Research on fault adaptive fault tolerant control of distributed wind solar hybrid generator

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ABSTRACT

Due to the poor accessibility, poor operating conditions, high failure rate, long maintenance time, and difficult maintenance of wind hybrid generators, the economic loss is huge once the failure stops. To this end, the fault adaptive fault-tolerant control of distributed wind and wind hybrid generators is studied, the historical operation data of offshore wind and wind hybrid generators and onshore wind and wind hybrid generators are counted and compared, and the fault characteristics of key components of offshore wind and wind hybrid generators are analyzed. The generator sets are summarized, and the common electrical faults of wind turbines and their impacts on the system are analyzed. This paper summarizes the current research status of fault-tolerant operation of existing offshore wind and wind complementary generators in terms of software fault tolerance and hardware fault tolerance, summarizes the current fault tolerance schemes for offshore wind and wind complementary generators, and analyzes the application feasibility of existing fault tolerance schemes. In addition, the main problems of fault-tolerant offshore wind and solar complementary generator sets are pointed out, and future research hotspots are foreseen.

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1. INTRODUCTION

Among the renewable energy utilization technologies, wind power generation technology is a promising and mature technology [1]. After years of rapid development, the global wind power industry has entered a stage of steady growth, and the scale of wind solar hybrid generators is expanding [2]. With the expansion of wind power grid and the development of wind solar hybrid generators in China, the reliability of wind power generation technology has higher requirements. Therefore, aiming at the most widely used doubly fed wind solar hybrid generator set, this paper studies the fault diagnosis of stator and rotor current detection system, fault diagnosis of speed detection system and fault-tolerant control of system after fault from the aspects of improving its safety and reliability [3]-[5]. The design of wind solar hybrid generator control system is usually carried out in continuous time domain, but in practical application, it is implemented in discrete time domain. In this paper, a reduced order observer of stator and rotor current for wind solar hybrid generator set is established, and a fault diagnosis scheme of current detection system based on current prediction is proposed. Through pole assignment, the current reduced order observer can track the actual current quickly and stably, realize the redundancy of current signal, and use the observed value to reconstruct the system after fault [6]. The fault diagnosis scheme based on current prediction can quickly diagnose the fault signal. Theoretically, it only needs at least one control cycle, and the fault diagnosis scheme is not affected by power fluctuation and grid fault. The research results show that through fault self diagnosis and fault-tolerant control, the power converter can keep grid connected and controllable operation in the case of partial detection signal fault, which can effectively improve the reliability of the system [7]-[9].

2. METHOD

2.1. Fault area characteristics of distributed wind solar hybrid generator

In variable speed constant frequency AC excited doubly fed wind power generation system, the generator adopts doubly fed induction machine, and its structure is basically the same as that of wound induction machine [10]. Variable speed constant frequency doubly fed wind power system is generally composed of wind turbine, gearbox, doubly fed wind turbine, and bidirectional power converter. The wind solar hybrid generator sets are excited by a back-to-back two-level voltage source PWM converter connected by DC link grid side converter and generator side converter, to realize variable speed constant frequency operation and maximum wind energy tracking control [11], [12]. Therefore, the research of wind solar hybrid generator control strategy mainly focuses on the control of AC excitation converter, as shown in Figure 1.

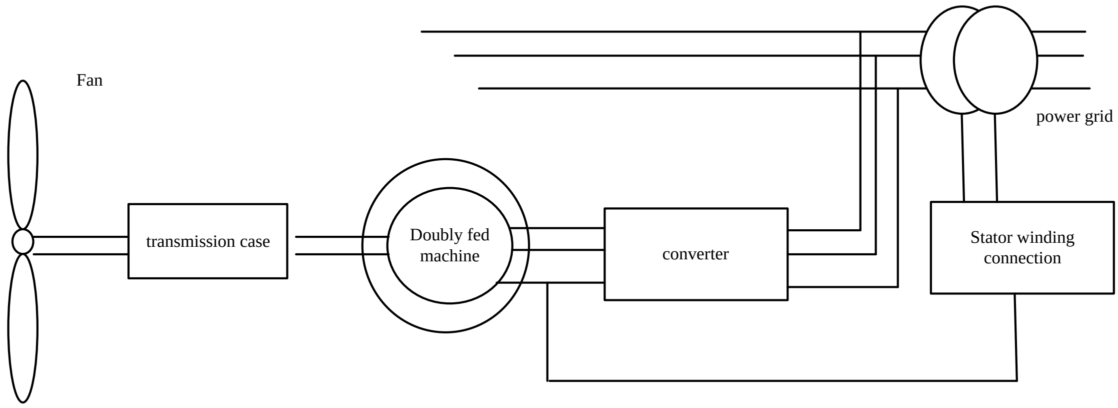

Figure 1. Schematic diagram of VSCF doubly fed wind power system

The wind-solar complementary generator and the wire-wound induction motor are identical in structure, and their mathematical models are the same [13]. The mathematical model based on the T-shaped equivalent circuit is the most widely used. In this paper, the mathematical model of the wind-solar complementary generator is derived based on the T-shaped equivalent circuit, as shown in Figure 2.

