Study on Power Angle Stability of Wind-fire Hybrid Transmission System Controlled by Virtual Synchronous Machine

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ABSTRACT

Wind-fire hybrid transmission system stability has always been a research hot spot, and as the wind turbine control strategy is more and more complex, the stability is more complicated. In recent years, the idea of virtual synchronous machine applied to the control scheme of wind turbines has been popularized, so it is necessary to discuss the power angle stability of wind-fire hybrid system considering the additional control of the wind turbines with the virtual synchronous machine. In this paper, a typical wind-fire hybrid transmission system model is established, and the operating characteristics of the wind turbine are analyzed and the wind turbine model is established. Then, a control strategy of virtual synchronous machine is proposed. At last, the power equivalence function of wind-fire hybrid transmission system is analyzed by Extended Area Equity Criterion (EEAC), and the simulation results in PSASP show that when the receiver is a strong system, the higher the wind-fire ratio, the better the system's angle stability is. The control of the virtual synchronous machine has less effect on the stability of the power angle. When the receiver is a weak system, with the increase of wind power ratio, the power angle stability first increases and then decreases, there is an optimal ratio, and the application of the virtual synchronous machine control can effectively enhance the system's power angle stability, thereby improving the optimal wind-fire ratio.

Keywords: Wind-fire hybrid transmission, power angle stability, virtual synchronous machine, wind-fire ratio, EEAC.

INTRODUCTION

In our country, wind power and thermal power are mostly distributed in the “Three Norths” regions, where the load level is usually low and the on-site capacity of wind power is not sufficient. Therefore, wind power and thermal power must be sent to the distant consumer, mostly by means of wind-fire hybrid delivery[1]. Thus, the system stability needs to be clear.

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In addition, the control strategy of wind turbines based on virtual synchronous machine has drawn much attention in recent years[2]. With this additional control, the angle stability characteristics of the system will be more complicated. Therefore, it is necessary to study the power angle stability of wind-fire hybrid system controlled by virtual synchronous machine.

Nowadays wind farms at home and abroad mainly use variable speed constant frequency doubly-fed induction asynchronous wind power generator (DFIG), which the research on power angle stability of wind power grid integration mainly focuses on. At present, there is still no conclusion about the research on the power angle stability of wind-fire hybrid system. There are mainly the following different views: One view is that access to a certain proportion of wind power is beneficial to the power angle stability of the system[3-4], while another view is that DFIG access is not conducive to the power angle stability of the system[5-6]. Another point of view is that the impact of wind power into the grid on power angle stability of the system needs to be considered synthetically, which has the potential to affect the system power angle power angle stability[7]. The Ref. [8] proposed cutting machine and control scheme that is conducive to the system power angle stability, and the Ref. [9] proposed different virtual synchronous machine control strategies. However, the existing literature does not apply the virtual synchronous machine control strategies to the wind-fire hybrid transmission system, and explores the effect of this additional control on the power angle stability of the system.

The purpose of this paper is to study the effect of the virtual synchronous machine control strategies and different wind-fire ratios on the power angle stability of wind-fire hybrid transmission System.

WIND-FIRE HYBRID TRANSMISSION SYSTEM MODELING

Wind-fire Hybrid Transmission System Model Overview

Wind-fire hybrid transmission system is shown in Figure 1. The electricity generated by the wind generator and the adjacent synchronous unit is sent out to the receiver with the same transmission line. According to the strength of the receiver system, it can be divided into two situations. One is that the receiver is a strong system, which inertia and capacity are strong compared to the sending end. The other is the system with the terminal being a weak system. The system inertia and capacity are comparable with the sending end. The characteristics of different wind turbines are very different. This paper focuses on the double fed wind generator (DFIG) which is widely used in the project. In the simulation, the 5-step synchronous generator model is adopted in the thermal power unit.

