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REVIEW ARTICLE

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Overview of condition monitoring and operation control of electric power conversion systems in direct-drive wind turbines under faults

Abstract Electric power conversion system (EPCS), which consists of a generator and power converter, is one of the most important subsystems in a direct-drive wind turbine (DD-WT). However, this component accounts for the most failures (approximately 60% of the total number) in the entire DD-WT system according to statistical data. To improve the reliability of EPCSs and reduce the operation and maintenance cost of DD-WTs, numerous researchers have studied condition monitoring (CM) and fault diagnostics (FD). Numerous CM and FD techniques, which have respective advantages and disadvantages, have emerged. This paper provides an overview of the CM, FD, and operation control of EPCSs in DD-WTs under faults. After introducing the functional principle and structure of EPCS, this survey discusses the common failures in wind generators and power converters; briefly reviewed CM and FD methods and operation control of these generators and power converters under faults; and discussed the grid voltage faults related to EPCSs in DD-WTs. These theories and their related technical concepts are systematically discussed. Finally, predicted development trends are presented. The paper provides a valuable reference for developing service quality evaluation methods and fault operation control systems to achieve high-performance and high-intelligence DD-WTs.

Keywords direct-drive wind turbine, electric power conversion system, condition monitoring, fault diagnosis, operation control under faults, fault tolerance

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1 Introduction

The development and utilization of renewable energy sources, such as wind energy, have received growing attention as the global energy crisis and environmental pollution worsen. Wind energy has become one of the most promising types of renewable energy that can be implemented on a large scale because of its relatively low cost and abundant global supply [1]. Furthermore, wind energy has been one of the fastest-growing renewable energy resources in the world in the last three decades according to statistical data. The new worldwide wind power capacity reached 432.42 GW by the end of 2015, with a recorded average growth of 21% in the past decades [2]. This growth momentum is expected to continue as an increasing number of countries set urgent targets for sustainability and reduction of pollutant emissions.

Geared doubly fed induction generators (DFIGs) systems have several drawbacks, such as short gearbox life span and frequent maintenance. Compared with conventional gearbox-coupled wind turbine generators, permanent-magnet synchronous generators (PMSGs) in direct-drive wind turbines (DD-WTs) allow for reduced overall size, low installation cost, and low maintenance cost. PMSGs require a simple and flexible control method. Furthermore, they can quickly respond to wind fluctuations and load variation. For large-capacity wind turbines, direct-drive permanent-magnet synchronous generators (DD-PMSGs) have become attractive because of their high efficiency, high power density, and robust rotor structure. The attractiveness of DD-PMSGs is further enhanced with the improvements in the characteristics of permanent magnets and the reduction in the cost of materials. In addition, water cooling systems are generally unnecessary for PMSGs [3]. Therefore, DD-WTs are expected to may be the future trend in the utilization of wind energy, particularly for offshore applications.

A DD-WT, which always operates in variable-speed constant-frequency mode, is connected to the power grid through full-power converters [4]. As shown in Fig. 1, a DD-WT is typically composed of blades, a hub, a generator, power converters, a pitch system, a tower, a yaw system, and an auxiliary hanger [5]. A low-speed PMSG is utilized in a DD-WT [6–7].

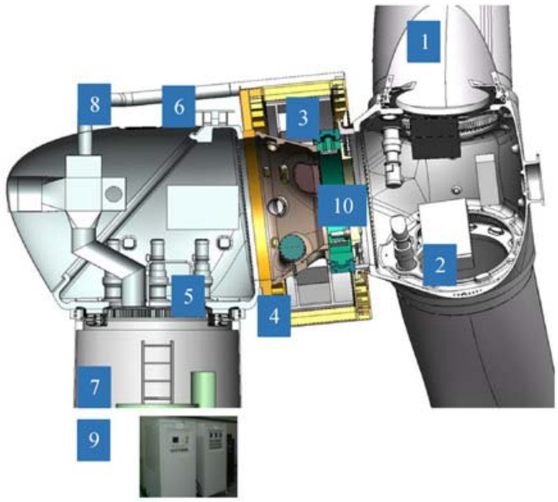

Fig. 1 Configuration of a typical DD-WT
1–Blades; 2–Pitch system; 3–Generator stator; 4–Generator rotor; 5–Yaw system; 6–Anemometer; 7–Tower; 8–Auxiliary hanger; 9–Power converters; 10–Bearing

Figure 2 shows the control system of a DD-WT. The control system consists of the WT main control system and power converter control system. The DD-WT is divided into two subsystems, namely, wind energy conversion system (WECS) and electric power conversion system (EPCS). The WECS, which converts wind energy into mechanical energy, is divided into four sections, namely, blades, hub, pitch system, and yaw system. The EPCS, which converts mechanical energy into electric power, comprises a PMSG and a power converter.

Figure 3 shows the structure of EPCS, which plays a key role in the DD-WT. The PMSG converts mechanical energy into variable-amplitude and variable-frequency electric power, which is then converted by the power converter into electric power with constant amplitude and frequency. The grid-side PWM converter converts the alternating current (AC) into direct current (DC), and the machine-side PWM inverter converts DC into AC with constant amplitude and frequency.

In a hostile operating environment, under harsh and highly variable weather conditions, the difficulty and cost of maintenance and operation of DD-WTs increase. Therefore, DD-WTs demand a high degree of maintenance to provide a safe, cost-efficient, and reliable power output with acceptable equipment life.

Most faults in a DD-WT occur in the generator and power converter, which account for 60% of all failures [8]. Thus, condition monitoring (CM), fault diagnostics (FD), and operation control under EPCS faults should be investigated to ensure reliable and safe operation of WTs (including grid and equipment) and to reduce the maintenance cost. Numerous techniques for CM, FD, and operation control under faults have been studied. Several of these techniques have shown considerable potential, whereas others present problems due to their inherent limitations. However, few published papers have provided comprehensive overviews of CM, FD, and operation control of EPCSs in DD-WTs under faults [9–10].

The objective of this paper is to provide a detailed overview of the methods and techniques for CM, FD, and

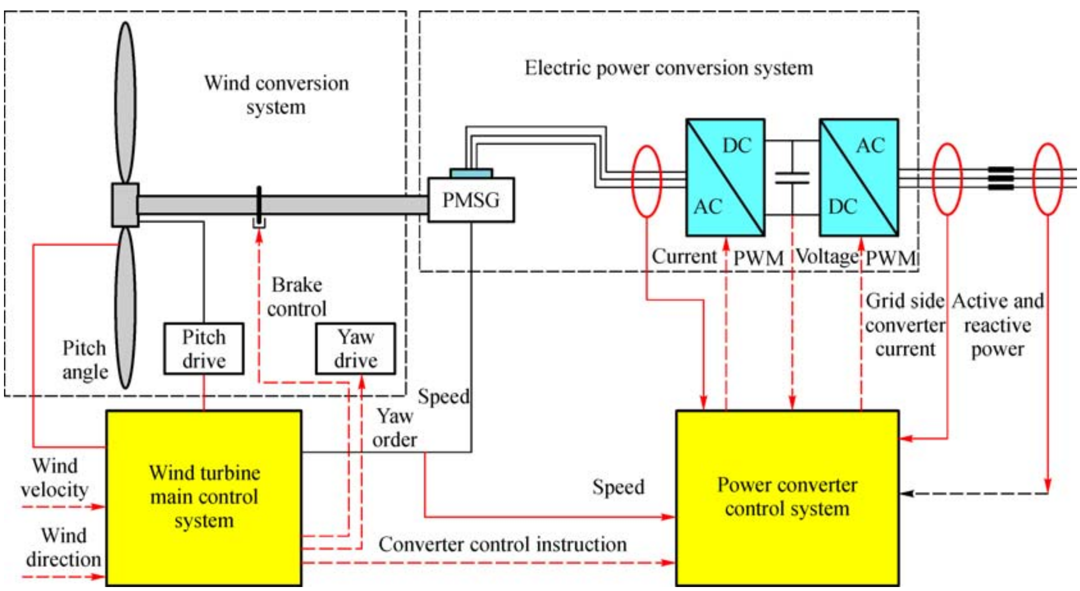

Fig. 2 Control system of a DD-WT

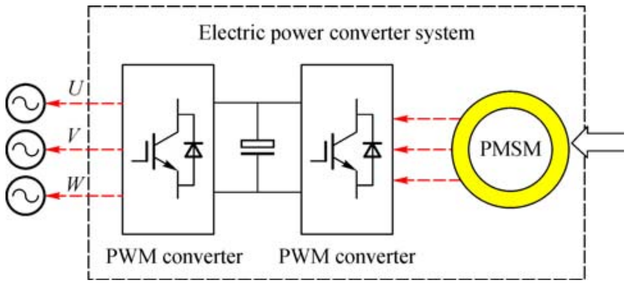

Fig. 3 Structure of EPCS in DD-WT

operation control of EPCSs in DD-WTs under faults. Different existing methods are sorted and compared, and future research directions are recommended.