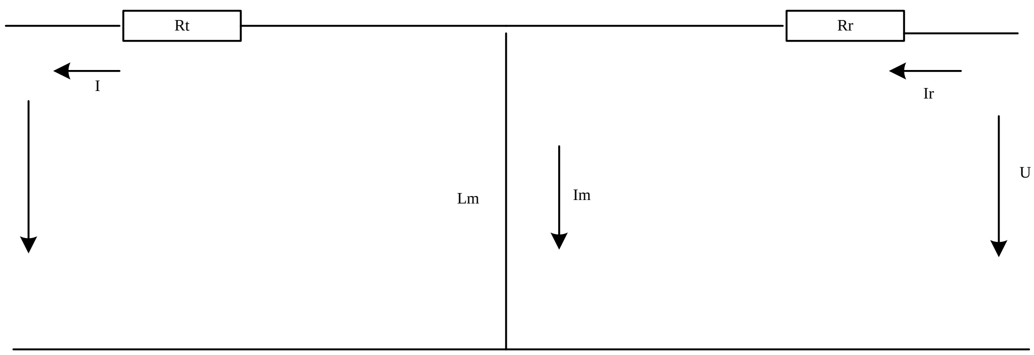

Figure 2. T-type equivalent circuit of doubly fed machine

In order to analyze more easily the mathematical model of the complementary scenery generator, the following assumptions were made in the derivation process: the three-phase stator and rotor windings of the motor are spatially symmetrically distributed, and the magnetic dynamic potential generated by the currents of each phase is sinusoidally distributed in the air gap, without considering the effects of magnetic circuit saturation and core losses [14]-[18]. In addition, it is necessary to state the direction of the stator and rotor currents. The direction of the stator current outflow is positive (power generation state); when the rotor current flows positively (electrical state), the mathematical model of the scenic complementary generator set in the three-phase stationary ABC coordinate system can be written as:

$$\begin{cases} u_A = -R_s i_A + \frac{d\psi_A}{dt} \\ u_B = -R_s i_B + \frac{d\psi_B}{dt} \\ u_c = -R_s i_c + \frac{d\psi_c}{dt} \end{cases} \tag{1}$$

$$\begin{cases} u_a = R_r i_a + \frac{d\psi_a}{dt} \\ u_b = R_r i_b + \frac{d\psi_b}{dt} \\ u_c = R_r i_c + \frac{d\psi_c}{dt} \end{cases} \tag{2}$$

$$\begin{cases} \psi_s = L_{\mathrm{ss}} i_s + L_{\mathrm{sr}} i_r \\ \psi_r = L_{\mathrm{sr}} i_s + L_{\mathrm{lr}} l_r \end{cases} \tag{3}$$

The expression of the equation of motion is:

$$T_L - T_{\mathrm{em}} = J\frac{d^2\theta_m}{d^2t} + R_n\frac{d\theta_m}{dt} \tag{4}$$

For the scenic complementary generator set, the scenic complementary generator set can be considered as a linear system near the operating point, provided that the temperature variation, excitation saturation and skin effect are neglected because the change of motor speed is relatively slow compared to the change of current and can be considered as a constant at a certain operating point. Under the above conditions, a fourth-order state-space equation can be used to describe the relationship between the variables of the wind and complementary solar generators. Different variables can be selected as state variables in doubly-fed wind power systems according to different control schemes [19]. According to the grid voltage directed vector control technique, the state space equation of the wind and complementary solar generators can be derived as (5).

$$i = Ai + Bu/T_L - T_{\mathrm{em}} \tag{5}$$

The choice of discretization methods will be based on different accuracy requirements. In general, it is easy to choose computationally convenient methods and meet the accuracy requirements, such as the forward difference method, the backward difference method, and the bilinear transformation method [20]. The bilinear transformation method is second-order accuracy. However, it is computationally intensive and can only be used for discretization processes with high accuracy [21]. This paper uses the commonly used forward difference method to discretize the state equations of the scenic complementary generator set. The system's sampling period and control period are set to *ts*, the departure walk length is *t*, and the transformation equation of the forward difference method is *t*.

$$\dot{x} = \frac{x(k+1)-x(k)}{T_s} \tag{6}$$

The forward difference of the continuous time equation of state is obtained.

$$\frac{i(k+1)-i(k)}{T_s} = Ai(k) + Bu(k) \tag{7}$$

$$i(k+1) = A_d i(k) + B_d u(k) \tag{8}$$

It can be seen from the above formula that the discrete-time state equation obtained by the forward difference method is consistent with the continuous-time state equation.