Wind turbine characteristics modeling

The model of DFIG is shown in Figure 2 and consists of a wind turbine, a gearbox, a doubly-fed induction generator, a rotor-side converter and a control system. The converter is used to exchange power with the grid.
In addition to the type of generator used, the operational control of DFIG is also closely related to the operating characteristics of the fan as a source of mechanical energy. The input power of the wind turbine can be expressed as:

$$P_v = \frac{1}{2}(\rho S_\omega v^2) = \frac{1}{2} \rho S_\omega v^3$$  \hspace{1cm} (1)

Where, $\rho$ is the air density, $S_\omega$ is the windward swept area of the wind turbine blade; $v$ is the air flow velocity before entering the swept surface of the wind turbine (i.e., undisturbed wind velocity).

And the output power of the wind turbine is as follows:

$$P_o = C_p P_v = \frac{1}{2} \rho S_\omega v^3 C_p = \frac{\pi}{8} \rho D_\omega^2 v^3 C_p$$  \hspace{1cm} (2)

$C_p$ is the coefficient of wind energy utilization, and $D_\omega$ is the diameter.

At a fixed wind speed $v$, with the wind turbine speed $n_\omega$ changes, the $C_p$ value will be changed accordingly, so that the output mechanical power $P_o$ of wind turbine will change. The relationship between the output power and speed of a fixed-pitch wind turbine can be shown in Figure 3.

In Figure 3, the connection between the maximum power point $P_{opt}$ on the wind turbine power-speed curve under different wind speeds is called the optimal power curve. When the system is in stable operation, the wind turbine runs on the optimal power curve:\hspace{1cm}[9]

The motion equation of the rotor of DFIG is formula (3):

$$P_L - P_e = \frac{J \omega_r}{n_p^2} \frac{d\omega_r}{dt}$$  \hspace{1cm} (3)

$P_L$ is the mechanical power of the wind turbine, $P_e$ is the electromagnetic power of the wind turbine, $J$ is the moment of inertia of the wind turbine, $n_p$ is the number of pole pairs of the wind turbine, and $\omega_r$ is the angular velocity of rotor.

**VIRTUAL SYNCHRONOUS MACHINE CONTROL MODEL**

At present, many scholars have different design methods for the control strategy of virtual synchronous machine. However, most of them introduce the feedback loop to
introduce the inertia and damping of the synchronous generator into the control.

It can be seen from the equation of rotor motion of synchronous generator that if the mechanical power of the generator is considered to be constant during the change of system frequency, the change of electromagnetic power of the generator, $\Delta P_e$, is proportional to the rate of change of speed, that is:

$$\Delta P_e = -\frac{J \omega_m d\omega_m}{n_i^2} \frac{dt}{\omega}$$  \hspace{1cm} (4)

Therefore, for the DFIG with independent active regulation capability, additional control of the active power can be provided by simulating the external characteristics of the synchronous machine. Taking the system frequency or the angular velocity of synchronous generator as the input signal, the additional control signals are superimposed on the signal of the maximum power point tracking control of the wind turbine, and the inertial response of the variable speed wind turbine is simulated by using the active power regulation of the unit. The output power signal $\Delta P$ of the additional inertial control can be expressed as follows:

$$\Delta P = -K \omega_m \frac{d\omega_m}{dt}$$  \hspace{1cm} (5)

where $K$ is the proportional coefficient of the derivative control, used to simulate the virtual synchronous machine of the wind turbine.

Based on the above principle, a control scheme of the virtual synchronous machine control strategy is obtained, and its control structure is as Figure 4.

![Figure 4. Structure of virtual synchronous machine control.](image)

In the Figure 4, $\omega_r$ is the angular velocity of the rotor, $P_{opt}$ is the power value obtained through the MPPT (Maximum Power Point Tracking) control, $f_{measure}$ is the measured value of the system frequency, $T_1$ is the time constant of the differential link, $K_{\omega}$ is the proportional coefficient of the virtual synchronous machine control link, and $K_{o}>0$, $T_2$ is the time constant of the limiter, $P_{ref}$ is the reference value obtained after the maximum power tracking control and the virtual synchronous machine control.

