Research Article

Synergetic Control Strategy of Front-End Speed Regulation Wind Turbine (FESRWT) for Fault Ride through

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1. Introduction

In recent years, wind power, as the renewable energy with the best large-scale development conditions and commercial development prospects, has developed rapidly. The capacity of single units and the total installed capacity have increased rapidly. The average annual coverage of wind power has increased year by year. However, the access of wind power has made power system more complicated, and the contradiction with the standard of “high efficiency, reliability, safety and grid friendly” becomes increasingly prominent [1,2]. Power departments and relevant authoritative companies in many countries around the world have formulated technical regulations for wind farms access to power system. It is required that wind farm can support the voltage of system connection point under normal working conditions, alleviate the interference caused by wind speed change to voltage fluctuation, and ensure that the voltage of wind farm connection point is always in a stable state. When the power system accident or disturbance causes voltage sags at the connection point, the wind turbine can ensure continuous operation without off-grid within a certain voltage sag range and time range [3–5]. Research on the fault ride through capability of wind turbines has become a hot issue in the field of wind power research.

At present, there are many literature on low voltage ride through (LVRT) capability of doubly fed induction generator (DFIG) and permanent magnet direct drive wind turbine, but there are few research on FESRWT. Aiming at the LVRT problem of FESRWT, reference [6] determined the control structure of the unit based on the characteristics of FESRWT. In case of three-phase short-circuit fault and single-phase grounding fault, this method can accelerate the attenuation of stator flux transient component and restrain the fluctuation of rotor speed, make generator produce large reactive power which will provide more reactive power support for power grid, and improve the fault ride through capability of FESRWT. By dynamic analysis of the proposed algorithm, the large range stability constraint condition satisfying the fault ride through is obtained, and the parameter range satisfying the condition is solved by Monte Carlo method. Taking 2 MW FESRWT as an example, the control strategy is verified and analyzed. Simulation results show that the proposed method can improve the fault ride through performance of FESRWT.

A synergetic control method is proposed to improve the fault ride through capability of front-end speed regulation wind turbine (FESRWT). In case of three-phase short-circuit fault and single-phase grounding fault, this method can accelerate the attenuation of stator flux transient component and restrain the fluctuation of rotor speed, make generator produce large reactive power which will provide more reactive power support for power grid, and improve the fault ride through capability of FESRWT. By dynamic analysis of the proposed algorithm, the large range stability constraint condition satisfying the fault ride through is obtained, and the parameter range satisfying the condition is solved by Monte Carlo method. Taking 2 MW FESRWT as an example, the control strategy is verified and analyzed. Simulation results show that the proposed method can improve the fault ride through performance of FESRWT.
based on the robust control of excitation system. The nonlinear controlled object is feedback linearized by constructing an extended state observer. The angle of attack deviation, angular velocity deviation, active power deviation, and terminal voltage deviation were selected as state variables, and a robust controller for excitation system was designed. The effectiveness of control algorithm was verified by simulation. Reference [8] carried out a simulation based on the operating characteristics of a 2.0 MW FESRWT, combined with actual parameters, and analyzed the dynamic response capability of generator’s LVRT when a short-circuit fault occurs in power grid. Reference [9] compared and analyzed the LVRT capability of wind farms with FESRWTs and wind farms with DFIGs, as well as their impact on transient stability of power grid. The transient stability of different fault points was studied. The LVRT characteristics of FESRWT have been studied in the above references and some achievements have been achieved, but the high voltage ride through (HVRT) performance of wind turbine and the large-scale stability analysis of the system have not been involved.

The synergistic control theory was proposed by Russian scholar A. Kolesnikov. It could reduce the order of the closed-loop system, simplify the design of the controller, and make the controlled system have good steady state and dynamic performance, as well as strong robustness [10–13]. At present, the research on synergistic control strategy of wind turbine is attracting more and more attention. Reference [14] designed a synergistic controller for permanent magnet direct drive wind turbine and verified the LVRT performance. Reference [15] proposed a synergistic control strategy of DFIG and verified the LVRT performance of the proposed control strategy through simulation. Reference [16] proposed a synergistic control algorithm, system stability constraints, and optimization method of control parameters for DFIG that could improve DFIG’s HVRT and LVRT capability.