2.2. Fault tolerant monitoring of generator set

Assuming that the system's state vector is n-dimensional if the m-dimensional vector is measurable, it can be assumed that no estimation is needed, and only the n-m dimensional vector needs to be observed. The stator current reduced-order state observer is designed using the stator-rotor voltage vector and rotor current vector so that the stator current observation is independent of the measured value and the actual stator current can be accurately observed even after a fault in the stator current signal detection system [22]. It is used for fault-tolerant control after a fault [23]. The design of the current observer is based on the discrete state equation of the wind and solar complementary power system, so the designed observer can be more easily programmed in the digital controller [24]. The state variables in the discrete state equation of the wind and complementary solar generator are divided into two parts.

$$i(k) = \begin{bmatrix} i_s(k) \\ i_r(k) \end{bmatrix} = \begin{bmatrix} i_{sd}(k) \\ i_{sq}(k) \\ \frac{i_{rd}(k)}{iq}(k) \end{bmatrix} \tag{9}$$

In order to make the measurement signals of the rotor current observer and the rotor current sensor independent of each other and to ensure that the accuracy of the observer is not affected after a failure of the rotor current sensor, a rotor current observer based on a reduced order observer is constructed by assuming that the rotor current is not measurable [25], [26]. In this case, the unmeasurable part of the state variable becomes $i_r(k)$ and the directly measurable part is $i_s(k)$. Only the output equation changes, and the rewritten system state equation is as (10) and (11):

$$\begin{bmatrix} i_s(k+1) \\ i_r(k+1) \end{bmatrix} = \begin{bmatrix} A_{d11} & A_{d12} \\ A_{d21} & A_{d22} \end{bmatrix} \begin{bmatrix} i_s(k) \\ i_r(k) \end{bmatrix} + \begin{bmatrix} B_{ds} \\ B_{dr} \end{bmatrix} u(k) \tag{10}$$

$$y_s(k) = \begin{bmatrix} C_s & 0 \end{bmatrix} \begin{bmatrix} i_s(k) \\ i_r(k) \end{bmatrix} \tag{11}$$

Method of selecting the feedback gain matrix Kr and k for the rotor current observer. The pole configuration method allows the rotor current observer to have a better dynamic response, and the specific configuration method is not described here [27]. The structure of the stator current observer based on the reduced-order observer is the same as that of the rotor current observer, and the coefficient matrix is symmetric and easy to program, as shown in Figure 3.