2 Condition monitoring of EPCSs in DD-WTs

Condition monitoring is conducted to monitor the status of critical components of an EPCS in a DD-WT, such as the PMSG, main bearings, and power converter. Monitoring can be either on-line, in which instantaneous feedback on the condition are provided, or off-line, in which data are collected at regular time intervals with measurement systems that are not integrated into the equipment [11].

2.1 Condition monitoring of PMSGs

2.1.1 Condition monitoring of stators of PMSGs

The stator of a PMSG is mainly composed of a stator core, windings, and base. The stator core and base are subject to various forces transferred from the drive chain of the DD-WT. Consequently, damage, cracks, and deformation are likely to occur in both of these parts after a long service period. Being costly and difficult to maintain, the stator base and core are not replaced even if they incur certain faults. As a result, safety during operation is compromised. Therefore, the stator core and base should be monitored in real time. The methods for monitoring stator windings are listed in Table 1 [12–34]. Current condition-monitoring methods include penetrate inspection, ultrasonic inspection, magnetic testing, X-ray detection, laser holographic detection, and acoustic emission technology.

When insulation damage occurs between the silicon steel sheets of the stator core, eddy currents may cause the stator core to overheat and consequently induce ground or phase-to-phase fault. The main methods for detecting the faults in the stator core are iron loss method [35] and electromagnetic core imperfection detector test [36].

The main stator winding faults include inter-turn short circuit, overheating, and insulation failure. The inter-turn short circuit is the foremost fault in the stator windings. If the incipient inter-turn fault is not monitored or the corresponding measures are not implemented in a timely manner, the more serious phase-to-phase or turn-to-ground fault may emerge [37]. At present, the practical monitoring methods for the inter-turn short-circuit fault are classified into the following five types:

1) Methods based on temperature signal analysis

The continuous monitoring of temperature signals can facilitate the observation of the winding insulation in the DD-WT and the condition of the wind turbine [25–29]. When the temperature in the DD-WT exceeds a certain value, the DD-WT must be shut down for maintenance. At present, thermistors and thermocouples are used to monitor the temperature in the stator slot, base, and cooling system [30]. Determining the best installation location for the temperature sensors for improved monitoring effectiveness is the main challenge in this type of method.

2) Methods based on partial discharge

Aside from temperature monitoring, partial discharge monitoring has become the most extensively used method for monitoring the stator winding insulation over the past 25 years, with more than 50% of large-scale North American utility generators employing this technology [31,32]. Partial discharge on-line monitoring systems

Table 1 Monitoring methods for stator windings

Methods	References	Monitoring results	Limitations
Spectral analysis of stator current	[12–14]	Monitoring stator winding fault	Judgment is not accurate, and it is related to load and power supply reliability
Symmetrical component method	[15,16]	Monitoring of inter-turn short-circuit fault	Insulation is not monitored
Park vector analysis of stator current	[17,18]	Monitoring of inter-turn short-circuit fault	Relationship between the ellipticity of the trajectory of (i_d, i_q) and the fault is unclear
Axial magnetic flux leakage	[19–21]	Monitoring of inter-turn short-circuit fault as well as phase-to-phase and phase-to-ground insulation deterioration	Installation of multiple probes with high concentricity is required
Vibration signal analysis	[22–24]	Monitoring of inter-turn short-circuit fault and winding insulation deterioration	Multiple vibration sensors should be installed
Temperature signal analysis	[25–30]	Monitoring of inter-turn short-circuit fault and phase-to-ground insulation deterioration	Temperature sensors, which are difficult to locate, should be installed
Partial discharge	[31–34]	Monitoring of inter-turn short-circuit fault and insulation deterioration	High cost

based on high-pass filters have been widely used [33]. However, extracting the discharge signals in strong-noise jamming environments is an issue in this type of method [34].

3) Methods based on vibration signal analysis

The inter-turn short circuit or interphase short circuit can cause an asymmetrical magnetic field in the air gap and form an electromagnetic pulse wave of a certain frequency; this pulse wave induces vibration in the DD-WT [22–24]. Numerous factors can cause vibration; thus, methods based on vibration signal analysis are not recommended.

4) Methods based on axial flux

Faults can be detected through shaft voltage and axial magnetic flux leakage [19–21]. However, methods based on axial flux have two drawbacks that can weaken monitoring efficiency [19]. First, multiple probes with high concentricity must be installed at the end of the winding coil. This configuration is difficult to realize. Second, the dependence on the load is strong.

5) Methods based on stator current signal

A. Spectral analysis of stator current

The spectral analysis of the stator current is based on fast Fourier decomposition. However, frequency spectrum analysis is easily affected by low-frequency resolution, and fault characteristic harmonics are difficult to extract. In addition, the monitoring accuracy under loaded conditions is low, and it is affected by inherent DD-WT asymmetry and power fluctuations [12–14].

B. Symmetrical component method

Monitoring a negative-sequence component of a stator current was proposed in Ref. [15] to determine whether an inter-turn short circuit has occurred. Nonetheless, this approach has limitations in practical applications as the experimental results show that the negative-sequence component of the current significantly changes along with the fluctuations in the power supply [16].

C. Park vector analysis of stator current

Park vector analysis of the stator current can be conducted in inter-turn short-circuit fault monitoring [17,18]. Under normal conditions, the trajectory of (i_d, i_q) is a circle. If the fault of the inter-turn short circuit appears in a one-phase winding, then the balance of the three-phase stator current will be destroyed. As shown in Fig. 4, the trajectory of the Park vector will change from a circle to an ellipse. However, certain problems in this method have to be solved, such as the relationship between the ellipticity of the trajectory of the Park vector and the inter-turn short-circuit fault.

2.1.2 Condition monitoring of rotors of PMSGs

The condition monitoring of rotors of wind power generators mainly uses the following indicators: Speed, torque, vibration, and temperature. Rotor faults mainly include rotor asymmetry, rotor eccentricity, and rotor demagnetization faults. Rotor asymmetry accounts for 35% of the total faults, and rotor eccentricity accounts for 40%.

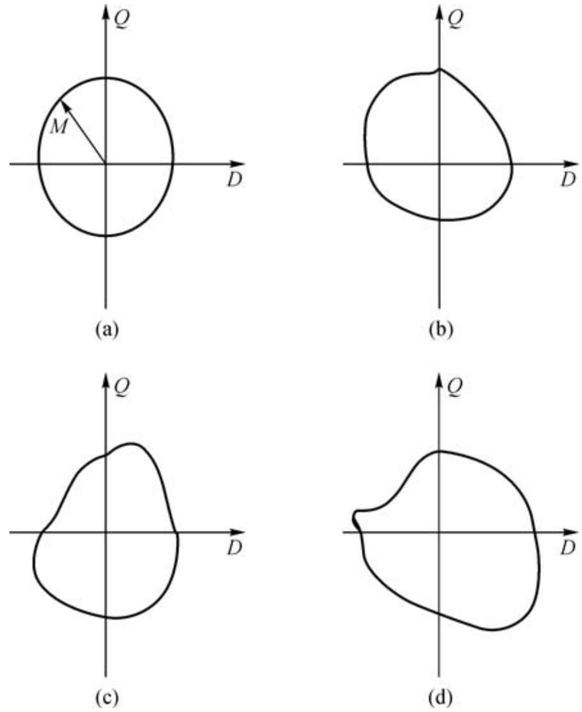

Fig. 4 Vector trajectory of Park vector. (a) Normal operation; (b) A phase 6 turns short circuit; (c) B phase 18 turns short circuit; (d) C phase 18 turns short circuit

1) Rotor asymmetry

The vibration monitoring method for rotor asymmetry faults uses vibration sensors to monitor the generator. The output signal of the vibration sensor is compared with the known fault characteristic frequency to determine fault properties and faulty parts [38]. A power spectrum extraction method based on wavelet energy feature coefficient was proposed in Ref. [39]. In this method, vibration signals generated from operating rotating machinery are analyzed.

2) Rotor eccentricity

An analytical calculation method for the static magnetic field of the eccentric gap was proposed in Ref. [40] for eccentricity detection; this method is based on the equivalent residual magnetism method. An alternate pole PMSG analytical model was established in Ref. [41] under the condition of rotor eccentricity. Both Poisson’s and Laplace’s equations were derived using a perturbation method. The magnetic field distribution of the motor eccentric gap was obtained to calculate the extent of rotor eccentricity by solving both equations.

3) Rotor demagnetization

In recent years, advancements in electromagnetic design and finite element analysis of electromagnetic and temperature fields of the PMSG have promoted the application of PMSGs in DD-WTs. However, rotor demagnetization adversely affects the reliability and stability of the DD-WTs in operation. Rotor demagnetization has three main causes. The first is overheating or the rise of the temperature beyond the threshold for the permanent-magnet material used. The second is large stator winding current, which exceeds the allowed scope for permanent magnets. The third is the gradual decay of the magnetic field of the permanent magnet after a long service time; this problem seriously affects PMSG performance and power efficiency [42,43]. Once demagnetization occurs in a PMSG, the output power quality deteriorates. Such deterioration can adversely affect the entire grid. Thus, on-line monitoring and evaluation of PMSG demagnetization rotor faults are necessary [44].

