Research on Aggregation Model of Wind Farm Based on SSO Complex Torque Coefficient Analysis

SU Xunwen¹,²*, CUI Hanqing², PEI Yuming², ZHANG Dongni², AN Pengyu²

¹Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Ministry of Education, Northeast Electric Power University, Jilin, China
²School of Electrical & Control Engineering, Heilongjiang University of Science & Technology, Harbin, Heilongjiang, China

*Corresponding author’s e-mail: 1999800453@usth.edu.cn

Abstract: In order to study the influence of the clustering aggregation of doubly-fed wind turbines (DFIG) in the wind-fire bundling system on the system subsynchronous oscillation (SSO), the expression of the DFIG output active power on the electrical damping De of thermal power units is first derived. Then the wind-thermal bundling system is built based on the IEEE first benchmark, and the wind farm is aggregated to several groups according to the rated power. The complex torque coefficient method is used to analyze the two cases of the same running state of the wind turbine and the difference of wind speed between the turbine and verified by time-domain simulation. The results show that the difference in wind speed within the DFIG groups has little effect on the system oscillation frequency before and after the aggregation of the wind farm, but there may be a slight error in the electrical damping coefficient before and after the aggregation, but the error does not affect the trend and analysis of damping characteristics of system. When studying the influencing factors of wind-fire bundling system SSO the aggregated model can be used to improve simulation efficiency.

1. Introduction

In the research of wind-fire bundling system, the wind power plant is generally composed of hundreds of wind turbines due to the small capacity of wind turbines¹². However, detailed modeling and simulation of each unit will greatly increase the workload and simulation time³⁵. Therefore, DFIG is generally treated as equivalent.

In this paper, a model of the wind-fire bundling system is built on the basis of the IEEE first standard model, and the equivalence is performed according to the method of grouping the rated power of wind turbines. The detailed model and the equivalent model were analyzed using the complex torque coefficient analysis method, and time-domain simulation was used to verify. The results show that the clustering equivalence does not affect the system SSO analysis.

2. System model

The structure of the wind-fire bundling system is shown in figure 1. Double-fed wind turbine (DFIG) and thermal power generators are respectively boosted by a step-up transformer and connected to the infinity system by series compensation lines. \( W_{T_1} \sim W_{T_3} \) is the same type DFIG with a rated power of 1.5MW, \( W_{T_4} \sim W_{T_7} \) is the same type DFIG with a rated power of 1MW.
3. DFIG cluster aggregation mechanism

Structure diagram of wind-fire bundling system after cluster aggregation is shown in Figure 2. The doubly-fed unit groups are clustered by the rated power grouping equivalent, that is, the doubly-fed unit \( WT_1 \sim WT_3 \) with a rated power of 1.5MW is unit 1, and the double-fed unit \( WT_4 \sim WT_7 \) with a rated power of 1MW is unit 2. Equivalent to the doubly-fed induction motor, the equivalent formula is as follows.

\[
\begin{align*}
S_{eq1} &= nS_G, \quad S_{eq2} = nS_T, \quad S_{eq} = nS_E \\
Z_{eq1} &= \frac{Z_G}{n}, \quad Z_{eq2} = \frac{Z_T}{n}, \quad Z_{eq} = \frac{Z_E}{n}
\end{align*}
\]

Where \( n \) is the number of wind turbines; \( S \) is the capacity; \( Xs \) the reactance parameter; subscript \( eq \) represents the equivalent value; subscript \( T \) represents the transformer; subscript \( G \) represents the wind turbine; subscript \( S \) represents the converte.

The power of each doubly-fed unit is obtained according to the wind speed-power (v-f) curve, and then the equivalent wind speed is calculated according to the v-f curve\(^6\).

\[
\begin{align*}
Z_{eq1} &= Z_{L1} + \frac{1}{Z_{L1} + \frac{1}{Z_{L2} + \frac{1}{Z_{L3}}}} \\
Z_{eq2} &= \frac{Z_{L4} + Z_{L5}}{Z_{L4} + Z_{L5} + Z_{L6} + Z_{L7}} + \frac{Z_{L6} + Z_{L7}}{Z_{L6} + Z_{L7} + \frac{1}{Z_{L8}(Z_{L6} + Z_{L7})} + \frac{1}{Z_{L9}(Z_{L6} + Z_{L7}) + Z_{L10}(Z_{L6} + Z_{L7})}}
\end{align*}
\]

