Renewable and Sustainable Energy Reviews 66 (2016) 345–359

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A survey of fault diagnosis for onshore grid-connected converter in wind energy conversion systems

Zhimin Yang, Yi Chai *

State Key Laboratory of Power Transmission Equipment and System Security and New Technology, College of Automation, Chongqing University, Chongqing 400044, China

A R T I C L E I N F O

Article history:
Received 20 February 2016
Received in revised form
4 July 2016
Accepted 3 August 2016
Available online 17 August 2016

Keywords:
Onshore grid-connected converter
Fault diagnosis
Converter failure
Open-circuit fault
Wind energy conversion system

A B S T R A C T

Wind energy is one of the most rapidly developing renewable energy sources during the past decade, supplying about 3% of global electricity consumption. Consequently, the power level and individual capacity of power converters in wind turbines (WTs) keep increasing. However, due to the severe operational environment and varying operational conditions, wind power converters (WPCs) are subjected to different sorts of component failures. According to the statistics, the failure rate of WPC is much higher than that of mechanical components and generator in wind energy conversion system (WECS). In an attempt to reduce system downtime and avoid catastrophic failure, the fault diagnosis (FD) of onshore grid-connected converters has gained increasing attention. Accordingly, this paper aims at presenting a state-of-the-art review on wind converter FDs including both model based and pattern based methods. It intends to provide a wide spectrum on converter operating stress, component failure modes, algorithm performance requirements, FDs for different converter topologies, and challenges in designing FDs. The main purpose of this paper is to provide the current research status of converter FDs and relevant references for the researchers in this area.

Contents

1. Introduction . . . 346
   1.1. Background . . . 346
   1.2. Existing literature surveys . . . 347
   1.3. Motivations . . . 347
2. Wind converter and its typical faults . . . 347
   2.1. Wind converter . . . 348
   2.2. Failures in wind converter . . . 348
      2.2.1. Semiconductor faults . . . 349
      2.2.2. DC-Link capacitor faults . . . 349
      2.2.3. Sensor faults . . . 349
      2.2.4. Passive component faults . . . 350
3. Fault diagnosis methods for WECS converter . . . 350
   3.1. Diagnosis methods for industrial converter . . . 350
   3.2. FD requirements of WPC . . . 351
      3.2.1. Robustness and sensitivity . . . 351
      3.2.2. Easy implementation and fast detection . . . 351
   3.3. Review of fault diagnosis methods for wind converter . . . 351
      3.3.1. Diagnosis of diode rectifier based converter . . . 351
      3.3.2. Fault diagnosis of 2L-BTB converter . . . 351
      3.3.3. Diagnosis of 3L-NPC-BTB converter . . . 353
      3.3.4. Fault diagnosis of MMC . . . 353

* Corresponding author.
E-mail addresses: yangzhimin@cqu.edu.cn (Z. Yang), chaiyi@cqu.edu.cn (Y. Chai).

http://dx.doi.org/10.1016/j.rser.2016.08.006
1364-0321/

4. Comparative study on fault diagnosis of wind converter . . . 354
4.1. Algorithm comparison . . . 354
4.1.1. Model complexity . . . 354
4.1.2. Multiple fault diagnosis . . . 355
4.1.3. Additional hardware requirement . . . 355
4.2. Challenges in designing FDs . . . 355
4.2.1. Effects of closed-loop control . . . 355
4.2.2. Early fault prediction . . . 355
4.2.3. WPC benchmark . . . 356
4.2.4. Application in wind parks . . . 356
5. Conclusions . . . 356
Acknowledgment . . . 356
References . . . 356

1. Introduction

1.1. Background

Due to fossil fuel consumption and environmental concerns about global warming, renewable energy sources have emerged as a new paradigm to fulfill the energy needs for clean and sustainable energy supplies [1,2]. Electricity generation from the solar (photovoltaic (PV) and concentrating solar power (CSP)), wind (offshore and onshore), hydropower (small and large scale) geothermal and biomass energy sources has gained enormous attention all over the world [3,4]. Among all these renewable energy resources, wind energy has seen an impressive development over the last two decades [5], from only 3.5 GW in 1994 to around 435 GW of cumulative global capacity at the end of 2015 [6] shown in Fig. 1. Wind energy is recognized worldwide as a cost-effective and environmentally friendly solution to energy problems. According to the statistic from World Wind Energy Association (WWEA): by the end of 2015, the worldwide wind capacity had reached 434,856 MW, out of which 63,690 MW were added within the year of 2015. The global growth rate of 17.2% was higher than that in 2014 (16.4%).

WECS is interfaced with the utility grid via power electronic converters which plays an important role in the integration of wind power into the electric grid. The early WTs with constant-speed squirrel-cage induction generator (SCIG) [7] connect directly to the grid. However, these solutions only capture the rated wind energy (limited slip range) and transfer power transients to the electrical grid. Modern power electronics makes it possible to achieve higher efficiency and performance for variable-speed wind turbine (VSWT) systems in which power converters are used to match characteristics of WTs and reach the requirements of grid connection, including grid frequency, voltage, harmonics etc. [8–10]. The partial-scale or full-scale converters are utilized in WECS with doubly fed induction generator (DFIG), permanent-magnet synchronous generator (PMSG), wound rotor synchronous generator (WRSG), and SCIG [7,11].

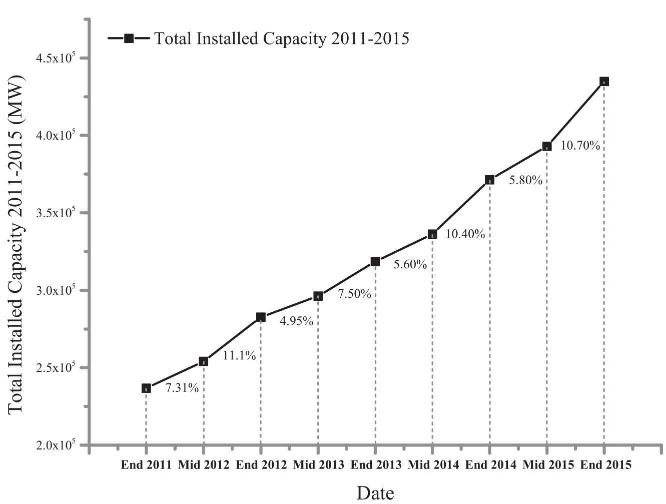

Fig. 1. The worldwide wind capacity between 2011 and 2015.
Source: WWEA

The technical availability of WECS is high, around 98%, which benefits from good reliability, maintenance management and logistical constraints [12,15]. The operating reliability and availability considered as key parameters to assess economic viability of wind farms are gaining more and more research attention. Fragile components in WECS include gearbox, power converter, generator, pitch and yaw control, rotor blades, among which bearings and sensors of gearbox, power converter, as well as pitch and yaw control are the most susceptible modules [12,16]. The annual failure rate and downtime are shown in Figs. 2 and 3 (in percentage). These component failures would reduce availability and energy production of WECS.

Failures in mechanical subassemblies and generators are usually straightforward, but converter faults are unable to be assigned unequivocally to exact components due to their complex system configuration [17]. As targets concerning efficiency of power electronics for WECS are within reach, the requirements of reliability and availability are rising due to the following factors [18].

- Long operation hours in the extreme environment.
- Continuous flow of high power density.
- Increasing system complexity.

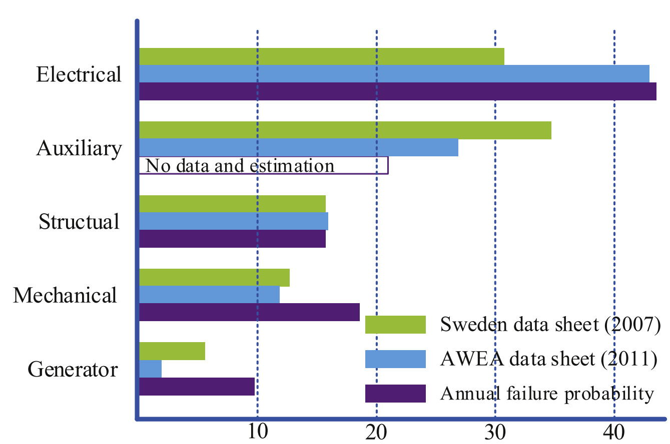

Fig. 2. Percentage of failure rate and annual failure probability per component in statistics [12–14].

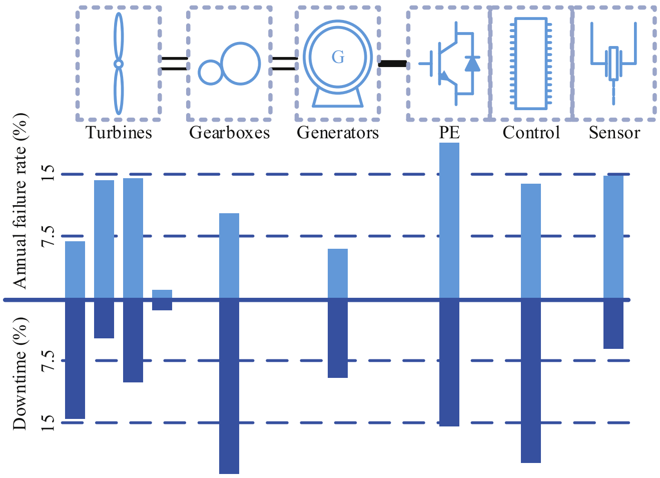

Fig. 3. Failure rate and downtimes of components in Germany over a period of 15 years [19,20].

These operational conditions bring great stresses to power converter, shorten component lifetime and cause downtime of fragile devices. According to Ref. [20], failures of the power electronics are the most frequent faults of WECS, which account for 25% of total failures in WTs as shown in Figs. 2 and 3. The failure rate of full-scale converter in recent direct-drive WECS is much higher than that of partial-scale converter in semi-variable speed WTs.

In the hope of increasing the availability and reducing maintenance cost, fault diagnosis is considered as an effective approach to detecting early fault in wind converters, preventing further damage to WECS, and reducing system downtime.

1.2. Existing literature surveys

WECSs are becoming increasingly popular, and the solution to integrating it to the power grid has experienced a great development [21]. Technical issues related to these configurations are discussed in [1,22], including the status of wind profile, wind potential estimation, configuration/design of wind energy conversion systems, wind generators, power converter topologies used for grid integration of wind power, energy storage systems for wind power applications. The existing converter topologies used in combination with wound rotor induction generator (WRIG), SCIG, DFIG, WRSG, and PMSG, along with different control schemes have been described in [8,10,23,24]. The control strategies are reviewed for both large WECSs [25] and small wind turbines [26]. In addition, Zin et al. [27] and Tripathi et al. [28] presented comprehensive reviews of control strategies and grid connection requirements in DFIG and PMSG applications, respectively.

The total installed and individual capacity of WTs grow rapidly and most WECSs are in the period of early failure. The common failure modes in the major WT components and subsystems are reviewed in [12,20,29]. Ribrant and Bertling [12] conducted an investigation of failure statistics from Sweden, Finland, and Germany. The statistical data revealed reliability performance of the different components within the wind turbine and presented that both high power WTs and small WTs have high failure rate over operational years. Lin et al. [29] summarized the failures of WT components including converters, generators, gearboxes, pitch systems, yaw systems, blades, braking systems and sub-synchronous machines in Chinese wind parks.