The thermal and time stabilities of the rare-earth permanent-magnet materials, such as cobalt and NdFeB, were studied in Ref. [45], and mathematical expressions for demagnetization were obtained under specific conditions. The influence mechanism of the alternating magnetic field produced by the phase currents on the permanent-magnet materials was investigated in Ref. [46]. Currently, the most commonly used method to prevent demagnetization is to optimize the magnetic circuit structure and reduce the risk of magnetic loss by optimally designing the motor [47]. These methods belong to static prevention measures. In off-line detection methods, the generators are shut down to detect the demagnetization fault when apparent failure occurs. An off-line detection method called "D-the Module" flux observation method was proposed in Ref. [48]; the method can respond to a change in the permanent-magnet chain. An improved back-electromotive force (EMF) method was presented in Ref. [49]; the method can be used to estimate the permanent-magnet flux. However, these two methods can only be used to observe flux linkage amplitude fluctuations of permanent magnets in a fixed direction, and the latter convergence is slow under low speeds. Thus, these methods are difficult to use in practical applications. The changing rotor flux is used to verify control robustness in Ref. [50]. In Ref. [51], a reactive power feedback method is employed to compensate for torque ripple caused by flux linkage. However, these methods only consider flux amplitude fluctuation, and the flux linkage wave of the amplitude jump is given. An on-line monitoring method for permanent-magnet flux linkage was proposed in Ref. [47]; the method is based on Kalman filter. This method achieved the optimal operation of a PMSG under the magnetic field fluctuations of the permanent magnet. The methods for demagnetization monitoring their features are shown in Table 2 [45–49,51].

2.1.3 Condition monitoring of bearings of PMSGs

Three methods are extensively used in monitoring the condition of PMSG bearings, namely, temperature monitoring-based, vibration analysis-based, and acoustic measurement-based methods [52,53].

1) Temperature monitoring-based method

Temperature monitoring is one of the most commonly used condition monitoring methods for the bearings of PMSG. Temperature is measured with a series of sensors. The temperature measurements can be used for predictive and preventive maintenance. Sensors of various types, such as resistance thermometers, resistance temperature detectors, and optical pyrometers, can be used in temperature measurement [54]. Every component or subcomponent has a set temperature operating range. If the real-time temperature is higher than its threshold, then the information is extracted and the fault is defined. However, this method is slow, thereby delaying the rectification of the signals, and is less efficient than other methods for incipient and precise detection.

Temperature data from a supervisory control and data acquisition (SCADA) system were analyzed in Ref. [55]. The generator bearings in a wind farm were examined and several abnormal PMSGs were detected. In Ref. [56], a novel condition monitoring method based on the speed of the DD-WT was proposed. The method was proved effective in monitoring bearings under varying wind speeds.

2) Vibration analysis-based method

The vibration analysis method has been widely used for fault diagnosis in rotating machinery and other generator systems. Favorable results have been achieved. This method is an effective condition monitoring technique for PMSG bearings. Accelerometers are often used as sensors in the vibration analyses of DD-WTs. These sensors allow for the preprocessing and post-processing of the vibration data in the time, frequency, and time-frequency domains. The performances of commonly used time-domain and frequency-domain vibration analysis methods are affected by the loads of wind turbines, which are smoothly variable. The fast Fourier transform (FFT) analysis method in signal processing needs to be improved. However, information can be extracted from both time-domain and frequency-domain signals by signal-processing algorithms and alarms, such as envelope signal and narrowband envelope alarms. Several statistical indicators, such as root mean square, peak-to-peak amplitude, and crest factor, can be used to extract useful information from acquired vibration signals [57,58].

Vibration analysis has been proved an efficient method to achieve improved frequency resolutions at both low and high frequencies. However, complex aliasing occurs in the high-frequency portion.

3) Acoustic measurement-based method

In the acoustic measurement-based method, acoustic sensors and sound-level meters are used to detect the components [59,60]. These sensors have a microphone that transforms variations or pressure levels into a voltage signal, which can be recorded on a meter [61]. Devices that have anti-aliasing properties, dynamic range, and high sampling rate are ideal for acoustic measurement [61,62].

Acoustic emission (AE) technique is effective for bearing health monitoring. AE is a transient impulse caused by a rapid release of strain energy in a solid material under stress conditions, such as mechanical or thermal loads. The AE technique is mainly applied to detect cracks. Therefore, it is often used to monitor bearing faults and shaft cracks. Sound pressure and intensity determine the accuracy of this method [53,63–64]. Surface and subsurface micro-damage can be captured using this technology. This method is also more inexpensive and simpler than other techniques [60]. Thus far, AE has been proved more effective than the vibration analysis-based method in detecting faults at an early stage [64].

2.2 Condition monitoring of power converters

Reference [65] asserted that power converters in large-capacity PMSGs exhibit high failure frequency. The downtime caused by the failures of the electronic subsystem constitutes approximately 24% of the total DD-WT downtime. Studies have revealed that the maintenance cost for power electronics is high, particularly for offshore PMSGs.

Data-driven methods and physical models are usually adopted in monitoring the condition of insulated gate bipolar transistor (IGBT) modules of wind power converters. Data-driven methods are either based on the end characteristic of the device or based on the sensor signal. The end characteristics of an IGBT are closely related to the degree of failure; thus, a thermal expansion coefficient mismatch (thermal stress) can lead to wire and welding layer fatigue of the IGBT as the power cycles increase. The IGBT gate valve voltage was studied in Ref. [66] from the aspects of transconductance and Tong state voltage drop under variable temperature. The experimental results showed that gate valve voltage, transconductance, and pressure drop of the electrical components can be used as parameters for monitoring the state of an IGBT module. However, the change in the power device end signal is weak, and it can be easily affected by other factors, such as temperature change and measurement difficulty. Therefore, depending only on the device end characteristics of the IGBT module for monitoring the state of the module may be unreliable in practical applications.

A method for monitoring the signal of the sensor was adopted in Ref. [67] to examine the disconnection problem in an IGBT.

As shown in Fig. 5, the S-terminal leading to the IGBT emitter is used to access the resistance, R_c, and auxiliary measurement circuit for condition monitoring. When the lead wire is off, the resistance values of the S and E ends change. Therefore, these values can be used to monitor the disconnection of IGBT. Although additional data can be obtained easily by increasing the amount of sensors inside the power module, the condition monitoring method based on sensor signals is limited because of the changing operating conditions of the wind power converter and the temperature of large inertia. A method based on model considering the correlation of the aging degree and the strength of the captured character signal should be established to achieve accurate condition monitoring for power converters in DD-WTs. This method can be used to characterize the remaining life of the module prior to failure by a scale process. Combining converter status monitoring and wind turbine/wind farm-level SCADA system to monitor the status of the IGBT module of a wind power converter presents a new method (Fig. 6). In addition, a model-based method based on the condition monitoring parameters and a data-driven method for evaluating the trend of the feature data can be combined to improve the effectiveness of the health status monitoring of a power module [68].

2.3 Supervisory control and data acquisition (SCADA)

An SCADA system, which is used in DD-WTs, has the following basic functions [69]: 1) Real-time monitoring function; 2) alarm function; 3) historical data down-

Table 2 Methods for demagnetization monitoring and their features

Methods for demagnetization detection	References	Features
Static prevention methods	[45]	Permanent-magnet materials were studied, and an expression for demagnetization in specific cases were derived by this method
	[46]	The effect of the alternating magnetic field on the permanent-magnetic material was studied by this method
Off-line detection methods	[48]	The method of “D-the Module” flux observation was proposed. The method can respond to the changing flux linkage, but it can only observe fluctuations in the flux amplitude in a fixed direction
	[49]	An improved back-EMF method was proposed. The method can be used to estimate the flux linkage, but it can only observe the fluctuations in the flux amplitude in a fixed direction
	[51]	A reactive power feedback method to compensate for the torque ripple caused by flux linkage was proposed. However, the method can only consider the fluctuations in the flux linkage amplitude
On-line detection methods	[47]	An on-line flux linkage monitoring method based on the Kalman filter was proposed. The method can ensure the optimal operation of PMSGs under fluctuating magnetic field of the permanent magnet

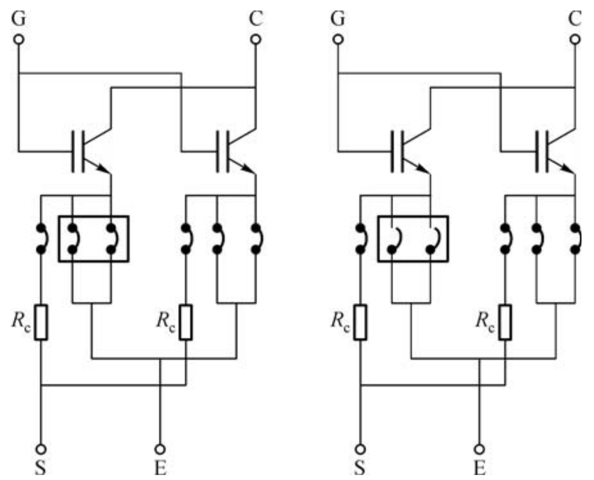

Fig. 5 Equivalent circuit of a power module

loading; 4) database functions; 5) landing function; and 6) self-diagnostic function. The network topology of the SCADA system is shown in Fig. 7.

