A dynamic equivalent method for DFIG wind farm based on the cloud model of rotor current

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Abstract. Affected by low voltage ride–through (LVRT) characteristics, random wind speed and terminal voltage dips, large scale doubly-fed induction generator (DFIG) wind farm has a dynamic characteristic of randomness and fuzziness. According to the theory of uncertainty mathematics, this paper presents a dynamic equivalent method for wind farm based on rotor current cloud model. The peak value of rotor current of DFIG is chosen as cloud droplet sample, which can be obtained by simulation under random wind speed and terminal voltage dip. The wind turbine generators can be clustered by three feature indices through backward cloud generator, including expectations, entropy and hyper entropy. Finally, the simulation based on DlgSILENT/PowerFactory is carried out. The results show that the proposed equivalent model can accurately reflect the transient fault characteristics of the detailed wind farm model, which is suitable for analysing and calculating the short-circuit current of wind farm.

1. Introduction

With the growing maturity technology of wind power generation and the effective incentive of energy policy, the proportion of the wind power represented by the clean energy in the power grid is increasing. As the size and number of DFIG wind farm plants increase largely, the impact and influence of large-scale wind farm on power system transient stability and power quality should be paid more attention. It is necessary to establish an accurate dynamic model for wind farms[1]. However, large scale wind farm consists of hundreds of wind turbines, so the detail model of wind farm is of time consuming, seriously affecting the data processing and calculation results analysis of the efficiency. Subsequently, the dynamic equivalent modeling of large-scale wind farms become the one of the important topics in the study of wind power system [3] [4].

At present, the dynamic equivalent modeling of DFIG wind farm mainly focus on the cluster coherent generators and parameters equivalence. Paper [5] takes the pitch action as classification index via Support vector machine (SVM) algorithm. Three input variables of SVM are wind speed, active power and terminal voltage respectively. According to the characteristic curve of the DFIG’s power, the input wind speed on the same section of curve is clustered one group [6].
Also, the index of rotor speed before fault and 13 state variables constituting the state matrix are introduced in [7]. Aimed at the influence of crowbar circuit, some studies on the operation state of crowbar have been carried out, and obtain the crowbar action zone under the factor of wind speed and terminal voltage, clustering the DFIG wind farm two group based on whether the crowbar circuit is put or not [8]. A weighted algorithm on parameter aggregation of detailed model of coherent unit groups is applied in [9] and [10] to get parameter aggregation of equivalent model of groups of coherent wind farms. In general, the dynamic equivalent modeling of wind farm is mainly concerned with the dynamic equivalence of the active and reactive power of DFIG wind farm, and the dynamic characteristics of the DFIG wind farm during the fault are neglected. There are many random factors should be considered, such as low voltage ride–through characteristics, wind speed and terminal voltage dip, etc.

In this paper, the influence of random factors on DFIG is described briefly at first. Then considering the dynamic characteristics of doubly fed wind power generator have strong randomness and fuzziness, a cluster method based on rotor current cloud model for DFIG wind farm dynamic equivalence is proposed. Three feature indices of each unit can be obtained by cloud algorithm. For validation purposes, the equivalent method is applied for 30×1.5MW DFIG wind farm. The simulation results show that the wind farm equivalent model based on the rotor current cloud model can accurately reflect the transient fault characteristics of the wind farm.

2. The model of DFIG

The basic configuration of a wind turbine based on a DFIG is shown in Figure. 1. As shown in the figure, the stator of the machine is directly connected to the grid, and only the rotor power must be handled by converters. Consequently, the control of the machine can be carried out with a converter that is sized for a power around 25%–35% of the rated power of the turbine [11].

![Figure 1. DFIG with crowbar protection of rotor side converter](image)

In order to meet the requirement of low voltage ride through, besides conventional protections, there are also some special protections called crowbar protecting the converter and preventing disconnecting the turbine from the grid. During the grid fault, the crowbar will be input and short converter if the rotor current exceeds its rated current 2~2.5 times. The transient over current will not flow through the converter, realizing the protection of the converter. On the other hand, the crowbar circuit consumes the unbalanced energy generated because of the system fault, implementing the low voltage ride–through of DFIG. During this process, DFIG will be the operation of asynchronous state until crowbar exits. Thus, the operation of crowbar obviously affects the dynamic characteristics of DFIG and dynamic equivalence of wind farm [12].