The state-of-the-art work related to WECS availability, reliability and failure modes has been reviewed in numerous literatures [15,30–33]. The techniques, methodologies and algorithms are summarized in [15,16,31,34,35] for monitoring the operating performance and detecting early fault of WTs. Moreover, de Azevedo et al. [36] provided a state-of-the-art review on WT bearing condition monitoring techniques including data acquisition, fault diagnose and remaining useful life estimation.

Ribrant and Bertling [12] presented a statistical analysis of Swedish wind power farms during 1997–2005 and indicated that power converter faults have a greater implication on the availability and repair cost of WECS. Failures in mechanical part of WTs and CM methods have been summarized in aforementioned references, while wind converter faults and causes are briefly reviewed in [20,29]. In addition, Fischer et al. [37] presented a field-experience based root-cause analysis of the frequent failure of power converters in WECS applications. However, there is a lack of comprehensive reviews on WPC fault modes, component failures and FD methods.

1.3. Motivations

In the recent decade, numerous FDs have been presented to detect open-switch fault, sensor fault and DC-Link capacitor fault for onshore wind converters. These studies aim at diagnosing fault in single leg, semiconductor and both side converters for various converter topologies. However, no state-of-the-art review on these methods is presented for wind converter.

Authors of this paper have investigated problems, methodologies and challenges for converter FDs in WECS, which contributes to a presentation about recent advances in WPC fault diagnosis. The major configurations and typical component failures of onshore wind converter are summarized in detail. Failure modes along with operating stress of components are presented including insulated gate bipolar transistor (IGBT), DC-Link capacitor, sensor and passive devices. The FDs are reviewed on the basis of converter topologies such as diode rectifier based converter, two-level back-to-back (2L-BTB) converter, 3-level neutral-point-clamped back-to-back converter (3L-NPC BTB) and modular multilevel converter (MMC). The qualitative study of existing FDs is presented via the comparison of model complexity, multiple fault diagnosis and additional hardware requirement.

The rest of this paper is organized as follows. Section 2 presents typical faults of wind converter and component failure mechanism. The fault diagnosis methods are emphasized in Section 3 including the requirements on wind converter FDs and reviews of state-of-the-art work. The comparative study and challenging problems are presented in Section 4. Finally, Section 5 presents the concluding remarks.

2. Wind converter and its typical faults

In VSWTs, advanced AC-DC-AC converter which is integrated into both DFIG based WECSs and SCIG or PMSG based WECSs [27,28], is the most popular topology in realization of two major objectives: (1) maximum power extraction tracking, and (2) regulation of reactive power exchange between the WT and the grid, as shown in Fig. 4. Various topologies of partial-scale and full-scale power converter for MW-level WTs are used for interfacing wind generation, and provide flexible operation and control during transient and steady operating conditions. As concluded in literature [10], 2L-BTB configuration is integrated in 1–3 WM WTs while the latter is deployed in the 3–7 WM variable-speed full-scale WECSs. The detailed topologies of high power converters are presented in literature [8–10, 21,23,24].

The development of power converters makes the performance of WECS improve significantly. It reduces the mechanical stress of

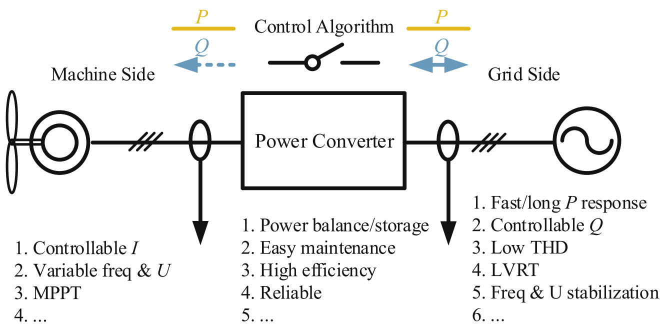

Fig. 4. WECS and its demands to power electronics [10,38].

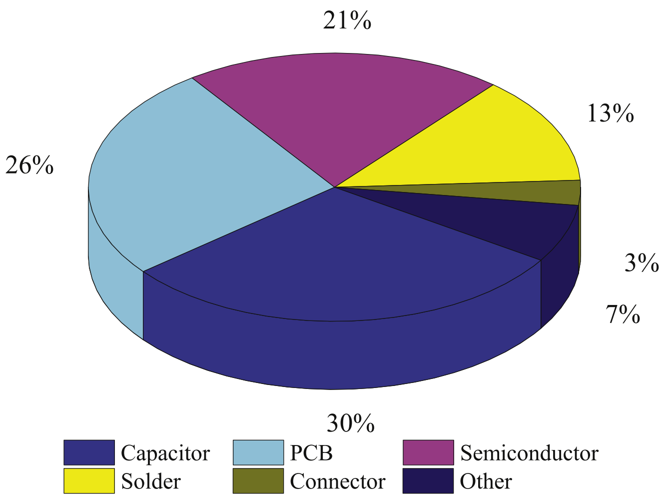

Fig. 5. Component failure rate of wind converter [39].

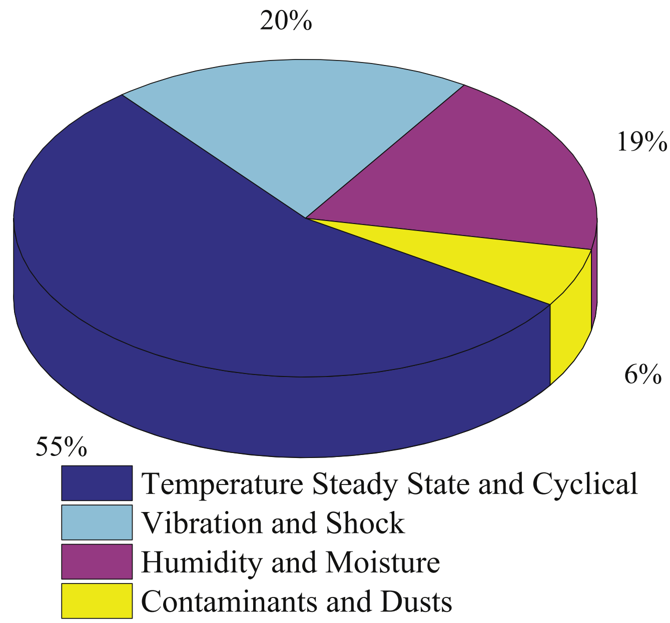

Fig. 6. Stress in power converter [46].

WTs and integrates WECS together as a total controllable generation system. However, the high power density makes the converter system more fragile than any other modules in WECS. According to WECS failure statistics in Sweden [12], China [29] and Germany [19], wind converter and its control circuit link to a high failure rate among all the components in WECS. Although electrical systems have less downtime than mechanical systems, the control system and power electronics have caused relatively high failure rate. Fig. 5 presents the statistic of failure distribution in power converter [39] where DC-link capacitor and semiconductor have caused 30% and 21% of the total failures respectively.

2.1. Wind converter

Onshore wind parks are deployed with low voltage or medium voltage AC interconnection, of which rated terminal voltages are set at 0.69 kV and 3–4 kV respectively [40,41]. Typical configurations of common commercial products are diode rectifier based converter, 2L-BTB, 3L-NPC-BTB and MMC [21]. Currently, WECS manufacturers provide variable-speed onshore WTs with the power range between 1.5 MW and 8 WM and utilize two-level or three-level topology. 2L-BTB topology with power ranging less than 3 MW is the common configuration in commercial WECSs available in wind energy market [42]. With the development of power electronics, various novel converter topologies are designed and marketed in succession for the application of higher power and operating performance. These converters are multiple 2L-BTB module (M-2L-BTB), Z-source inverter based converter and matrix converter [22,28,43].

The aforementioned configurations are the main topologies of the converter in the literature review while the power converters in commercial WECSs are deployed with abundant additional modules including the power module, auxiliary control unit (ACU), protective devices and embedded protection. In the power module, machine-side rectifier, DC-link, grid-side inverter, dv/dt module, LCL filter are essential for the main configuration; ACU includes the control board, various sensors, fieldbus interface as well as voltage transformer and uninterruptible power supply (UPS). The protective modules are of great importance to converter system which is composed of cooling system, DC chopper, precharge module, crowbar and some protective devices such as breakers, fuses and relays. With regard to the high power density and system complexity, numerous strategies and components have been developed to protect converters from thermal overload, over-voltage, over-current, under-voltage, and so forth.

2.2. Failures in wind converter

For all configurations of onshore WECS, the WPC consists of reactors, power switches, grid-side filters, sensors and protective devices like fuses, breaker, etc. As the interface between the grid and generator, it suffers from numerous stresses such as severe environment, thermal variation, grease dirt and alternating electromagnetic interference (EMI) as shown in Fig. 6. Consequently, its components and modules are more likely to link to high failure rate. The causes of these failures can be attributed to unpredictable features of wind energy, reactive/active power controllability under demands, high power density conversion, component degradation operations, malfunctioning of the driver board, auxiliary power supply failure, transient disturbance, and so on. A recent study is conducted in a WECS company[1] which tends to integrate 1.5–3 MW WECS for wind parks. According to studies conducted, the major fault phenomena of wind converter are imputed to DC-Link over-voltage, over-current, under-voltage, over-temperature of power switch, total harmonic distortion (THD) change, and so forth. Some typical faults of WPC are presented as follows. Generally, the faults of switch and its control circuit lead to the major failures in power converters among aforementioned failures [44,45]. The component failures are presented as follows including semiconductor fault, DC-Link capacitor, sensor fault and other passive components fault.

[1] Dongfang Electric new energy equipment (Hangzhou) Co., Ltd.

Table 1
IGBT failures in power converter.

Fault type	Fault mechanisms
Open-circuit	Gate driver failure Bond wire lift-off Solder fatigue
Short-circuit	High voltage breakdown Static/dynamic latch-up Second breakdown High temperature via power dissipation Impact ionization
Wear-out	Thermal cycling

2.2.1. Semiconductor faults

Semiconductor is an essential part in utility interfaces of WECS. Refs. [47,48] show that more than 34% of the faults in power converters are caused by semiconductors. According to the investigation on the user manuals from manufacturers, the major power semiconductors adopted in WECS converter include Wire-Bond IGBT Module, Press-Pack IGBT Module and IGCT Module [46,49]. The typical faults of power switch are divided into wear-out failure and catastrophic failure [18,46,50] as shown in Table 1. The major difference is that wear-out failure results from long-term degradation, and yet catastrophic faults are usually caused by single overstress event. In general, both wear-out and catastrophic failures result from thermal-over-temperature or thermal-cycling-induced failures [51,52] and could generate the same fault mechanisms. Wang et al. [18] found that thermal cycling caused the majority of failures of IGBT module.

Furthermore, both open-circuit and short-circuit faults [18,50,53] would cause irreparable and irreversible damage to the converter system. But the survey [53,54] emphasize that IGBT can handle short-circuit currents within 10 μs. As a result, crucial embedded protections have been employed to avoid the damage of short circuit such as fuses, circuit breakers as well as over-current monitoring [54]. Open circuit becomes the major concern of IGBT failure. Researchers have studied the mechanism of open-switch fault. Brunson et al. [39] declared the causes of open circuit include gate drive faults, wire bond lift-off and cracking of solder layers while Lee et al. [55] concluded that thermal cycling, extremely high collector current and gate driver fault are the major causes of IGBT open-circuit faults. Furthermore, wire bond lift-off and cracking of solder layers are the results of long time operation under thermal cycling or extremely high collector currents.

