d$-axis current of the $i$th PMSG-WTG in cluster I can be derived as follows:

\[
P_{0i} = f(V_{wi}) \\
I_{di} = \frac{2P_{0i}}{3e}
\] (15)

The $q$-axis current to be supplied by the $i$th PMSG-WTG during a fault is:

\[
I_{qi} = 1.5 \left( 0.9 - \alpha_i^{f-} \right) I_{N,i} \left( 0.2 \leq \alpha_i^{f-} \leq 0.9 \right)
\] (16)

where $\alpha_i^{f-}$ and $I_{N,i}$ are the terminal voltage magnitude and the reference value of $q$-axis current of the $i$th PMSG-WTG at the moment before the fault clearance in per unit.

Since the $d$-axis currents of PMSG-WTGs in cluster I all reach $I_{d,\text{max}}^f$ during the fault, the $d$-axis current of the $i$th PMSG-WTG can be derived as follows according to (9):

\[
I_{di}^f = \sqrt{I_{d,\text{max}}^2 - 2.25 \times (0.9 - \alpha_i^{f-})^2 I_{N,i}^2}
\] (17)

Due to the limitation of the recovery rate of the $d$-axis current, the time duration of the ramp recovery process of the $i$th PMSG-WTG is:

\[
t_i = \frac{(I_{d0i} - I_{d,\text{max}}^f)}{k}
\] (18)

where $k$ is the maximum recovery rate of $d$-axis current; $t_i$ is the time duration of the slope recovery process of the $i$th PMSG-WTG.

Substituting (15) and (17) into (18), the time duration of the $i$th PMSG-WTG can be derived as follows:

\[
t_i = \left( \frac{2f(V_{wi})}{3e} - \sqrt{I_{d,\text{max}}^2 - 2.25 \times (0.9 - \alpha_i^{f-})^2 I_{N,i}^2} \right) / k
\] (19)

According to (19), $t_i$ is only related to $\alpha_i^{f-}$ and $V_{wi}$. Sorting $t_i$ from the smallest to the largest and the recovery rate limitation of $d$-axis current of the equivalent model after fault clearance is
where \( \alpha_{equ,c,1,2} \) are the two solutions of (23). \( \alpha_{equ,c} \) is finally determined by:

\[
\alpha_{equ,c} = \begin{cases} 
\alpha_{equ,c,1} & \text{if } |\alpha_{equ,c,1} - \alpha_{pcc}| \leq |\alpha_{equ,c,2} - \alpha_{pcc}| \\
\alpha_{equ,c,2} & \text{if } |\alpha_{equ,c,1} - \alpha_{pcc}| > |\alpha_{equ,c,2} - \alpha_{pcc}| 
\end{cases}
\]  

(25)

where \( \alpha_{pcc} \) is the voltage of PCC; \( \alpha_{equ,c} \) is the terminal voltage of the equivalent model of cluster \( c \).

From the conclusion of Section III-C, the active power of equivalent model of each cluster at the moment of fault clearance can be expressed by:

\[
\begin{align*}
\begin{cases}
P_{equ,1} &= 1.5N_1\alpha_{equ,1} - \frac{1}{\alpha_{equ,1}} \left( J^2 - 2.25 \times (0.9 - \alpha_{equ,1})^2 I_N^2 \right) \\
P_{equ,2} &= 1.5N_2\alpha_{equ,2} - \frac{1}{\alpha_{equ,2}} \left( J^2 - 2.25 \times (0.9 - \alpha_{equ,2})^2 I_N^2 \right) \\
P_{equ,3} &= N_3f(V_{eq,3})
\end{cases}
\end{align*}
\]

(26)

where \( P_{equ,c} \) is the output active power of equivalent model of cluster \( c; \alpha_{equ,1} \) and \( \alpha_{equ,2} \) are the terminal voltages of the equivalent models of cluster I and cluster II, respectively. The longitudinal component and the lateral component of the voltage drop on the equivalent collector line are:

\[
\begin{align*}
\Delta \alpha_c &= \left( P_{equ,c}R_c + Q_{equ,c}X_c \right) / \alpha_{equ,c} \\
\delta \alpha_c &= \left( P_{equ,c}X_c - Q_{equ,c}R_c \right) / \alpha_{equ,c}
\end{align*}
\]

(27)

where \( \Delta \alpha_c \) and \( \delta \alpha_c \) are the longitudinal component and the lateral component of the voltage drop on the collector line of cluster \( c \), respectively; \( R_c \) and \( X_c \) are the resistance and reactance of the equivalent line of cluster \( c \).