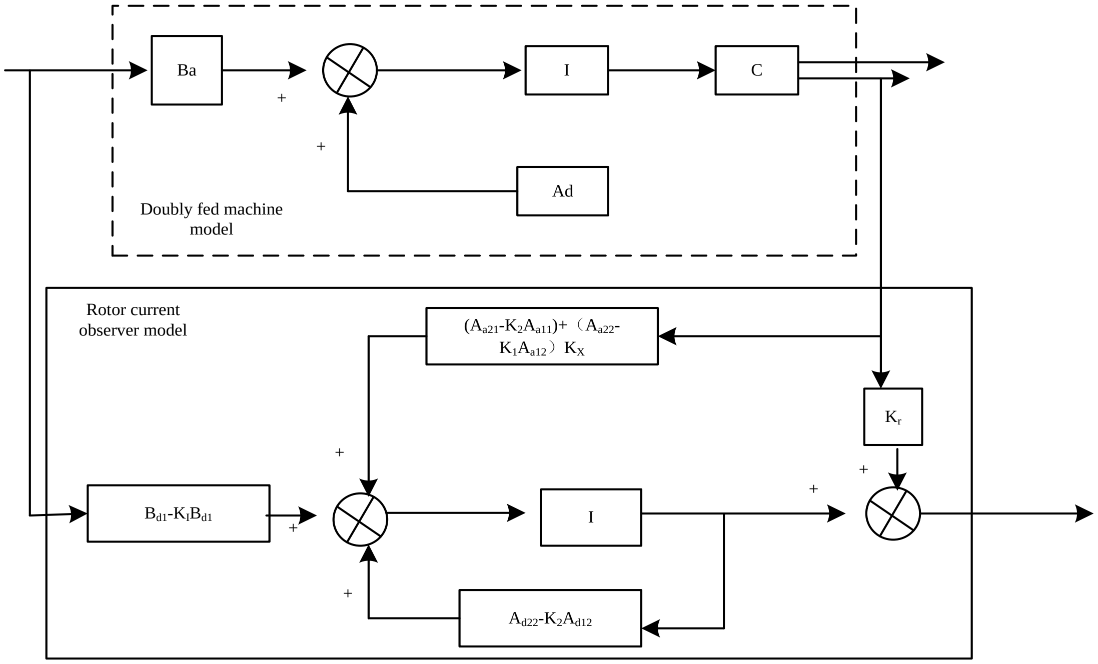

Figure 3. Schematic diagram of rotor current observer

The double-fed converter current detection system mainly includes the processes of the current sensor, signal conditioning, and digital signal processor AD sampling. Any signal processing failure will cause the failure of the signal detection system and affect the control system. Current sensor failure is inevitable if the wind and solar complementary generator set works for a long time or operates in a harsh environment [28]. The current sensor faults can be classified as amplitude variation, DC offset, and output saturation. Under fault-free conditions, the three-phase instantaneous current can be expressed as (12):

$$\begin{cases} i_a = I\,sin(\,\omega t) \\ i_b = I\,sin\left(\omega t - \frac{2}{3}\pi\right) \\ i_c = I\,sin\left(\omega t + \frac{2}{3}\pi\right) \end{cases} \tag{12}$$

If the current sensor has the fault of amplitude change, the current measurement value will change to:

$$l_a^m = (1-\varepsilon) I\,sin(\,\omega t) \tag{13}$$

The measurement error is:

$$i_{\text{eror}} = i_a - i_a^{m\,sin(\omega t)} \tag{14}$$

The fault type of current sensor and the expression of current after fault can be expressed in Table 1. Faults in other links in the current detection system can be classified as signal transmission faults, circuit board faults, signal processing chip faults, and AD sampling faults. This link is more complex and has different types of faults. Therefore, for the convenience of expression, the current sensor is used to indicate the current of the signal detection system, and the current sensor fault is used to indicate the fault of the signal detection system [29], [30]. Then, the processed data is used to determine the sensor's status and the type of fault [31]. If a position sensor fault is determined, the sensor signal is cut off, a fault-tolerant signal is used, and the fault-tolerant control unit is notified for dynamic reconfiguration; the block diagram of the fault monitoring unit is shown in Figure 4.

Table 1. Fault type and mathematical model

Fault type	Current expression
DC offset	$Isin(wt)+I_{\alpha ffset}$
Excessive noise	$Isin(wt)+I_{noise}(t)$
Amplitude variation	(1-ε) I sin(wt)
Output saturation	I_{sat}
Sensor disconnected	0

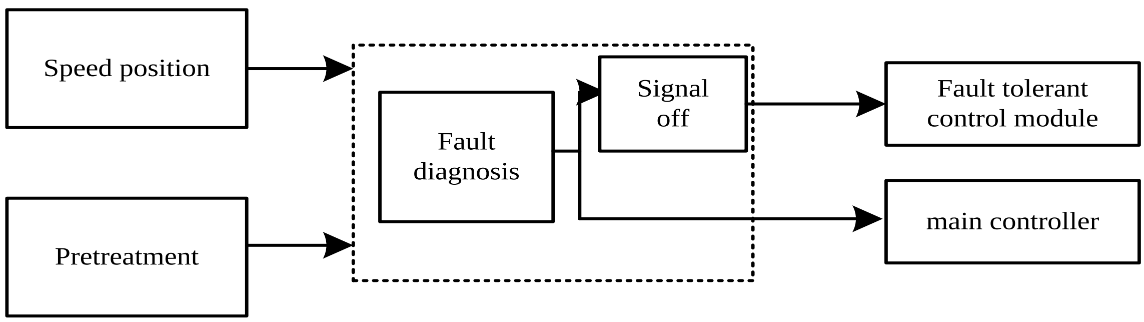

Figure 4. Structure block diagram of fault monitoring unit

In order to accurately determine the status of the position sensor, three sets of data residual comparisons were used to vote on the status of the position sensor. In addition to the position sensor data, the other two sets are the speed estimates obtained from the stator voltage and current estimation and the processed historical data [32]. Also, in order to improve the credibility of the historical data, two types of data are selected in this paper, one is the velocity values of the historical data obtained from the RBF neural network, and the other is the velocity values of the first six data obtained from the Lagrangian interpolation polynomial. The two kinds of data are weighted to obtain the second reference signal.