Based on the above-mentioned references, this paper firstly establishes the mathematical model of FESRWT. Then the synergistic control algorithm is used to realize the fault ride through of FESRWT. The dynamic analysis of proposed algorithm is carried out, and the large-scale stability constraint conditions satisfying the fault ride through are given. The Monte Carlo method is used to solve the parameters that meet the conditions. Finally, based on the actual operation data of FESRWT, the proposed control strategy is verified and compared with existing control strategy.

2. FESRWT Mathematical Model and Transient Current Analysis

The structure of FESRWT is shown in Figure 1. Its components include wind wheel, speed-increasing gear box, hydraulic speed converter, and Electrically Excited Synchronous Generator (EESG). The electric energy generated by the unit is merged into power grid through transformer.

2.1. Mathematical Modeling of EESG. The 5th-order practical mathematical model of EESG is as follows [17]:

(1) Stator voltage equation:

\[
\begin{align*}
\frac{du_d}{dt} &= E_d' + X_d'' i_d - i_d r_d, \\
\frac{du_q}{dt} &= E_q' - X_q'' i_q - i_q r_q.
\end{align*}
\]

(2) Voltage equation of rotor f winding:

\[
T_d \frac{dE_d'}{dt} = E_f + \frac{X_d''}{X_d'} E_d' + \frac{X_d''}{X_d'} X_d'' i_d.
\]

(3) Voltage equation of rotor D winding:

\[
T_d \frac{dE_q'}{dt} = E_q' + (X_d'' - X_d') i_d.
\]

(4) Voltage equation of rotor Q winding:

\[
T_q \frac{dE_q''}{dt} = -E_q'' + (X_q'' - X_q') i_q.
\]

(5) Rotor motion equation:

\[
\begin{align*}
2H \frac{d\omega}{dt} &= P_m - P_e - D(\omega - 1), \\
\frac{d\delta}{dt} &= \omega - 1,
\end{align*}
\]

where \(u_d\) is the stator \(d\)-axis voltage, \(u_q\) is the stator \(q\)-axis voltage, \(i_d\) is the \(d\)-axis current, \(i_q\) is the \(q\)-axis current, \(r_d\) is the stator A-phase winding resistance, \(E_d'\) is the motor \(q\)-axis transient electromotive force, \(E_q'\) is the motor \(d\)-axis transient electromotive force, \(E_d''\) is the \(q\)-axis supertransient electromotive force, \(E_q''\) is the \(d\)-axis supertransient electromotive force, \(E_j\) is the stator excitation electromotive force, \(X_d''\) is the \(q\)-axis synchronous reactance, \(X_q''\) is the \(q\)-axis supertransient reactance, \(X_d''\) is the \(d\)-axis synchronous reactance, \(X_j\) is the \(d\)-axis transient reactance, \(X_d'\) is the \(d\)-axis supertransient reactance, \(T_d\) is the \(d\)-axis open-circuit transient time, \(T_d\) is the \(d\)-axis open-circuit supertransient time, \(H\) is the unit inertia time constant, \(\omega\) is the electrical angular velocity, \(P_m\) is the mechanical power, and \(P_e\) is the electromagnetic power. The previously mentioned parameters are all unit values using \(X_d'\) as the base value, \(D\) is the constant damping coefficient, \(\delta\) is the angle of the \(q\)-axis leading the real axis of the synchronous coordinate system, and the unit is rad.

Under the conditions of ignoring the voltage sag caused by resistance of stator winding and omitting the flux linkage generated by damping winding current, the above parameters meet the following relationship [18]:

\[
\begin{align*}
U_q &= E_q' - i_d X_d',
\end{align*}
\]
2.2. Transient Characteristic Analysis of EESG during Power Grid Voltage Sag.

(1) Transient characteristics of EESG: When the generator is suddenly short circuited, the current of each stator winding will include fundamental frequency component, frequency doubling component, and DC component. After reaching the steady state, the DC component and the double frequency component in stator current will attenuate from its initial value to zero; and the fundamental frequency component will attenuate to the steady state value [19]. Similarly, the rotor winding also contains DC component and AC component with the same frequency. After introducing the attenuation factor, the d-axis and q-axis components of stator current are

\[
i_d = \frac{E_{q[0]}}{x_d} + \frac{E_{q''}}{x_d} \exp \left( \frac{t}{T_d} \right) + \left( \frac{E_{q'[0]} - E_{q'[0]}}{x_d} \right) \exp \left( \frac{t}{T_d} \right) - \frac{V_{[0]}}{x_q} \exp \left( \frac{t}{T_a} \right) \cos (wt + \alpha_0),
\]

\[
i_q = \frac{E_{q''}}{x_q} \exp \left( \frac{t}{T_q} \right) + \frac{V_{[0]}}{x_q} \exp \left( \frac{t}{T_a} \right) \sin (wt + \alpha_0).
\]

