Keywords: shared transmission of wind power and thermal power; transient stability; wind disturbance

Abstract

In this paper, transient stability of power system with shared transmission of wind power and thermal power (PSWT) is studied. First, the wind disturbance models are built. And the wind turbine generator models are established, which include wind turbine with squirrel-cage induction generator (IG) and wind turbine with doubly fed induction generator (DFIG). Second, the influence of various types of wind farms with various types of wind disturbance on the system transient stability is studied in details. Especially the impact of wind disturbance accompany with the fault on the system transient process should be considered for getting more accurate and correct results of transient stability analysis. And IG wind farms with gust wind disturbance can have the worst impact on the transient stability of PSWT.

1 Introduction

In China, wind power has been developed in large scale and transmitted to the loads through long distance[1-2]. Due to wind power having characteristics of stochastic fluctuation and non-scheduling, peaking power sources are needed to reduce adverse impact of wind power on the system stability. Therefore, the thermal power units should be built simultaneously around the large-scale wind power bases for stabilizing the fluctuation of wind power output. Shared transmission of wind power and thermal power has become the main mode of large-scale wind power connected to the power system[3].

In this paper, the transient stability of power system with shared transmission of wind power and thermal power (PSWT) is studied based on the actual Gansu Grid. Some papers set wind speed to be constant in the transient process (PSWT) is studied based on the actual Gansu Grid. Some papers set wind speed to be constant in the transient process of wind power system for simplification [4]. But that way of research cannot comprehensively reflect the transient characteristics of wind power systems. So the impact of wind disturbance accompany with the fault on the PSWT transient stability is intensively studied in this work. The wind speed is not unchangeable during the transient period of system. The Prony method is adopted to quantitatively analyze the transient characteristics of system. And the mechanism of simulation results is also discussed. In the end, some conclusions are obtained through the research.

2 Wind disturbance models

2.1 Gust wind model

Three common types of wind disturbance are considered: gust wind, ramp wind and stochastic wind [5]. Gust wind is used to indicate a sudden change in wind speed. The model of gust wind is,

\[ v_G = \begin{cases} 
0 & t < T_1 \\
0.5V_G \left(1 - \cos \left(2\pi \frac{(t-T_1)}{(T_2-T_1)} \right) \right) & T_1 \leq t \leq T_2 \\
0 & t > T_2 
\end{cases} \]  

where, \( T_1 \) and \( T_2 \) are start and end time of gust wind. \( V_G \) is amplitude of gust wind.

2.2 Ramp wind model

Ramp wind is used to indicate that wind speed changes gradually. Its mathematical model is,

\[ v_R = \begin{cases} 
0 & t < T_s \\
\frac{V_R}{T_s} (t-T_s) / T_s & T_s \leq t < T_e + T_s \\
\frac{V_R}{T_e} (T_e - t) / T_e & T_e - T_d \leq t < T_e \\
0 & t \geq T_e 
\end{cases} \]  

where, \( T_s \) and \( T_e \) are start and end time of ramp wind. \( V_R \) is amplitude. \( T_s \) is the time which taken by wind speed changes from zero to amplitude. \( T_d \) is the time which taken by wind speed changes from amplitude to zero.

2.3 Stochastic wind model

Stochastic wind is used to indicate the uncertainty and random characteristics of wind speed. Its model is,

\[ v_S = 2 \sum_{i=1}^{N} \left( \int_{t_i}^{t_{i+1}} \Delta \omega \cos (\omega_i t + \phi_i) \right) \]  

\[ \omega_i = \left( i - 0.5 \right) \Delta \omega \]
\[ S_n(q) = 2K_N F^2 |\phi_1| \left( 2 \pi \left( 1 + \left( \frac{F \phi_1}{\mu \pi} \right)^2 \right) \right)^{4/3} \] 

where, \( N \) is number of wind speed statistic samples, \( i \) is tab number, \( \Delta \omega \) is interval of noise sampling frequency. \( \phi_1 \) is a random variable which uniformly distributes between zero and 2 \( \pi \). \( K_N \) is roughness coefficient of earth surface. \( F \) is disturbance scale of stochastic wind. \( \bar{u} \) is average wind speed.

3 Wind turbine generator models

3.1 Squirrel-cage induction generator model

Wind turbine with squirrel-cage induction generator (IG) belongs to fixed speed wind turbine generator. Its rotor speed has small range of variation, which is determined by the difference between stator frequency and slip frequency. Wind turbine with IG cannot obtain maximum power in different wind speed conditions due to the unchangeable rotor speed. It has low efficiency of energy conversion. The mathematical model of IG is [6],

\[
\begin{align*}
\frac{d\phi_{ds}}{dt} &= u_{ds} + \omega_{m} \psi_{qs} + R_{ds} i_{ds} \\
\frac{d\phi_{qs}}{dt} &= u_{qs} - \omega_{m} \psi_{ds} + R_{qs} i_{qs} \\
\frac{d\psi_{ds}}{dt} &= u_{ds} + \omega_{m} \phi_{qs} - R_{ds} i_{ds} \\
\frac{d\psi_{qs}}{dt} &= u_{qs} - \omega_{m} \phi_{ds} - R_{qs} i_{qs} \\
\frac{d\theta_{m}}{dt} &= \frac{1}{\omega_{m}} \left( T_{m} - T_{s} \right)
\end{align*}
\]