Due to the wake effect and time delay effect, the input speed of each unit in wind farm is different, which influences the active power of generator. On the other hand, each unit terminal voltage during the fault is different because of the collector line impedance. So, whether the crowbar circuit is activated or not depends the wind speed and terminal voltage drop of each unit.

The principle of wind farm equivalence is to cluster the similar state characteristics of the doubly-fed induction generator, which is fuzzy principle [13]. On the other hand, wind farm is composed of a large number of wind turbines, occupying a large area in space. So, input wind speed of each unit and
voltage drop are random, which influence the operation state of DFIG during the fault. On the whole, the fuzziness and randomness of wind farm equivalence should be considered.

3. The Cloud model of rotor current

3.1. Basic concept of cloud model

Cloud model is a new model provided by Li Deyi of China for concept representation and realizes the uncertain transition between qualitative concept and its quantitative representation. It is more flexible and effective than the conventional fuzzy reasoning methods in uncertainty representation, which is a kind of data analysis and data mining technology[14].

The definition of cloud model: Let $U$ be a quantitative domain with numerical value, $C$ be a linguistic term associated with $U$. If the value of $x \in U$ is the membership degree of qualitative concept $C$, $\mu(x) \in [0,1]$ is a random number with stable tendency. That is $\mu : U \rightarrow [0,1], \forall x \in U, x \rightarrow \mu(x)$.

The distribution of $x$ in $U$ domain is called the cloud, denoted as $C(X)$. $X$ is a collection of quantitative $x$ called cloud drop.

3.2. Normal cloud model & its numerical character

Forward cloud is the most basic cloud and it is a natural language to express the value of the basic language. Normal distribution is the basic distribution of the probability theory with universal. The forward cloud model is a basic cloud model on the basis of normal distribution, which is also a powerful tool for conceptual representation.

The cloud model uses expectation ($Ex$), entropy ($En$) and hyper entropy ($He$) to describe the overall concept of data, which will integrate the fuzziness and randomness of spatial concepts in unified way as shown in figure 2. For example, the concept of "youth" is different from one person to another, the answer to this concept is uncertain. The concept of "youth" can be depicted using cloud model, as shown in figure 2.

![Figure 2. Cloud model for characterizing the concept of youth](image)

**Expectation**: $Ex$ is the expectation of the cloud drops distributions and is the best position representing the qualitative concept, corresponding to the centre of the cloud’s gravity.

**Entropy**: $En$ is the discrete degree of cloud drops which can represent the concept, so-called randomness. On the other hand, it reflects the interval of cloud drop accepted by the concept, so-called fuzziness.

**Hyper Entropy**: $He$ is a measure of uncertainty, namely the entropy of entropy. It reflects the dispersion degree of cloud drops which is determined by the entropy of randomness and fuzziness.

3.3. Backward cloud generator and calculation of clustering index

Backward cloud generator is used to obtain distribution characteristics of a certain number of data sample, and it is converted into qualitative concept with digital features. Set $A = \{x_1, x_2, x_3, \cdots x_M\}$, it
means cloud droplet sample data randomly generated. Three digital characteristics of cloud model can be obtained through following steps.

