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Fault-Tolerant Converter Design for High-Reliability Wind Turbine Drives

Dhananjay Thakur, Amar Nath Pandey, Abdul Shahil Rasidi
Associate Professor, Assistant Professor
Department of Electromechanical Drives
Government Arts College, Krishnagiri, India
Email ID: *Dhananjaythakur65@rediffmial.com, amarnathpande3y@gmail.com, abdulshahilrasidi9j@yahoo.com*

ABSTRACT

In recent decades, wind energy systems have witnessed substantial growth as a sustainable and renewable energy source. The reliability of wind turbine drives is crucial for efficient energy conversion and minimal operational downtime. Power electronic converters play a central role in the electrical interface of wind turbines, and their failure can lead to expensive maintenance and energy production losses. This paper presents a comprehensive review of ***fault-tolerant converter design*** *focused on high-reliability wind turbine drives. We explore converter topologies, fault mechanisms, fault detection and mitigation techniques, redundant design strategies, and the integration of advanced control methods. Additionally, the paper highlights practical challenges, recent developments, and future research directions. Emphasis is placed on making converter systems resilient to faults while maintaining performance and cost effectiveness. The review includes comparison tables and illustrative figures to clarify design trade-offs and reliability metrics.*

KEYWORDS: - *Wind turbine drives, fault-tolerant converter, power electronics, redundancy, reliability, fault detection, modular multilevel converter, reliability design.*

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INTRODUCTION

Wind turbine systems convert mechanical energy into electrical energy by means of power electronics converters. These converters must operate reliably under mechanical stress, fluctuating wind speeds, grid disturbances, and harsh environmental conditions. In addition, the shift towards **permanent magnet synchronous generators (PMSGs)** and **full-scale converter wind turbines** increases the dependency on converter reliability for system uptime. Failure in converter units, such as semiconductor switches, capacitors, or gate drivers, can lead to cascading faults, resulting in expensive unscheduled maintenance or even turbine shutdown. Hence, designing **fault-tolerant converters (FTCs)** has become an essential research area for improving wind turbine system reliability.

The purpose of this review is to overview the state of the art in fault-tolerant converter design for wind turbine drives, examining design strategies, fault diagnosis methods, and reliability metrics. We aim to provide insights for researchers and engineers who want to improve fault tolerance without significantly compromising cost or efficiency.

In Section 2, we discuss the role of converters in wind turbine systems and common fault types. Sections 3 and 4 cover fault detection and tolerance techniques, respectively. Section 5 reviews redundancy strategies, and Section 6 discusses challenges and research directions. Finally, the conclusion summarizes key findings and ongoing problems.

WIND TURBINE DRIVE CONVERTERS AND FAULT MECHANISMS

1. Role of Converters in Wind Turbines

Power electronic converters are a core component in modern wind turbine drive systems, as they enable efficient electrical energy conversion under continuously varying wind conditions. Since wind speed is inherently unpredictable, the rotational speed of the turbine rotor and generator also varies, making direct grid connection impractical in most cases. Converters provide the required interface between the generator and the utility grid, allowing variable-speed operation while maintaining fixed grid frequency and voltage.

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In general, wind turbine systems employ two main converter configurations: **partial-scale converters** used in doubly fed induction generator (DFIG) systems, and **full-scale converters** used in permanent magnet synchronous generator (PMSG) and squirrel-cage induction generator (SCIG) systems.

In **DFIG-based wind turbines**, the stator is directly connected to the grid, while the rotor is connected through a back-to-back power converter rated at approximately 25–30% of the total turbine power. This partial-scale converter consists of a rotor-side converter (RSC), a DC-link capacitor, and a grid-side converter (GSC). The RSC controls the rotor currents to regulate active and reactive power, whereas the GSC maintains DC-link voltage and ensures grid compliance. The advantage of this configuration is lower converter cost and reduced losses due to smaller rating. However, because the stator is directly connected to the grid, DFIG systems are more sensitive to grid disturbances, and converter faults can lead to severe stress on the generator windings.