After transformation, the A-phase current of stator is

\[
i_a = -\frac{E_{d[0]}}{x_d} \cos (wt + \alpha_0) - \left( \frac{E_{d''}}{x_d} \right) \exp \left( \frac{t}{T_d} \right) \cos (wt + \alpha_0)
- \left( \frac{E_{q'[0]} - E_{q'[0]}}{x_d} \right) \exp \left( \frac{t}{T_d} \right) \cos (wt + \alpha_0)
- \frac{E_{q''}}{x_q} \exp \left( \frac{t}{T_q} \right) \sin (wt + \alpha_0)
+ \frac{V_{[0]}}{2} \left( \frac{1}{x_d} + \frac{1}{x_q} \right) \exp \left( \frac{t}{T_a} \right) \cos (\delta - \alpha_0)
+ \frac{V_{[0]}}{2} \left( \frac{1}{x_d} + \frac{1}{x_q} \right) \exp \left( \frac{t}{T_a} \right) \cos (2wt + \delta + \alpha_0).
\]

The current in rotor winding is

\[
i_f = i_{f[0]} + \left[ \frac{x_{ad}x_{qD}V_{[0]} \cos \delta_0}{x_{ad}x_{qD} - x_{d}^2} - \frac{(x_{qD} - x_{d}^2)V_{[0]} \cos \delta_0}{x_{ad}x_{d}^2} \right] \exp \left( \frac{t}{T_d} \right)
+ \frac{(x_{qD} - x_{d}^2)V_{[0]} \cos \delta_0}{x_{ad}x_{d}^2} \exp \left( \frac{t}{T_a} \right) \cos (wt + \alpha_0).
\]

In the above equation, \(x_f\) is the armature reaction reactance between longitudinal axis windings, \(x_{ad}\) and \(x_{aq}\) are the reactances of d-axis and q-axis of the rotor, \(x_{D}\) and \(x_{Q}\) represent the reactances of D and Q damping windings, \(x_{ad}\) is the leakage reactance of D damping winding, and \(E_{q[0]}\) and \(V_{[0]}\) are the instantaneous no-load potential and terminal voltage before short circuit.

(2) Based on the above analysis, taking three-phase symmetrical short-circuit and single-phase grounding fault of power grid as examples, the transient characteristics of EESG are simulated and analyzed. As shown in Figures 2 and 3, the simulation waveforms are A-phase current of stator, d-axis component of stator current, q-axis component...
of stator current, active power output of generator, and rotor speed in sequence. Under the normal operation of FESRWT, the active power delivered by generator to power grid is equal to the mechanical power input by wind turbine, and the current in stator winding is a symmetrical, positive-sequence three-phase current. When a three-phase symmetrical short-circuit fault occurs in grid, it can be seen from Figure 2 that the mechanical power input by wind turbine remains unchanged, while the power delivered by generator to grid decreases; at this time, large excess power is generated, the rotor speed

| t (s) | Ia (p.u.) | Id (p.u.) | Iq (p.u.) | Pe (p.u.) | Speed (p.u.) |
|------|-----------|-----------|-----------|-----------|--------------|
| 0.98 | -5        | 0         | -5        | 0         | 0.2          |
| 1    | 0         | -5        | 0         | -5        | 0.4          |
| 1.02 | -5        | 0         | -5        | 0         | 0.6          |
| 1.2  | -5        | 0         | -5        | 0         | 0.8          |
| 1.4  | -5        | 0         | -5        | 0         | 1            |
| 1.6  | -5        | 0         | -5        | 0         | 1.2          |
| 1.8  | -5        | 0         | -5        | 0         | 1.4          |
| 2    | -5        | 0         | -5        | 0         | 1.6          |

Figure 2: Transient simulation results of EESG in case of three-phase short-circuit fault.

Figure 3: Transient simulation results of EESG in case of single-phase grounding fault.
increases, and there is a large short-circuit current in generator stator winding. When a single-phase grounding fault occurs in power grid, it can be seen from Figure 3 that the stator current contains a large number of harmonic components, and the transient oscillation of EESG is large during the fault.