where, all variables are per unit value. \( \psi_{ds} \) and \( \psi_{qs} \) are stator flux linkage. \( u_{ds} \) and \( u_{qs} \) are rotor flux linkage. \( u_{ds} \) and \( u_{qs} \) are stator voltage. \( \omega_{m} \) is rotor angular velocity. \( \omega_0 \) is the rotor speed. \( \omega_{m} \) is the mechanical angular velocity of rotor. \( \omega_{gen} \) is the mechanical angular velocity of generator. \( T_{m} \) and \( T_{s} \) are mechanical and electrical torque. \( s \) is the slip speed. We have,

\[ s = \frac{\omega_{m} - \omega_{gen}}{\omega_{m}} \]

4 Simulation research of PSWT

4.1 Test system

The simulation model of PSWT is established by using Power System Analysis Software Package (PSASP) based on the Gansu power grid. The model of synchronous generator used in this paper is the nine-order model [7]. The structure of simulation system is shown in Figure 2.

![Figure 1: Block diagram of DFIG control model.](image1)

Figure 1: Block diagram of DFIG control model.

The control strategy of generator side converter, rotor speed is controlled by \( i_{qr} \) for realizing maximum power point tracking (MPPT) and the reactive power is controlled by \( i_{dr} \) with stator flux linkage oriented. The value of mechanical power is calculated by MPPT module according to the wind speed. By checking the curve of MPPT, the rotor speed is obtained based on the mechanical power and it is delivered to the generator side rotor speed controller as the reference value of the rotor velocity. In the control strategy of grid side converter, the active power is controlled by \( i_{dq} \) which is the d-axis component of grid side converter output current to get the constant voltage of DC link and the reactive power is controlled by \( i_{dq} \) which is the q-axis component of grid side converter output current with grid voltage oriented. The value of pitch angle is maintained to zero by pitch angle controller for MPPT when rotor speed does not exceed the limitation. The value of pitch angle is increased to reduce the wind energy input when rotor speed exceeds the limitation and to keep the rotor velocity within the range of normal operation.

![Figure 2: Simulation system of PSWT.](image2)

Figure 2: Simulation system of PSWT.
In Figure 2, W1, W3, W5 are the wind farms with DFIGs. W2, W4, W6 are the wind farms with IGs. A single wind turbine generator is used to represent a wind farm with same capacity as the wind farm [8]. S1 and S2 are synchronous generation units. Three-phase short circuit happens on the transmission line between node N2 and node N3, close to N2. Fault duration is 100 ms. The wind disturbance is one of the main factors that might lead to the wind power variation and the stability problems of the power grid. In this paper, wind disturbance is considered when the fault happens.

4.2 Gust wind disturbance

The gust wind disturbance, which last a second, occurs in the wind farms simultaneously with the system fault. Figure 3 shows the rotor angle difference between S1 and S2 under these situations. The rotor angle difference between S1 and S2 is represented by $\theta$ in the rest of this paper. The Base means that there is no wind disturbance when short-circuit fault happens. W1G+7 and W2G+7 are the cases with gust wind disturbance occurring in the wind farm W1 and W2 respectively. The last numbers in the case names mean the amplitude of gust wind. The rest of case names follow the same principle.

For IG wind farm cases, the results are different from the Base case. The impact of gust wind speed on the curve oscillation level is relatively clear. And the system in W2G-7 has the worst transient characteristics, namely the biggest magnitude and the smallest damping. The transient stability of system is weakened in that case.

In case WSG-7, the gust wind disturbance occurs in all IG wind farms during fault period. The amplitude of gust wind is -7 m/s. The simulation results are shown in Figure 4 and the Prony analysis results are listed in Table 2.

4.3 Other wind disturbance

Assume W2R+7 and W2R-7 are the cases with ramp wind disturbance occurring in W2 during fault period. The last numbers in the case names mean the amplitude of ramp wind. W2R+3 and W2R-3 follow the same principle. W2S is the case that stochastic wind disturbance occurs in W2 during fault period. In W2S, the random magnitude of wind speed change is between -7 m/s and +7 m/s. The duration of wind disturbance is one second in these cases. The corresponding simulation and Prony analysis results are shown in Figure 5 and Table 3.

The Prony analysis results of the cases in Figure 3 are shown in Table 1. It can be seen that 1) For DFIG wind farm cases, the Prony analysis results of curves are all similar to the Base case no matter how much the amplitude of gust wind is. 2) For IG wind farm cases, the results are different from the Base case. The impact of gust wind speed on the curve oscillation level is relatively clear. And the system in W2G-7 has the worst transient characteristics, namely the biggest magnitude and the smallest damping. The transient stability of system is weakened in that case.