2.2.2. DC-Link capacitor faults

Capacitor is widely used in WPC for DC-Links to minimize the voltage variation and balance the power transients to an acceptable level [56]. Currently, three typical capacitors are available for the high power density converter in WECS, which are Aluminum Electrolytic Capacitors (AL-Caps), Metallized Polypropylene Film Capacitors (MPPF-Caps) and high capacitance Multi-Layer Ceramic Capacitors (MLC-Caps) [18,57]. For commercial use of WPCs, the DC-Link capacitor is selected concerning the requirements of cost, characteristics and parameters under various environmental, electrical and mechanical stresses in wind farms. The faults of DC-Link capacitors are mainly caused by the design defect, material wear, operational temperature, voltage, current, moisture and mechanical stress, which can be divided into two major categories: intrinsic and extrinsic factors. These failures can also be classified as catastrophic failures and wear-out failures as shown in Table 2. The mechanisms of the catastrophic failures in capacitor are discussed in [58–60].

Since the dielectric materials of the three capacitors differ from one another, the property and performance therefore exhibit specific advantages and shortcomings. Therefore, the fault mechanisms and dominant faults are different. The transients in WECS vary frequently, which brings great stress to the capacitor and leads to high failures of wind converter, as shown in Fig. 5. Generally, Al-Caps and MPPF-Caps suffer from open-circuit fault while the MLC-Caps is prone to short-circuit failure. Self-healing dielectric breakdown is the major cause of failures in Al-Caps and MPPF-Caps while Dielectric breakdown is prone to be the root cause of MLC-Caps failure. Meanwhile, the long-time operation in the degradation state will cause wear-out failure of DC-Link capacitors.

Table 2
DC-Link capacitor failures.

Failure type	Cap. Type	Failure mechanisms
Open-circuit	Al-Caps	Self-healing dielectric breakdown Disconnection of terminals
	MPPF-Caps	Self-healing dielectric breakdown Connection instability by heat contraction of a dielectric film Reduction in electrode area by oxidation of evaporated metal
Short-circuit	Al-Caps	Dielectric breakdown of oxide layer
	MPPF-Caps	Dielectric film breakdown Self-healing due to overcurrent Moisture absorption by film
	MLC-Caps	Dielectric breakdown Cracking (damage to capacitor body)
Wear-out; electrical parameter drift	Al-Caps	Aging effect Electrolytic reaction Effects of temperature, frequency, and humidity
	MPPF-Caps	Dielectric loss
	MLC-Caps	Oxide vacancy migration Dielectric puncture Insulation degradation Micro-crack within ceramic

2.2.3. Sensor faults

The VSWT is a typical distributed and multi-closed-loop control system. Plenty of sensors are deployed to obtain feedbacks such as torque, rotor speed, current, voltage, grid voltage, grid-side current, DC-Link voltage and so on [61]. The generator voltage, current, speed, grid voltage and grid current are essential for control of maximum power point tracking (MPPT), DC-Link voltage stability and requirements of grid codes. With regard to the sensor fault in wind converter, three typical faults are listed in Table 3 including offset faults, scaling faults and wear-out failure. Due to the nonlinearity of the sensors, the thermal drift of the analog devices and the nonlinearity of the analog to digital converter (ADC), sensor errors are generated from the measurement paths inevitably. There are also some other sensor faults such as pulse error, periodic error and spike error.

The offset error can be caused by potential imbalance of sensors, measurement path, etc. [62]. Since the positive and negative supply voltage of the current sensor may be unbalanced and the

Table 3
Common sensor faults.

Failure type	Failure mechanisms
Offset error,	Nonlinearity of sensor itself, match circuit or AD converter Thermal drift of the analog devices
Scaling error,	Broken or bad connections Bad communication
Wear out	Hardware or software malfunction Potential imbalance of sensors and measurement path

current measurement path contains many analog devices, DC offset is an inevitable problem [63]. Scaling error is another type of current measurement error which may be caused by the non-linearity of the sensor itself [64]. Given that the output of sensors should be scaled to the input range of ADC, a matching circuit is adopted to rescale the real value of the sensors. In WECS, the offset in a current sensor may be detected by integration of the sensor output over a period; however, this approach does not work if the current transducer problem is caused by inaccurate gain [65]. The voltage measurements in WECS are important and any drift will introduce deterioration of parameter estimators and state observers.

2.2.4. Passive component faults

The passive components are widely used in WPC like fuses, breakers and reactors. The fuses are deployed in pre-charge module, grid-side LCL filter, DC-Link, DC Chopper while the reactors are included in the generator-side dv/dt module and grid-side LCL filter. Because of the high power density and operational environment, these passive devices suffer from aging failures, short-circuit and open-circuit faults.

The faults of reactors in both side converters are prone to be short-circuit, open-circuit and over-temperature of winding. When a short-circuit occurs, the three phase currents are asymmetric, therefore resulting in unbalanced input of machine-side rectifier or output of grid-side inverter. The open-circuit of dv/dt reactor or LCL filter, the input or output current of faulty phase drops to around zero. The over-temperature of reactor is attributed to various causes like over voltage, over current, current harmonic, parameter drift and operational condition variation. If the reactor operates in the over-temperature condition, it would accelerate performance degradation and shorten its remaining useful life (URL).

Fuses are used to protect power components from over-current or short-circuit failures and integrated in various modules of WPC. The fuse is mainly composed of ceramic or glass, quartz sand and the melt material. The typical faults of fuse include short-circuit, open-circuit and fatigue failure. When short-circuit failure or fatigue failure occurs, fuse can no longer disconnect circuit loop in the over-current condition; when it suffers from open-circuit, the circuit is disconnected. Aging is the major cause of fuse fault. With continuous operation under the high power density and condition variations, the performance of melt and electrode will gradually degenerate. Furthermore, the following reasons can also lead to fuse fault including increase of wire terminal contact resistance, nonstandard installation and quality problem.

The electrical component failure accounts for the most part of failure rate in WECS as shown in Figs. 2 and 3. The challenging problems of component failures are shown in Fig. 6 including the high power density, complex design of the circuit and operational stresses. Each of these factors can cause catastrophic damage to WECS. Component failures may reduce the power supply quality and lead to system shutdown. Moreover, if the fault is not quickly detected and compensated, it may cause damage to WECS such as system shutdown, structural failure, turbines on fire and large-scale WTs trip-off [66]. Hence, fast fault diagnosis and isolation (FDI) must be adopted to reduce component failure rate and prevent unexpected generation system shutdown.

3. Fault diagnosis methods for WECS converter

Detecting abnormal conditions and early fault improve the reliability and availability of converter and reduce energy production losses. Wind converter FD involves fault detection, identification, fault isolation, fault estimation and fault decision-making [67]. Fault diagnosis is realized by using system model of both normal and faulty behavior of the converter. Diagnosis methods, in general, can be divided into two major categories: the pattern based and model based methods, as shown in Fig. 7. The model based methods identify system fault via building a mathematical or analytical model and exploit the physical knowledge about the system dynamics and system structures, while pattern recognition based methods exploit the system behaviors by using the historical operating data and expert knowledge. Moreover, the signal processing based and artificial intelligence based diagnosis methods are also included in the scope of pattern recognition based category.

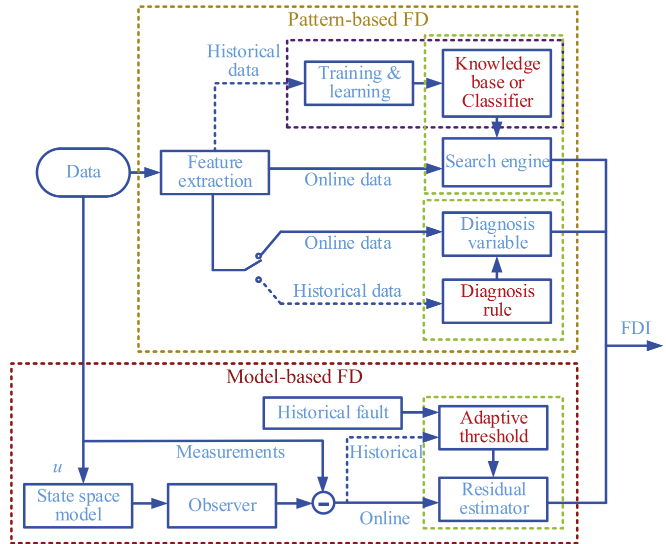

Fig. 7. FDs for wind converter.

3.1. Diagnosis methods for industrial converter

Considering the robustness, efficiency and implementation efforts for diagnosis algorithm, researchers have proposed numerous FDI methods for wind power converter, most of which are derived from diagnosis methods for industrial power electronics such as motor drive, photovoltaic inverter and traction inverter. As power converter provides compact and high-efficient power conversion solutions, it is widely used for adjustable-speed drive, unified power quality correction, utility interface with renewable energy resource, energy storage system, and electric vehicle or hybrid electric vehicle [51].

Industrial converters may suffer from faults resulting from aging, overloading or unpredicted operational conditions [68]. Although fault phenomena of component failures are generally the same in power electronics, failure mechanisms and root-causes differ significantly from specific applications such as electric vehicle converters, renewable converters and motor drives. FDIs for power converter are proposed for electrical vehicle [69–71], motor drive [72–74] and power generation plant [75–78]. Most FDs detect and diagnose component-level faults: open or short circuit of IGBT, DC-Link capacitor, sensor and passive device.

According to state-of-the-art review [47,57,79], FDs for power applications are well developed and can be generally divided into two typical categories as the analytical model based and pattern based methods, which need to monitor certain input or output variables such as phase currents, phase voltages, gate driver voltage, rotor velocity or some state signals. Furthermore, the pattern-based methods include the artificial intelligence (AI) based and signal processing (SP) based FDs [67,80,81]. Herein, a detailed list of the recent FDs are presented in Table 4.

With increasing requirements on system reliability, availability and fault-tolerance, fault diagnosis of WPC is becoming an increasingly important issue for WECS. Most component failures of WECS can cause system shutdown. The conventional FDs in Table 4 cannot be directly implemented like normalized average current, average current Parks vector, error voltage, Switching Function Model because of the unique configuration and system topology.

3.2. FD requirements of WPC

The major difference between the wind converter and other power electronics in industrial applications is listed as follows.

(1) Control configuration
The two control loops, the electrical side and generator side, are designed for active/reactive power control and maximum wind energy capture under the demands of power dispatching as shown in Fig. 4. Taking this into account, two control modules are developed with independent dual-closed-loop structures. The system is integrated with these functions such as adjustable power factor, automatic soft cut-in operation and MPPT control. Furthermore, WPC is also equipped with certain low voltage ride through (LVRT) circuit and corresponding control algorithm.

(2) Operating condition
As variation of both wind power and grid power dispatching, the operational condition of WPC is designed to meet the demands of maximum wind power tracking and reactive power control. WPC suffers from numerous stresses and operating condition variation. The stresses come from the rural location and harsh operating environment of wind parks while the operational conditions change with the variation of wind speed, wind direction and grid power dispatching. Meanwhile, WPC is required to operate in safety and provide desired reactive power compensation under transient voltage drop or grid faults.

