Inside-wind-farm/Wind-farm-grid sub-synchronous oscillation characteristics analysis in grid-connected system of multiple DFIGs

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Abstract—Aiming at the sub-synchronous oscillation (SSO) problem of the grid-connected system of multiple DFIGs, most of the existing theoretical studies take the entire wind farm as a single-machine model, the stand-alone model cannot reflect the inside-wind-farm oscillation mode produced by the interactions among DFIGs in the wind farm. Therefore, this paper takes the equivalent value of DFIG-based wind farm to three DFIGs, establishes a mathematical model of the grid-connected system of three DFIGs, and studies the sub-synchronous oscillation modes existing in the system through eigenvalue analysis and participation factor analysis. The results show: When the length of transmission line increases, the oscillation frequency of the inside-wind-farm/wind-farm-grid sub-synchronous oscillation mode increases, the damping decreases and the stability weakens; when the number of grid-connected DFIGs increases, the oscillation frequency of the inside-wind-farm/wind-farm-grid sub-synchronous oscillation mode decreases, the damping increases and the stability enhances. Finally, a time-domain simulation model of the grid-connected system of multiple DFIGs was built in PSCAD/EMTDC to verify the correctness of the theoretical analysis results.

1. Introduction

As the installed capacity of wind power has increased year by year, there have been many sub-synchronous oscillation accidents caused by the grid connection of wind farms at home and abroad. Sub-synchronous oscillations involving DFIG-based or direct-drive wind farms have occurred successively in the Texas Power Grid in the United States, the Guyuan area in northern Hebei of China, and the northern Hami Mountains in Xinjiang, causing a series of serious consequences such as wind turbine disconnection and equipment damage. The above phenomenon shows that there is an urgent need to conduct in-depth research on the oscillation mechanism and influencing factors of the sub-synchronous oscillation problem caused by wind power grid connection.

At present, scholars at home and abroad have conducted preliminary research on this. Literature [1] conducted a small disturbance stability analysis on a power system with asynchronous wind turbines, and concluded that the connection of wind turbines has a certain impact on the operating characteristics of the system. In the reference [2], the equivalent value of the DFIG-based wind farm is a small signal model, and the oscillation characteristics of the sub-synchronous oscillation caused by
the DFIG-based wind farm through the series compensation system are compared. Literature [3] considered the coupling relationship between the phase-locked loop (PLL) of the DFIG and the power grid strength, and studied the influence of different operating states on the oscillation modes of the DFIG grid-connected system under weak grids, but when applying small signal modeling methods to complex systems, the model is not accurate enough. Literature [4] believes that when a large number of wind power is connected to the system, the damping characteristics of the system will change due to the different operating states of the wind turbines, and the changes in the operation mode of the system may have a certain impact on the oscillation mode, however, the inside-wind-farm oscillation mode generated by the interaction between wind turbines in the wind farm is ignored. In the above analysis, there are different conclusions on the influence of the vibration characteristics of the DFIGs connected to the system, but there are currently few literature studies on the inside-wind-farm sub-synchronous oscillations generated between the DFIGs.

Firstly, this paper first establishes a 94-order small signal model based on the mathematical model of the grid-connected system of multiple DFIGs. Secondly, using the eigenvalue analysis method to solve the sub-synchronous oscillation modes and participation factors in the system, the influence of the length of the transmission line and the number of grid-connected wind turbines on the oscillation characteristics of the system is also analyzed. Finally, the correctness of the theoretical analysis results is verified by time-domain simulation.

2. Structure of Grid-connected System of Multiple DFIGs

This article takes the DFIG-based wind farm composed of three DFIGs connected to the weak AC grid as the research background, and the grid-connected system structure diagram is shown in Fig.1.

![Fig.1 Structural diagram of grid-connected system of DFIGs](image)

Each DFIG passes through a back-to-back converter and is converged to the 35kV busbar through the machine-end transformer, and then is boosted to 110kV again through the transformer T2, and finally connected to the AC grid. Among them, $i_s$, $i_r$, $i_g$ and $i_l$ are stator current, rotor current, grid-side converter current, and transmission line current, respectively. $u_r$, $u_g$, $U_{dc}$ are the rotor-side converter port voltage, the grid-side converter port voltage, and the DC capacitor voltage, respectively. $e$ is the point of common coupling (PCC). $R_{ss}$, $L_{ss}$ and $C_l$ are the resistance, inductance and capacitance to ground of the grid-connected wind farm.