3. Synergetic Control Strategy

By taking advantage of the system’s own nonlinearity and the self-organization ability of open system far from the equilibrium state, the synergetic control can stably converge to the manifold and ensure the global asymptotic stability of high-dimensional nonlinear system through manifold. Therefore, in the case of power grid failure, according to the transient characteristics of EESG, the synergetic control strategy of excitation system is designed to make the generator work in the overexcitation state for forced excitation, so as to increase the excitation current, prevent the generator voltage from falling, and transmit a large amount of reactive power to the power grid to maintain the stability of system and realize the fault ride through control of FESRWT.

3.1. Synergetic Control Theory. Synergetic control is a state space method proposed by Russian scholars. The design of controller can be divided into three steps: defining macro variables, defining manifolds, and obtaining control laws [20, 21].

Suppose that there is an N-dimensional nonlinear system as follows:

$$\frac{dx}{dt} = f(x, d, t),$$

where $x$ is the state vector of system, $d$ is the control vector of system, and $t$ is time. Macro variables should be defined according to control objectives and dynamic performance indicators of system, and specific state variables should be contained, taking macro variable $\psi = \psi(x)$. In general, a linear combination of state variables can be simply selected. For systems with multiple control outputs, the same number of macro variables needs to be defined. The system manifold is constructed as $\psi(x) = 0$. According to the macro variable, the control law of system is solved by the manifold, so that the system converges from any initial state in finite time and remains on the manifold and approaches the equilibrium point of controlled system along the manifold.

The following equation is generally used to solve the control law:

$$T\frac{d\psi}{dt} + \psi = 0,$$

where $T$ is a time constant, and $T > 0$. $T$ determines the time when the macro variable converges to $\psi(x) = 0$. On the premise of system stability, the smaller $T$ is, the faster the dynamic response of system is. The control variable $d$ can be obtained from equation (11). Through $d$, the system converges from initial state to manifold $\psi(x) = 0$ to ensure that the system operates at the equilibrium point. Because the nonlinear model of system is used in the process of solving the control law, the obtained control law can not only maintain stability at each operating point but also make the system have better dynamic characteristics.

3.2. Synergetic Control Strategy of FESRWT. The control objective of synergetic excitation controller is to obtain appropriate control law $E_f$, so that, after the grid voltage sags, the generator terminal voltage and rotor speed can be maintained at set values, and the power oscillation of system can be suppressed. Combined with the mathematical model of EESG, the macro variable can be selected as linear combination of generator terminal voltage and rotor angular speed deviation, as shown in the following formula:

$$\psi = (U_{\text{ref}} - U_s) + k_1(\omega_{\text{ref}} - \omega),$$

where $U_{\text{ref}}$ and $\omega_{\text{ref}}$ are reference values of generator terminal voltage and rotor angular velocity, respectively, and $k_1$ is the coefficient, which defines the proportional relationship between generator terminal voltage deviation and rotor angular velocity deviation. The goal of synergetic control is to make the system converge to manifold $\psi(x) = 0$ after grid voltage sags and finally reach the equilibrium point along the manifold. By substituting formula (2), formula (5), formula (6), and formula (12) into formula (11), the control law of the synergetic excitation controller can be obtained:

$$E_f = \frac{X_d - X_d''}{X_d' - X_d''} E_q - \frac{X_d' - X_d''}{X_d' - X_d''} P'' + \psi T_d U_s - \frac{k_1 T_d U_s \omega}{U_q} + T_d P'' U_s - \frac{X_d - X_d''}{X_d' - X_d''} E_q - \frac{X_d' - X_d''}{X_d' - X_d''} P'' + \frac{((U_{\text{ref}} - U_s) + k_1(\omega_{\text{ref}} - \omega))T_d U_s}{U_q} - \frac{k_1 T_d U_s}{2 H U q} (P_m - P_e - D(\omega - 1)) - \frac{T_d U_s \omega}{U_q} + I_d X_d T_d'$$

4. Stability Analysis of Synergetic Controller

Although the structure of synergetic control algorithm can be determined by formula (13), appropriate control parameters should be selected to make the unit meet requirements of system in normal and fault conditions of power grid. Selecting reasonable control parameters to keep the disturbed system stable is a high-dimensional and strong nonlinear problem, it is very difficult to select control parameters by experience, and the system cannot be guaranteed to have good dynamic response characteristics [22, 23].
For FESRWT, it is necessary to not only ensure good operation under normal grid voltage but also have a certain fault ride through capability. Therefore, the normal operating state of FESRWT needs to be located in the gradually stable attraction domain of fault ride through state.