In contrast, **full-scale converter systems** completely decouple the generator from the grid by placing a power converter between the generator terminals and the grid. This approach is commonly used with PMSGs and SCIGs. The full-scale converter typically consists of an active rectifier on the generator side, a DC-link stage, and a voltage source inverter (VSI) on the grid side. Since the entire generated power flows through the converter, full-scale systems allow wide-speed operation, improved fault ride-through capability, and better control over power quality. However, the higher converter rating increases component stress and raises reliability concerns, making fault-tolerant design more critical.

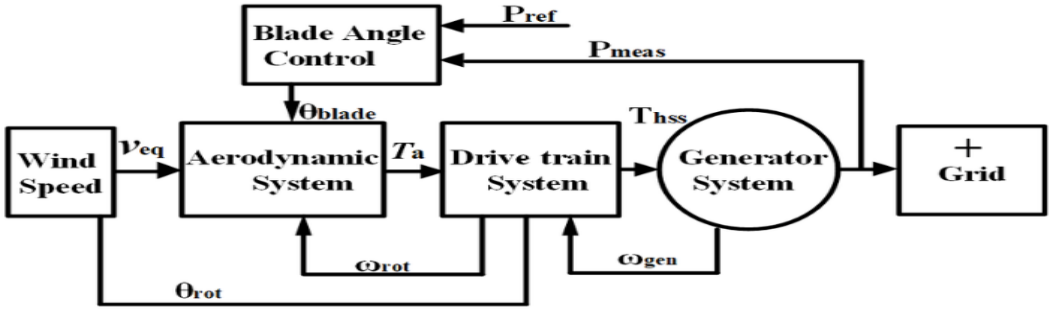


Figure 1: Typical wind turbine drive block diagram

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COMMON FAULT TYPES

Power electronic converters in wind turbine drive systems are exposed to electrical, thermal, and mechanical stresses due to variable wind conditions, frequent load changes, and harsh operating environments. Over time, these stresses can lead to different types of faults within the converter. In general, converter faults can be broadly classified into **semiconductor faults**, **passive component faults**, and **control and sensing faults**. Each category affects system performance and reliability in a different manner.

1. Semiconductor Faults

Semiconductor devices such as **IGBTs, MOSFETs, and diodes** are the most critical and failure-prone components in wind turbine converters. These devices operate under high switching frequencies and experience significant thermal cycling, especially in full-scale converters where the entire generated power flows through the converter.

Semiconductor faults are typically categorized as **open-circuit faults** and **short-circuit faults**. Open-circuit faults often occur due to bond wire lift-off, solder joint fatigue, or gate driver malfunction. When an open-circuit fault occurs, the affected switch stops conducting, leading to current imbalance, increased harmonic distortion, and torque ripple in the generator. Although open-circuit faults may not cause immediate system shutdown, they can significantly degrade performance and accelerate aging of remaining healthy components.

Short-circuit faults are more severe and usually result from insulation breakdown, excessive current stress, or improper gate control. These faults cause a sudden surge in current, which can damage the converter and connected equipment if not quickly detected and isolated. In many cases, short-circuit faults trigger protective mechanisms such as fuses or crowbar circuits, leading to turbine shutdown. Due to their destructive nature, short-circuit faults are a major concern in high-power wind turbine converters.

2. Passive Component Faults

Passive components, including **DC-link capacitors, inductors, and transformers**, also play a

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vital role in converter operation and reliability. Among these, DC-link capacitors are particularly vulnerable to aging and degradation. Electrolytic capacitors suffer from electrolyte evaporation over time, while film capacitors may experience dielectric breakdown due to voltage stress and temperature variations.

Capacitor degradation results in increased voltage ripple on the DC-link, which in turn places additional stress on semiconductor devices and control circuits. If left unaddressed, this can lead to cascading failures within the converter. Inductor faults, such as core saturation or winding insulation damage, may occur under high current conditions or due to mechanical vibrations. These faults reduce filtering effectiveness and may cause overheating.

Transformers used in isolation or medium-voltage wind turbine converters can develop winding faults due to insulation aging or moisture ingress, especially in offshore installations. Such faults may lead to partial discharge, reduced efficiency, and eventually complete failure if not detected early.