The condition monitoring of important components, such as power chain and transmission chain, and supporting parts can be achieved by modeling and analyzing the data of the SCADA system. In Ref. [70], an on-line evaluation scheme based on a regression prediction model and SCADA alarm system was proposed, and a regression forecasting model based on a support vector regression algorithm was established. In the model, a portion of the monitoring project in the SCADA system is the input, and the active power of the wind power generator is the output. In Ref. [71], a nonlinear condition estimation technique was used as a modeling method; the wind vibration characteristics of a generator tower and their influencing factors were analyzed in detail, and a tower vibration model was established. In Ref. [72], SCADA engine room vibration data and other operational parameters were extracted. Tower modal frequencies and the corresponding vibration modes were obtained using a finite element simulation method, and the effects of wind speed, rotating speed, and pitch and yaw motions on the vibration were analyzed.

3 Fault diagnosis of EPCSs in DD-WTs

3.1 Fault diagnosis of PMSGs

3.1.1 Fault diagnosis of stators of PMSGs

Current methods for the fault diagnosis of stator windings are grouped into two: Model-based fault identification methods and signal detection-based diagnostic methods. For the first group of methods, a mathematical model of motor fault is established for fault identification, and parameter estimation method is a representative of this group. In the second group of methods, fault feature information is extracted from the current, voltage of the PMSG, vibration and magnetic signals.

Stator faults include inter-turn short circuit, overheating, insulation faults, and cracks and deformation failure in the core and base, as shown in Table 3 [31,73–92]. The diagnostic methods for phase-to-phase and turn-to-ground short-circuit faults are similar to inter-turn short-circuit fault diagnosis methods.

1) Inter-turn short-circuit fault diagnosis methods

At present, the three commonly used types of methods to diagnose inter-turn short-circuit faults are the following: Analytical model-based methods, signal-based diagnostic methods, and knowledge-based diagnostic methods:

A. Analytical model-based diagnostic methods

The accuracy of the diagnosis based on a mathematical model is easily affected by environmental conditions, loads on the DD-WT, and other factors. Therefore, the results based on the model analysis are likely to lead to misjudgment [73,74]. Fault diagnosis in DD-WTs based on parameter identification method need to be studied further [75,76].

B. Signal-based diagnostic methods

Numerous operational parameters of DD-WTs are detected, such as voltage, current, power, flux, speed, and vibration. The methods based on signal processing, such as current spectrum analysis, motor current signature analysis, Fourier transform, symmetrical component method, coordinate transform, and wavelet transform, are adopted to diagnose the operating conditions of DD-WTs [77–82].

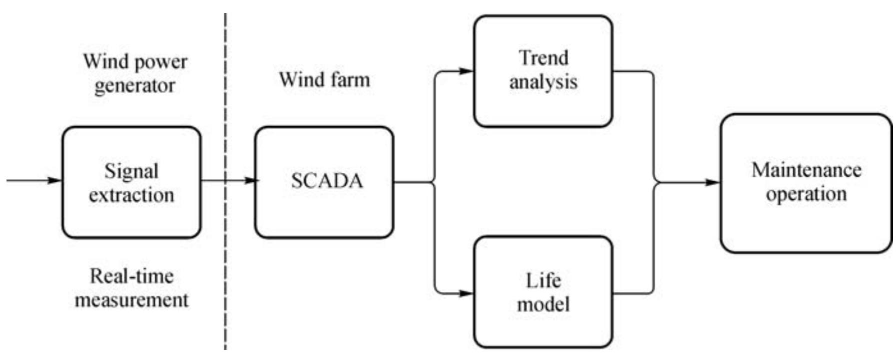

Fig. 6 Condition monitoring method for wind power converters based on SCADA

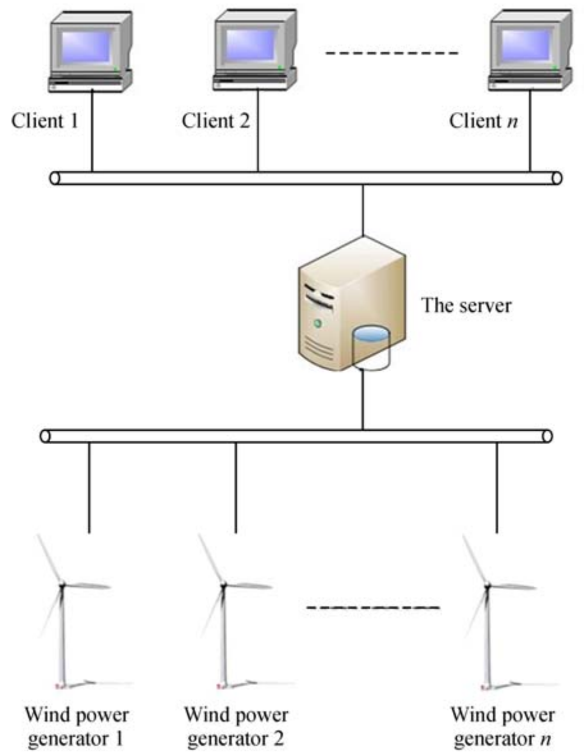

Fig. 7 SCADA network structure diagram

C. Knowledge-based diagnostic methods

The knowledge-based diagnostic methods for the inter-turn fault include expert system [83], fuzzy logic [84,85], information fusion [86], pattern recognition [87], and artificial neural network (ANN) [88]. The diagnostic process in which system modeling and fault modeling are eliminated can be divided into three steps: Fault signal extraction, fault identification, and fault evaluation. The drawbacks of knowledge-based methods include local optimum trapping and overlearning.

A single-fault diagnosis technology can hardly meet the requirements for the fault diagnosis of DD-WT equipment. Thus, integrated intelligent diagnostic systems have become a hot research topic in the fault diagnosis of DD-WTs. For example, combinations of fuzzy logic and ANN, wavelet transform and information fusion, chaos theory and ANN, fuzzy neural network and expert system, Park vector method and information fusion were investigated. The characteristics of stator winding faults are unremarkable at the early stage. Thus, an accurate diagnosis is difficult to achieve under complex external conditions. However, several features may manifest in a fault and several faults may manifest the same features. In summary, the accurate localization and timely diagnosis of stator inter-turn short-circuit faults in DD-WTs are difficult to achieve with only a single theory or method as basis.

2) Diagnostic methods for insulation faults

The partial discharge phenomenon is the most obvious early sign of insulation damage; thus, the insulation condition of stator windings can be evaluated by checking for partial discharge. Methods based on partial discharge have gradually matured. The rated voltages of the generator and motor are higher than 4 kV. For this reason, the results of on-line partial discharge testing are highly reliable. A portable test instrument called TGA-B is available for this purpose [89]. A by-product of the partial discharge, ozone can also be used to monitor the insulation condition [31].

3) Detection methods for cracks and deformation in stator core and base

The stress nephogram database, stress nephogram module, critical crack-length calculation module, and inspection cycle module were established by the finite element analysis software platform to detect cracks and deformation in the stator core and base [90–92]. These methods provide the basis for the timely detection and treatment of incipient faults. Electrical diagnostic methods can also be used. A deformation in the stator core or base can lead to an unbalanced air gap. Inevitably, a specific harmonic and noise will occur. In core and base deformation diagnosis, the voltage, current, and vibration signals of the generator are first extracted and then processed using a wavelet transform to obtain its features.

3.1.2 Fault diagnosis of rotors of PMSGs

Faults that frequently occur in the rotors of PMSGs include rotor asymmetry, eccentricity, and demagnetization.