In the analysis of dynamic system problems, the fault ride through stability analysis of FESRWT belongs to large-scale stability analysis. The Lyapunov direct method can be used to determine the stability of FESRWT and solve the range of parameters that satisfy fault ride through stability. Selecting the appropriate Lyapunov function is the key to judge the stability of system and solve the range of control parameters [24].

According to formulas (1)–(6), formula (13) takes the state variable \( x = [U_s, E'_q, E''_d, E'_d, \omega, \delta]^T \). Then, the mathematical model of FESRWT can be expressed by the following formula:

\[
\dot{x} = Ax + BI + U, \tag{14}
\]

where

\[
A = \begin{bmatrix}
\frac{-1}{T} & 0 & 0 & 0 & \frac{k_1 D - k_1}{2H} & 0 \\
0 & \frac{X_d - X_d''}{T_{d0}} & \frac{X'_d - X_d}{T_{d0}} & 0 & 0 & 0 \\
0 & \frac{1}{T_{d0}} & -\frac{1}{T_{d0}} & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{T_{d0}} & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{D}{2H} & 0 \\
0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix},
\]

\[
B = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
\frac{(X'_q - X'_d)}{T_{q0}} & 0 \\
\frac{(X_q - X''_d)}{T_{q0}} & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix},
\]

\[
U = \begin{bmatrix}
U_{\text{ref}} + k_1 \omega_{\text{ref}} \\
\frac{k_1 (P_m - P_e + D)}{2H} E'_f \\
0 \\
0
\end{bmatrix}^T.
\]

Let the Lyapunov function be

\[
\nu(x) = x^T P x, \tag{16}
\]

\[
\nu(x) = x^T (-Q)x.
\]

Taking \( Q = I \), the \( P \) matrix is determined by formula (16).

\[
A^T P + PA = -I. \tag{17}
\]
According to the relevant theorem of Lyapunov’s second method, when FESRWT satisfies \( \nu(x,t) > 0 \) and \( \nu(x,t) < 0 \), it can be judged that FESRWT is asymptotically stable in the neighborhood of this operating point.

Due to the large number of state variables in FESRWT, it is difficult to solve the range of control parameters by analytical method to make it meet the conditions of large-scale asymptotic stability. Therefore, the Monte Carlo method is used to obtain the range of control parameters. Monte Carlo method is also called computer stochastic simulation method. The principle is to understand a system through a large number of random samples and then obtain the value to be calculated.

Let \( H \) be a matrix composed of control parameters; that is, \( H = \{h_1, h_2, \ldots, h_n\} \), and divide each element in \( H \) into intervals; that is, \( h_i \in (a_i, b_i) \), \( i = 1, 2, \ldots, n \), and \( a_i < b_i \). Monte Carlo points are taken in \( n \)-dimensional state space region formed by \( h_i \), and different \( H \) is got. The value range of the control parameters satisfying control requirements can be solved by screening the points through numerical calculation.

Taking \( H = [T, k_1] \), according to the method of constructing Lyapunov function above, the state equation of FESRWT is substituted into formula (16) to obtain matrix \( P \). The positive characterization of \( P \) is tested by Sylvester’s criterion. The stable control parameter range of system is to satisfy the parameter range where \( A \) is a positive definite matrix. The solution can be obtained: \( T \in (0.005, 1) \) and \( k_1 \in (-120, -20) \). It should be noted that the range of parameters obtained is relatively conservative.

### 5. Simulation Verification

In order to verify the effectiveness of proposed synergetic control strategy, a 2 MW FESRWT simulation model was built by Matlab/Simulink software. The simulation experiment of fault ride through control is carried out in the cases of three-phase symmetrical short circuit and single-phase grounding short circuit. The basic parameters of FESRWT are shown in Table 1. Due to the short simulation time, it can be assumed that wind speed is constant during the fault period, and the wind speed is taken as 12.5 m/s.