According to inherent characteristics of WECS, some concerns should be taken into account when designing wind converter FDs including robustness, sensitivity, implementation effort and diagnosis time.

3.2.1. Robustness and sensitivity

As demonstrated in [44], WECS involves high dynamic behaviors. Thus, the system state appears with transients when operating condition changes. Since wind power varies fast and grid load changes frequently, the load and torque of WECS vary correspondingly. All the transients of load and torque result in the power flow variation in WPC. Furthermore, failures in WPC would also cause variation in measurements. As most FD methods need to monitor state variables like currents, voltages and mechanical velocity, it is challenging to diagnose WPC faults by feature extraction and residual generation. Consequently, the FDs of WPC are required to have acceptable robustness to various transients as well as superior sensitivity to faulty states. In terms of reducing false alarms and missed alarms, certain robustness and sensitivity are required for the proposed FD of WPC.

3.2.2. Easy implementation and fast detection

WECS is a complex system with plenty of components such as power modules, auxiliary control system, cooling system, mechanical system and embedded protection. Nevertheless, converter FDs is an additional module to the wind converter system. The minimal increase of the hardware is essential to develop easy-to-implement FDs. Because of the high power flow density, failures in WPC will quickly lead to damage to the system even cause emergency shutdown and cut-off of whole system. The FD algorithms need to detect fault fastly and generate fault alarming quickly. As shown in Table 4, most of the FD algorithms for power converter can be achieved in several fundamental periods. This could also be essential to the failure diagnosis of WPC.

FDs share the same diagnosis frameworks and processing techniques. As shown in Fig. 8, certain observer-based FD and feature traction method are integrated in fault diagnosis frame and are used to diagnose faults occurrence in different power electronics. Because of the system configuration and varying transients in WPC, the pattern recognition based and model-based FD should be designed specifically for locating faults and identifying the fault types as well as isolating the devices. Furthermore, some researchers have addressed the fault-tolerant problem in WPC [108–112] in recent years.

3.3. Review of fault diagnosis methods for wind converter

According to the classification of FDs in Fig. 7, model based algorithms utilize current observer [113], sliding-mode observer (SMO) [114], Kalman filter (KF) [115] and adaptive observer [116] to generate residuals with measurements while pattern recognition based methods analyze variables of devices [44,45,75,117–120] or construct data model to identify faulty operating condition [121,122]. The fault-tolerant control for faults of sensors and DC-Link capacitors is also discussed in [109,123–125]. A general framework is required to detect fault occurrence and localize faulty components in both side converters as shown in Fig. 7. Wind converter FDs are divided into four categories according to the system topologies: diode rectifier based converter [117,118], 2L-BTB converter [44,75,113,119,120], 3L-NPC-BTB converter [55,126], and MMC [114–116,121,122].

3.3.1. Diagnosis of diode rectifier based converter

Diode rectifier based converter is widely used to interface direct-drive VTs. It connects a voltage source or current source inverter via a DC-Link. The utilization of boosting DC-DC converter provides a stable DC-Link voltage and makes the generator work within a wide range of wind speeds [127]. Kamel et al. [117,118] proposed two multiple fault diagnosis methods for this kind of converter consisting of three-phase uncontrolled rectifier, the boost chopper, and the single-phase inverter circuits. Both methods are pattern based FDs and SP based approaches are utilized to extract fault features in feature space. The spectrum analysis along with the DC components of the voltage and current measurements available in the converter is utilized for detecting and locating the fault in rectifier, chopper and inverter [117]. It has addressed the selection of threshold, system transients, and nonideal operating conditions. In [118], the Fourier series expansion of the rectifier output voltage, estimation of phase currents and average values of chopper voltage are introduced to detect corresponding fault in each module. However, the former one in [117] is implemented to detect faults online within 90% of the fundamental period while the latter in [118] only realized detection of multiple faults with certain algorithm complexity.

3.3.2. Fault diagnosis of 2L-BTB converter

2L-BTB converter is utilized for both DFIG and PMSG wind generation systems with power range 1–3 MW [128,129]. The back-to-back topology and DC-Link capacitor provide bidirectional power flow and acceptable LVRT performance. However this topology requires more semiconductors and suffers from great dv/dt stress introduced by output voltage. Researchers have presented several methods to diagnosis single or multiple fault and sensor fault, among which include the FPGA implementation fast method

Table 4
Overview of the FD algorithms for power converter in industrial applications.

Component	Fault	Method	Diagnosis time	Variable	Complexity	Additional hardware
Power switch	Open-circuit	Current vector shape method [80,82]	Within 2 fundamental periods	3-phase currents	Low	No
Power switch	Open-circuit	Slope of space vector's trajectory method [83]	Average 2 fundamental periods	3-phase currents	Low	No
Power switch	Open-circuit	Direct average current method [84]	Within 1.5 fundamental periods	3-phase currents	Low	No
Power switch	Open-circuit	Modified normalized average current method [85]	Within 1.5 fundamental periods	3-phase currents	Low	No
Power switch	Open-circuit	Method based on switching function model [86]	Fast but not defined	Switch voltage, and signal	Medium	Yes
Power switch	Open-circuit	Lower-switch voltage measuring method [87]	Approximately 2.7 ms	Lower-switch voltage	Medium	Yes
Power switch	Open-circuit	Error Voltage Based Method [75]	Within 10 μs	Phase voltage	High	Yes
Power switch	Open-circuit	Voltage Analytical Model Method [88]	Within 0.25 fundamental periods	Phase voltage, line voltage, gate voltage	Medium	Yes
Power switch	Open-circuit	C-ANFI Method [89]	Exceeding 1.5 fundamental periods	3-phase currents	High	No
Power switch	Open-circuit	Fuzzy Logic Method [90]	Exceeding 1 fundamental periods	3-phase currents	High	No
Power switch	Open-circuit	Subtractive Clustering Method [91]	Within 0.25 fundamental periods	3-phase currents	High	No
Power switch	Open-circuit	Current Deviation Method [92]	Within 2 fundamental periods	3-phase currents	Medium	No
Power switch	Open-circuit	Wavelet-Neural Network Method [93]	Not defined	3-phase currents	High	No
Power switch	Open-circuit	Wavelet-Fuzzy Algorithm [94]	Not defined	3-phase currents	High	No
Power switch	Short-circuit	Desaturation detection method [95]	Additional hardware for fast detection	Collector voltage	Low	Yes
Power switch	Short-circuit	di/dt feedback control method [96]	Additional hardware for fast detection	Device current	High	Yes
Power switch	Short-circuit	Gate voltage monitoring method [97]	Additional hardware for fast detection	Gate voltage	Low	Yes
Power switch	Short-circuit	Gate voltage comparison method [98]	Additional hardware for fast detection	Device current	Low	Yes
Power switch	Short-circuit	Protection using snubber and clamped circuit [99]	Additional hardware for fast detection	Device voltage	High	Yes
Power switch	Short-circuit	Protection by slow turn-off of IGBT [99]	Additional hardware for fast detection	Gate voltage	High	Yes
Power switch	Multiple open-circuit	Luenberger observers [73]	Within 20 ms	mechanical velocity, stator currents		No
Power switch	DC component of the actuator fault	Non-linear proportional-integral observers [67]	Within 1.5 fundamental periods	stator currents, mechanical velocity	Low	No
Power switch	Open-circuit	Model reference adaptive system [74]	Within 1 ms	rotor angular speed, 3-phase currents	Low	No
Power switch	Open/short circuit	Voltage observer [100]	Within 10 ms	back EMF voltages, input and output voltages	Medium	No
DC-Link Capacitor	Capacitor degradation	Equivalent series resistance (ESR) estimation [101]	Online	Injected current and voltage	High	Yes
DC-Link Capacitor	Capacitor degradation	Detection of ESR rise [102]	Online	Capacitor voltage	Medium	Yes
Sensor	Offset and scaling fault	Adaptive Observer [65]	Online	Currents, DC-Link voltage, rotor speed	Medium	No
Sensor	Current and voltage sensor	Parity space [103]	Within two consecutive control sampling times	Sensor outputs and inputs	Medium	Yes
Sensor	Simultaneous diagnosis of speed, dc-link voltage, and current sensor faults	Extended Kalman filter [104]	Fast but not defined	Phase currents, rotor speed	Medium	No
Sensor	Current sensor and dc link voltage sensor failures	Open loop estimator + a Luenberger state observer [105]	Fast but not defined	DC-Link voltage, load current, capacitor current, catenary inverse current	Medium	Yes
Sensor	Multiple sensor failure	Model reference adaptive system [106]	Fast but not defined	Phase current, speed velocity	Medium	No

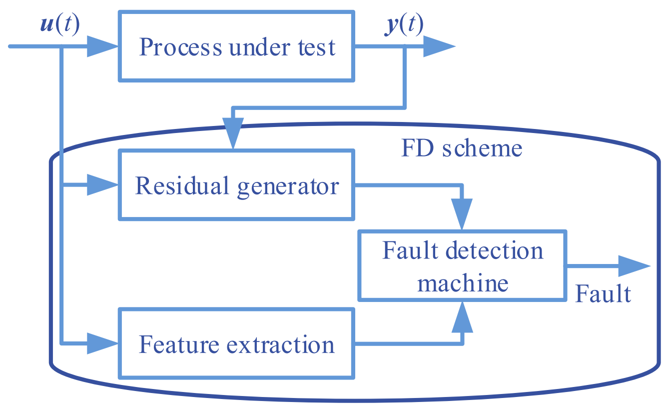

Fig. 8. General framework of FD for wind converter [107].

[75], model based method [113] and pattern recognition based methods [44,119,120] for DFIG and PMSG WECSs.

Karimi et al. [75] proposed a "FPGA in the loop" based single-switch fault detection method for WPC in DFIG configuration. The pole voltage estimator and corresponding diagnosis rules are implemented via analyzing power flow in converter which is characterized for both open-circuit and short-circuit fault of power switches. Although it achieves fast detection time within 10 μs, it only identifies the fault leg and cannot locate the fault switch. Furthermore, it requires additional pole voltage detection circuit and FPGA based process module, which leads to the increase in system complexity and implementation cost.

With regard to dealing with multiple faults, Jlassi et al. [113] proposed a model-based method for diagnosing open-circuit of the BTB converter in PMSG based WT. The Luenberger state observer derives from the joint dynamic model of generator-side and grid-side converters, which is used to obtain the desired estimations. The current form factor (CFF) is calculated from measured and observed currents of each phase respectively. As the open-circuit fault would influence the behaviors of CFFs, the residual between measured and observed CFFs is used to detect and identify faulty leg. The diagnosis is achieved within one fundamental current period. However, it suffers from the model uncertainty because of the average model of WPC. In addition, the robustness of the algorithm is also influenced by the detection threshold.

In [119], a fault detection and localization method is proposed for DFIG converter. It adopts the load current analysis and average value of current to detect both single and double open-switch faults. As it analyzes variables in control loop, no additional hardware is required. However, the measurements in WPC are influenced by the variation of wind power and reactive power control. Meanwhile, the detection thresholds are set empirically in accordance with the characteristics of WECS.

Freire et al. [44] proposed a general framework for open-circuit fault of full-scale converter in PMSG system, where fault detection and fault identification are implemented by making use of the derivative of the absolute current Parks vector, current polarity and errors of the normalized current average absolute values. These methods are used to detect faults in both side converters and identify fault switch. This method only demands variables in control loop like the mechanical speed, generator side and grid side current, but several thresholds are required to guarantee algorithm performance.