1) Rotor asymmetry

Rotor asymmetry is mainly due to the mass eccentricity of the rotor system and other defects in the rotor. The asymmetrical quality of a rotor, which is also known as initial asymmetry, can be attributed to manufacturing

Table 3 Stator fault types

Stator fault types	References	Number of faults	Diagnostic methods
Inter-turn short circuit	[73–88]	50	a. Model-based diagnostic methods b. Signal-based diagnostic methods c. Knowledge-based diagnostic methods
Insulation fault	[31,89]	45	TGA-B diagnostic instrument; O_3 monitoring
Cracks and deformation in core and base	[90–92]	5	a. Finite-element diagnosis b. Electrical signal-based diagnosis

errors, rotor assembly errors, and uneven material. The main rotor defects are local damage on and loss of rotor parts as a result of corrosion, wear, medium scale, and fatigue stress. In addition, the damage on blades commonly induces the defects in the rotors of PMSGs. As the unit capacity of DD-WTs increases, so does the blade diameter. Freezing and blade material loss promote rotor imbalance, which causes the entire generator structure to vibrate. Consequently, fatigue stress is produced in the drive chain, and the service life of the unit is significantly reduced. Most of the existing studies extract fault features from the electrical signals of the PMSGs. The influence of mass unbalance of the wind turbine blades on the electric power of a PMSG was studied by analyzing the formation mechanism of this fault in Ref. [93]. The rotor asymmetry caused by blade mass imbalance was studied in Ref. [94]; the frequency and time-frequency domain features of the output power and vibration signals obtained from the PMSG were analyzed to detect asymmetry in the rotor. However, this method is unsuitable for large-capacity WTs, and its scope of application is narrower than those of the methods based on spectral and time-frequency domain analyses of vibration signals [95].

2) Rotor eccentricity

Rotor eccentricity is due to the uneven air gap between the rotor and stator. Many factors can induce rotor eccentricity, such as motor bearing deformation due to long-term operation, low machining accuracy, and imprecise installation. An additional component in the stator current will appear after this fault occurs. Thus, a signal detection method based on the output current, voltage, and power can effectively identify rotor eccentricity [96]. In Ref. [97], output signals were analyzed using a continuous wavelet transform to detect generator rotor eccentricity failure. This method is commonly used to detect rotor eccentricity in engineering.

3) Rotor demagnetization

Rotor-demagnetization fault-diagnosis methods are divided into those based on signal transformation and those based on an equivalent magnetic circuit.

A. Demagnetization fault diagnosis based on signal transformation

A PMSG excitation-loss fault can induce a particular stator current harmonic [98,99]. This harmonic component can be the basis for analyzing the stator current spectrum to judge whether a failure has occurred. The main methods for demagnetization diagnosis based on signal processing include Hilbert-Huang transform (HHT) [100], continuous wavelet transform (CWT) [101], discrete wavelet transform (DWT) [101], and FFT [102]. The entire time-frequency energy distribution of a signal is given by HHT, which is suitable for the analysis of nonlinear and non-static signals. An empirical mode decomposition method was proposed in Ref. [100] for the analysis of the stator current to obtain the intrinsic mode function. For each intrinsic mode function, the space signal is converted into a time-frequency signal by the HHT, the instantaneous frequency is gained, and then fault occurrence is determined. The simulation and experimental results showed that this method can determine steady-state dynamic situations of demagnetization fault. CWT and DWT were proposed to analyze the stator current in a previous study [101]. The application of specific harmonics, namely, 1/3 fs (full scale) and 5/3, can be used as basis to judge whether a fault has occurred. The simulation results showed that CWT can rapidly diagnose faults, and DWT can acquire the entire spectrum of the stator current. Setting the inductance value to 1 was proposed in Ref. [102] so that the short circuit current would not exceed the rated current of the electrical system, but the machine performance would decline. The methods for diagnosing demagnetization at different rotational speeds are divided into two. In the first group of methods, FFT is used to analyze the stator, harmonic, and zero-sequence currents. In the second group of methods, the zero-sequence and q-axis currents are analyzed on the basis of the rated torque. Although several methods can diagnose demagnetization fault, they do not apply to changing loads. Furthermore, harmonic frequency, which is the basis for judging fault occurrence, varies with speed. Therefore, this type of method is relatively complex to implement.

B. Demagnetization fault diagnosis based on equivalent magnetic circuit

An equivalent magnetic network is based on the principle of equivalent magnetic flux. Flux distribution, which is relatively uniform, geometry and more rules part is divided as a unit in the motor, and is calculated the equivalent permeability. Through the node connection between each unit, the magnetic potential of each node and/or relevant parameters of the magnetic flux unit are obtained using the similarities between the magnetic network and electric network. A magnetic network model presents high precision and significantly reduces computer storage and computing time. This model provides an effective calculation method for the optimal design of permanent-magnet motor and dynamic performance simulations. A semi-analytical equivalent model was proposed in Ref. [103], and the equivalent magnetic network was used to simulate the performance of a permanent-magnet motor. The EMF and electromagnetic torque calculated or measured under faults are compared with that under normal operation of the motor to judge whether demagnetization fault has occurred. Compared with traditional methods, this method is characterized by relatively low accuracy, but its speed is high. The various demagnetization fault diagnosis methods and their features are summarized in Table 4 [100–103].

3.1.3 Fault diagnosis of bearings of generators

DD-PMSG spindle bearings are key components of DD-WTs. The main shaft bearing of a DD-WT suffers from

Table 4 Demagnetization fault diagnosis methods and their features

Demagnetization fault diagnosis methods	Methods presented in references	References	Features
Demagnetization fault diagnosis based on signal transformation	HHT	[100]	This method can detect demagnetization fault under steady-state dynamic situations
	CWT	[101]	This method can rapidly diagnose faults
	DWT	[101]	This method can acquire the spectrum of the stator current
	FFT	[102]	This method is capable of detecting demagnetization, but it is not applicable under conditions of changing loads and variable speed
Demagnetization fault diagnosis based on an equivalent magnetic circuit	Semi-analytical equivalent model	[103]	The accuracy of calculation is low, but the computational speed is fast

continuous damage because of complex operating conditions, such as high torque, fluctuating rotation speed, and transmission load mutation. The operating conditions of the main bearings directly affect the performance, life, and reliability of wind turbines. Generally, the main bearings of DD-WT are spherical roller bearings. Spindle bearings must have the heart function owing to the influence of the stress from the wind rotor and the deformation of the spindle.

DD-WTs can be divided into two types according to the number of main bearings, namely, double-bearing wind turbines and single-bearing wind turbines. Figure 8 shows a diagram of a double-bearing outer-rotor permanent-magnet DD-WT, which was designed by Xinjiang Goldwind Science & Technology Co. Ltd. [104]. Together with Vensys, Goldwind produced a permanent-magnet DD-WT [105]. Component 10 in Fig. 1 is the bearing of a single-bearing rotor permanent-magnet DD-WT designed by XEMC. XEMC manufactures MW-class wind turbines, with 2 MW permanent-magnet DD-WT as its key product [106–108]. Researchers in China and other countries have also investigated the faults of main bearings.

On the basis of the nonstationary and nonlinear characteristics of the vibration signals of wind turbine

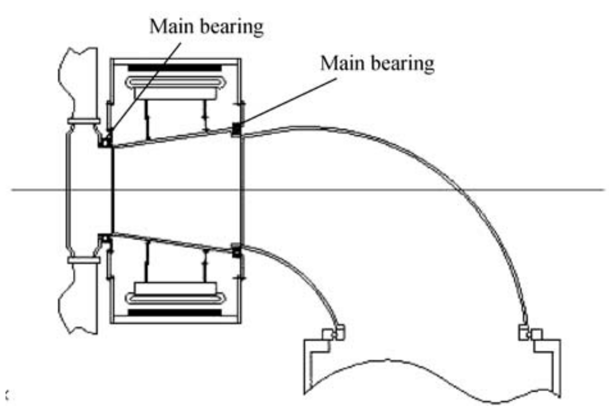

Fig. 8 Diagram of a double-bearing outer-rotor permanent-magnet DD-WT

bearings, a previous study [109] proposed a DD-WT bearing fault diagnosis method based on a least-squares support vector machine (LS-SVM) and intrinsic time deposition (ITD). First, ITD was used to decompose complex vibration signals effectively and derive several intrinsic rotational components. Spectral analysis was conducted to examine the instantaneous amplitude of the intrinsic rotational component with an apparent periodic shock component. The amplitude of the fault characteristic frequency was extracted as the feature vector for bearing fault diagnosis, and then the LS-SVM was used as a classifier to identify the operating status of the DD-WT bearings. The experimental results showed that the fault diagnosis method based on ITK and LS-SVM can effectively identify the DD-WT bearing fault [110–112]. The feature vectors obtained from the fault data of the experiment of Case Western Reserve University were presented and studied in Ref. [113]. The standard SVM method was combined with other parameter optimization methods, such as cross-validation, grid search, particle swarm optimization, and genetic algorithm, to optimize the parameters. The condition for the signal was classified and identified according to the conditions of the bearing, namely, the fault conditions of the inner ring, outer ring, and rolling body [114]. The selected depths of the bearing fault were 7 and 21 mil (1 mil = 0.0254 mm) on the basis of the fault severity. A total of 20 samples were included in each fault training set, and testing sets were constructed for testing. The most common SVM kernel function is the radial-basis kernel function [115]. The classification results for the optimized parameters were analyzed. The genetic algorithm exhibited the best parameter optimization capability, whereas the SVM was superior to other methods in terms of accuracy in classifying fault signals in wind turbine bearings.