1) Calculate the sample mean of statistical data: 
\[
x = \frac{1}{M} \sum_{i=1}^{M} x_i
\]  
(1)

Calculate sample data two order centre distance:
\[
c_2 = \frac{1}{M-1} \sum_{i=1}^{M} (x_i - \bar{x})^2
\]  
(2)

Calculate sample data four order centre distance:
\[
c_4 = \frac{1}{M-1} \sum_{i=1}^{M} (x_i - \bar{x})^4
\]  
(3)

2) Calculate the expected value of sample data:
\[
E_x = \bar{x}
\]  
(4)

3) Calculate the entropy and the hyper entropy of sample data:
\[
E_n = \left( \frac{9c_2^2 - c_4}{6} \right)^{1/4}, \quad H_n = \left[ c_2 - \left( \frac{9c_2^2 - c_4}{6} \right)^{1/2} \right]^{1/4}
\]  
(5)

Three digital characteristics based on rotor current cloud model of each DFIG are realized by relying on backward cloud generator. The original data of rotor current is randomly generated by considering two factors, that is, input wind speed of each unit and voltage drop.

For the large wind farm dynamic equivalence, there are many random factors needed to be considered, such as, low voltage ride-through characteristics, wind input speed and terminal voltage dip. These factors all influence the dynamic characteristic of rotor current, especially, the peak value of rotor current during the fault, which is mainly affects whether the crowbar circuit is activated or not. So, the paper chooses the rotor current peak value of each DFIG as cloud droplet sample, which can be obtained under random wind speed and terminal voltage dip. Then, calculate the numerical characteristics of cloud droplet sample, expectations, entropy and hyper entropy through the improved backward cloud generator.

According to the three digital characteristics of each unit above, the wind turbine generators in wind farm can be clustered by these feature indices through the k-means cluster algorithm[15].

4. Capacity-weighted equivalence
For the coherent group of wind farm with \( m \) wind generators, the total capacity, active power is given by (6), where the subscript \( eq \) denotes the equivalent parameters.
\[
S_{eq} = \sum_{i=1}^{m} S_i, \quad P_{eq} = \sum_{i=1}^{m} P_i
\]  
(6)

4.1. Equivalence of wind turbine
The wind turbine captures the wind energy through the blades, and converts it into the mechanical power \( P_m \) on the shaft.
\[
P_m = \frac{1}{2} \rho \pi R^2 C_p (\lambda, \beta) v^3
\]  
(7)

Where \( \rho \) is air density, \( R \) denotes the blade radius, \( v \) is the wind speed, \( \lambda \) is the tip speed ratio of wind turbine and \( \beta \) is the pitch angle. \( C_p \) is power coefficient that is nonlinear function of \( \lambda \) and \( \beta \). For different input wind speed, the parameter \( C_p \) is adjusted to track the maximum power by the control of the tip speed ratio \( \lambda \) and pitch angle \( \beta \). So, the wind speed and the power curve of the wind turbine can be fitted. The equivalent wind speed can be obtained by (8) based on the principle of equivalent model output active power equaling to the detail model.
\[ v_{eq} = f^{-1}\left(\frac{1}{m} \sum_{i=1}^{m} P(v_i)\right) \]  

(8)

Where \( f \) is the fitting function of wind speed power curve, \( P(v_i) \) is the active power of the \( i^{th} \) wind turbine.

4.2. Equivalence of drive train and induction generator

With the capacity-weighted method [9], the equivalent drive train is given by (9), where \( \rho_i = S_i / \sum_{i=1}^{n} S_i \) is the weighted proportional of the \( i^{th} \) generator in the total capacity of coherent group.

\[ H_{eq} = \sum_{i=1}^{n} \rho_i H_i \cdot D_{eq} = \sum_{i=1}^{n} \rho_i D_i \cdot K_{eq} = \sum_{i=1}^{n} \rho_i K_i \]  

(9)

Where \( H, D, K \) are the time constant of inertia, shaft damping, shaft stiffness, respectively.

The induction generators in the same group are expressed by parallel \( \Gamma \) circuit[16]. The equivalent parameters of Induction Generator can be deduced by (10):

\[
\begin{align*}
\frac{1}{R_{i,eq} + jX_{i,eq}} &= \sum_{i=1}^{n} \frac{\rho_i}{R_{i} + jX_{i}} \\
\frac{1}{R_{i,eq} / s_i + jX_{i,eq}} &= \sum_{i=1}^{n} \frac{\rho_i}{R_{i} / s_i + jX_{i}} \\
\frac{1}{X_{i,eq}} &= \sum_{i=1}^{n} \frac{\rho_i}{X_{i}}
\end{align*}
\]

(10)

Where \( X_s, X_r, R_s, R_r, X_m \) are the generator stator reactance, rotor reactance, magnetizing reactance, stator resistance, rotor resistance, respectively. \( s_i \) is the slip of the \( i^{th} \) generator.