System disturbances, such as a generator trip, often result in a transient drop in system frequency. The speed, depth, and frequency recovery of the frequency decrease are limited by the dynamic characteristics of the network connected to the generator. Due to the large wind farm off-grid, the system’s dynamic frequency is determined by the generator's inertial response in the first few seconds of the frequency drop. Traditional synchronous machines have some inherent inertial energy stored in the network, and cooperate with the slow speed governor to act, which can reduce the speed of initial frequency descent and stabilize the system frequency. Most modern megawatt wind turbines no longer have an inertial response; for large areas of low-frequency accidents, the virtual synchronous machine characteristics make the wind turbine has an inertial response capability. Rotor inertia control is the fast compensation control added to the wind turbine's rapid electrical power and mechanical power control. This command can last for a few seconds during power recovery. In the case
of low-frequency accidents, this control is beneficial to the grid, allowing enough time for other non-wind turbines to restore power output.

THE INFLUENCE MECHANISM OF WIND-FIRE RATIO ON POWER ANGLE STABILITY

Extended equal-area criterion (EEAC) is based on the principle of kinetic transient unbalanced energy, and the sending end system and the receiver system are taken as the severely disturbed group and the rest group, respectively. The mechanism of system instability is analyzed by analyzing the law how the proportion of wind power affects the stability of relative power angles between the severely disturbed group and the rest group. The essence of its theory is the direct method, the same area rules extended to multi-machine system. For a complex system, the instability of the system in the transient process is not determined by the system-wide energy but is caused by a few generators deviating from the system with the most serious out-of-synchronization. However, most of the generators can still keep in sync with each other in the early stage of instability. Therefore, in a given fault, the instability of any multi-group mode is always dominated by two sets of power angles relative to each other, so that all units of multi-machine system can be divided into the severe group and remaining group, equivalent to two systems. Based on this, the stability of the system is quantified by the application of the equal-area criterion.

According to EEAC, no matter in which way to change the stability of the system, it is ultimately achieved by changing the equivalent kinetic energy of the dominant image of the system. The dominant image, i.e. equivalent acceleration energy $P'$, can be expressed as (6):

$$
P' = \frac{M_\Delta P_\Delta - M_s D_\Delta P_s}{M_s + M_r} = \frac{\Delta P_\Delta + \Delta P_r}{M_r / M_s + 1}
$$

Where $M_i$ is the inertia of the ith operating thermal power unit in the severely disturbed group; $M_j$ is the inertia of the jth operating thermal power unit in the rest group; $M_s$ and $M_r$ are the equivalent inertia of the severely disturbed group and the rest group, respectively; $\Delta P_\Delta$ and $\Delta P_r$ are the accelerating power of the severely disturbed group and the rest group respectively. The sending system can be classified as a severely disturbed group, and the receiving system can be classified as the rest group.

When the rest group is a strong system, that is, when $M_r = \infty$, (6) can be simplified as:

$$
P' = \frac{M_\Delta P_\Delta - M_s D_\Delta P_s}{M_s + M_r} = \Delta P_\Delta - \frac{\Delta P_\Delta + \Delta P_r}{M_r / M_s + 1} \approx \Delta P_\Delta
$$

Therefore the acceleration power of the whole system is approximately equal to the acceleration power of the sending end system and has almost no correlation with the inertia of the sending end. According to the analysis of 1.2, for DFIG, unlike synchronous generators, when the three-phase short-circuit fault occurs, the mechanical power of DFIG will decrease with the acceleration of the rotor due to the imbalance between the mechanical energy of the input generator and the output of the generator, when the rotor starts to accelerate. When the acceleration energy is greater than the deceleration energy, the mechanical power will be further reduced when the rotor will continue to accelerate. According to the extended equal area criterion, this phenomenon is equivalent to reducing the acceleration area. Thus, as the proportion of wind power increases and that of thermal power is reduced, the total acceleration power of the system is reduced, and the power angle stability is improved. So
when the receiver is a strong system, the power angle stability increases with the increase of the ratio of wind power in the sending end.