In terms of the fault of current sensor with null output, literature [120] proposes a real-time and computation-efficient method for diagnosing 2L-BTB converter in PMSG. The fault detection and localization are implemented with the average absolute value of the sum of the normalized three phase currents and the average absolute values of the normalized currents. Additionally, this algorithm can also identify faults of power switch and current sensor. Although the computational burden is preferable for real-time analysis, the current signal processing based method may suffer from system transients and detection thresholds, which are influenced by operational condition and system performance.

3.3.3. *Diagnosis of 3L-NPC-BTB converter*

In high power WTs like 5-8 WM direct-drive system, the 3L-NPC-BTB configuration is a promising technique which is adopted by various products including ABB PCS6000, Sungrow WG7500, Areva M5000. Compared with 2L-BTB configuration, 3L converter obtains one more output voltage level and less dv/dt stress, which make it become one of the most commercialized multi-level converters in PMSG wind applications. Research into open-circuit fault diagnosis methods for 3L-NPC converter is presented in several Refs. [55,130,126].

Since current pattern of normal operating condition is different from that of faulty conditions, Choi et al. [126] presented a fault detection method for an open switch fault in a single switch for a grid-connected NPC inverter by using the radius of the current patterns. This method is advantageous in that it does not require additional sensors and avoids complex calculations. The open-switch fault can be detected within half of the fundamental period and located within two fundamental periods. Although it is appropriate for inverters or rectifiers considered independently, it cannot be applied to both side converters due to that current patterns of the rectifier are different from those of the inverter.

As rectifier is an essential part of BTB converter in WECS, Lee et al. [55] proposed a FD method for open-circuit fault by considering open-switch fault in both side converters simultaneously. By the comprehensive analysis of the power flow behaviors in each IGBT modules, several diagnosis variables are defined such as the time of the zero range and two detection parameters. It also consists of two procedures of detecting fault side converter and identifying fault leg. With predefined algorithm parameters, it detects open-switch of both upper and bottom IGBTs in 3L-NPC-BTB converter. However, these parameters are highly dependent on the system configuration, component performance and operational condition, which contain numerical uncertainties. Furthermore, it only detects open-circuit fault of upper-side and lower-side and cannot locate the faulty switch.

3.3.4. *Fault diagnosis of MMC*

The MMC is a kind of state-of-the-art multilevel converters and is receiving great interest from the wind energy industry. It delivers an output voltage with several levels and smaller output filter. They are commonly classified as NPC, flying capacitor converter, and the cascaded H-bridge modular multilevel converter [21]. Since a number of power semiconductors are used and each one may be considered as a potential failure component. FDIs for MMC are essential to detect and locate its component failures within limited time. The diagnosis methods are presented for both PMSG and DFIG WTs, which aim at handling the open-circuit or short-circuit fault of submodular and parametric drift of capacitors [114–116,121,122].

A data-mining based method [121] is proposed for diagnosing multiple parametric fault of MCC capacitor in DFIG wind energy system. The approach consists of dynamical feature generation, auto-adaptive dynamical Clustering, and Classifier learning and updating. In this method, capacitor degradation is considered as a continuous drift of the normal operating condition over time. It is implemented online monitoring and detecting multiple capacitor degradation, but no exact detection time is defined in both simulation and experiment. In [122], a method for detecting open-switch faults is proposed for three-parallel converter in PMSG based wind turbines. Pattern recognition and neural network (NN) are utilized to generate and classify features of three phase current measurements. Three feature parameters are defined and calculated in the stationary $d-q$ frame of three phase currents. But it requires training algorithm to obtain numerous parameters, and this requires complex computation and historical data.

The model based diagnosis methods are adopted to detect open-circuit in MMCs. Shao et al. [114] presented a FDI method for open-circuit faults of power semiconductor devices in a MMC. The sliding mode observer (SMO) is designed to generate circulating current residuals with measurements, in which an injection term based on the observer is introduced to estimate model uncertainties and disturbances. Moreover, it can be implemented in a FPGA to achieve location time within 50 ms. By analyzing failure characteristics of electronic submodules in the MMC, MMC fault can be detected by comparing the measured the measured inner difference current and the estimated inner difference current with a KF [115]. This method requires additional sensors and relatively long detection time. To deal with these issues, Liu et al. [116] presented a fault detection and localization method based on a nonlinear adaptive observer for both open-circuit faults and short-circuit faults of a MMC. The nonlinear adaptive observer is utilized to estimate the MMC current behaviors under normal and faulty operating conditions. The fault characteristics are required in this method to design detection variables and generate diagnosis features.

4. Comparative study on fault diagnosis of wind converter

Fault diagnosis of wind converter is an emerging issue due to that the availability and reliability of power electronic converter are becoming more and more critical with the increase of power rating and operating years of WECS. Since the first method [75] was presented by FPGA implementation of real-time fault diagnosis of DFIG converter, plenty of work has been proposed to detect and locate component fault for numerous converter configurations. A comparison of the state-of-the-art methods is presented in Table 5 including feature extraction method, fault detection method, fault types, detection time, the number of faults and converter types. A detailed comparison is presented for both model based and pattern based methods.

4.1. Algorithm comparison

Wind converter FDs are required to detect the failure occurrence timely and to locate the failure component accurately. At present, there is no state-of-the-art work on diagnosis of component failure mechanism. For example, the gate driver malfunction and IGBT chip failure are considered as open-circuit or short-circuit fault of power switch. Methods reviewed in this paper are proposed for numerous converter topologies and all of them perform with acceptable efficiency and performance. However, they cannot be easily implemented in the same laboratory prototype to compare the detection performance. The quantitative analysis of detection time and the number of faults are generated from each reference, and the qualitative analysis is presented from the aspect of model complexity, multiple fault diagnosis and additional hardware requirement.

4.1.1. Model complexity

Model based algorithms require physical models of the power converter to generate variable estimations. A well-defined model can be used to detect and identify arbitrary faults of components and sensors in wind converter. Moreover, it allows multiple fault

Table 5
Summary of wind converter FDs.

Feature extraction method	FD method	Fault types	Detection time	Number of faults	Converter & WT type
Spectrum analysis [117]	Limiting Checking	Open-circuit fault	Within 90% of the fundamental period	Multiple fault	Diode based rectifiers, PMSG
Fast Fourier transform, average of voltages [118]	Limiting Checking	Open circuit	Not defined	Multiple fault	Diode based rectifiers, PMSG
Pole voltage estimator [75]	Limiting Checking, look-up table	Short/open-circuit	Within 10 μs	Fault leg	2L-BTB, DFIG
State estimator [113]	Residual analysis, look-up table	Open-circuit	within 1 fundamental periods	Multiple faults	2L-BTB, PMSG
Current Parks vector [44]	Limiting Checking, look-up table	Open-circuit	Within 0.5 fundamental periods	Single open-circuit	2L-BTB PMSG
Average of the phase currents [119]	Limiting Checking, look-up table	Open-switch	Fast but not defined	At most 2 open-switch	2L-BTB, DFIG
Normalized phase currents [120]	Limiting Checking	Current sensor fault with null output	Within 0.5 fundamental periods	Single sensor	2L-BTB, PMSG
Zero current pattern [55]	Limiting Checking, look-up table	Open-switch	Fast but not defined	Single switch	3L-NPC-BTB, PMSG
Voltage residuals [121]	Hybrid dynamic classifier	Parametric degradation of capacitor	Online detection but not defined	Multiple drift faults	MCC, DFIG
$d-q$ transformation [122]	NN	Open-circuit	Within 1.5 fundamental periods	At most 2 open-switch	Multiple Cell, PMSG
SMO [114]	Residual analysis	Open-circuit	less than 50 ms	Single fault	MMC
KF [115]	Residual analysis	Submodule open-circuit	Locating fault Within 7 fundamental periods	Multiple fault	MMC
Adaptive observer [116]	Limiting Checking, residual analysis	Submodule open-circuit/short-circuit	Within 1 fundamental period	Single fault	MMC, PMSG

diagnosis and real-time localization. The current observer [113], SMO [114], KF [115] and adaptive observer [116] are all involved in complex modeling and calculation. From Table 5, it is clear to find that the detection time of model based methods is relatively longer than pattern based FDs. However, the AI based methods such as NN [122] and hybrid dynamical classifier [121] are implemented with several procedures including feature definition, clustering generation, classifier training and updating as well as online detection. In these procedures, a large amount of historical operating data is used to construct classes and update classifiers.

Signal processing FDs, one branch of the pattern based methods, are proposed for all kinds of the converters. These approaches are derived via fault characteristics of converter faulty conditions. As the relationship between detection variables and fault components is listed in a table, the performance is highly dependent on the fault features. Consequently, the first procedure of pattern based FDs is to investigate system behaviors of different component failure. Then the corresponding detection variables and thresholds are generated via certain features and system parameters. The performance of these methods is affected by fault propagation and closed-loop control. Meanwhile, the multiple fault diagnosis should be further expanded by investigating the relationship between fault behavior and detection variables.

4.1.2. Multiple fault diagnosis

Open-circuit fault of IGBT and degradation fault of passive devices do not cause serious damage to the converter [131], but it will affect the behaviors of other side converter and feedbacks in control loop. Certain component fault in one-side converter may cause faulty behaviors of current or voltage in other side converter. The methods in [117,118] detect and locate multiple faults in the same side converter such as rectifier, boost chopper and single phase inverter. It cannot handle multiple faults in both side converters simultaneously. Similarly, the fault-tolerant scheme for DFIG converter [119] detects at most two open-switch faults occurring in the same side converter. Model based method in [113] detects multiple faults by modeling both side converters as a state space equation. Methods proposed in [115] detect two open-switch faults in one submodule and can be extended to detect multiple faults in arbitrary submodule unit. However, the coupling effects between rotor side and grid side converters are not taken into consideration, which would affect the FD performance significantly. For multi-parallel converter in high-power WTs, the AI based method in [121,122] can detect and locate all the faults in both side converters on the basis that all historical data of faulty operating conditions is available and fault features are robust to operating disturbances.

4.1.3. Additional hardware requirement

FDs requiring more state variables [115,121] are usually excluded, because additional voltage or current sensors and ADCs increase the system cost and structural complexity and even bring unknown disturbances into wind converter [132]. Most FDs utilize quantities which are available in the main control system such as phase current [44,55,75,113,117,119,120,122], circulating current [114], submodule unit current [116], input or output voltage [117,118], pole voltage [75], mechanical speed [44], angular frequency [118], and reference signals [116]. The current based FDs are widely adopted since they are independent of the system parameters.

4.2. Challenges in designing FDs

According to the literature reviews available related to issues of fault diagnosis, the researches on fault analysis of WPC include failures statistics [12], physics-of-failures, the root-cause [18,37] and IGBT module failures [46,133]. The proposed algorithms in Table 5 are implemented on laboratory prototype or simulation analysis under well-defined stress conditions. Most FDs depend on the predefined thresholds to detect fault and meet the requirements in Subsection 3.2. Furthermore, issues in Subsection 4.1 are essential for developing wind converter fault diagnosis methods. The algorithm performance and integration efforts should also be taken into consideration.