4.3. Equivalence of control system and crowbar

For the DFIG, induction generator is not only connected to the grid at the stator terminal but also at the rotor via a variable frequency converter, which consists a rotor-side converter and a grid-side converter. The rotor-side converter is applied in realizing Maximum power point tracking (MPPT) and power decoupling control. The grid-side converter can maintain DC voltage stability and keep the DFIG operating in unit power factor. They can be expressed by double loop control system based on PI control algorithm.

The control parameters of converter can be obtained as:

\[ k_{p,eq} = \sum_{i=1}^{n} \rho_i k_{i,eq} \]

(11)

There are two main parameters in the Crowbar circuit: the input time after fault occurs \( T \) and the resistance \( R \). However, under the same switching control strategy, input time of crowbar is almost the same. So, the parameter \( T \) has little influence on the equivalence. By using the method of capacity weighting, the equivalent resistance \( R \) is:

\[ R_{eq} = \sum_{i=1}^{n} \rho_i R_i \]  

(12)

4.4. Equivalence of collector system

The collector system mainly consists of collector lines and box-type transformers. The mainly collector line type is cable, which has a significant contribution to the power balance. To ensure that the detailed model and the aggregate model represent the same amount of power transfer and power losses, collector lines should be considered. According to the same total power loss, the equivalent impedance of cable line for single series daisy-chain and transformers is presented in Ref [17].

5. Case study
5.1. Clustering of coherent generators

The 30×1.5MW Doubly-fed wind farm is built in the software of Digsilent/PowerFactory, as shown in Figure.3. The wind field contains three branches, connecting 8, 12, 10 doubly-fed generators respectively. The length of cable line between the generator is different. The parameters of double-fed wind turbine are attached to the Appendix.

To validate the aggregation effect with the wind speed, the wake flow effect of wind speed is presented by Jensen model[18]. Based on the detail model, the cloud droplet sample of rotor current peak value of each DFIG is obtained under random wind speed and terminal voltage dip, and grid faults of three phase short circuit occur in the different point of line L1 at t=1s and is cleared at 1.5s. Low voltage ride through capability takes the default settings of the software Digsilent/PowerFactory. That is, the crowbar will be input if the rotor current exceeds rated current 2.5 times.

According to the gained cloud droplet sample of rotor current peak value (p.u.), the numerical characteristics of cloud droplet sample, expectations, entropy and hyper entropy can be calculated through the backward cloud generator, as shown in Table 1.

Table 1. Numerical characteristic value of rotor current cloud model.

| DFIG | Ex   | En   | He   | DFIG | Ex   | En   | He   | DFIG | Ex   | En   | He   |
|------|------|------|------|------|------|------|------|------|------|------|------|
| G0   | 2.4718 | 0.7168 | 0.0763 | G10  | 2.3367 | 0.6438 | 0.0712 | G20  | 2.4568 | 0.7112 | 0.0734 |
| G1   | 2.4249 | 0.6933 | 0.0868 | G11  | 2.2888 | 0.6215 | 0.0831 | G21  | 2.4177 | 0.6887 | 0.0924 |
| G2   | 2.3931 | 0.6737 | 0.0699 | G12  | 2.2483 | 0.5906 | 0.0611 | G22  | 2.3685 | 0.6595 | 0.0843 |
| G3   | 2.3648 | 0.6586 | 0.0764 | G13  | 2.2235 | 0.5645 | 0.0427 | G23  | 2.3463 | 0.6470 | 0.0891 |
| G4   | 2.3478 | 0.6494 | 0.0765 | G14  | 2.1835 | 0.5569 | 0.0640 | G24  | 2.3208 | 0.6331 | 0.0348 |
| G5   | 2.3313 | 0.6402 | 0.0800 | G15  | 2.1637 | 0.5421 | 0.0839 | G25  | 2.2931 | 0.6176 | 0.0499 |
| G6   | 2.3234 | 0.6353 | 0.0828 | G16  | 2.1528 | 0.5298 | 0.0815 | G26  | 2.2733 | 0.6071 | 0.0508 |
| G7   | 2.3170 | 0.6324 | 0.0822 | G17  | 2.1270 | 0.5186 | 0.0839 | G27  | 2.2516 | 0.5810 | 0.0480 |
| G8   | 2.4433 | 0.7044 | 0.0771 | G18  | 2.1170 | 0.5161 | 0.0893 | G28  | 2.2347 | 0.5845 | 0.0760 |
| G9   | 2.3802 | 0.6678 | 0.0676 | G19  | 2.1147 | 0.5125 | 0.0881 | G29  | 2.2297 | 0.5822 | 0.0773 |