The parameters of collector line are designed to make the terminal voltage drop of the equivalent model equal to \( \alpha_{equ,c} \).

Thus, the parameters of collector line will satisfy the following equation:

\[
\left( \alpha_{equ,c} - \Delta \alpha_c \right)^2 + \delta \alpha_c^2 = \alpha_{pcc}^2
\]

(28)

The (27) and (28) has three equations with four unknowns \( (\Delta \alpha_c, \delta \alpha_c, R_c, \text{ and } X_c) \), which means an additional equation is still required. In this article, the per unit length impedance parameters of the equivalent collector line are designed the same as that before the equivalence. Only the line length is changed to satisfy (28). That is to say, the additional equation is:

\[
\frac{R_c}{X_c} = \frac{R_0}{X_0} = K_0
\]

(29)

where \( R_0 \) and \( X_0 \) are the per unit length resistance and reactance of collector line before the equivalence.

According to (27)–(29), the parameters of equivalent line of each cluster are:

\[
\begin{align*}
X_{c,1,2} &= \frac{\alpha_{equ,c} f - \Delta \alpha_c}{A + \sqrt{A^2 - B \left( \alpha_{equ,c} f - \alpha_{pcc} f \right)^2}} \\
R_{c,1,2} &= K_0 X_{c,1,2} \\
A &= \alpha_{equ,c} f (K_0 P_{equ,c} + Q_{equ,c}) \\
B &= \left( P_{equ,c}^2 + Q_{equ,c}^2 \right) (1 + K_0^2)
\end{align*}
\]

(30)
where $X_{c1,2}$ and $R_{c1,2}$ are the two sets of solutions of equations, as shown in Fig. 10. The phase angle difference between $\alpha_{equ,c}^f$ and $\alpha_{pcc}^f$ exceeds $\pi/2$, which does not meet the requirements of static stability [33]. Thus, $R_{c1}$ and $X_{c1}$ are chosen as the equivalent line parameters, that is:

$$X_c = \frac{\alpha_{equ,c}^f - (A - \sqrt{A^2 - B (\alpha_{equ,c}^f - \alpha_{pcc}^f)^2})}{B}$$
$$R_c = K_0 X_c$$

(31)

V. Calculation Method for Terminal Voltages of PMSG-WTGs

Wind speeds and terminal voltages are the clustering indicators of the dynamic equivalent method proposed in Sections III and IV. When simulation analysis is performed for expected contingencies, the operating wind speed of each PMSG-WTG can be obtained by the historical wind speed data or wind speed forecast [34], [35]. However, when an external fault occurs in a real power system, terminal voltages of PMSG-WTGs at the moment of fault clearance cannot be predicted in advance because it is not only related to the output characteristics of PMSG-WTG, but also to the time duration of the fault and the response characteristics of the components in the power system. Thus, it is difficult to solve the voltages analytically. Therefore, this section proposes a method for solving the terminal voltage of each PMSG-WTG in a wind farm when the PCC voltage is given. Moreover, a simulation-based iterative method is proposed to get the value of PCC voltage.

A. A Calculation Method for PMSG-WTG Terminal Voltages

This section presents a calculation method for the terminal voltage of each PMSG-WTG based on a real wind farm topology in China. The topology of the wind farm is shown in Fig. 11.

When the voltage of PCC is given, the calculation of the terminal voltages at a certain moment is similar to the power flow calculation assuming that the PMSG-WTGs have adjusted the output dq-axis currents to the reference value.

According to (3), (4) and (7), the output active and reactive power of each PMSG-WTG are:

$$P_i = 1.5|\hat{U}_i| \times \min \left\{ \frac{I_{dmi}}{|\hat{U}_i|}, I_{dmaxi} \right\}$$
$$Q_i = 1.5|\hat{U}_i| I_{qrefi}$$
$$I_{qrefi} = 1.5 \times (0.9 - |\hat{U}_i|) I_N, (0.2 \leq |\hat{U}_i| \leq 0.9)$$

$$I_{dmaxi} = \sqrt{I_{dmi}^2 - I_{qrefi}^2}$$

(32)

where $\hat{U}_i$ is the terminal voltage phasor of the $i$th PMSG-WTG; $P_i$ and $Q_i$ are the output active and reactive power of the $i$th PMSG-WTG, respectively. Then, the current injected by the $i$th PMSG-WTG is:

$$\hat{I}_{ni} = \left( \frac{P_i + j Q_i}{\hat{U}_i} \right)^*$$

(33)

where $\hat{I}_{ni}$ is the current injected by the $i$th PMSG-WTG.