3. Small Signal Model of Grid-connected System of Multiple DFIGs

The small signal model of DFIG-based farm mainly includes shafting model, double fed induction generator model, back-to-back converter model, wind power transmission line model and phase-locked loop model. Literature [5] has built the shafting model of the DFIG, the double fed induction
generator model, the back-to-back converter model, PLL model, and the wind power transmission line model. This paper uses the above models for research. The dynamic model of the wind farm grid-connected line adopts the RLC line model, and the specific dynamic model is shown by the following formula.

\[
\begin{align*}
C_f \frac{du_{dss}}{dt} - \omega_q C_f u_{qss} &= \frac{1}{k_2} i_d - i_{dss} \\
C_f \frac{du_{qss}}{dt} + \omega_q C_f u_{dss} &= \frac{1}{k_2} i_q - i_{qss} \\
L_{ss} \frac{di_{dss}}{dt} - \omega_q L_{ss} i_{qss} &= u_{dss} - u_{di} - i_{dss} R_{ss} \\
L_{ss} \frac{di_{qss}}{dt} + \omega_q L_{ss} i_{dss} &= u_{qss} - u_{qi} - i_{qss} R_{ss}
\end{align*}
\]  

(1)

Where: \( k_2 \) is the transformer \( T_2 \) transformation ratio after the busbar. \( u_{dss} \) and \( u_{qss} \) are the \( d \)-axis and \( q \)-axis voltage components at the outlet of the transformer \( T_2 \), respectively, and \( i_{dss} \) and \( i_{qss} \) are the \( d \)-axis and \( q \)-axis current components of the grid-connected wind farm.

The linearized small-signal model of the system is as follows:

\[
\frac{d\Delta x}{dt} = A\Delta x + B\Delta u
\]

(2)

Where: \( \Delta x \) is the state variable after linearization; \( \Delta u \) is the input variable after linearization, \( A \) is the state matrix, and \( B \) is the input matrix.

Table 1 Loading scene of specimens

| System                     | Module               | State Variable Number |
|----------------------------|----------------------|-----------------------|
| Grid-connected line        | RLC line             | 1-4                   |
| DFIG                       | Shunting             | 5                     |
|                            | Induction generator  | 6-9                   |
|                            | Shunt capacitance    | 10-11                 |
|                            | Back-to-back inverter| 12-21                 |
|                            | Transmission line    | 22-23                 |
|                            | PLL                  | 24-27                 |
|                            | DC capacitor link    | 28                    |
|                            | Voltage coordinate conversion | 29-30 |
|                            | Current coordinate conversion | 31-32 |
|                            | Stator and rotor variable conversion | 33-34 |

For the above-mentioned grid-connected system of multiple DFIGs, there are 94 state variables in the system. The grouping of state variables is shown in Table 1.

4. Analysis of the Oscillation Mode of Grid-connected System of Multiple DFIGs

In this paper, the above-mentioned small signal model is used to analyze the oscillation mode through the eigenvalue analysis method. According to Table 2, the system has the following oscillation modes.

Table 2 Main oscillation modes of grid-connected system of DFIGs

| Serial Number | Eigenvalues          | Damping Ratio | Modal Frequency /Hz |
|---------------|----------------------|---------------|---------------------|
| \( \lambda_1, \lambda_2 \) | -40.702±j286.876     | 0.1405        | 45.658              |
| \( \lambda_3, \lambda_4 \) | -33.327±j285.531     | 0.1159        | 45.444              |
| \( \lambda_5, \lambda_6 \) | -33.327±j285.531     | 0.1159        | 45.444              |

Using the participation factor analysis method to study the above three SSO models, the normalized participation factor results are shown in Fig.2.
Fig. 2 Normalized participation factors of the SSO modes of grid-connected system of DFIGs