3. Control and Sensing Faults

Control and sensing faults are often less visible but can be equally detrimental to system operation. These faults include errors in current, voltage, or speed sensors, as well as failures in communication links between control units. Sensor faults may arise from calibration drift, electromagnetic interference, or physical damage, leading to inaccurate measurements.

When control algorithms rely on faulty sensor data, improper switching commands may be generated, causing unstable operation or excessive stress on converter components. Communication faults, such as delays or data loss in digital control systems, can disrupt coordinated control actions, especially in modular or multi-converter systems.

Additionally, software-related faults, including incorrect parameter tuning or unexpected interactions between control loops, may lead to oscillations or reduced fault ride-through capability. Although control and sensing faults do not always result in immediate hardware

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damage, they can significantly reduce system reliability and complicate fault diagnosis.

4. Impact of Faults on Wind Turbine Operation

The impact of converter faults extends beyond the electrical subsystem. Electrical faults can propagate to mechanical components, causing torque pulsations, increased vibration, and mechanical wear in the gearbox and bearings. In wind turbines installed in remote or offshore locations, even minor faults can lead to extended downtime due to delayed maintenance.

Therefore, understanding the nature and behavior of common fault types is essential for developing effective fault detection, isolation, and tolerance strategies. By identifying early fault indicators and designing converters capable of continued operation under fault conditions, the overall reliability and availability of wind turbine systems can be significantly improved.

A survey of field failure data indicates that **semiconductor device failure accounts for over 60%** of converter related outages in wind turbines (Table 1).

Table 1. Common converter fault mechanisms

Fault Mechanism	Typical Cause	Relative Occurrence
IGBT/MOSFET failure	Thermal stress, switching stress	High
Diode failure	Reverse recovery stress	Medium
Capacitor degradation	Aging, voltage ripple	Medium
Control sensor fault	Noise, drift	Low
Gate driver circuit fault	Power supply issues	Low

Understanding such faults is critical in designing converters that either **tolerate** faults without significant degradation or facilitate **graceful degradation** while maintaining safe operation.

FAULT DETECTION AND DIAGNOSIS TECHNIQUES

Fault detection and diagnosis play a vital role in improving the reliability and safety of wind turbine drive converters. Since converters are subjected to continuous electrical and thermal stress, early

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identification of abnormal conditions is necessary to prevent catastrophic failures and reduce maintenance costs. An effective fault detection system allows the converter either to reconfigure its operation or to shut down affected components in a controlled manner. This section discusses commonly used fault detection and diagnosis techniques, including monitoring-based methods, model-based approaches, and emerging machine learning techniques.

1. Monitoring and Sensing Methods

Monitoring and sensing methods are the most widely adopted techniques for fault detection in wind turbine converters due to their simplicity and direct implementation. These methods rely on real-time measurements of electrical and thermal quantities such as voltage, current, and temperature. High-resolution sensors, combined with fast sampling microcontrollers or digital signal processors (DSPs), enable continuous monitoring of converter health during normal operation.

One commonly used approach is **current signature analysis (CSA)**, where phase currents are analyzed for abnormal patterns. Open-circuit faults in power semiconductor switches often cause distortion or imbalance in phase currents, which can be detected by monitoring changes in current amplitude, waveform symmetry, or harmonic content. CSA is attractive because it does not require additional hardware and can be implemented using existing current sensors.

Thermal monitoring is another important sensing-based method. Semiconductor devices and passive components such as DC-link capacitors are sensitive to temperature variations. Thermocouples or embedded temperature sensors are often placed near critical components to monitor junction or case temperature. A sudden temperature rise or abnormal thermal gradient may indicate excessive losses, cooling system failure, or impending device malfunction.

Voltage imbalance detection focuses on monitoring DC-link voltage ripple or phase voltage symmetry. Faults such as capacitor degradation or diode failures often result in increased voltage ripple or unequal phase voltages. These deviations can be detected using threshold-based methods or frequency-domain analysis.