2.3. Realization of adaptive fault tolerant control for generating set

The function of the fault-tolerant control unit is to reconfigure the closed-loop control of permanent magnet synchronous motor (PMSM) during fault and recovery. After receiving the reconfiguration command, the fault-tolerant control unit first calculates the initial values of generator speed and position at the fault point. It then calculates the fault-tolerant output values of speed and position during the reconfiguration process to realize the continuity and consistency of the reconfiguration process and finally completes the dynamic and disturbance-free reconfiguration of the control strategy [33].

The generator torque segment control is designed based on the generator torque speed control curve without wind speed information. *A1Bcde* torque speed tracking control curve is usually used to design the generator torque controller [34]. Segment *A1B* is the first stage, which is the start-up stage. *e* point is followed by the third stage, where the generator torque is fixed at the rated speed, and the pitch control starts. Therefore, the segment controller for generators is usually designed as (15):

$$T_{em} = \begin{cases} 0 \\ k_{opt}\omega_g^2 \\ T_1 + \frac{T_{\text{rated}} - T_1}{\omega_{\text{rated}} - \omega_1}\left(\omega_g - \omega_1\right) \\ T_{\text{raled}} \end{cases} \tag{15}$$

Stress sensors are used to measure the root load on each blade, and the *d-q* transform is used to obtain two components on the orthogonal coordinate axes: the yaw component and pitch component. The *PI* controller is used to minimize the blade deformation on the *d-q* axis, and then the *d-q* inverse transform is used to obtain the pitch angle compensation value on each blade, which is superimposed with the constant pitch control command value to obtain the final pitch angle of each blade, as shown in Figure 5.

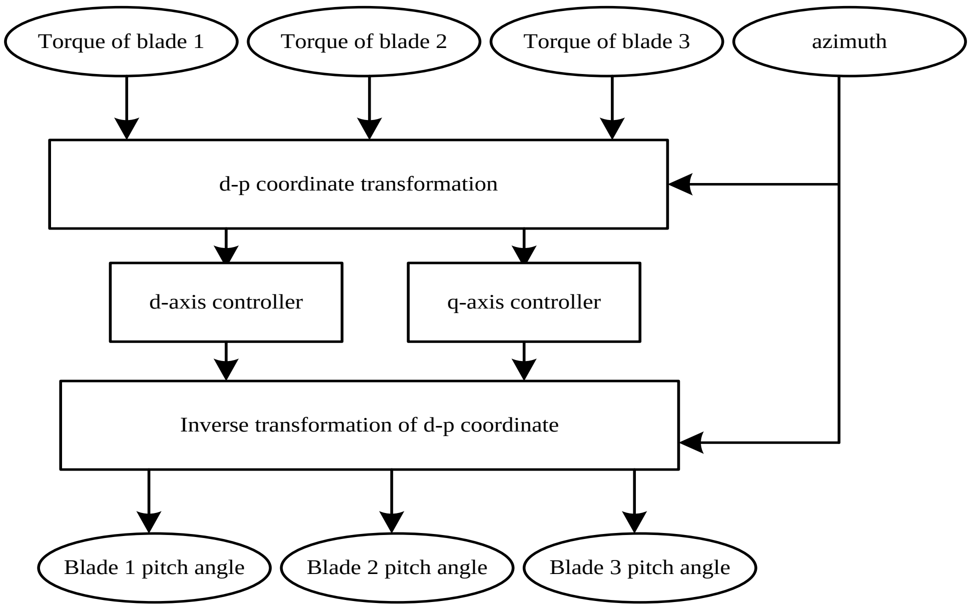

Figure 5. Structure block diagram of fault tolerant control unit

For the tracking control of a class of uncertain nonlinear systems, adaptive output feedback control is proposed, whose input-output transfer functions themselves do not necessarily satisfy strictly positive real conditions [35]. The controller not only achieves the consistent transient performance of the system input and output states but also does not depend on the system model information. Compared with traditional adaptive control, the L1 adaptive controller can achieve decoupling between adaptive law updating and robustness. It is easier to achieve a reasonable trade-off between system control performance and robustness by choosing the bandwidth of the low-pass filter in the controller [36]. Therefore, this particular control structure would be well suited for controller design of large-scale wind and solar complementary power systems with model parameter uncertainties and external disturbances. Consider a system like single input single output (SISO).

$$y(s) = A(s)(u(s) + d(s)) \tag{16}$$

The nonlinear mapping satisfies the following Lipschitz hypothesis.

$$|f(t, y_1) - f(t, y_2)| \leq L|y_1 - y_2|$$
$$|f(t, y)| \leq L|y| + L_0 \tag{17}$$