To further calculate the current of each branch on the feeder, a branch-node matrix needs to be created. The rows of the matrix represent branches, and the columns of the matrix represent nodes. If the injected current of node $j$ flows through the $i$th branch, the value of the $i$-th row and $j$-th column of the matrix is 1, otherwise it is 0.

The branch current column vector of a feeder is:

$$\hat{I}_b = C \hat{I}_n$$

(34)

where $C$ is the branch-node matrix of a feeder line; $\hat{I}_n$ is column vector of the nodal injection current consisting of $\hat{I}_{ni}$; $\hat{I}_b$ is the branch current column vector. Further, based on the branch current, the branch voltage drop and node voltage drop are:

$$\Delta \hat{U}_b = Z \hat{I}_b$$
$$\Delta \hat{U}_n = C^T \Delta \hat{U}_b$$

(35)

where $\Delta \hat{U}_b$ and $\Delta \hat{U}_n$ are the branch voltage drop and node voltage drop column vectors of the feeder, respectively; $Z$ is the branch impedance matrix of feeder. Only the values of the diagonal elements of $Z$ are the branch impedance, the values of other non-diagonal elements are 0. Then, the voltage of each node on the feeder can be obtained as:

$$\hat{U}' = \hat{U}_{pcc} + \Delta \hat{U}_n$$

(36)
where \( U_{pcc} \) is the voltage of PCC; \( \hat{U} \) is the revised voltage of each node on the feeder.

Substituting (34), (35) into (36), the revised voltage can be derived as:

\[
\hat{U} = U_{pcc} + C^T ZC \hat{I}_n
\]

When the voltage at PCC is known, the terminal voltage of each PMSG-WTG can be calculated by the following steps:

1) Branch impedance matrix and branch-node matrix are formed for each feeder based on the wind farm topology data. Set all terminal voltages of PMSG-WTGs to the PCC voltage.
2) Use (32), (33) and (37) to calculate the revised terminal voltage of each PMSG-WTG.
3) If |\( \hat{U}_t - \hat{U} \)| < \( \sigma_1 \), turn to step 4. If not, assign the value of \( \hat{U}_t \) to \( \hat{U} \) and turn to step 2. Where \( \sigma_1 \) is the iteration tolerance of the voltage.
4) Output the \( \hat{U} \).

B. Simulation-Based Iterative Method for Solving the Voltage at PCC

As the PCC voltage is difficult to solve analytically, this section proposes a simulation-based iterative method for solving the voltage at PCC, which can improve both the computational efficiency and accuracy. The steps are as follows:

1) Input the wind speed of each PMSG-WTG during normal operation and let \( \alpha_{pcc}^f = 1 \).
2) Let \( \hat{U}_{pcc} = \alpha_{pcc}^f \hat{U} \). Calculate the terminal voltage of each PMSG-WTG using the method proposed in Section V-A.
3) The equivalent model can be performed by the method proposed in Sections III and IV.
4) Simulation analysis of the expected contingency is carried out using the established equivalent model in step 3). Moreover, the PCC voltage at the moment of fault clearance (\( \alpha_{pcc}^f \)) can be obtained by the result of the simulation.
5) If |\( \alpha_{pcc}^f - \alpha_{pcc}^c \)| < \( \sigma_2 \), turn to step 6. If not, assign the value of \( \alpha_{pcc}^f \) to \( \alpha_{pcc}^c \) and turn to step 2. \( \sigma_2 \) is the iteration tolerance of the PCC voltage.
6) Since the cluster indicators are known, the equivalent model can be obtained by the method proposed in Sections III and IV.

The above method avoids the analytical solution for \( \alpha_{pcc}^f \). In the case study section, it is demonstrated that the method can meet the convergence accuracy after 1–2 iterations. The overall flow chart of the proposed equivalent method is shown in Fig. 12.