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Although monitoring and sensing techniques provide direct and intuitive fault information, they are vulnerable to measurement noise, sensor drift, and electromagnetic interference. As a result, careful signal conditioning, filtering, and sensor redundancy are often required to avoid false alarms or missed detections.

2. Model-Based Methods

Model-based fault detection techniques utilize mathematical models of the converter and generator system to predict expected behavior under normal operating conditions. By comparing measured signals with model outputs, faults can be detected when deviations exceed predefined thresholds. One widely used approach is the **Extended Kalman Filter (EKF)**, which estimates system states such as currents and voltages in real time. When the estimation error grows beyond acceptable limits, it indicates the presence of a fault. EKF-based methods are particularly useful for detecting sensor faults and parameter variations in wind turbine converters.

Another popular technique involves **observer-based residual generation**. In this approach, a state observer is designed to reconstruct system variables using measured inputs and outputs. The difference between the observed and measured signals, known as the residual, is analyzed for fault detection. Residual patterns can also be used to identify the type and location of the fault.

Model-based methods are generally robust against noise and can detect faults that are not easily observable through direct measurement. However, their performance strongly depends on the accuracy of the system model. Parameter uncertainties, aging effects, and operating condition changes may reduce detection accuracy. Additionally, developing accurate models for complex converter systems can be time-consuming and computationally demanding.

3. Machine Learning Approaches

In recent years, **machine learning (ML)** techniques have gained attention for fault detection and diagnosis in wind turbine converters. ML-based methods can automatically learn patterns associated with healthy and faulty operating conditions from historical or real-time data.

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Support Vector Machines (SVMs) are commonly used for fault classification due to their strong generalization capability and relatively low computational complexity. By extracting features such as current harmonics, voltage ripple, or temperature trends, SVMs can distinguish between different fault types with good accuracy.

More advanced approaches involve **deep neural networks (DNNs)**, including convolutional neural networks (CNNs) and recurrent neural networks (RNNs). These methods can process large datasets and capture complex nonlinear relationships between measured signals and fault conditions. Deep learning models are particularly effective in handling noisy data and overlapping fault signatures.

Despite their advantages, ML-based methods have several limitations. They require a large amount of labeled training data, which is often difficult to obtain for rare fault events. In addition, the decision-making process of deep learning models is not always transparent, making it harder to interpret results and gain operator trust. Computational complexity and real-time implementation constraints also pose challenges for practical deployment.

FAULT-TOLERANT DESIGN STRATEGIES

Fault-tolerant design focuses on maintaining safe and acceptable operation of wind turbine converters after a fault has occurred. Unlike fault detection, which aims at identifying abnormal conditions, fault-tolerant strategies deal with minimizing the impact of these faults on system performance and availability. In wind turbine drive systems, where access for maintenance is limited and downtime is costly, fault tolerance is especially important. The main approaches to fault-tolerant design include **redundancy**, **system reconfiguration**, and **robust topology selection**.

1. Redundant Converter Architectures

Redundancy is one of the most widely used strategies for improving converter reliability. It involves incorporating spare components or subsystems that can replace faulty elements when a failure is detected. By allowing the system to continue operating after a fault, redundancy

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significantly reduces downtime and prevents complete system shutdown.

Redundant architectures can be implemented at different levels, ranging from full converter duplication to selective backup of critical components. The choice of redundancy level depends on cost constraints, reliability requirements, and system complexity.

1. Full Redundancy

In full redundancy, an entire converter module or subsystem is duplicated and kept available as a backup. When a fault occurs in the primary converter, the system automatically switches to the redundant unit, allowing uninterrupted operation. This approach is often used in high-power or offshore wind turbines, where maintenance costs are extremely high and reliability is a top priority. The main advantage of full redundancy is **high system reliability**, as the backup unit can immediately take over all functions of the faulty converter. It also simplifies fault handling, since the faulty module can be completely isolated without affecting system control.

However, the major drawback of full redundancy is its **high cost**. Duplicating an entire converter increases capital investment, space requirements, and system weight. Additionally, the presence of redundant hardware may increase system complexity in terms of switching mechanisms and protection coordination. As a result, full redundancy is typically reserved for critical applications where maximum availability is required.