The major difference between the differential gearbox front-end speed regulation wind turbine and the traditional dynamics modelling is introducing the differential gearbox speed regulation mechanism in the drive chain [37]. Therefore, establishing the dynamic model of the new front-end variable speed wind turbine is the basis and prerequisite for the subsequent control system design and performance analysis, and the laboratory team members have made some attempts in the early stage. The core components of the unit mainly consist of a wind blade, impeller, fixed speed ratio gearbox, differential gearbox, speed regulation motor and synchronous generator. According to the principle of the equivalent moment of inertia, the moments of inertia of the wind turbine, fixed ratio gearbox, drive shaft, planetary frame and planetary gear are converted to the input of the low-speed shaft of the differential (i.e., the speed of the low-speed shaft is taken as the reference), and the total equivalent moment of inertia is shown in (18).

$$J_L = \frac{1}{\mu_r^2}(J_r + J_8) + J_7 + J_4 + m_2(R_1 + R_2)^2 \tag{18}$$

In the same way, the equivalent moment of inertia of the high speed shaft and the speed regulating shaft of the differential gearbox can also be obtained.

$$\begin{cases} J_H = J_3 + J_g \\ J_A = J_1 + J_5 + \mu_m^2(J_6 + J_m) \end{cases} \tag{19}$$

Before linearizing the unit model, it is necessary to know which operating points linearize the unit to ensure the model's accuracy. The unit's steady-state operating point consists of the displacement, velocity, acceleration, control input and current wind speed when the unit reaches a steady state. The core idea is to make the final state of the unit converge to a predefined accuracy range and reach the steady state by adjusting the orientation position of the unit and the external control input at a certain wind speed. The unit's state, control input and current wind speed are taken as the current steady-state operating point [38]. For the design of the controller, it is necessary first to calculate several steady-state operating points of the set in the wind turbine plane, then linearize the model at each operating point, and finally average these linearized models to obtain the final linearized model of the set. In the existing converter controllers for direct-drive wind and solar complementary generating units, the generator-side converter is configured with only one control strategy: a vector control strategy or a direct torque control strategy. In the case of position sensor failure, the direct-drive wind power generation system can ensure the safe operation of the wind and solar complementary generators with a slight reduction of the output power performance index.

The position sensor fault tolerance mechanism's design should focus on fault diagnosis and fault-tolerant control. The control system structure of generator-side converter with position sensor fault tolerance mechanism is shown in Figure 6, which consists of a sensor, actuator, fault monitoring unit and fault tolerant control unit. The fault monitoring unit is responsible for real-time monitoring of the position sensors in the generator-side converter control system to cut off the fault source; the fault-tolerant control unit further processes the analysis results of the fault detection unit on the fault characteristics and dynamically reconfigures the closed-loop control structure of the permanent magnet synchronous motor in real-time to ensure that the direct-drive wind-solar hybrid generator can generate stable power within the allowed performance deviation after the position sensor failure.

The main control strategy is an *LD=0* vector control strategy with position sensor mode, and another control strategy without position sensor mode is the backup. The core algorithm of the sensorless control strategy is also *LD=0* vector control, only the source of speed and position information is different. In the sensorless mode, the stator voltage and current signals are used to obtain speed and position estimates through the core algorithm's digital phase-locked loop (DPLL) technique. The *LD=0* vector control strategy with position sensor mode is used during normal operation of the wind turbine complementary generator set with relatively better control performance and a more stable unit; it reconfigures to the vector control strategy without position sensor mode after the fault diagnosis unit detects a fault in the position sensor and sends a reconfiguration signal. Although the operation performance is not as stable as the mode with a position sensor, it can ensure the fault-continuous operation of the scenery complementary generator set and minimize the number of fault emergency shutdowns and losses.