The branch-node matrices, branch impedance matrices and clustering boundaries can be get offline. Thus, the wind farm equivalent model can be rapidly obtained if the wind speeds and the fault information can be known. In general, the wind speeds can be obtained from wind speed forecasts and the fault information is known in the DSA. Therefore, the proposed equivalent method is adapted to the online DSA. In addition, the terminal voltage calculation method is based on short-term iterative simulation, which is applicable for symmetrical faults with different locations and durations. At the same time, the equivalent result depends only on the operating wind speed and the simulated terminal voltage, which is also applicable for different fault conditions. Thus, the proposed method is general for the expected symmetrical faults.

VI. METHOD VERIFICATION

In this section, the effectiveness of the proposed approach is illustrated by a case study on the CloudPSS platform [36], [37]. All simulation tests are carried out on an Intel(R) Core(TM) i9-9900 K 3.60 GHz desktop computer with 32 GB RAM. The study is conducted on an actual wind farm in China, as shown in Fig. 11. The wind farm includes 100 PMSG-WTGs with the rated capacity of 1.5 MW. The distance between two wind turbines on the same feeder is 0.5 km, the distance between the feeder and the PCC is 2 km. The detailed model of the wind farm is connected to node 30 of the IEEE 39-bus system through a transformer, replacing the original generator, as shown in Fig. 13. The main information of the PMSG-WTG based wind farm is listed in Appendix B.

Assuming that the distance between the feeders is far enough, wind speeds among different feeders do not affect each other. The wind speeds of PMSG-WTGs on the same feeder are modeled with Jensen model, which can be derived as:

\[
V_{\text{wind}} = V_{\text{wind}} \text{deg} \cdot \text{deg}^{-1} \\
decc = \left( 1 - \left( 1 - (1 - C_1 \gamma X)^2 \right) \frac{\gamma}{\gamma + kX} \right) \quad (38)
\]

where \( V_{\text{wind}} \) is the initial input wind speed of the feeder; \( C_1 \) is the thrust coefficient; \( k \) is the wake decay constant; \( \gamma \) is the radius of wind turbine. The initial input wind speed of each feeder is an
uniform random distribution between 9 and 11 m/s. The thrust
coefficient is 0.2, the wake decay constant is 0.04. The wind
speeds of PMSG-WTGs using in the following case are shown
in Fig. 14. The numbering of PMSG-WTGs starts at the node
nearest to the PCC of feeder 1 and ends at the farthest node of
feeder 16. The proposed equivalent method is validated below
based on three different expected contingencies.

A. Case I: Verification of the Proposed Method When a
Nearby Fault Occurs

The three-phase short circuit fault starts at 3.0 s and clears at
3.1 s at node 30. The PCC voltage is obtained by the method
proposed in Section V-B. The results of each iteration are shown
in Table I.

When \( \alpha_{f_{pcc}}' = 0.2250 \), the terminal voltages of PMSG-WTGs
at the moment before fault clearance can be calculated using
the method proposed in Section V-A. The calculation results
are compared with the simulation results of detailed model, as
shown in Fig. 15. The maximum error percentage of all nodes
is 0.21%, which proves the validity of the method proposed in
Section V-A.

Further, the PMSG-WTGs are clustered based on the terminal
voltages and wind speeds. The clustering result is shown in
Table II.

The active power responses of individual PMSG-WTG in
the same cluster are shown in Fig. 16. It can be found that
the response characteristics of the PMSG-WTGs in the same
cluster are basically consistent with each other, which indicates the correctness of the method proposed in Section III. In order to prove the efficiency and correctness of the proposed equivalent method, we compare the proposed equivalent model with the detailed model and two existing equivalent models. The PCC active power and reactive power of different models are presented in Figs. 17 and 18, where DM, TM, SM and FM denote the detailed wind farm model, the proposed three-machine equivalent model in this article, the single-machine equivalent model in [10] and the four-machine equivalent model in [15], respectively. In addition, the detailed model refers to detailed modeling of each PMSG-WTG in the wind farm.

The results show that the proposed model is more accurate than the traditional model and can significantly reduce the simulation time compared to the detailed model, as shown in Table IV. The simulation time of the proposed method is the sum of the time spent in each iteration and the errors are calculated from the mean absolute percentage error between the active responses.

B. Case II: Verification of the Proposed Method When a More Severe Fault Occurs

In order to show the differences between the TM and the FM more significantly, we reduce the short-circuit impedance to simulate a more severe fault, making $\alpha_{pcc}^{f_{pcc}} = 0.126$. Since the FM clusters PMSG-WTGs according to the wind speeds, the clustering results remain unchanged when the fault is more serious. As for the proposed method, all PMSG-WTGs are clustered into cluster I under a severe fault.