Where \( Z_{eq1} \) is the line equivalent impedance of machine group 1; \( Z_{eq2} \) is the line equivalent impedance of machine group 2.
4. Influence of cluster aggregation of doubly-fed wind farm on system damping characteristics

Based on the principle of the complex torque coefficient method and the system power angle characteristics\cite{7}, the active power output by the thermal power unit and the active power flowing to the infinity bus at the grid-connected end of the DFIG unit can be expressed as:

\[
\begin{align*}
P_r &= \frac{EU_r \sin(\delta - \theta)}{Z_1} \\
P_m &= \frac{U_r U_z \sin \theta}{Z_2}
\end{align*}
\]

(3)

Add a small amplitude disturbance \(\Delta \omega\) with frequency \(\omega_0\) and amplitude \(A\) on the rotor side of the thermal power unit, and linearize (3):

\[
\begin{align*}
\Delta P_r &= \frac{EU_r \cos \gamma}{Z_1} (\Delta \delta - \Delta \theta) \\
\Delta P_m &= \frac{U_r U_z \cos \theta_0}{Z_2} \Delta \theta
\end{align*}
\]

(4)

Where \(\gamma = \delta_0 - \theta_0\), the subscript 0 represents the initial value. According to the active power balance, the following formula can be obtained:

\[
\Delta \theta = k_1 \Delta \delta + k_2 \Delta P_g
\]

(5)

\[
\begin{align*}
k_1 &= \frac{Z_r E U_r \cos \gamma}{U_r U_z Z_1 \cos \theta_0 + Z_r E U_r \cos \gamma} \\
k_2 &= \frac{Z_r Z_z}{U_r U_z Z_1 \cos \theta_0 + Z_r E U_r \cos \gamma}
\end{align*}
\]

Electric torque increment of thermal power unit \(\Delta T_e\) is given by:

\[
\Delta T_e = \frac{\Delta P_e}{\omega_0} = k_1 \Delta \delta + D_e \Delta \omega
\]

(6)

\[
D_e = \frac{k_2 E U_r \cos \gamma}{Z_r \omega_0 A \Delta \omega}\Delta P_g
\]

(7)

According to the principle of the complex torque coefficient method, if the value of \(D_e\) does not change before and after the aggregation, the aggregation does not affect the analysis of the thermal power unit SSO. From equation (7), it can be obtained that if the value of \(\Delta P_g\) does not change before and after the aggregation, \(D_e\) does not change. Since the wind speed and the output of active power are proportional, the impact on the SSO of the thermal power unit before and after the aggregation is the same.

5. Analysis of example

In order to explore the impact of DFIG clustering aggregation on SSO, two cases of the same wind speed and different wind speeds of the DFIG in the cluster were tested, hereinafter referred to as case one and case two.

In the case one, the wind speed of the three fans in the first cluster is 11m/s, and the wind speed in the second cluster is 9m/s. Then the equivalent wind speeds of cluster one and cluster two are 11m/s
and 9 m/s respectively. In the case two, the wind speeds of the fans in the first group are 11 m/s, 9 m/s, and 7 m/s respectively. The wind speeds of the fans in the second group are 11 m/s, 10 m/s, 9 m/s, and 8 m/s, respectively. Then the equivalent wind speeds of cluster one and cluster two are 10.26 m/s and 9.66 m/s respectively.

Before After

| Time(s) | Output power(MW) |
|---------|------------------|
| 0       | 5                |
| 1       | 3                |
| 2       | 1                |
| 3       | 0                |
| 4       | -1               |
| 5       | -3               |

Figure 4. Output power before and after aggregation in case one

In order to verify the accuracy of the aggregation, the output active power of the DFIG before and after the aggregation is measured in the two cases as shown in figure (4) (5). Take the stable running power after 2 s to calculate the error before and after the equivalent value. The calculation formula is:

\[ E = \frac{\int_{0}^{t} |p_1 - p_2| \, dt}{\int_{0}^{t} p_1 \, dt} \]

Where \( p_1 \) is the detailed model DFIG output power, and \( p_2 \) is the aggregate DFIG output power.

After calculation, the error is 0.175% in the case one, and 0.189% in the case two. It can be seen that after DFIG runs stably, the active power output characteristics of the aggregate model are basically consistent with the detailed model.

5.1. Complex Torque Analysis of DFIG Aggregation at Same Wind Speed

The detailed model and the aggregate model are analyzed for complex torque. Get electrical damping \( D_e \) as shown in figure (6).