3.2 Fault diagnosis of power converters

The power converter is a key component of the EPCS; thus, its reliability has captured the interest of researchers and engineers on a global scale. Power converter failures have the highest frequency among the faults in DD-WTs [116,117]. Power converter failures include open-circuit and short-circuit faults. They are caused by thermal stress, high electrical, wire disconnection, or gate driver failure [118–121].

The Park vector approach was first proposed in Ref. [122] as a diagnostic tool for voltage source inverter faults. However, this approach is unsuitable for integration into the drive controller because it requires highly complex pattern-recognition algorithms. In Ref. [123], a new algorithm was presented for multiple open-circuit fault diagnosis in full-scale back-to-back converters, which are used in the PMSG drives of wind turbine systems. The proposed method is based on a Luenberger observer and an adaptive threshold, which can independently guarantee a reliable diagnosis of the drive operating conditions. In Ref. [124], a fault-detection method was proposed for an open-circuit fault of the switches of grid-connected neutral-point clamped inverter systems. The proposed method can not only detect the fault condition but also identify the location of the faulty switch in two fundamental periods without using additional sensors or performing complex calculations. Open-circuit fault diagnosis of two power converters of a PMSG drive for wind turbines was presented in Ref. [125]. A diagnostic method was proposed for each power converter to allow for real-time detection and localization of multiple open-circuit faults. The proposed methods can be suitably integrated into the drive controller and can trigger remedial actions.

Short-circuit faults due to unpredictable factors can adversely affect converters in DD-WTs. This problem was addressed in 2003 when a DC–AC converter known as Z-source inverter (ZSI) was proposed by Peng [126]. The reliability of the inverter is substantially improved because the shoot-through state, which is forbidden in the voltage source inverter, is feasible in ZSI. ZSI can prevent short-circuit faults in the power converters of EPCS in DD-WTs.

4 Operation control of EPCSs in DD-WTs under faults

The large-scale centralized energy transport causes a DD-WT in a grid to present unbalanced harmonic distortion after a long operating period. This distortion, in turn, leads to current harmonic distortion and various negative effects, including fluctuations in power, torque, and vibration. DD-WT serious faults lead to grid operation failures. In recent years, large-scale off-grid accidents have occurred in several wind farms, including those in Yumen, Gansu, and Helan Mountain, Ningxia [127]. These accidents demonstrate that DD-WT failures pose challenges to the safety, stability, and efficiency of a grid. Not only does DD-WT fault downtime result in economic losses for wind farms but off-grid faults also result in grid failure, which negatively affects the stable operation of the grid. Faults that may occur during operation must be considered to meet increasing demand for high reliability. In the research on the protection and control of PMSGs and power converters, fault-tolerant (FT) operation control technologies under typical faults have been designed. The control technologies can improve the equipment operation safety, enhance the stability of grid operation, reduce the operation cost, and avoid devastating accidents.

Operation control under faults, that is, the operational control technology for EPCSs in the DD-WTs under fault conditions, mainly includes: 1) On-line monitoring and condition maintenance technology, 2) FT control for PMSGs and power converters, and 3) operation control under grid faults.

1) On-line monitoring and condition maintenance technology

On-line monitoring and condition maintenance is an extended operation control under faults. It is necessary to guarantee that the components continue to perform the functions for which they are designed. The basic objective of an on-line maintenance activity is to deploy the minimum resources required to ensure that the components perform their intended functions properly, safeguard system reliability, and facilitate recovery from a breakdown [128].

2) FT control of PMSGs and power converters

The concept of fault tolerance [129] was proposed formally in a seminar on control held in the United Santa Clara University in the 1980s. In engineering systems that consists of power electronic equipment similar to converters in DD-WT, three fault tolerance techniques are widely used, namely, hardware redundancy [130], software redundancy [131], and the combination of both [132]. FT grid converters and PMSGs for EPCSs in the DD-WTs are strongly related to the system topology adopted in normal operation. Various FT control strategies, which differ in terms of the machine and fault type, are presented in the literature.

3) Operation control under grid faults

Grid voltage faults include symmetrical grid voltage drop and asymmetrical grid voltage drop. The latter presents a grid voltage imbalance of less than 2%. The continuous operation control process for power converters under symmetrical voltage drops and asymmetrical voltage drop faults is called low-voltage ride-through or fault ride-through [133]. The grid codes of different countries have specific requirements for low-voltage ride-through. The low-voltage operation capability of DD-WTs directly impacts grid stability.

4.1 Operation control of PMSGs under faults

4.1.1 Magnetic field-adjusting control of PMSG

When the wind speed jumps, a weak magnetic control can adjust the back EMF and prevent the overvoltage of the converter. A closed-loop field-weakening control for generator-side converters was introduced in Ref. [134]. The parameters of the current control loop and field-weakening control loop were designed by the eigenvalue method for state-space equations, in consideration of the large inertia property of DD-WTs. In addition, excitation losses of different degrees occur in PMSG rotors as the service time of DD-WTs extends [135]. Similar to the weak magnetic principle of permanent magnets, i_d is used to increase the magnetic field to realize instantaneous excitation loss or partial demagnetization for reliable operation. A direct-torque control strategy for PMSGs was proposed in Ref. [136] to improve the reference flux-linkage amplitude of the rotor and enhance the torque output capacity of the motor. This control strategy can be applied to wind turbines to increase the magnetic field of the rotor [137].

4.1.2 Harmonic suppression and spectral analysis of PMSGs

Stator current harmonics can not only increase the copper and iron losses of a motor but also induce motor saturation and runaway phenomenon. Consequently, these harmonics seriously affect the stability of the system and reduce power generation efficiency. The following methods for inhibiting stator current harmonics have been presented in the literature:

1) In Ref. [138], the fifth and seventh harmonics were detected with a low-pass filter and by coordinate transformation. The current harmonic component was extracted by a feedforward control method and the corresponding compensation was investigated. Through this method, the current harmonics were suppressed and the current dynamic response was improved.

2) Resonant controllers were used in Ref. [139] and added to the current control loop. The gain of a resonant controller at a given resonant frequency is infinite; thus, the controller can completely suppress the harmonic at this frequency. However, when the input is a step signal, an overshoot occurs in the current response. A command feedforward compensation method was used in Ref. [140] to eliminate this overshoot and improve the dynamic response of the current, with the effects of the digital control delay considered. A fast-current response without overshoot behavior was achieved.

3) In Ref. [141], a feedforward compensation method was presented to suppress the current harmonics in a PMSG. The harmonics of different frequencies were compensated by the developed system. The phases and amplitudes of the compensation voltage for different motor conditions were obtained using an auto-search algorithm for on-line compensation.

4) A control strategy for machine-side converters was proposed in Ref. [142] (Fig. 9). The strategy uses a frequency variable proportional-integral-resonant (PI-RES) controller to regulate the stator current and inhibit

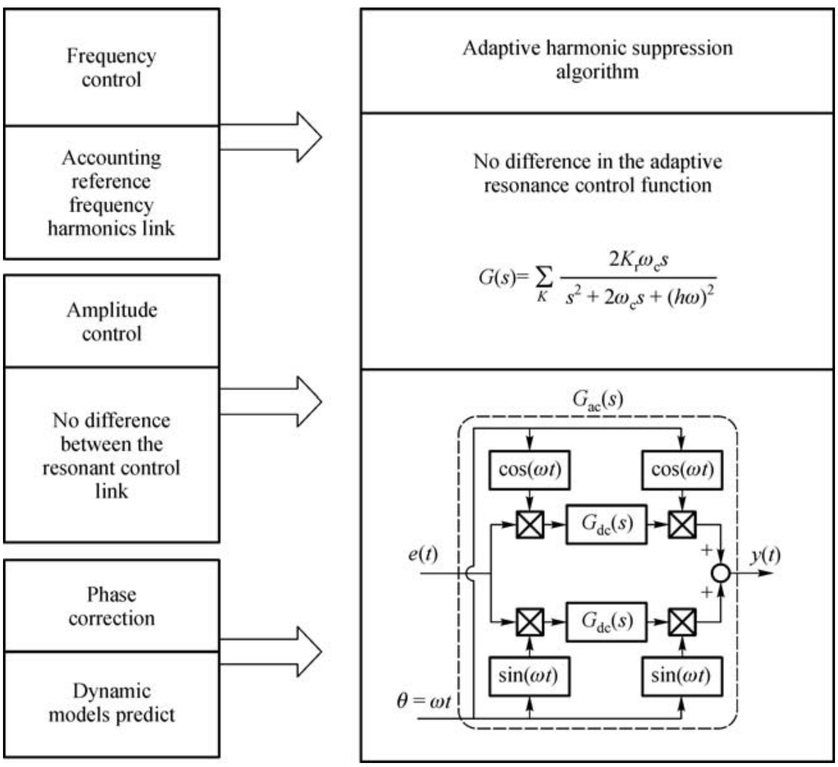

Fig. 9 Motor-side converter control strategy for suppressing second-order voltage ripple

the main stator harmonic current in the synchronous rotating coordinate system of the rotor.