2. Partial Redundancy

Partial redundancy provides a more cost-effective alternative by backing up only selected critical components instead of duplicating the entire converter. Common examples include redundant power switches, parallel converter legs, or spare submodules in modular converter designs.

In this approach, when a fault occurs in a critical component, the system isolates the faulty part and activates the redundant element. For instance, in a multi-leg inverter, a faulty switch can be bypassed while a spare leg takes over its function. Partial redundancy offers a good balance between reliability improvement and cost reduction.

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The main advantage of partial redundancy is its **lower cost** compared to full redundancy, making it suitable for commercial wind turbine systems. It also allows more flexible design options, especially in modular converter structures.

However, partial redundancy introduces **additional control complexity**. The control system must detect the fault, identify the faulty component, and reconfigure the converter operation accordingly, often in real time. Ensuring stable operation during and after reconfiguration is challenging, particularly under varying wind and grid conditions.

Table 2. Redundancy approaches in converter design

Redundancy Type	Cost Impact	Reliability Improvement	Control Complexity
No redundancy	Low	None	Low
Partial redundancy	Medium	Moderate	Medium
Full redundancy	High	High	High
Distributed redundancy	Medium	High	High

2. Reconfigurable Converter Systems

Reconfigurable converter systems are designed to maintain operation by modifying their internal structure when a fault occurs. Instead of completely shutting down the wind turbine, these systems isolate faulty segments and reroute the power flow through healthy components. This capability is particularly valuable in wind energy applications, where uninterrupted operation and reduced downtime are critical.

A well-known example of a reconfigurable architecture is the **modular multilevel converter (MMC)**. MMCs consist of multiple submodules connected in series and parallel combinations to generate the required output voltage. Each submodule typically includes power switches, capacitors, and bypass circuits. When a fault is detected in one submodule, it can be electrically bypassed while the remaining healthy submodules continue operating. This allows the converter to deliver power at a slightly reduced voltage level rather than experiencing a complete shutdown.

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Reconfigurable systems also include multi-leg and multi-phase converters, where additional legs or phases can be activated in case of failure. Such designs provide flexibility in redistributing currents and maintaining balanced operation even under fault conditions. However, this flexibility comes at the cost of increased hardware complexity and more sophisticated control requirements. One of the main challenges in reconfigurable converter systems is the **speed of reconfiguration**.

Fault isolation and topology adjustment must be completed within a very short time to avoid excessive current surges, voltage spikes, or loss of synchronization with the grid. Delayed reconfiguration can result in system instability or secondary faults in healthy components. Therefore, fast fault detection and high-speed switching devices are essential for effective reconfiguration.

3. Robust Control Techniques

Robust control techniques play a key role in ensuring stable and reliable operation of wind turbine converters in the presence of faults and parameter variations. Unlike conventional control methods that are designed for nominal operating conditions, robust control strategies can tolerate uncertainties caused by component aging, temperature variations, or partial failures.

Fault-tolerant control (FTC) algorithms are specifically designed to maintain system performance after a fault occurs. These algorithms modify control references, switching patterns, or modulation schemes to compensate for faulty components. For example, in the event of an open-circuit fault in a converter leg, an FTC algorithm may redistribute currents among the remaining healthy legs to reduce torque ripple and maintain acceptable power quality.

Adaptive sliding mode control is another robust control approach that has gained attention for wind turbine applications. Sliding mode control offers strong robustness against parameter uncertainties and external disturbances. By adapting control gains in real time, adaptive sliding mode controllers can handle changing system dynamics due to faults or degradation. However, issues such as chattering and increased switching losses must be carefully managed.

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The main advantage of robust control techniques is their ability to maintain stability without relying solely on hardware redundancy. However, their effectiveness depends on accurate fault information and sufficient computational capability, which can increase system complexity and implementation cost.

4. Use of Wide Bandgap Semiconductors

The adoption of **wide bandgap (WBG) semiconductor devices**, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), has emerged as an important trend in fault-tolerant converter design. Compared to traditional silicon-based devices, GaN and SiC devices offer higher breakdown voltage, faster switching speed, and improved thermal performance.

