An Emergency Control Method for Wind-Thermal Bundled System

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Abstract. Wind and thermal power bundling is an effective means to solve the problem of power delivery from energy bases. In this paper, an emergency control method for wind-thermal bundled system is proposed. After the system is out of step, the stability of the system can be assessed quickly by using phase measurement unit (PMU) data and the power angle threshold can be determined. When the power angle threshold is reached, using power electronic equipment quickly to exchange the connection by disconnecting the primary side phase of the line at the synchronizer outlet. Then, the A, B, C three-phase series are connected to the C, a, B three-phase series, and the angle is reduced by 120°instantaneously. This preventing the system from falling out-of-step while maintaining the integrity of the system and the inertia level. The higher the wind power permeability, the better the performance of the proposed control method is. A case study is provided to verify the effectiveness of the proposed method.

1. Introduction
Wind and thermal power bundling delivery is an effective way to solve the bottleneck of power consumption in Northwest, North and Northeast China, but large-scale wind and thermal power delivery in wind and thermal power bundling manner has changed the transient stability characteristics of the system.

When serious faults occur in wind-thermal bundled system, the emergency control method of tripping is usually adopted [1]. Many research studies have been conducted on this topic. There has been a greater focus on the calculation of wind power and thermal power tripping. It is usually impossible to restore synchronization by tripping only the wind power. The cost of tripping thermal power is too high and the inertia of the system will be reduced. In a high-permeability wind power system, inertia is an important factor to maintain the stable operation of the system. If the inertia is too low, there may be more serious consequences, such as the blackout that occurred in Britain in 2019 [2]. If the system can be re-synchronized while maintaining the system stability and ensuring system inertia is of great significance to the stable operation of wind-thermal bundled system.

Phase sequence exchange (PSE) is a recently developed emergency control method [3]. In [3], the mechanism of improving system stability via PSE was described. In [4], the conditions under which the system can endure PSE were determined. A PSE control mode of split-phase switching control, which greatly reduces the impact of PSE, was also proposed. In this study, we analyze the effect of the PSE on a wind-thermal bundled system; an optimal PSE control method is developed and the influence of changes in wind power permeability on the PSE performance is investigated.
2. Model of wind-thermal bundled system

The equivalent circuit of the wind-thermal bundled system is shown in Figure 1.

![Figure 1. Wind-thermal bundled system.](image1)

For the synchronizer, second-order classical model is adopted and ignore the dynamic characteristics of the prime mover, governor, and excitation system. The doubly-fed wind turbine has a GE 1.5 MW fan with low voltage traversing ability; the dynamic characteristics of the converter and changes in the wind speed are ignored. Constant power factor control mode is adopted for reactive power and a dual-mass block model is used for the mechanical parts of the rotor; the line and transformer resistance are ignored [4]-[6].

The equivalent circuit of the power system integrated (Figure 1) is shown in Figure 2.

![Figure 2. Equivalent circuit](image2)

Equation (1) is used to derive the power angle curve of the synchronous generator after the DFIG has been accessed.

$$P_{stc} = E'' G''_{eq} + E' U_{i} | y_{ao}' | \sin(\delta + \varphi')$$

where $G''_{eq} = -\lambda' (1-k) k U_{a}^{2} P_{o} x_{a}^{2}$

$$y_{ao}' = \lambda' (1-k) k U_{a}^{2} P_{o} x_{a} x_{o} + j \lambda' U_{a}^{2} (x_{o} + (1-k)x_{o})$$

$$\tan \varphi' = \frac{(1-k) P_{o} x_{o}}{U_{a}^{2} x_{o} + (1-k)x_{o}}$$

$$\lambda' = \frac{1}{k^{2} x_{o}^{2} + U_{a}^{2} (x_{o} + (1-k)x_{o})^{2}}$$

Equation (1) is used to derive the power angle curve of the synchronous generator after the DFIG has been accessed.

The equivalent power angle relationship of the synchronous machine consists of a DC offset and a sinusoidal quantity, in which the DC offset $E'' G_{eq} < 0$ is a downward translation of the power angle curve. In the sinusoidal component, $\varphi > 0$ is a left translation of the power angle curve; the sinusoidal limit amplitude changes from $E' U_{i} / |x_{o} + x_{o}|$ to $E' U_{i} / |y_{ao}'|$ and because $U / |x_{o} + x_{o}| < |y_{ao}'|$, the amplitude of the sinusoidal quantity increases [7].