4.1.3 FT control of multiphase PMSGs

Compared with three-phase machines, multiphase machines offer additional degrees of freedom; thus, they can be used for FT operation [143]. The remaining healthy phases in a multiphase machine can be used to compensate for the faults and continue to drive operation under fault conditions [144,145]. The FT operation of a multiphase machine can be achieved by modifying the existing control technique without any additional hardware. Multi-phase PMSGs have received wide acceptance in applications that require fault tolerance. Reference [146] presented FT control techniques for a nine-phase PMSG with trapezoidal back-EMF forces under various open-circuit conditions. The multiphase PMSG is shown in Fig. 10. The proposed control strategy uses only the fundamental and third-harmonic current components to excite the healthy stator phases.

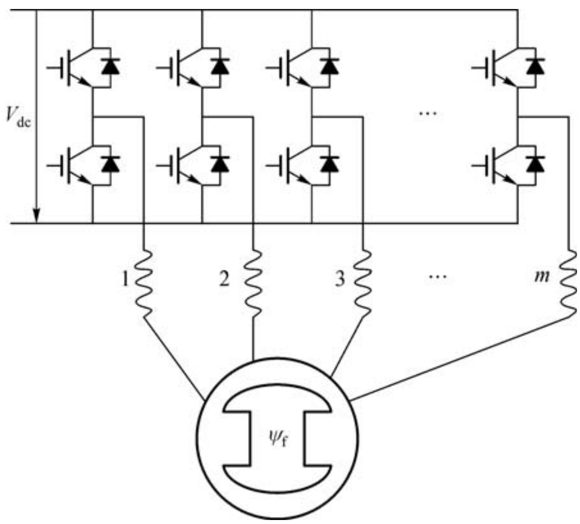

Fig. 10 Multiphase permanent-magnet synchronous generator

4.2 Fault tolerance in power converters

Fault tolerance in EPCSs has been proposed for three-phase PMSGs that suffer from an external phase-loss fault. Fault tolerance has been introduced for Y-connected three-phase PMSGs in which an auxiliary fourth leg is added to the standard two-level inverter topology [147,148], and the fourth leg is connected to the neutral point of the motor stator windings, as shown in Fig. 11. A split DC-bus capacitor branch can also be used as the fourth leg [149]. The fourth leg in Fig. 11 provides a post-fault normal operation with two running phases, whereas the other phase open circuited. A similar fault tolerance technique can be implemented for Δ-connected machines without a neutral point [150].

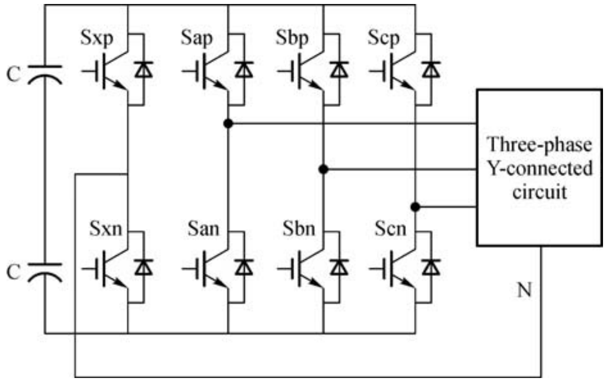

Fig. 11 Schematic of two-level three-phase reconfigurable inverter for external single phase-loss faults [149]

The circuit topologies shown in Figs. 12(a) and 12(b) can tolerate open- and short-circuit switch faults with unique post-fault behavior [151]. In both circuits, the fourth leg is connected to the main legs through a set of triacs. Under healthy conditions, the triacs are switched off and the system operates normally. Adding a fourth leg to two-level inverters can be applied to various technologies, such as mechanical relay usage, to isolate a faulty leg [152].

4.3 Operation and control of EPCSs in DD-WTs under grid faults

Grid voltage dips are classified as symmetrical or asymmetrical. In the operation of power systems, symmetrical voltage dips often occur, whereas asymmetrical voltage dips rarely happen. In terms of performance, both types of voltage dips rapidly increase the energy of the conversion system. This rapid energy increase leads to a remarkable increase in DC-bus voltage, damages the capacitance and power devices, and even destroys the entire power system [153]. In addition, when the power-grid voltage dips are not symmetrical, the grid-side converter under the influence of a negative-sequence component and the outlets of the converter produces double-frequency fluctuations in the DC-bus voltage; consequently, the stator current of the generator is affected [154]. In a mechanism analysis model, an asymmetrical fault voltage drop can be transformed into a positive- and negative-sequence separation problem of symmetrical voltage drop by using the symmetrical component method [155,156]. Therefore, the asymmetry of the power-grid voltage drop may be considered a complex form of symmetrical voltage drop. In summary, the operation control for grid voltage dips includes: 1) The control of the energy balance on the machine side and grid side, and

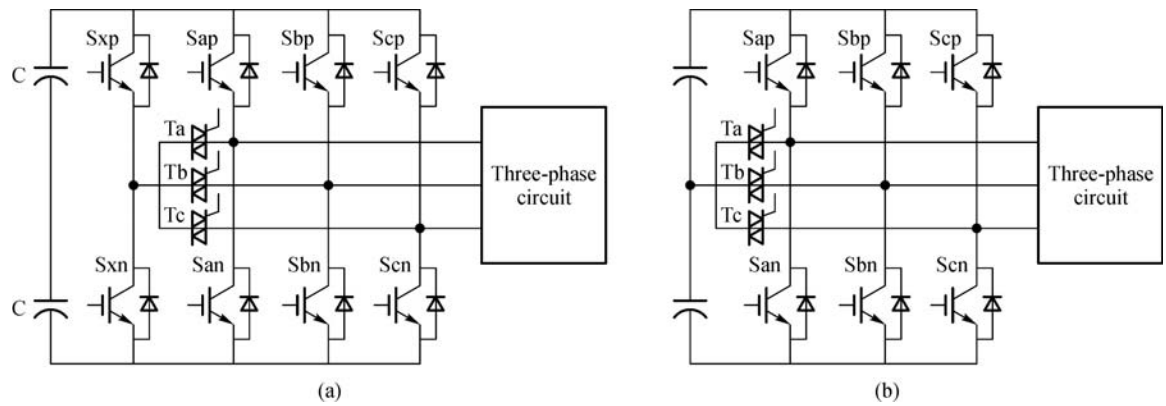

Fig. 12 Schematics of two-level three-phase FT inverters [151]. (a) Switch-based four-leg inverter; (b) capacitor-based four-leg inverter

2) the second-order frequency fluctuation suppression of the DC-bus voltage (Table 5).

Energy balance problem in a variable-flow system: A DD-WT with full-power back-to-back converter and grid-side converter is controlled by the power grid voltage orientation [157]. When a network voltage drop occurs, the power grid voltage dips from e_{gd} to e'_{gd}. No direct link exists between the machine-side converter and the power grid; thus, the output power of the machine-side converter remains the same. The active current of the grid should change to i_{gd} from i'_{gd}. Thus,

$$P_{dc} = \frac{3}{2} e_{gd} i_{gd} = \frac{3}{2} e'_{gd} i'_{gd}. \tag{1}$$

The actual instantaneous active current is i''_{gd}, where $i''_{gd} < i'_{gd}$. Then,

$$P_{dc} = \frac{3}{2} e_{gd} i_{gd} > \frac{3}{2} e'_{gd} i''_{gd}. \tag{2}$$

In accordance with the principle of power balance,

$$P_{dc} = \frac{3}{2} e'_{gd} i''_{gd} + \Delta P. \tag{3}$$

Although the actual capacity of the current transformer is limited, a current-limiting protection is necessary for the current transformer to prevent damage to the overcurrent converter. Therefore, storing extra energy ΔP in the DC-bus capacitor can increase the energy and DC-bus voltage, such that the DC-side capacitor voltage is much higher than the rated voltage.

Scholars have suggested the following methods to address failures under variable-flow system energy balance [153–161]:

1) The energy balance method based on crowbar energy consumption connects the DC side and power devices through unloading resistance to prevent the bus voltage from increasing substantially. This method is simple and highly reliable. However, the energy consumed is in the form of heat. Furthermore, a high impedance load is required. Thus, this method cannot effectively protect the DC bus from undervoltage failure.

2) A unit-energy balance method based on the energy storage can detect whether the DC-bus voltage is excessive. When the DC-bus voltage is too high, an energy storage unit can transfer excess energy. The energy equilibrium scheme integrating this energy storage device is shown in Fig. 13 [158]. After recovery, the stored energy is fed back into the grid. This method reduces energy consumption because of the effect of feeding back the energy. However, the effectiveness of the protection is dependent on the energy storage crowbar with sufficient capacity in the energy storage device. As the degree of grid drop and duration of spin increase, the cost-efficiency of this scheme is reduced significantly.