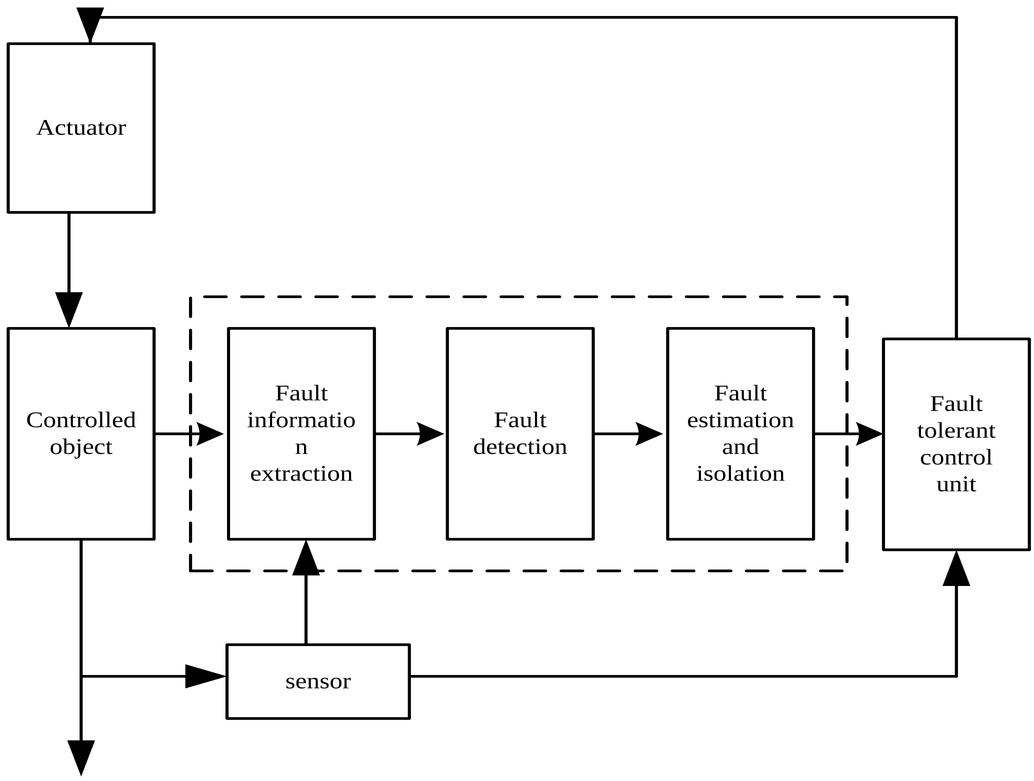

Figure 6. Block diagram of fault tolerant control system

3. RESULTS

In order to verify the accuracy of the control algorithm, the cart2 model of the U.S. Energy Laboratory is still used as the simulation object. A joint simulation using fast software and Simulink was also performed to compare the control algorithm with the classical control algorithm and the higher-order sliding mode control algorithm to prove the effectiveness of the algorithm. Turbulent winds with a mean wind speed of 8 MGS and a turbulence intensity of 18% were generated using turbine software of fast software. The sampling period is 50 ms, and the simulation time is 500 s. Here, the 6th-order memory prediction algorithm is used for wind speed prediction to obtain higher wind speed prediction accuracy. It can be seen that the 6th-order memory prediction algorithm requires more historical wind speed information than the 2nd-order prediction algorithm. However, in general, the algorithm structure is simple. The simulation results are shown in Figure 7. After statistical analysis, it is found that the average error of the predicted wind speed is 0.25 mg, which is a relatively high prediction accuracy. Therefore, it can be used to generate the desired wind speed.

In order to verify the ability of the proposed fault-tolerant control strategy to cope with the actuator failure, the simulation and comparative study related to the case of partial torque failure of the generator are carried out in this paper. Firstly, it is assumed that the generator is in good condition for the first 250 seconds, and the generator torque output fails after 250 seconds, as shown in Figure 8. Since the generator fails after 250 seconds, it can be seen that the wind turbine speed under the action of the classical control algorithm and the sliding mode control algorithm fluctuates more compared to the first 250 seconds, while the fault tolerant control algorithm is still able to track effectively. The mean squared deviation of rotor speed under the controller action is found to be 2.7363 rpm and 1.0996 rpm, respectively, which indicates that the fault-tolerant control algorithm continues to maintain good maximum power point tracking (MPPT) control performance in the case of generator failure.