When the system inertia of the rest group (receiver) and the severely disturbed group (sending end) is comparable, not only the acceleration power but also the influence of system inertia on the stability should be considered. So equation (7) at this time cannot directly determine whether the entire system equivalent acceleration power is larger or smaller. Therefore, it is necessary to calculate the first derivative of the sending inertia of the equivalent acceleration power equation (6), and get the equation (8).

$$\frac{\partial P'}{\partial M_s} = \frac{1}{M_s + M_r} \left( M_r \frac{\partial \Delta P_s}{\partial M_r} - M_s \frac{\partial \Delta P_r}{\partial M_s} \right) - \frac{M_r \left( \Delta P_s + \Delta P_r \right)}{(M_s + M_r)} \quad (8)$$

When \( P' \) takes the extreme value, the equation (8) should be satisfied as 0 and the equation (9) is obtained.

$$\left( M_r \frac{\partial \Delta P_s}{\partial M_r} - M_s \frac{\partial \Delta P_r}{\partial M_s} \right) = \frac{M_r \left( \Delta P_s + \Delta P_r \right)}{(M_s + M_r)} \quad (9)$$

The equivalent acceleration power \( P' \) is a concave function of the inertia \( M_s \) of the sending end. Because the MS decreases with the increase of the proportion of wind power, the equivalent acceleration power is also a concave function of the proportion of wind power, that is, when the proportion of wind power increases, it first decreases and then increases, and the power angle stability margin of the system increases first and then decreases, and there is a minimum value. Therefore, when the receiving system is a weak system, there is an optimal wind power ratio, and the system power angle stability is the best\(^3\).

**SIMULATION VERIFICATION**

The simulation analysis needs to consider the two conditions of the receiving system as strong system and weak system.

**Strong System**

In the Power System Analysis Software Package (PSASP), a simulation example that the receiver is strong is built, as shown in Figure 5. G1 for the thermal power unit model, G2 for the DFIG model, the rated capacity of both units are 200MW. Wind power and thermal power are converged by 220kV buses and sent to the strong system through two transmission lines. The infinity system is realized by connecting to the actual northeast power grid in China.

Maintain a total power output of 300MW and adjust the output of thermal power units and wind power units to set the proportion of total output of wind power to 10%, 20%, 30%, 40%, 50% and 60% respectively. At \( t = 1s \), a three-phase short-circuit fault occurs at 50% of the transmission line and the fault is removed at \( t = 2s \). In different wind and fire ratio, the thermal power unit’s power angle is shown in Figure 6.
Figure 6. Angle curves under different wind power proportion.

It can be seen from the figure that under the above conditions, the power angle is unstable when the proportion of wind power accounts for 10%-50%, and the power angle stability is restored only when the proportion of wind power is 60%. From the magnitude of the swing angle of wind power, the power angle stability is better than 60%. When considering the additional control, the power angle curve of the thermal power unit did not change significantly. The paper also calculated and analyzed the critical clearing time (CCT) of the above systems at different wind power ratios and whether or not to adopt the additional control of virtual synchronous machine. The results are shown in Table 1.

Table 1. CCT in different case.

<table>
<thead>
<tr>
<th>Wind power ratio/%</th>
<th>CCT (without control)/s</th>
<th>CCT (with control)/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>20%</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>30%</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>40%</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>50%</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>60%</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

As can be seen from Table 1, when the receiver system is a strong system, the higher the proportion of wind power is, the longer the CCT is and the better the power angle stability of the system is. When the additional control is considered, the power angle curve of the thermal power unit does not change obviously and the fault limit removal time does not change, so it can be judged that when the receiver is an strong system, the additional control of the virtual synchronous machine of the wind turbine has little effect on the power angle stability of the system.