The higher thermal tolerance of WBG devices allows converters to operate at elevated temperatures without significant performance degradation. This reduces thermal stress and slows down aging processes, indirectly improving converter reliability. Faster switching capability also enables more efficient modulation techniques and reduced passive component size, contributing to compact and robust converter designs.

However, the use of WBG devices introduces new challenges. High switching speeds can lead to increased electromagnetic interference (EMI) and voltage overshoots, which may negatively affect insulation and neighboring components. In addition, thermal management becomes more critical, as localized hot spots can still cause premature failure if not properly addressed.

Although WBG semiconductors do not directly provide fault tolerance, their improved performance and reliability characteristics support the development of converters that are more resilient to stress and degradation. As device costs continue to decrease, GaN and SiC technologies are expected to play a growing role in high-reliability wind turbine drive systems.

CASE STUDIES IN FAULT-TOLERANT CONVERTER DESIGN

Here we discuss practical implementations and evaluation of fault tolerance in wind turbine converters.

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1. Modular Multilevel Converter (MMC)

MMC technology divides a converter into submodules, each contributing to the output voltage. Fault tolerance is achieved by bypassing faulty submodules via built-in switches.

Key benefits:

- Scalable architecture
- Fault isolation without full shutdown

However, increased control complexity and cost remain challenges.

2. Dual Active Bridge (DAB) Converters

DAB converters with bidirectional power flow can be designed with phase-shift control, which allows certain faults to be bypassed. They are suitable for medium voltage applications but require complex control and protection strategies.

3. Redundant Parallel Converters

In this approach, multiple converters operate in parallel. If one fails, the remaining ones share the load.

Advantages:

- Increased reliability
- Load sharing reduces stress

Challenges include current balancing and synchronization.

RELIABILITY METRICS AND EVALUATION

Converter reliability is often quantified using the **Mean Time Between Failures (MTBF)** and **Failure Rate (λ)**.

1. Evaluating MTBF

MTBF is affected by:

- Semiconductor device life
- Thermal cycling
- Operating environment

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Using reliability block diagrams (RBD), designers can estimate system reliability based on component MTBF values.

2. Failure Modes and Effects Analysis (FMEA)

FMEA systematically identifies potential failure modes, their effects, and severity. Coupled with probabilistic risk assessment, it helps prioritize design improvements.

IMPLEMENTATION CHALLENGES

Despite progress, fault-tolerant converter design faces several challenges:

1. Cost vs. Reliability Trade-off

Higher reliability often means more redundancy or robust components, which increase cost. Optimizing this balance is difficult in competitive energy markets.

2. Control System Complexity

Fault-tolerant control algorithms require real-time decision making and fast actuators. Implementation on robust hardware raises design complexity.

3. Environmental Stress

Wind turbines operate outdoors under temperature swings, humidity, and mechanical stress, which accelerates aging and complicates reliability prediction.

4. Lack of Standardized Testing Procedures

Standard tests for fault tolerance under field conditions are limited, making it hard to benchmark different designs.

FUTURE RESEARCH DIRECTIONS

To further enhance fault-tolerant design for wind turbine drives, future research can focus on:

- **AI-powered predictive maintenance**, using real-time data to forecast failures before they occur.
- **Improved redundancy optimization algorithms** to balance cost and reliability.
- **Integration of SiC and GaN devices** at higher power levels.
- **Development of industry standards** for fault tolerance evaluation.

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CONCLUSION

Fault-tolerant converter design is essential for improving reliability in wind turbine drives. The increasing complexity of power electronics in wind turbines has made reliability a central design concern. This review examined common fault mechanisms, detection methods, redundancy strategies, and practical implementations. Design approaches such as partial redundancy, reconfigurable systems, and robust control strategies can significantly enhance reliability.

However, challenges remain in cost optimization, control complexity, and standardized assessment. Continued research in AI-based predictive diagnostics and next-generation semiconductor technologies could offer further improvements. This paper contributes a consolidated perspective for researchers and practitioners to evaluate and implement fault-tolerant converters in wind energy systems.

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