Ex is the sample mean of rotor current peak value, representing the centre of the cloud model. En reflects the randomness of the sampling rotor current and the fuzziness of cloud model. He is corresponding to the dispersion degree of rotor current cloud model. The difference of the three indexes together reflects the difference of the rotor current peak value in the random condition.

According to the three digital characteristics of each unit above, the wind turbine generators in wind farm can be clustered 3 group by these feature indices through the k-means cluster algorithm, as shown in Table 2.

Table 2. The clustering result of DFIGs.

| Groups | No. of the DFIG       | Number |
|--------|-----------------------|--------|
| No.1   | G0—G4, G8—G9, G20—G23 | 11     |
| No.2   | G5—G7, G10—G13, G24—G29 | 13     |
| No.3   | G14—G19               | 6      |

Based on the group result of the wind farm, capacity-weighted method is applied to calculate the equivalent wind machine's parameter, establishing the multi-machine equivalent model.

5.2. Simulation analysis

A grid fault of three phase short circuit occurs in the line L1 at t=1s and is cleared at 1.5s. The initial wind speeds are shown in Figure.4.
Figure 3. Primary system diagram of the Doubly-fed wind farm.

Figure 4. Initial wind speeds of DFIGs.

The relative error $\varepsilon$ for terminal voltage is 0.00429%, for active power is 0.58%, for reactive power is 0.47%, and for current is 0.01397%, as shown in figure 5. The results show that the equivalent model yields desirable accuracy.

Figure 5. Parameters of wind farm with grid fault.

6. Conclusion
An equivalence method for doubly-fed induction generator wind farm based on the cloud model of rotor current is proposed in this paper, and outlines are given as following.

(1) The random factors are considered, which can be presented by cloud model theory of uncertainty mathematics. For the generators grouping and clustering in dynamic equivalence problem of doubly-fed wind farms, this article takes three digital characteristics of cloud model as the grouping indexes, describing the influence of random speed and terminal voltage drop on DFIG. Then the parameters of wind turbine, drive train and induction generator, control system and crowbar, collector system are aggregated.
(2) The terminal voltage, the active, reactive outputs and current of the wind farms yield desirable accuracy before and after the equivalence. The method can be well used in DFIG wind farm transient equivalent analysis. In addition, the equivalent model is suitable for analysing and calculating the short-circuit current of DFIG wind farm.

**Appendix**

Parameters of the 1.5 MW DFIGs:

\[ P_e=1.5\text{MW},\ U_e=690\text{kV},\ H=4.02\text{s},\ D=1.5\text{s},\ K=80.27,\ Rs/p.u.=0.01,\ Xs/p.u.,\ s=0.1,\ Rr/p.u.=0.01,\ Xr/p.u.=0.1,\ Xm/p.u.=3.5 \]

**Acknowledgements**

The authors are deeply grateful to the Research Project of State Grid Corporation of China: Simulation and Evaluation Technology for Renewable Power Grid Integration and Technical Standard Development. The authors are also grateful to the China Electric Power Research Institute for its technical expertise.

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