3. Phase Sequence Exchange

PSE is a recently developed emergency control method for power systems and is used to prevent out-of-step conditions. PSE can be used if an OMIB system has experienced a disturbance in which the power angle has changed to 90°-180°. The power angle threshold of the PSE is $\delta_{m}$. When the system is out-of-step and the power angle moves to $\delta_{m}$, the use of electronic equipment quickly misaligns the connection by disconnecting the primary side phase of the contact line. The A, B, C three-phase
sequence then connects to the three-phase C, A, B sequence, instantaneously reducing the angle by 120°, thus preventing an out-of-step condition of the system [3].

When the power angle is \( \delta = \delta_n \), the following steps must be followed. In phase A, the power angle \( \delta_A \) prior to implementing the PSE is the angle between the phasor \( \vec{E}_A \) and \( \vec{U}_A \). After the PSE has been implemented, the power angle \( \delta'_A \) is the angle between the phasor \( \vec{E}_A \) (which has changed to \( \vec{E}_B \)) and \( \vec{U}_A \).

The vector diagram of phase A and the phase sequence connection diagram are provided in Figure 3; it is evident that the PSE reduces the power angle of the system by 120°.

Since the PSE is an emergency control method for synchronous generators and the DFIG has no power angle, in the following analysis, it is assumed that the PSE device will be installed after the synchronous generators.

4. Optimal Control Strategy

The curve of the electromagnetic power of the synchronous machine after the connection of the DFIG to the grid is a sinusoidal curve as shown in Figure 4. Therefore, the stability of the synchronous machine can be determined by using the equal-area criterion (EAC).

Assuming that a three-phase fault occurs on a circuit in the system as shown in Figure 1, the fault line is removed after a period of \( \Delta t \) and the mechanical power of the synchronous machine remains unchanged [8]. The stability of the system is analyzed by using the EAC as shown in Figure 4.

The stability margin of the synchronizer prior to PSE is

\[ \eta = \frac{S_A - S_B}{S_B} \]

The stability margin of the synchronizer after PSE is

\[ \eta' = \frac{S_A + S_D - S_B - S_C - S_E}{S_B + S_C + S_E} \]

First, if \( S_B + S_C + S_E < S_A + S_D \) then the deceleration area of the system is greater than the acceleration area after the phase sequence exchange, and the system can resume synchronization.

Second, if \( S_B + S_C + S_E > S_A + S_D \) but \( S_C + S_E < S_D \), the deceleration area of the system is smaller than the acceleration area after the PSE. However, the increase in the deceleration area due to the PSE is
larger than that of the acceleration area. Therefore, after several PSEs, the deceleration area of the system will eventually be larger than the acceleration area and the system is synchronized.

Third, if \( S_{a} + S_{c} + S_{e} > S_{a} + S_{b} \) and \( S_{a} + S_{e} > S_{b} \), the deceleration area is smaller than the acceleration area, indicating that the PSE cannot stabilize the system. In this case, the PSE operation is ineffective.

The greater the stability margin of the system, the better the PSE performance. In order to achieve the optimal PSE performance, \( S_{a} - (S_{c} + S_{e}) \) should be maximized:

\[
S_{a} - (S_{c} + S_{e}) = \int_{\delta_{m}}^{\delta_{n}} (P_{c} - P_{r}) d\delta
\]

\[
= \frac{2}{3} \pi(E''G_{m} - P_{r}) - \left| y'' \right| \sin(\delta_{n} - \frac{1}{3} \pi + \phi')
\]

and

\[
\frac{d[S_{a} - (S_{c} + S_{e})]}{d\delta_{m}} = -E'U_{l} | y'' | \cos(\delta_{n} - \frac{1}{3} \pi + \phi')
\]

when \( \delta_{n} = \frac{150^\circ - \phi'}{3} \).

Therefore, when \( \delta_{n} = \frac{150^\circ - \phi'}{3} \), \( S_{a} - (S_{c} + S_{e}) \) is the largest and the PSE control effect is maximized. Therefore, the power angle threshold of the PSE is set to \( \delta_{n} = \frac{150^\circ - \phi'}{3} \).