Before After

| Frequency(Hz) | \( D_e \)(p.u.) |
|---------------|-----------------|
| 10            | -20             |
| 20            | -10             |
| 30            | 0               |
| 40            | 10              |
| 50            | 20              |
| 60            | 30              |

Figure 6. \( D_e \) before and after aggregation in case one

It can be seen that \( D_e \) is negative in case 1, and the value of \( D_e \) before aggregation is slightly lower than that after aggregation. The frequency corresponding to the lowest point is 34.5 Hz, which is close to the fourth modal frequency (32.28 Hz) of the thermal power unit, so the system is judged Subsynchronous oscillations with a frequency of 32 Hz will occur before and after aggregation. And the system oscillates violently before aggregation.

A three-phase short-circuit fault lasting 0.075 s was input at the end of the series compensation line during the 3 s of system operation. The torque comparison diagram between the two low pressure cylinders shown in Figure 10 can be obtained. The analysis shows that SSO with a frequency of 32 Hz occurred before and after the aggregation, but the oscillation was slightly weakened after the polymerization, with an error of 7.8%. It is consistent with the conclusion of the complex torque coefficient method.
5.2. Analysis of Complex Torque Considering the Wind Speed Difference of Fans in the Group

Perform complex torque analysis on the detailed model and aggregate model described in Case 2, and the electrical damping $D_{e}$ shown in Figure (8) can be obtained.

![Fig8. De before and after aggregation in case two](image1)

![Fig9. Torque between LPA and LPB before and after polymerization in case two](image2)

The frequency corresponding to the lowest point of $D_{e}$ is 34.5 Hz. It is judged that SSO with a frequency of mode four will occur in the system, and the oscillation will be more severe before aggregation. A three-phase short-circuit fault of 0.075s is applied at the end of the series compensation line in the third second of system operation. Torque comparison chart. Through analysis and calculation, it can be seen that SSO with a frequency of mode four occurs before and after aggregation, and the oscillation before the equivalence is severe, with an error of 8.2%.

6. Conclusion

1. Theoretically deduced the expression of the influence of DFIG cluster aggregation on the electrical damping $D_{e}$ of thermal power unit. That is, when the output $A$ is the same before and after the DFIG aggregation under small disturbance, the aggregation has no effect on the SSO of the thermal power unit.

2. The doubly-fed units with the same wind speed and the units with different wind speeds get the same SSO frequency before and after aggregation. The system damping coefficient $D_{e}$ may have a slight error. However, this error does not affect the change trend of system damping characteristics, so it does not affect the analysis of system damping characteristics and can be ignored.

3. Adopting the aggregation model does not affect the analysis and judgment of the system SSO, and can greatly reduce the simulation time, improve the simulation efficiency, and reduce the difficulty of modeling.

Acknowledgments

This work was supported by the National Science Foundation of China under Grant (51677057), Heilongjiang Postdoctoral Scientific Research Developmental Fund (LBH-Q15125) and Key Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Ministry of Education (MPSS2019-05).

References

[1] Zhang J.(2018)Research on the mechanism of subsynchronous oscillations of wind farms in Hami. J. Proceedings of the CSEE., 38(18):5447-5460.

[2] An Z., Shen C., Zheng Z., et al.(2018)Assessment method for equivalent models of wind farms based on direct-driven wind Generators Considering Randomness. J. Proceedings of the CSEE.,38(8):6511-6520.

[3] Gao C., Niu X., Luo C., et al.(2018)Comparison of impact on sub-synchronous oscillation characteristics between single-and multi-generator equivalent model in DFIG wind farm.J.Electric Power Automation Equipment.,38(8):152-157.

[4] Liu H., Xie X., Gao X., et al.(2018)Stability Analysis of SSR in Multiple Wind Farms Connected to Series-Compensated Systems using Impedance Network Model.J. IEEE Transactions on
[5] Yang W., Zhu L., Li W., et al. (2019) Study on subsynchronous oscillation and propagation characteristics of wind-fire bundled sending system. J. Power System Protection and Control, 47(20):58-64.

[6] Mi Z., Su X., Yu Y., et al. (2010) Study on dynamic equivalence model of wind farms with wind turbine driven doubly fed induction generator. J. Automation of Electric Power Systems, 34(17):72-77.

[7] Li H., Chen Y., Zhao B., et al., (2015) Analysis and control strategies for depressing system sub-synchronous oscillation of DFIG-based wind farms. J. Proceedings of the CSEE, 35(7): 1613-1620.