#### 5.1. Analysis of Fault Ride through Characteristics When Three-Phase Symmetrical Short-Circuit Fault Occurs

The wind farm adopts the unit wiring method of “wind turbine-box-type substation.” 35 kV overhead lines are used to connect the box-type substations in each group. 35 kV cable is used to connect the high-voltage side of the box-type transformer to the 35 kV overhead line. There are 2 overhead lines to 110 kV boost substation in wind farm. Suppose that, at \( t = 0.3 \) s, a three-phase symmetrical short-circuit fault occurs on the high voltage side of transformer on one circuit of the transmission line, and the voltage sags to 20% of the rated voltage, lasting 625 ms; when \( t = 0.925 \) s, the fault is removed and the double circuit is resumed. Simulation waveform using synergetic control strategy is shown in Figure 4.

#### 5.2. Analysis of Fault Ride through Characteristics under Single-Phase Grounding Fault

Suppose that, at \( t = 0.3 \) s, a single-phase grounding fault occurs on a loop of the transmission line on the high voltage side of the transformer, the voltage sags to 40% of rated voltage, and the fault is removed at \( t = 0.925 \) s. The simulation waveform of synergetic control strategy is shown in Figure 5. It can be seen from Figures 5(a)–5(f) that the synergetic control strategy adopted in this paper can make wind turbines meet the requirements of grid connection. Reference [7] used a robust control strategy to carry out the simulation under the above conditions. Compared with robust control strategy, although the short-circuit current in three-phase winding of

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**Table 1: Simulation parameters table.**

| Parameter | Value |
|-----------|-------|
| \( S \) (MW) | 2 |
| \( U_{\text{dem}} \) (V) | 690 |
| \( n \) (rpm) | 1500 |
| \( r_a \) (pu) | 0.0074 |
| \( X_f \) (pu) | 1.97 |
| \( X_f' \) (pu) | 0.15 |
| \( X_f'' \) (pu) | 0.125 |
| \( X_f''' \) (pu) | 0.823 |
| \( X_f^* \) (pu) | 0.186 |
| \( T_d^* \) (s) | 2.757 |
| \( T_q' \) (s) | 0.013 |
| \( T_q'' \) (s) | 0.212 |
| \( H \) (Pu) | 0.14 |
| \( D \) (Pu) | 0.02056 |

The technical regulations of wind farm access to the power system require that when the voltage at the grid connection point sags to 20% of nominal voltage, the wind turbine in the wind farm shall ensure the continuous operation of 625 ms without off-grid. When the voltage of wind farm connection point can be restored to 90% of nominal voltage within 2 s after falling, the wind turbines in wind farm are guaranteed not to be off-grid and run continuously. It can be seen from Figures 4(a)–(f) that the synergetic control strategy can restore FESRWT to normal operation state more quickly and provide reactive power support to power grid in time after the three-phase symmetrical short-circuit fault is cleared.
Figure 4: Fault ride through characteristics of FESRWT under three-phase symmetrical short-circuit fault. (a) Voltage at grid connection. (b) $d$-axis component of stator current. (c) $q$-axis component of stator current. (d) Output active power. (e) Output reactive power. (f) Mechanical rotor speed.
Figure 5: Continued.
stator increases, the oscillation amplitude and transition time of active power generated by the generator and rotor speed are shortened. The generated reactive power is greatly increased. It is realized that wind turbines can operate without off-grid when a single-phase grounding short-circuit fault occurs.

6. Conclusion
Combined with the characteristics of FESRWT, this paper analyzes the transient characteristics of $d$-axis and $q$-axis components of stator current, active power, reactive power, and rotor speed of EESG in case of power grid fault, and a fault ride through method for the synergetic control of excitation system is proposed. The simulation verification is carried out in the case of three-phase symmetrical short circuit and single-phase grounding short circuit, respectively. The simulation results show that the synergetic control strategy proposed in this paper can greatly increase the fault ride through capability of FESRWT, and the control effect is better than that of the robust control method used in the existing reference.

This paper mainly studies the fault ride through control of FESRWT and has achieved certain results, but there are still some problems that have not been deeply understood and studied, which need to be considered and improved: (1) more detailed analysis and more accurate modeling of the excitation system of synchronous generator and (2) further optimization of synergetic control parameters.

Data Availability
The project research is in progress. The data used in the paper involves the key technologies of the project. In order to maintain competitiveness, the data used will not be disclosed temporarily.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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