In case WSG-7, the gust wind disturbance occurs in all IG wind farms during fault period. The amplitude of gust wind is -7 m/s. The simulation results are shown in Figure 4 and the Prony analysis results are listed in Table 2.

**Table 1: Prony analysis results with gust wind disturbance during three-phase short circuit.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Magnitude</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>2.5748</td>
<td>12.729%</td>
</tr>
<tr>
<td>W1G+7</td>
<td>2.5691</td>
<td>12.706%</td>
</tr>
<tr>
<td>W1G+3</td>
<td>2.5723</td>
<td>12.721%</td>
</tr>
<tr>
<td>W1G-3</td>
<td>2.5771</td>
<td>12.735%</td>
</tr>
<tr>
<td>W1G-7</td>
<td>2.5792</td>
<td>12.740%</td>
</tr>
<tr>
<td>W2G+7</td>
<td>1.8248</td>
<td>13.063%</td>
</tr>
<tr>
<td>W2G+3</td>
<td>2.4783</td>
<td>10.402%</td>
</tr>
<tr>
<td>W2G-3</td>
<td>2.6180</td>
<td>7.836%</td>
</tr>
<tr>
<td>W2G-7</td>
<td>2.6317</td>
<td>7.805%</td>
</tr>
</tbody>
</table>

**Table 2: Prony analysis results in case WSG-7.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Magnitude</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSG-7</td>
<td>2.7442</td>
<td>7.473%</td>
</tr>
</tbody>
</table>

It can be found that the oscillation level of $\theta$ in WSG-7 is more serious than the W2G-7 case. Therefore, the negative effect of gust wind disturbance on the system transient stability would be magnified if a great amount of IG wind farms connected to the grid.

**Table 3: Prony analysis results of $\theta$ curves in other wind disturbance cases.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Magnitude</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2R+7</td>
<td>1.8039</td>
<td>9.238%</td>
</tr>
<tr>
<td>W2R+3</td>
<td>2.4671</td>
<td>10.465%</td>
</tr>
<tr>
<td>W2R-3</td>
<td>2.6227</td>
<td>7.847%</td>
</tr>
<tr>
<td>W2R-7</td>
<td>2.6302</td>
<td>7.851%</td>
</tr>
<tr>
<td>W2S</td>
<td>2.4783</td>
<td>11.010%</td>
</tr>
</tbody>
</table>
It can be seen that the oscillation levels of the \( \theta \) curves in these cases are different from the Base case. But they are all better than the W2G-7 case. That is, the gust wind disturbance can have the worst impact on the transient stability of the simulation system.

4.4 Results analysis

The comparison results of various cases are shown in Figure 6. \( \omega \) is the rotor speed of the equivalent wind turbine generator. \( P_m \) is the mechanical power inputted to the equivalent machine. \( P \) is the electrical power which the equivalent machine outputs. The subscripts W1 and W2 indicate W1 and W2 wind farms respectively.

![Comparison results of various cases](image)

Figure 6: Comparison results of various cases.

The variation range of \( \omega_{w1} \) is much larger than it of \( \omega_{w2} \). The variation of \( \omega_{w1} \) is between -4.58% and +5.83% of its steady state value. And the variation of \( \omega_{w2} \) is between -0.17% and +0.899%.

In case W1G+7, the rotor speed of the equivalent machine increases to absorb a part of the mechanical energy. The increment of the wind farm output active power is reduced by the rotor speed acceleration. In case W1G-7, the rotor speed decreases to release a part of the rotor kinetic energy. The decline of the wind farm output active power is compensated by the rotor speed deceleration. The rotor of the wind turbine with DFIG plays a buffer role in facing the wind disturbance. It is helpful to maintain the system transient stability.

In W2G+7 and W2G-7 cases, the input mechanical power fluctuation is directly reflected on the variation of output active power. Due to the little change in the IG rotor speed, there is no buffering effect to weaken the impact of wind disturbance. Therefore, the influence of wind disturbance on the system transient stability is relatively significant in IG cases.

5 Conclusions

In this paper, the impact of wind disturbance accompany with the faults on the PSWT transient stability is mainly studied. Following conclusions are obtained according to the simulation results.

1) The wind disturbance that occurs simultaneously with the system faults indeed has some influence on the PSWT transient characteristics. For getting more accurate and correct results, the variation of wind speed during system transient period should be considered in the analysis of PSWT transient stability.

2) The wind disturbance in the IG wind farms has larger impact on the system than the DFIG cases. Especially, sometimes the system transient characteristics become worse due to the wind disturbance in the IG wind farms. And with the number of IG wind farms that have wind disturbance increasing, the negative condition can be more critical.

3) In different wind disturbance types, the gust wind can have the worst impact on the PSWT transient stability.

4) Because of the DFIG rotor speed variation capability, the DFIG wind farms can weaken the influence of wind disturbance. DFIG wind farms are helpful to maintain the transient stability of PSWT.

References