3) The energy balance method for a parallel converter uses an auxiliary converter to transfer excess energy. The energy balance method is shown in Fig. 14 [160]. When a voltage drop is detected, the auxiliary converter assists the grid-side converter to transfer redundant energy through a parallel set of electronic devices.

4) Suppressing the circulation between parallel converters is an effective method to protect the security of the

Table 5 Types and features of voltage drop faults

Fault types	Symptoms	Control
Symmetrical voltage drop	Conversion system energy accumulation and DC-bus voltage rapid increase	Energy balance control
Asymmetrical voltage drop	1) Conversion system energy accumulation and DC-bus voltage rapid increase 2) Double-frequency DC-bus voltage fluctuations affecting the generator stator current	Energy balance control and suppression of second-order frequency fluctuation

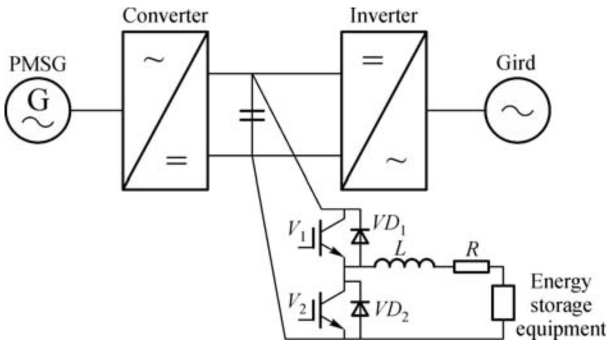

Fig. 13 Diagram of energy equilibrium scheme using an energy storage device [158]

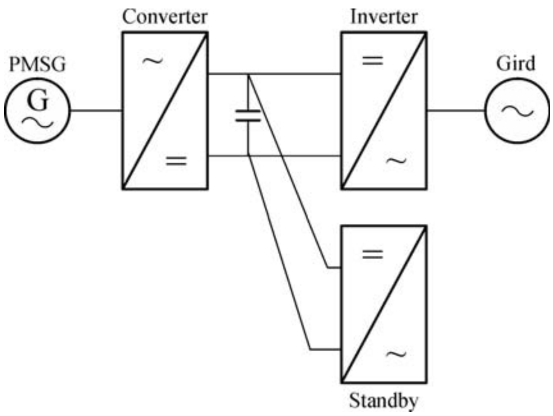

Fig. 14 Schematic of energy balance method for a parallel converter [160]

system. However, the current level of the auxiliary converter is dependent on the magnitude of the allowed grid voltage drop. When the voltage drop is serious, the capacity of the auxiliary converter is large; thus, the economic benefit is low.

Double-frequency fluctuation problem in the DC-bus voltage: A DD-WT often connects to the grid through a three-phase line without a neutral network. In this situation, the unbalanced voltage and unbalanced current can be decomposed into a positive-sequence component and negative-sequence component by the symmetrical component method. However, the zero-sequence component is eliminated.

According to instantaneous power theory, the complex power of the grid-side converter can be expressed as

$$S = P_g + jQ_g = \frac{3}{2} e_g i_g^* = \frac{3}{2}\left(e_{gdq}^P e^{j\omega_g t} + e_{gdq}^N e^{j\omega_g t}\right)\left(i_{gdq}^P e^{j\omega_g t} + i_{gdq}^N e^{-j\omega_g t}\right). \quad (4)$$

Equation (4) is rewritten in algebraic form and decomposed into active and reactive power components as follows:

$$\begin{cases} P_g = P_0 + P_1\cos(2\omega_g t) + P_2\sin(2\omega_g t) \\ Q_g = Q_0 + Q_1\cos(2\omega_g t) + Q_2\sin(2\omega_g t) \end{cases}. \quad (5)$$

Therefore, a harmonic two times the power grid frequency exists in the system output; as a result, double-frequency fluctuations occur in the DC-bus voltage and affect the generator stator current.

Scholars have proposed various solutions to the double-frequency fluctuations in the DC-bus voltage [162–168].

A. Methods based on device improvement

1) For an improved variable-flow structure topology, a previous study [169] suggested mounting the grid-side inverter on the AC side to the band-pass filter to filter out the negative-sequence component in the power grid voltage. Although this method achieved a favorable effect, it requires additional filter parts. Consequently, the wind farm construction cost is increased.

2) Flexible AC transmission system (FACTS) devices can be used. Static compensators (STATCOMs) and static var compensators (SVCs) are used in induction generator-based wind farms to enhance the reactive power control. STATCOM and SVC are two main shunt-connected FACTS devices connected at the predict current control to improve the transient and steady-state performance of the system. However, one of the main drawbacks of this method is the use of high-cost devices. As a result, this method is higher in cost that the other related methods discussed in this paper.

B. Methods based on control system improvement

1) A double-current-loop vector control method was proposed using the positive- and negative-sequence synchronous rotating coordinates. The phase sequence is decomposed by the symmetrical component method, and the positive- and negative-sequence component control method for the inverter output voltage is used.

2) A single-current-loop vector control strategy was proposed to suppress AC disturbance in the frequency of a double power grid with a PI-RES controller in a positive-sequence synchronous rotating reference frame. This method can control the positive-sequence current and eliminate the negative-sequence current without positive- and negative-sequence decomposition.

5 Future trends and directions

With the increasing proportion of DD-WTs in power grids, wind power is expected to become an important energy resource in the future. As regards the development of EPCSs in DD-WTs, the following future trends and directions of CM, FD, and operation control under faults can be deduced.

1) Although condition monitoring and fault diagnosis methods vary at present, the fault characteristic signals of

mechanical parameters and electrical parameters are relatively independent. Their effective and thorough integration has not been explored. Therefore, condition monitoring and fault diagnosis in the future are expected to emphasize the in-depth and effective integration of the fault characteristic signals of both types of parameters. As a result, the Fault diagnosis of wind turbines will be more efficient and reliable.

2) Rotor eccentricity, rotor asymmetry, and base failure can induce harmonics during operation. They can also cause motor vibration and noise. Therefore, harmonics need to be monitored and suppressed to eliminate the vibration and noise and achieve effective operation control of wind turbines.

3) A new generation of on-line maintenance strategies for EPCSs is emerging. Thus, intelligent systems for condition monitoring, fault diagnosis, and operation control under faults are expected in the future. These systems will be based on reliability-centered maintenance mechanisms.

4) Service quality, condition monitoring, and maintenance quality control technologies constitute the future trend in the development of DD-WTs. Therefore, the following may be future research directions: Wind power system access to information technology based on compressed sensing, effective technologies for condition monitoring of DD-WTs, and warning cloud platform technology for large wind turbines based on Internet Plus and big data. A service quality index system for system state characterization needs to be established. Analysis and evaluation of service quality and maintenance quality control methods should be conducted. Operating norms, standards, and improvement methods for service quality and maintenance quality need to be formulated.

6 Conclusions

This paper mainly reviewed the technologies and methods for the CM, FD, and operation control of EPCSs in DD-WTs under faults. The highlights are summarized as follows:

1) CM technologies for EPCSs in DD-WTs are reviewed. These technologies include the PMSGs, grid power converters, and SCADA system. CM technologies and systems for the entire wind turbines are expected to be the development trends.

2) FD technologies for EPCSs in DD-WTs, such as those for PMSGs (including generator stator windings, rotor, and bearings), grid power converters, and other components are reviewed. Few studies have focused on rotor demagnetization faults, which should be the next research focus.

3) Operation control of EPCSs in DD-WTs under faults are discussed, including on-line maintenance and repair, FT control, and operation control under grid voltage faults for EPCS. The low-voltage ride-through capability of wind turbines has been one of the hot topics over the last two decades because it is essential for the safe operation of the EPCS in the DD-WT.

4) Both service quality condition monitoring and maintenance quality control technologies will be the development trends for DD-WTs.

Notations

WT	Wind turbine
AC	Alternating current
DC	Direct current
PWM	Pulse width modulation
IGBT	Insulated gate bipolar transistor
EMF	Electromotive force
EPCS	Electric power conversion system
DD-WT	Direct-drive wind turbine
CM	Condition monitoring
FD	Fault diagnostics
DFIG	Doubly fed induction generator
PMSG	Permanent-magnet synchronous generator
DD-PMSG	Direct-drive permanent-magnet synchronous generator
WECS	Wind-energy conversion system
AE	Acoustic emission
SCADA	Supervisory control and data acquisition
ANN	Artificial neural network
HHT	Hilbert-Huang transform
CWT	Continuous wavelet transform
DWT	Discrete wavelet transform
FFT	Fast Fourier transform
ZSI	Z-source inverter
FT	Fault tolerant
STATCOM	Static compensator
SVC	Static var compensator
FACTS	Flexible alternative current transmission system
ITD	Intrinsic time deposition
LS-SVM	Least-squares support vector machine
SVM	Support vector machine
PI-RES	Proportional-integral-resonant

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