As numerous topologies and configurations are proposed for high power WTs, the complex configurations also pose great challenges to development of converter FDs. The proposed methods detect faults by monitoring the variation of measurements. WPC is a typical closed-loop system, the component faulty behaviors are delivered by control feedbacks. No instructional tutorials have been addressed for investigating fault dynamics and failure propagation mechanisms in WPC.

4.2.1. Effects of closed-loop control

Closed-loop control of power converter is introduced into WECS to reach the requirements of power quality and performance optimization. Several features must be taken into account in designing converter FDs.

(1) Nonstationary operating condition
Wind turbine has diverse operating points corresponding to variations of wind speed and direction. The converter output power and reactive power also vary with grid-connected requirements. The detection thresholds are required to be robust to these system transients introduced by operating condition variation. Moreover, SP based methods are challenged by the nonstationary state signals in the frequency domain.
(2) Error elimination
Wind converters utilize dual-closed-loop in both side converters. The closed-loop control configurations affect the operating states and force them to track the references. Consequently, errors of currents and voltages caused by component aging or some incipient faults will be significantly reduced to guarantee the desired operation. Thus, fault characteristics are weakened and detection thresholds may fail.

On the whole, the methods in Table 5 (apart from NN in [122] and hybrid classifier in [121]) all require the predefined detection thresholds. But, control effects and their feasibility have been less considered in these methods.

4.2.2. Early fault prediction

The FDs detect failures that have occurred while the fault prediction deals with the impending failure. The state-of-the-art methods focus on detecting and locating exact faulty devices via post-fault behavior analysis. Condition monitoring and early fault prediction help to avoid further catastrophic loss in WECS caused by possible failures of system and components. Fault prediction allows a reasonable time for maintenance preparation.

(1) Operating condition monitoring
CM is an efficient technique to monitor the operational condition of WPC, which can be combined with FD algorithms to achieve superior performance in abnormal operation detection. The fault in circuit board may also trigger intermittent characteristics of circuit failures [134]. When the failure mechanism, fault model and closed-loop effect of incipient and weak fault are clarified, the CM methods can give early warning of abnormal operation and identify system states continuously.
(2) Fault prediction
In the framework of fault prediction, it demands for characteristics of components, operational modes of system as

well as the past and current status of converters. If the prediction model is obtained, the impending fault can be detected earlier through failure prediction, root-cause analysis and prognostic technique.

4.2.3. WPC benchmark

As WPC is a large and complex system, it is hard to perform a comparison of algorithms in Table 5, which is beneficial in the process to find the best scheme to deal with different faults. Currently, most of the proposed methods are implemented in simulation environment and tested in laboratory prototype. The increasing interest in WECSs, coming from both the academia and the industry, will motivate the proposal of a WPC benchmark for FD and fault tolerant control which models the WPC on a system level and provides validation of the robustness and the reliability of FDs. It also includes a fault setup module and provides interface to set faults of the power switch, sensor, actuator and passive component faults. Thus, the researchers work in the field of fault diagnosis can test the proposed method and compare it with other methods under this model.

4.2.4. Application in wind parks

According to our investigation in Dongfang Electric, some wind converter manufacturers like ABB and The Switch have integrated some basic fault diagnosis tools to condition monitoring systems. These systems may generate fault codes by checking certain measurements and trigger corresponding protection. Although numerous FDs have been proposed, most of which are verified in the laboratory prototype and illustrated preferable performance under the experimental setup. But in the real WECS, both system configuration and power capacity differ from the experimental facilities. Moreover, plenty of factors would affect the performance of FDs such as operational environment, wind variation and grid voltage shocks. Thus, several concerns like stability, efficiency, and implementation effort, should be considered in applying the proposed methods to wind parks.

5. Conclusions

The fault diagnosis of wind converter is in continuous development in recent years. It reduces the downtime and maintenance cost of WECS, and improves the system availability and operational safety. This paper has surveyed typical fault modes of the fragile components in wind converter and has provided a comprehensive review of the fault diagnosis methods used for numerous converter topologies. The issues of FDs performance and designing challenges have also been specifically discussed.

As the power rating and density increasing, the failure and availability of wind converter become crucial. Numerous factors directly or indirectly cause the converter failures including severe operational environment, thermal cycling, EMI, etc. The fault modes of fragile components are summarized on the analysis of the state-of-the-art work. Wind converter failures are diverse and mostly are short-circuit, open-circuit and ware-out fault of IGBTs, DC-Link capacitors and passive devices. The sensor faults are different from these components and mainly are offset fault, scaling fault, and measurement perturbation. Typical fault diagnosis methods along with algorithm performance requirements are presented according to the topologies of wind converter. The implementation effort, detection efficiency and algorithm robustness need to be considered in developing an appropriate FD. Both model based and pattern based fault diagnosis methods have been reviewed for diode rectifier based converter, 2L-BTB, 3L-NPC-BTB and MMC.

- The model based methods are used to detect and locate multiple faults in real time on the basis of exact physical models. However, the performance of model-based FD is restrained by the model uncertainty and high nonlinearity. Since the converter contains both discrete and continuous states, it would influence the robustness and stability as well as residual sensitivity to observer and FD detection.
- Pattern based methods need to monitor certain system quantities to identify normal operation and faulty conditions. Thus, these methods utilize several detection variables for rotor side rectifier, DC-Link converter and grid side inverter and are subjected to system transients and load variation. It is difficult to use pattern based methods to detect multiple faults, because different fault modes may lead to similar patterns and operating states.

Generally, the existing FDs detect and identify converter faults on the basis of significant variation of system states. But all cannot well handle the multiple faults and incipient faults. Moreover, the effects of closed-loop control have not been clearly analyzed, which limits the sensitivity and accuracy of FD methods. The future work can be related to condition monitoring, impending fault prediction, benchmark model of wind converter as well as the application in real wind parks.

Acknowledgment

This work is supported in part by the National Natural Science Foundation of China under Grant 61374135.

References

[1] Yaramasu V, Wu B, Sen PC, Kouro S, Narimani M. High-power wind energy conversion systems: state-of-the-art and emerging technologies. Proc IEEE 2015;103(5):740–88.
[2] Saleh SA, Aljankawey AS, Abu-Khaizaran MS, Alsayid B. Influences of power electronic converters on voltage-current behaviors during faults in DGUs–Part I: wind energy conversion systems. IEEE Trans Ind Appl 2015;51 (4):2819–31.
[3] Izadyar N, Ong HC, Chong WT, Leong KY. Resource assessment of the renewable energy potential for a remote area: a review. Renew Sustain Energy Rev 2016;62:908–23.
[4] Hossain MS, Madlool NA, Rahim NA, Selvaraj J, Pandey AK, Khan AF. Role of smart grid in renewable energy: an overview. Renew Sustain Energy Rev 2016;60:1168–84.
[5] Pao LY, Johnson KE. Control of wind turbines. IEEE Control Syst 2011;31 (2):44–62.
[6] Xu J, Li L, Zheng B. Wind energy generation technological paradigm diffusion. Renew Sustain Energy Rev 2016;59:436–49.
[7] Polinder H, Ferreira J, Jensen B, Abrahamsen A, Atallah K, McMahon R. Trends in wind turbine generator systems. IEEE J Emerg Sel Top Power Electron 2013;1(3):174–85.
[8] Chen Z, Guerrero J, Blaabjerg F. A review of the state of the art of power electronics for wind turbines. IEEE Trans Power Electron 2009;24(8): 1859–1875.
[9] Carrasco J, Franquelo L, Bialasiewicz J, Galvan E, Guisado R, Prats M, et al. Power-electronic systems for the grid integration of renewable energy sources: a survey. IEEE Trans Ind Electron 2006;53(4):1002–16.
[10] Blaabjerg F, Liserre M, Ma K. Power electronics converters for wind turbine systems. IEEE Trans Ind Appl 2012;48(2):708–19.
[11] Duran M, Barrero F, Pozo-Ruz A, Guzman F, Fernandez J, Guzman H. Understanding power electronics and electrical machines in multidisciplinary wind energy conversion system courses. IEEE Trans Educ 2013;56(2):174–82.
[12] Ribrant J, Bertling L. Survey of failures in wind power systems with focus on swedish wind power plants during 1997–2005. IEEE Trans Energy Convers 2007;22(1):167–73.
[13] McMillan D, Ault GW. Specification of reliability benchmarks for offshore wind farms. In: Proceedings of the European safety and reliability; 2008. p. 2601–6.
[14] Bala S, Pan J, Das D, Apeldoorn O, Ebner S. Lowering failure rates and improving serviceability in offshore wind conversion-collection systems. In: Proceedings of power electronics and machines in wind applications (PEMWA). IEEE; 2012. p. 1–7.