During the period from fault occurrence to fault clearing, the state variables of the generators are measured by the phase measurement unit (PMU) and transmitted to the control center at high speed to calculate the acceleration area. Using several data points measured after the fault clearance, the electromagnetic power curve and the deceleration area are derived to assess the stability of the system. Subsequently, the power angle threshold of the PSE and the number of PSE events can be determined to determine the stability of the system after the PSE.

5. Case study
Using Simulink software, a simulation model of wind-thermal bundled system is established as shown in Figure 1. The total capacity of the system is 515 MW, \( x'_{1} = 1.673, x'_{2} = 0.14, x'_{3} = 0.155, x'_{4} = 0.1, x'_{5} = x'_{6} = 0.0887 \). Fifty percent of one circuit of the double-circuit lines experience three-phase short-circuit faults and the fault lines are removed after a period of time. Using the emergency control measures proposed in this paper, the optimal PSE power angles at wind power permeability values of 0%, 25%, 50%, and 75% are shown in Table 1.

| \( k \)/% | 0  | 25  | 50  | 75  |
|----------|----|-----|-----|-----|
| \( \delta_{m} \)/deg | 171.5 | 171.2 | 162.1 | 142.5 |

After the system is out of step, the power angle increases continuously. When the power angle reaches \( \delta_{m} \), the phase sequence is exchanged. Take \( k = 75\% \) as an example, the electromagnetic curve of synchronous generator with and without PSE is shown in Figure 5.

![Figure 5. Electromagnetic curve (k = 75%)](image-url)
Figure 5 illustrates how the originally reduced electromagnetic power increases once again, expanding the deceleration area of the system and suppressing system out-of-step.

The power angle curve and speed curve of the synchronous generator at wind power permeability values of 0%, 25%, 50%, and 75% after the PSE are shown in Figure 6, Figure 7.

![Power angle curve](image)

**Figure 6. Power angle curve**

Figure 6 shows that the higher the wind power permeability, the smaller the maximum power angle of the first swing is after the PSE. At $k = 75\%$, the power angle of the second swing is even less than that of the first swing at $k = 0\%$.

As shown in Figure 7, the higher the permeability of the wind power, the smaller the speed difference of the system is after the PSE. At $k = 75\%$, the speed difference of the second swing is even less than that of the first swing at $k = 0\%$. The higher the wind power permeability, the longer the oscillation period of the system is after the PSE. At $k = 75\%$, the peak value of the second swing is reached and at $k = 0\%$, only the peak value of the first swing is reached.

In conclusion, the higher the wind power permeability, the shorter the oscillation time and the smaller the oscillation amplitude are after the PSE, indicating a better PSE performance.

When $k = 75\%$, under the same fault, the generator tripping method proposed in [9] is used for emergency control. Compared with the PSE proposed in this paper, the power angle curve are shown in Figure 8.

![Power angle curve](image)

**Figure 8. Power angle curve**

It can be seen from Figure 8 that due to the high wind power penetration rate, the choice of synchronous generators to be tripped is limited. Although the emergency control can prevent the instability of the system, it takes a long time to oscillate to stabilize. However, the PSE method proposed in this paper has a later action time than the tripping, the decision time left to the central control center is longer, and can prevent the instability of the system while maintaining the system inertia level, so the oscillation time is shorter, and the accident expansion caused by the excessive tripping cutting is avoided.

6. Conclusions

An emergency control method was proposed for wind-thermal bundled system. After the occurrence of serious faults, the stability of the system was determined based on PMU-derived data. The electromagnetic power of the synchronous machine after fault clearing was predicted and the PSE threshold was determined. After the power angle threshold was reached, the power angle of the
synchronous machine was reduced by 120° by using the PSE device installed at the outlet of the synchronous machine. This prevented the instability of the system while maintaining the system structure and the inertia level.

After the occurrence of serious faults in a high-permeability wind power system, it is usually impossible to restore synchronization by tripping only the wind power. Tripping of the synchronous generator will further reduce the inertia of the system, which will lead to more serious accidents. The PSE method proposed in this paper has a later action time than the tripping, the decision time left to the central control center is longer, and can prevent the instability of the system while maintaining the system inertia level. At the same time, the higher the wind power permeability, the better the PSE performance was. The reason is that when the penetration rate of wind power is high, the PSE can make the system obtain a larger deceleration area.

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