It can be seen from Fig. 2 that the dominant state variables of $\lambda_{1,2}$ are $\psi_{sd1,2,3}, \psi_{sq1,2,3}, \psi_{rd1,2,3}, i_{1d1,2,3}, i_{1q1,2,3}$ in the three DFIGs and the $i_{dss}$ and $i_{qss}$ in the grid-connected line of the wind farm. Therefore, the SSO mode $\lambda_{1,2}$ is called the wind-farm-grid oscillation mode. The dominant state variables of $\lambda_{3,4}$ and $\lambda_{5,6}$ are $\psi_{sd1,2,3}, \psi_{sq1,2,3}, \psi_{rd1,2,3}, i_{1d1,2,3}, i_{1q1,2,3}$ in the three DFIGs. Therefore, the SSO modes $\lambda_{3,4}$ and $\lambda_{5,6}$ are called inside-wind-farm oscillation modes.
A time-domain simulation model of the grid-connected system of three DFIGs was built in PSCAD/EMTDC to verify the analysis results of the oscillation modes shown in Table 2. It can be seen from Fig.3 that for the electromagnetic torque $T_e$ of the DFIG, an oscillation at a frequency close to $45.444$ Hz can be observed, which can reflect the inside-wind-farm oscillation mode in the eigenvalue analysis. For the phase-locked loop angular velocity $\omega_{pll}$, the oscillation at a frequency close to $45.658$ Hz can be observed, which can reflect the wind-farm-grid oscillation mode in the eigenvalue analysis.

5. Analysis of Influencing Factors

5.1. Transmission line length

When the other parameters of the system remain unchanged, the length of the transmission line increases from 0.2 times the standard value to 4 times, and the trend of the system root locus is shown in Fig.5. Observing Fig.4, it can be seen that as the length of the transmission line increases, the damping of the inside-wind-farm/wind-farm-grid oscillation mode decreases, the oscillation frequency increases, and the system stability decreases.

Perform time-domain simulation in PSCAD/EMTDC. When the transmission line length is set to be 0.5, 1.0, and 1.5 times the length of the standard condition line, the change curves of the DFIG electromagnetic torque $T_e$ and the phase-locked loop angular velocity $\omega_{pll}$ are shown in Fig.5. It can be seen from Fig.5 that when the transmission line length is 1.5 times the standard condition, the oscillation period of the electromagnetic torque $T_e$ is $T=21.7$ms, and the oscillation frequency $f=1/T=46.08$Hz. The oscillation period of the phase-locked loop angular velocity $\omega_{pll}$ is $T=21.2$ms, and the oscillation frequency is $f=1/T=47.17$Hz. They are respectively close to the oscillating frequency $45.444$ Hz of the field oscillation mode and $45.658$ Hz of the field network oscillation mode in the eigenvalue analysis results. In addition, the amplitude of electromagnetic torque $T_e$ and phase-locked loop angular velocity $\omega_{pll}$ increase, and the time required for complete oscillation attenuation increases, which can verify the conclusion of the eigenvalue root locus analysis.

5.2. Number of grid-connected DFIGs

Set the number of grid-connected DFIGs from 25 to 75, and the other parameters of the system remain unchanged. The trend of the system root locus is shown in Fig.6. Observing Fig.6 we can see that with the increase in the number of grid-connected DFIGs, the oscillation frequency of the inside-wind-
farm/wind-farm-grid oscillation mode decreases, the damping increases, and the system stability increases.

Perform time-domain simulation and set the number of grid-connected DFIGs as 25, 50, and 75. It can be seen from Fig. 7 that with the increase of the number of grid-connected DFIGs, the amplitude of electromagnetic torque $T_e$ and phase-locked loop angular velocity $\omega_{\text{PLL}}$ decreases, which can verify the conclusion of the eigenvalue root locus analysis. With the increase in the number of grid-connected DFIGs, the damping of the inside-wind-farm/wind-farm-grid oscillation modes both increase, and the system stability is enhanced.

6. Conclusion
The main work and research conclusions are as follows:

1. This paper establishes a grid-connected system model of multiple DFIGs including a 90-order DFIG-based wind farm small-signal model and a 4-order grid-connected line small-signal model.
2. Participation factor analysis results show that there are both inside-wind-farm oscillation mode and wind-farm-grid oscillation mode in the grid-connected system of multiple DFIGs.
3. When the length of the transmission line is increased, the oscillation frequency of the inside-wind-farm/wind-farm-grid sub-synchronous oscillation mode will increase, the damping will be reduced, and the stability will be weakened. When the number of grid-connected DFIGs is increased, the oscillation frequency of the inside-wind-farm/wind-farm-grid sub-synchronous oscillation mode will be reduced, the damping will be increased, and the stability will be enhanced. It has important guiding significance for actual engineering applications.

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