Weak System

In PSASP, the 11 node system shown in Figure 7 is built.
G1, G3 and G4 are synchronous generators. The rated capacity of the 4 generating units is 400MW, and the actual generating capacity of the sending end is different. The G3 of the receiving units is actually 200MW, G4 is the balancing machine, the load is 200MW and 400MW respectively. Both the power plant and the wind farm are sent through the same bus through the 220 kV transmission line. Maintain a total power output of 300MW and adjust the output of thermal power units and wind power units to set the proportion of total output of wind power to 10%, 20%, 30%, 40%, 50% and 60% respectively. When t = 1s, three-phase short circuit fault occurs at 50% of one transmission line from node 8 to node 9, and the fault is removed when t = 1.08s. In different wind and fire ratio, the thermal power unit's power angle is shown in Figure 8.

![Figure 8. Angle curves under different wind power proportion.](image)

It can be seen that when the proportion of wind power is 10% to 40% and the failure time is 0.08s, the power angle of the thermal power unit is already unstable. When the proportion of wind power is 60%, although the power angle of thermal power unit is not stable, the swing amplitude is more than 50%, and the recovery time is longer. In this case, when the ratio of wind power is 50%, the power angle stability of the system is the best.

When the wind turbine adopts the additional control of the virtual synchronous machine, under the same conditions, the angle curves of the thermal power units are shown in Figure 9. When the proportion is between 10% and 60%, the power angle is stable, and the power angle swing is the minimum at 60%.

![Figure 9. Angle curves under different wind power proportion.](image)

The paper also calculated and analyzed the critical clearing time (CCT) of the systems shown in Figure 7 at different wind power ratios and whether or not to adopt the additional control of virtual synchronous machine. The results are shown in Table 2.
Table 2. CCT in different cases.

<table>
<thead>
<tr>
<th>Wind power ratio/%</th>
<th>CCT (without control)/s</th>
<th>CCT (with control)/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>20%</td>
<td>0.06</td>
<td>0.18</td>
</tr>
<tr>
<td>30%</td>
<td>0.06</td>
<td>0.24</td>
</tr>
<tr>
<td>40%</td>
<td>0.06</td>
<td>0.28</td>
</tr>
<tr>
<td>50%</td>
<td>0.07</td>
<td>0.32</td>
</tr>
<tr>
<td>60%</td>
<td>0.07</td>
<td>0.37</td>
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</tbody>
</table>

As can be seen from Table 2, with the power angle curve, when the receiver is a weak system, the power angle stability of the system is best when the proportion of wind power is 50%. When the control of virtual synchronous machine is adopted, the power angle stability of the system can be effectively improved regardless of the ratio of wind and fire, and the greater the proportion of wind power is, the more obvious the effect of improving the stability is and the optimal allocation ratio of the system is increased.

CONCLUSION

It is of great significance to study the influence of the wind power ratio and control method on the power angle stability of the wind-binding system. Based on the theory of EEAC, this paper carries out theoretical analysis and simulation verification on the problem, and obtains the conclusion of the relationship between wind power ratio, virtual synchronous machine control strategy and the power angle power angle stability of the system, as follows:

When the equivalent inertia and the capacity of the receiver are strong, as the proportion of wind power increases, the equivalent accelerating power of the system decreases when the system fails, so that the power angle stability of the system is better. In this case, the effect of the virtual synchronous machine control of the wind turbine is not affected obviously.

When the equivalent inertia and the capacity of the receiver are weak, with the increase of wind power ratio, the power angle stability of the system first increases and then decreases. The best ratio needs to consider the system structure, determined by simulation. In this case, if the wind turbine adopts the virtual synchronous machine control, the power angle stability of the system can be effectively improved, and the greater the effect of wind power accounting is, the more obvious the effect will be. With virtual synchronous machine additional control, the system can effectively enhance the best proportion of the wind power.

REFERENCES