When $\alpha_{pcc}^{f_{pcc}} = 0.126$, the PCC active power and reactive power are presented in Figs. 19 and 20. At this time, all of the PMSG-WTGs have a slope recovery process. The simulation times and equivalent errors are shown in Table IV. As we can see in Fig. 19, the FM fits the fault recovery part only with two different slopes, whereas our method can accurately fit any number of slopes during the fault recovery. Thus, when the number of PMSG-WTGs increases, the error of the FM will gradually increase while the proposed method can still maintain the accuracy.

C. Case III: Verification of the Proposed Method When a Distant Fault Occurs

When a three-phase short circuit fault occurs at node 24, the proposed method can be used to calculate the PCC voltage and terminal voltage of each PMSG-WTG, which is similar to the procedure in Case I. The final result of PCC voltage is $\alpha_{pcc}^{f_{pcc}} = 0.62$. The clustering result is shown in Table III.

The active power responses of individual PMSG-WTG in the same cluster are shown in Fig. 21. The response characteristics of PMSG-WTGs in cluster II and III are consistent with the results of the theoretical analysis in Section III. The active power and reactive power at PCC of different models are presented in Figs. 22 and 23. The simulation times and equivalent errors are compared in Table IV.
TABLE III
CLUSTERING RESULTS OF CASE III

| Cluster  | Number of PMSG-WTGs |
|----------|---------------------|
| Cluster 1 |                     |
| Cluster 2 | 1, 13, 14, 19, 26, 32, 33, 38, 44, 45, 50, 51, 56, 57, 68, 69, 80 |
| Cluster 3 | 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 27, 28, 29 |
| Cluster 4 | 30, 31, 34, 35, 36, 37, 40, 41, 42, 43, 46, 47, 48, 49, 52, 53, 54, 55, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100 |

Fig. 21. Active power responses of individual PMSG-WTG in the same cluster in Case III.

Fig. 22. Comparison of PCC active power in Case III.

According to case I and case II, when there are some PMSG-WTGs belonging to cluster I, the SM and the FM are less capable of equating the active power response during the fault recovery. In case III, there are some PMSG-WTGs belonging to cluster III and no PMSG-WTG belonging to cluster I. The TM, SM and FM can properly reflect the active power response during the fault recovery. However, the SM and the FM are relatively inaccurate compared to the TM during the fault. The above three cases illustrate that different fault severity degrees have great impacts on the clustering results. Thus, the equivalent methods without considering the faults are not accurate. As can be seen from Table IV, the proposed method improves the simulation efficiency of the DM while substantially increasing the accuracy of the SM and FM, which verifies the effectiveness of the proposed method.

VII. CONCLUSION

Based on the analysis of the active transient response characteristics of PMSG-WTGs under symmetrical faults, a clustering method considering wind speeds and PMSG-WTG terminal voltages is proposed. Moreover, single-machine equivalent models are presented for each cluster of PMSG-WTGs. For the cluster of PMSG-WTGs with active power ramp recovery process, an equivalent model with segmented ramp rate limitation for active current is introduced, which can more accurately characterize the dynamic responses of wind farm during fault recovery.

The simulation results show that the proposed method greatly improves the simulation efficiency compared with the DM. Compared with the SM, the proposed method has greatly improved the accuracy. Compared with the FM, the proposed method can better fit the active power response during fault recovery and improves the accuracy of the equivalent model.

TABLE IV
SIMULATION TIMES AND EQUIVALENT ERRORS OF DIFFERENT METHODS

|      | DM | TM | SM | FM |
|------|----|----|----|----|
| Case I | 1071 | 19.77 | 7.35 | 13.43 |
| Simulation time (s) | Simulation error (%) |
| Case II | 1134 | 19.86 | 7.56 | 14.37 |
| Simulation time (s) | Simulation error (%) |
| Case III | 1037 | 18.73 | 7.22 | 12.42 |
| Simulation time (s) | Simulation error (%) |

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The wind power curve of the used PMSG-WTG in this article can be expressed as:

\[
Pg = \begin{cases} 
0, & V_w \leq 3.5 \\
967V_w^3 + 1922V_w^2 - 11639V_w + 24797, & 3.5 < V_w \leq 10.428 \\
392740V_w - 2886620, & 10.428 < V_w \leq 11.17 \\
1500000, & V_w \geq 11.17
\end{cases}
\]
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