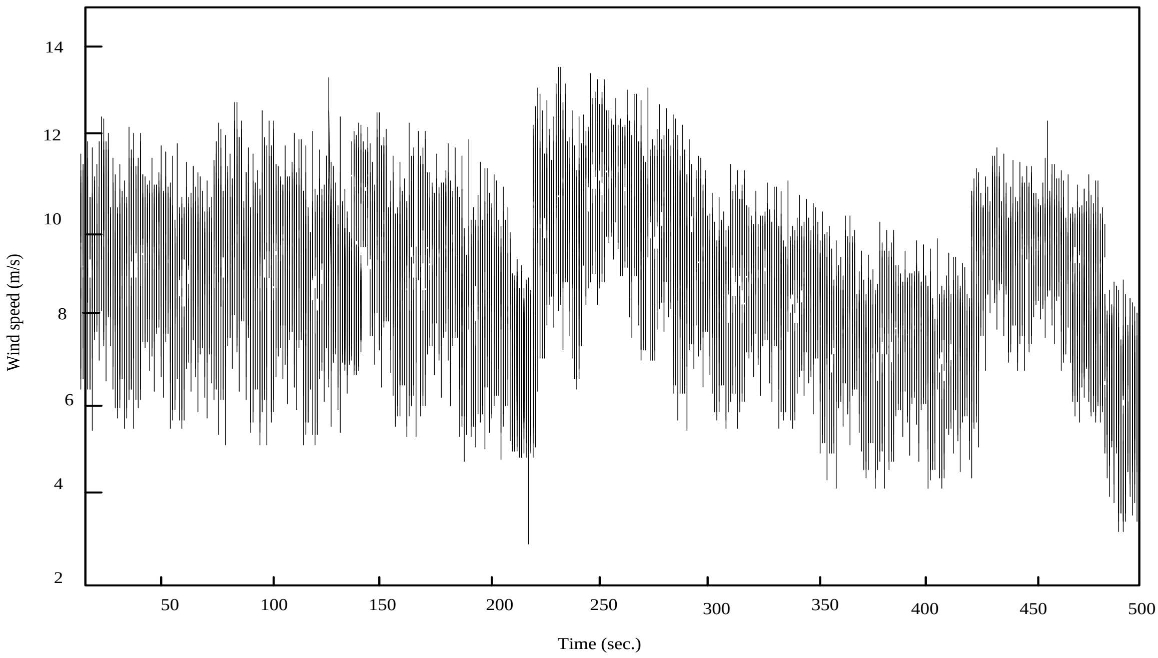

Figure 7. Comparison of predicted wind speed and real wind speed

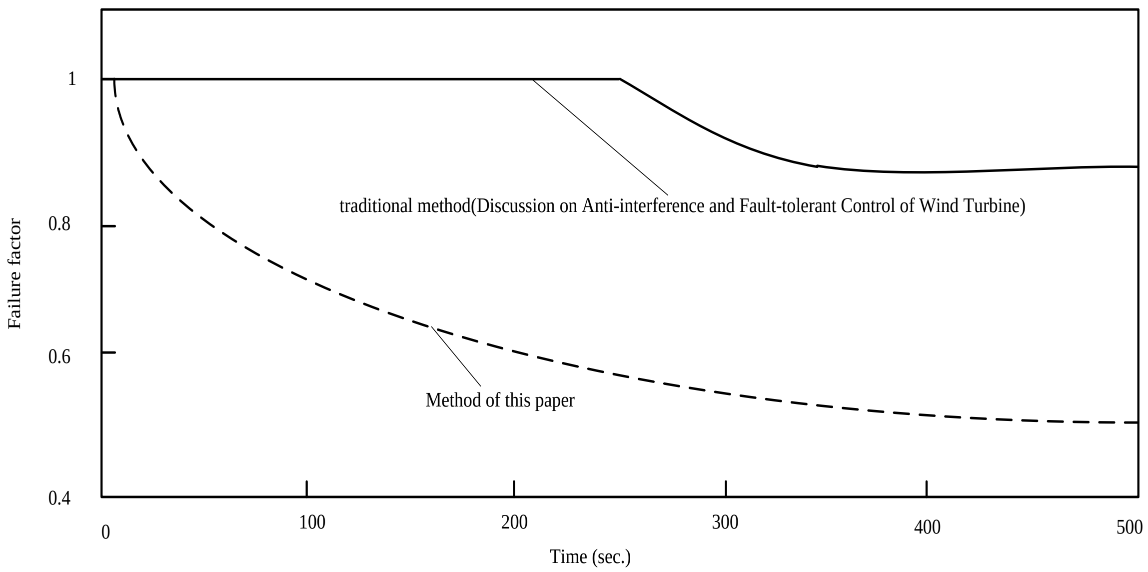

Figure 8. Schematic diagram of actuator failure factor

4. CONCLUSION

In order to improve the effect of fault adaptive fault-tolerant control of scenic complementary generators, a new adaptive fault-tolerant control method is proposed in this paper. According to the inherent characteristics of the wind-solar complementary generators and their operation, maintenance and servicing characteristics, the historical operation data of wind-solar complementary generators and land-based wind-solar complementary generators are obtained. The characteristics of key components of the generating sets are determined according to the data characteristics, the fault tolerance mechanism of the position sensors is designed, and the fault control strategy is set according to the designed fault tolerance mechanism of the position sensors to complete the fault adaptive, the fault-tolerant control is completed. The experimental results show that the method is effective and feasible for the fault adaptive control of distributed wind and solar hybrid generator sets.

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