[15] Hameed Z, Hong Y, Cho Y, Ahn S, Song C. Condition monitoring and fault detection of wind turbines and related algorithms: a review. Renew Sustain Energy Rev 2009;13(1):1–39.
[16] Amirat Y, Benbouzid M, Al-Ahmar E, Bensaker B, Turri S. A brief status on condition monitoring and fault diagnosis in wind energy conversion systems. Renew Sustain Energy Rev 2009;13(9):2629–36.
[17] Guo H, Watson S, Tavner P, Xiang J. Reliability analysis for wind turbines with incomplete failure data collected from after the date of initial installation. Reliab Eng Syst Saf 2009;94(6):1057–63.
[18] Wang H, Liserre M. Transitioning to physics-of-failure as a reliability driver in power electronics. IEEE J Emerg Sel Top Power Electron 2014;2(1):97–114.
[19] Hahn B, Durstewitz M, Rohrig K. Reliability of wind turbines. In: Wind energy. Berlin, Heidelberg: Springer; 2007. p. 329–32. ISBN978-3-540-33865-9.
[20] Qiao W, Lu D. A survey on wind turbine condition monitoring and fault diagnosis-Part I: components and subsystems. IEEE Trans Ind Electron 2015;62 (10):6536–45.
[21] de Freitas TR, Menegz PJ, Simonetti DS. Rectifier topologies for permanent magnet synchronous generator on wind energy conversion systems: a review. Renew Sustain Energy Rev 2016;54:1334–44.
[22] Mahela OP, Shaik AG. Comprehensive overview of grid interfaced wind energy generation systems. Renew Sustain Energy Rev 2016;57:260–81.
[23] Baroudi JA, Dinavahi V, Knight AM. A review of power converter topologies for wind generators. Renew Energy 2007;32(14):2369–85.
[24] Blaabjerg F, Ma K. Future on power electronics for wind turbine systems. IEEE J Emerg Sel Top Power Electron 2013;1(3):139–52.
[25] Njiri JG, Söffker D. State-of-the-art in wind turbine control: trends and challenges. Renew Sustain Energy Rev 2016;60:377–93.
[26] Orlando N, Liserre M, Mastromauro R, Dell'Aquila A. A survey of control issues in PMSG-based small wind-turbine systems. IEEE Trans Ind Inform 2013;9(3):1211–21.
[27] Abdullah Asuhaimi BMZ, Mahmoud Pesaran HA, Azhar BK, Jahanshaloo L, Shariati O. An overview on doubly fed induction generators' controls and contributions to wind based electricity generation. Renew Sustain Energy Rev 2013;27:692–708.
[28] Tripathi S, Tiwari A, Singh D. Grid-integrated permanent magnet synchronous generator based wind energy conversion systems: a technology review. Renew Sustain Energy Rev 2015;51:1288–305.
[29] Lin Y, Tu L, Liu H, Li W. Fault analysis of wind turbines in china. Renew Sustain Energy Rev 2016;55:482–90.
[30] Liu WY, Tang BP, Han JG, Lu XN, Hu N, He ZZ. The structure healthy condition monitoring and fault diagnosis methods in wind turbines: a review. Renew Sustain Energy Rev 2015;44:466–72.
[31] Qiao W, Lu D. A survey on wind turbine condition monitoring and fault diagnosis-Part II: signals and signal processing methods. IEEE Trans Ind Electron 2015;62(10):6546–57.
[32] Ashrafi M, Davoudpour H, Khodakarami V. Risk assessment of wind turbines: transition from pure mechanistic paradigm to modern complexity paradigm. Renew Sustain Energy Rev 2015;51:347–55.
[33] Sinha Y, Steel JA. A progressive study into offshore wind farm maintenance optimisation using risk based failure analysis. Renew Sustain Energy Rev 2015;42:735–42.
[34] Igba J, Alemzadeh K, Durugbo C, Henningsen K. Performance assessment of wind turbine gearboxes using in-service data: current approaches and future trends. Renew Sustain Energy Rev 2015;50:144–59.
[35] Wymore ML, Dam JEV, Ceylan H, Qiao D. A survey of health monitoring systems for wind turbines. Renew Sustain Energy Rev 2015;52:976–90.
[36] de Azevedo HDM, Araújo AM, Bouchonneau N. A review of wind turbine bearing condition monitoring: state of the art and challenges. Renew Sustain Energy Rev 2016;56:368–79.
[37] Fischer K, Stalin T, Ramberg H, Wenske J, Wetter G, Karlsson R, et al. Field-experience based root-cause analysis of power-converter failure in wind turbines. IEEE Trans Power Electron 2015;30(5):2481–92.
[38] Blaabjerg F, Yang Y, Ma K. Power electronics – key technology for renewable energy systems – status and future. In: Proceedings of the 2013 3rd international conference on electric power and energy conversion systems (EPECS); 2013. p. 1–6.
[39] Brunson C, Empringham L, De Lillo L, Wheeler P, Clare J. Open-circuit fault detection and diagnosis in matrix converters. IEEE Trans Power Electron 2015;30(5):2840–7.
[40] Karaagac U, Faried S, Mahseredjian J, Edris AA. Coordinated control of wind energy conversion systems for mitigating subsynchronous interaction in DFIG-based wind farms. IEEE Trans Smart Grid 2014;5(5):2440–9.
[41] Muyeen S, Takahashi R, Murata T, Tamura J. A variable speed wind turbine control strategy to meet wind farm grid code requirements. IEEE Trans Power Syst 2010;25(1):331–40.
[42] Liserre M, Cardenas R, Molinas M, Rodriguez J. Overview of multi-mw wind turbines and wind parks. IEEE Trans Ind Electron 2011;58(4):1081–95.
[43] Yaramasu V, Wu B. Predictive control of a three-level boost converter and an NPC inverter for high-power PMSG-based medium voltage wind energy conversion systems. IEEE Trans Power Electron 2014;29(10):5308–22.
[44] Freire NMA, Estima JO, Marques Cardoso AJ. Open-circuit fault diagnosis in PMSG drives for wind turbine applications. IEEE Trans Ind Electron 2013;60 (9):3957–67.
[45] Freire N, Estima J, Cardoso A. Converters fault-diagnosis in PMSG drives for wind turbine applications. In: Proceedings of the IECON 2010 – 36th annual conference on IEEE industrial electronics society; 2010. p. 403–8.
[46] Choi UM, Blaabjerg F, Lee KB. Study and handling methods of power IGBT module failures in power electronic converter systems. IEEE Trans Power Electron 2015;30(5):2517–33.
[47] Yang S, Bryant A, Mawby P, Xiang D, Ran L, Tavner P. An industry-based survey of reliability in power electronic converters. IEEE Trans Ind Appl 2011;47(3):1441–51.
[48] Fuchs F. Some diagnosis methods for voltage source inverters in variable speed drives with induction machines - a survey. In: Proceedings of the 29th annual conference of the IEEE on industrial electronics society (IECON '03); vol. 2, 2003. p. 1378–85.
[49] Filsecker F, Alvarez R, Bernet S. Comparison of 4.5-kV press-pack IGBTs and IGCTs for medium-voltage converters. IEEE Trans Ind Electron 2013;60 (2):440–9.
[50] Wu R, Blaabjerg F, Wang H, Liserre M, Iannuzzo F. Catastrophic failure and fault-tolerant design of IGBT power electronic converters - an overview. In: Proceedings of the 39th annual conference of the IEEE on industrial electronics society (IECON 2013); 2013. p. 507–13.
[51] Song Y, Wang B. Survey on reliability of power electronic systems. IEEE Trans Power Electron 2013;28(1):591–604.
[52] Murdock D, Torres J, Connors J, Lorenz R. Active thermal control of power electronic modules. IEEE Trans Ind Appl 2006;42(2):552–8.
[53] Lu B, Sharma S. A literature review of IGBT fault diagnostic and protection methods for power inverters. IEEE Trans Ind Appl 2009;45(5):1770–7.
[54] Pei X, Kang Y. Short-circuit fault protection strategy for high-power three-phase three-wire inverter. IEEE Trans Ind Inform 2012;8(3):545–53.
[55] Lee JS, Lee KB, Blaabjerg F. Open-switch fault detection method of a back-to-back converter using NPC topology for wind turbine systems. IEEE Trans Ind Appl 2015;51(1):325–35.
[56] Lai R, Wang F, Burgos R, Pei Y, Boroyevich D, Wang B, et al. A systematic topology evaluation methodology for high-density three-phase PWM AC-AC converters. IEEE Trans Power Electron 2008;23(6):2665–80.
[57] Wang H, Blaabjerg F. Reliability of capacitors for dc-link applications in power electronic converters-an overview. IEEE Trans Ind Appl 2014;50 (5):3569–78.
[58] Alwitt R, Hills R. The chemistry of failure of aluminum electrolytic capacitors. IEEE Trans Parts Mater Packag 1965;1(2):28–34.
[59] Sun Q, Tang Y, Feng J, Jin T. Reliability assessment of metallized film capacitors using reduced degradation test sample. Qual Reliab Eng Int 2013;29 (2):259–65.
[60] Liu DD, Sampson MJ. Some aspects of the failure mechanisms in batio3-based multilayer ceramic capacitors. In: Proceedings of the CARTS International ; 2012. p. 49–61.
[61] Zhao Y, Wei C, Zhang Z, Qiao W. A review on position/speed sensorless control for permanent-magnet synchronous machine-based wind energy conversion systems. IEEE J Emerg Sel Top Power Electron 2013;1(4):203–16.
[62] Jung HS, Hwang SH, Kim JM, Kim CU, Choi C. Diminution of current-measurement error for vector-controlled ac motor drives. IEEE Trans Ind Appl 2006;42(5):1249–56.
[63] Chung DW, Sul SK. Analysis and compensation of current measurement error in vector-controlled ac motor drives. IEEE Trans Ind Appl 1998;34(2):340–5.
[64] Jang JH, Sul SK, Son YC. Current measurement issues in sensorless control algorithm using high frequency signal injection method. In: Proceedings of the conference record of the industry applications conference on 38th IAS annual meeting; vol. 2, 2003. p. 1134–41.
[65] Najafabadi T, Salmasi F, Jabehdar-Maralani P. Detection and isolation of speed-, dc-link voltage-, and current-sensor faults based on an adaptive observer in induction-motor drives. IEEE Trans Ind Electron 2011;58 (5):1662–72.
[66] Summary of wind turbine accident data to 31 december 2014. Tech. Rep.; Caithness Windfarm Information Forum; 2015.
[67] Espinoza-Trejo D, Campos-Delgado D, Bárcenas E, Martínez-López F. Robust fault diagnosis scheme for open-circuit faults in voltage source inverters feeding induction motors by using non-linear proportional-integral observers. IET Power Electron 2012;5(7):1204–16.
[68] Alavi M, Wang D, Luo M. Short-circuit fault diagnosis for three-phase inverters based on voltage-space patterns. IEEE Trans Ind Electron 2014;61 (10):5558–69.
[69] Jayabalan R, Fahimi B. Monitoring and fault diagnosis of multiconverter systems in hybrid electric vehicles. IEEE Trans Veh Technol 2006;55 (5):1475–84.
[70] Kwak S, Kim T, Park G. Phase-redundant-based reliable direct ac/ac converter drive for series hybrid off-highway heavy electric vehicles. IEEE Trans Veh Technol 2010;59(6):2674–88.
[71] Xiong Y, Cheng X, Shen Z, Mi C, Wu H, Garg V. Prognostic and warning system for power-electronic modules in electric, hybrid electric, and fuel-cell vehicles. IEEE Trans Ind Electron 2008;55(6):2268–76.
[72] Murphey Y, Masrur M, Chen Z, Zhang B. Model-based fault diagnosis in electric drives using machine learning. IEEE/ASME Trans Mechatron 2006;11 (3):290–303.
[73] Campos-Delgado D, Espinoza-Trejo D. An observer-based diagnosis scheme for single and simultaneous open-switch faults in induction motor drives. IEEE Trans Ind Electron 2011;58(2):671–9.
[74] Jung SM, Park JS, Kim HW, Cho KY, Youn MJ. An MRAS-based diagnosis of open-circuit fault in PWM voltage-source inverters for pm synchronous motor drive systems. IEEE Trans Power Electron 2013;28(5):2514–26.
[75] Karimi S, Gaillard A, Poure P, Saadate S. FPGA-based real-time power

converter failure diagnosis for wind energy conversion systems. IEEE Trans Ind Electron 2008;55(12):4299–308.
[76] Ribeiro E, Cardoso A, Boccaletti C. Fault-tolerant strategy for a photovoltaic dc–dc converter. IEEE Trans Power Electron 2013;28(6):3008–18.
[77] Ribeiro E, Cardoso A, Boccaletti C. Open-circuit fault diagnosis in interleaved dc-dc converters. IEEE Trans Power Electron 2014;29(6):3091–102.
[78] Geyer T, Schroder S. Reliability considerations and fault-handling strategies for multi-MW modular drive systems. IEEE Trans Ind Appl 2010;46(6): 2442–2451.
[79] Sami M, Patton R. Wind turbine power maximisation based on adaptive sensor fault tolerant sliding mode control. In: Proceedings of the 2012 20th mediterranean conference on control automation (MED); 2012. p. 1183–8.
[80] Diallo D, Benbouzid M, Hamad D, Pierre X. Fault detection and diagnosis in an induction machine drive: a pattern recognition approach based on concordia stator mean current vector. IEEE Trans Energy Convers 2005;20 (3):512–9.
[81] Estima J, Marques Cardoso A. A new algorithm for real-time multiple open-circuit fault diagnosis in voltage-fed PWM motor drives by the reference current errors. IEEE Trans Ind Electron 2013;60(8):3496–505.
[82] Zidani F, Benbouzid M, Diallo D, Nait-Said M. Induction motor stator faults diagnosis by a current concordia pattern-based fuzzy decision system. IEEE Trans Energy Convers 2003;18(4):469–75.
[83] Peuget R, Courtine S, Rognon JP. Fault detection and isolation on a PWM inverter by knowledge-based model. IEEE Trans Ind Appl 1998;34(6): 1318–1326.
[84] Rothenhagen K, Fuchs F. Performance of diagnosis methods for IGBT open circuit faults in three phase voltage source inverters for ac variable speed drives. In: Proceedings of the 2005 European conference on power electronics and applications; 2005. p. 10pp.–P.7.
[85] Sleszynski W, Nieznanski J, Cichowski A. Open-transistor fault diagnostics in voltage-source inverters by analyzing the load currents. IEEE Trans Ind Electron 2009;56(11):4681–8.
[86] An QT, Sun LZ, Zhao K, Sun L. Switching function model-based fast-diagnostic method of open-switch faults in inverters without sensors. IEEE Trans Power Electron 2011;26(1):119–26.
[87] Yu OS, ju Park N, seok Hyun D. A novel fault detection scheme for voltage fed PWM inverter. In: Proceedings of the IECON 2006 - 32nd annual conference on IEEE industrial electronics; 2006. p. 2654–9.
[88] de Araujo Ribeiro R, Jacobina C, Cabral da Silva E, Lima A. Fault detection of open-switch damage in voltage-fed PWM motor drive systems. IEEE Trans Power Electron 2003;18(2):587–93.
[89] Park JH, Kim DH, Kim SS, Lee DJ, Chun MG. C-anfis based fault diagnosis for voltage-fed PWM motor drive systems. In: Proceedings of the IEEE annual meeting of the fuzzy information. Processing NAFIPS '04; vol. 1, 2004. p. 379–83.
[90] Zidani F, Diallo D, Benbouzid M, Nait-Said R. A fuzzy-based approach for the diagnosis of fault modes in a voltage-fed PWM inverter induction motor drive. IEEE Trans Ind Electron 2008;55(2):586–93.
[91] Guan Y, Sun D, He Y. Mean current vector based online real-time fault diagnosis for voltage source inverter fed induction motor drives. In: Proceedings of the IEEE international electric machines drives conference (IEMDC '07); vol. 2. 2007. p. 1114–8.
[92] Kral C, Kafka K. Power electronics monitoring for a controlled voltage source inverter drive with induction machines. In: Proceedings of the IEEE 31st annual power electronics specialists conference (PESC 2000); vol. 1, 2000. p. 213–7.
[93] Charfi F, Sellami F, Al-Haddad K. Fault diagnostic in power system using wavelet transforms and neural networks. In: Proceedings of the 2006 IEEE international symposium on industrial electronics; vol. 2. 2006. p. 1143–8.
[94] Awadallah M, Morcos M. Automatic diagnosis and location of open-switch fault in brushless dc motor drives using wavelets and neuro-fuzzy systems. IEEE Trans Energy Convers 2006;21(1):104–11.
[95] Jain A, Ranganathan V. V_{CE} sensing for IGBT protection in NPC three level converters-causes for spurious trippings and their elimination. IEEE Trans Power Electron 2011;26(1):298–307.
[96] Wang Z, Shi X, Tolbert L, Wang F, Blalock B. A di/dt feedback-based active gate driver for smart switching and fast overcurrent protection of IGBT modules. IEEE Trans Power Electron 2014;29(7):3720–32.
[97] Rodríguez-Blanco M, Claudio-Sánchez A, Theilliol D, Vela-Valdés L, Sibaja-Terán P, Hernández-González L, et al. A failure-detection strategy for IGBT based on gate-voltage behavior applied to a motor drive system. IEEE Trans Ind Electron 2011;58(5):1625–33.
[98] Kim MS, Park BG, young Kim R, seok Hyun D. A novel fault detection circuit for short-circuit faults of IGBT. In: Proceedings of the 2011 twenty-sixth annual IEEE applied power electronics conference and exposition (APEC); 2011. p. 359–63.
[99] Chokhawala R, Sobhani S. Switching voltage transient protection schemes for high-current IGBT modules. IEEE Trans Ind Appl 1997;33(6):1601–10.
[100] Fang J, Li W, Li H, Xu X. Online inverter fault diagnosis of buck-converter BLDC motor combinations. IEEE Trans Power Electron 2015;30(5):2674–88.
[101] Pu XS, Nguyen TH, Lee DC, Lee KB, Kim JM. Fault diagnosis of dc-link capacitors in three-phase ac/dc PWM converters by online estimation of equivalent series resistance. IEEE Trans Ind Electron 2013;60(9):4118–27.
[102] Chen YM, Wu HC, Chou MW, Lee KY. Online failure prediction of the electrolytic capacitor for LC filter of switching-mode power converters. IEEE Trans Ind Electron 2008;55(1):400–6.
[103] Berriri H, Naouar M, Slama-Belkhodja I. Easy and fast sensor fault detection and isolation algorithm for electrical drives. IEEE Trans Power Electron 2012;27(2):490–9.
[104] Foo G, Zhang X, Vilathgamuwa D. A sensor fault detection and isolation method in interior permanent-magnet synchronous motor drives based on an extended Kalman filter. IEEE Trans Ind Electron 2013;60(8):3485–95.
[105] Youssef A, El Khil S, Slama-Belkhodja I. State observer-based sensor fault detection and isolation and fault tolerant control of a single-phase PWM rectifier for electric railway traction. IEEE Trans Power Electron 2013;28 (12):5842–53.
[106] Chakraborty C, Verma V. Speed and current sensor fault detection and isolation technique for induction motor drive using axes transformation. IEEE Trans Ind Electron 2015;62(3):1943–54.
[107] Rodríguez-Blanco M, Vázquez-Pérez A, Hernández-González L, Golikov V, Aguayo-Alquicira J, May-Alarcón M. Fault detection for IGBT using adaptive thresholds during the turn-on transient. IEEE Trans Ind Electron 2015;62 (3):1975–83.
[108] Freire N, Marques Cardoso A. A fault-tolerant pmsg drive for wind turbine applications with minimal increase of the hardware requirements. IEEE Trans Ind Appl 2014;50(3):2039–49.
[109] Freire N, Cardoso A. Fault-tolerant pmsg drive with reduced dc-link ratings for wind turbine applications. IEEE J Emerg Sel Top Power Electron 2014;2 (1):26–34.
[110] Freire N, Marques Cardoso A. A fault-tolerant direct controlled pmsg drive for wind energy conversion systems. IEEE Trans Ind Electron 2014;61(2):821–34.
[111] Karimi S, Gaillard A, Poure P, Saadate S. Current sensor fault-tolerant control for wecs with DFIG. IEEE Trans Ind Electron 2009;56(11):4660–70.
[112] Parker M, Ng C, Ran L. Fault-tolerant control for a modular generator-converter scheme for direct-drive wind turbines. IEEE Trans Ind Electron 2011;58 (1):305–15.
[113] Jlassi I, Estima J, El Khil S, Bellaaj N, Marques Cardoso A. Multiple open-circuit faults diagnosis in back-to-back converters of PMSG drives for wind turbine systems. IEEE Trans Power Electron 2015;30(5):2689–702.
[114] Shao S, Watson AJ, Clare JC, Wheeler PW. Robustness analysis and experimental validation of a fault detection and isolation method for the modular multilevel converter. IEEE Trans Power Electron 2016;31(5):3794–805.
[115] Deng F, Chen Z, Khan MR, Zhu R. Fault detection and localization method for modular multilevel converters. IEEE Trans Power Electron 2015;30(5): 2721–2732.
[116] Liu H, Ma K, Loh PC, Blaabjerg F. Online fault identification based on an adaptive observer for modular multilevel converters applied to wind power generation systems. Energies 2015;8(7):7140–60.
[117] Kamel T, Biletskiy Y, Chang L. Real-time diagnosis for open-circuited and unbalance faults in electronic converters connected to residential wind systems. IEEE Trans Ind Electron 2016;63(3):1781–92.
[118] Kamel T, Biletskiy Y, Chang L. Fault diagnoses for industrial grid-connected converters in the power distribution systems. IEEE Trans Ind Electron 2015;62(10):6496–507.
[119] Duan P, gui Xie K, Zhang L, Rong X. Open-switch fault diagnosis and system reconfiguration of doubly fed wind power converter used in a microgrid. IEEE Trans Power Electron 2011;26(3):816–21.
[120] Freire N, Estima J, Cardoso A. A new approach for current sensor fault diagnosis in PMSG drives for wind energy conversion systems. IEEE Trans Ind Appl 2014;50(2):1206–14.
[121] Toubakh H, Sayed-Mouchaweh M. Hybrid dynamic classifier for drift-like fault diagnosis in a class of hybrid dynamic systems: application to wind turbine converters. Neurocomputing 2016;171:1496–516.
[122] Ko YJ, Lee KB, Lee DC, Kim JM. Fault diagnosis of three-parallel voltage-source converter for a high-power wind turbine. IET Power Electron 2012;5 (7):1058–67.
[123] Rajendran S, Govindarajan U, Senthilvadivelu S, Uandai S. Intelligent sensor fault-tolerant control for variable speed wind electrical systems. IET Power Electron 2013;6(7):1308–19.
[124] Li H, Yang C, Hu Y, Zhao B, Zhao M, Chen Z. Fault-tolerant control for current sensors of doubly fed induction generators based on an improved fault detection method. Measurement 2014;47(0):929–37.
[125] Kamal E, Aitouche A, Ghorbani R, Bayart M. Robust fuzzy fault-tolerant control of wind energy conversion systems subject to sensor faults. IEEE Trans Sustain Energy 2012;3(2):231–41.
[126] Choi UM, Jeong HG, Lee KB, Blaabjerg F. Method for detecting an open-switch fault in a grid-connected NPC inverter system. IEEE Trans Power Electron 2012;27(6):2726–39.
[127] Rajaei A, Mohamadian M, Varjani AY. Vienna-rectifier-based direct torque control of PMSG for wind energy application. IEEE Trans Ind Electron 2013;60 (7):2919–29.
[128] Li S, Haskew T, Swatloski R, Gathings W. Optimal and direct-current vector control of direct-driven pmsg wind turbines. IEEE Trans Power Electron 2012;27(5):2325–37.
[129] Cardenas R, Pena R, Alepuz S, Asher G. Overview of control systems for the operation of DFIGs in wind energy applications. IEEE Trans Ind Electron 2013;60(7):2776–98.

[130] Lee JS, Lee KB. Open-switch fault tolerance control for a three-level NPC/t-type rectifier in wind turbine systems. IEEE Trans Ind Electron 2015;62(2):1012–21.
[131] Choi UM, Lee JS, Blaabjerg F, Lee KB. Open-circuit fault diagnosis and fault-tolerant control for a grid-connected NPC inverter. IEEE Trans Power Electron 2016;31(10):7234–47.
[132] Freire NMA, Estima JO, Cardoso AJM. A voltage-based approach without extra hardware for open-circuit fault diagnosis in closed-loop PWM ac regenerative drives. IEEE Trans Ind Electron 2014;61(9):4960–70.
[133] Wei L, Kerkman R, Lukaszewski R, Lu H, Yuan Z. Analysis of IGBT power cycling capabilities used in doubly fed induction generator wind power system. IEEE Trans Ind Appl 2011;47(4):1794–801.
[134] Correcher A, Garcia E, Morant F, Quiles E, Rodriguez L. Intermittent failure dynamics characterization. IEEE Trans Reliab 2012;61(3):649–58.