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Research on Fault Diagnosis of Converters and Sensors in Doubly-Fed Wind Power Generation Systems

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Abstract: Due to harsh environmental conditions like high temperatures, humidity, vibrations, and electromagnetic interference, the power electronic converters and sensors of doubly-fed wind turbines are susceptible to damage and malfunction. This may lead to the failure of other components, cause wind turbines to shut down, reduce wind power generation, and affect the stable operation of the power grid. This paper explores fault diagnosis algorithm integration for doubly-fed wind power systems under grid voltage balance and imbalance conditions, considering system model uncertainties in scenarios involving multiple complex faults in converters and sensors. By combining model-based observers with data-driven deep learning techniques, a hybrid model-and-data-driven fault diagnosis method is proposed to enhance the safety and reliability of doubly-fed wind power generation systems. The study proposes a proportional resonant observer and a hybrid model-data driven algorithm, which are applied to fault diagnosis of converter and sensor systems in both balanced and unbalanced grid conditions. The research is of great practical significance for improving the safety and reliability of doubly-fed wind power generation systems and reducing the operation and maintenance costs. It also provides new ideas for research on wind power system condition monitoring, robust fault observer design, and complex system fault diagnosis.

Keywords: Doubly-Fed Wind Power System; Power Converter; Sensor Failure; Fault Diagnosis

1. Introduction

The doubly-fed induction generator-based wind turbine (DFIG-WT) achieves variable-speed constant-frequency operation and maximum power tracking through back-to-back converter control. With advantages including compact converter design, high energy conversion efficiency, full power control capability, and four-quadrant operation, it has become one of the mainstream models in commercial wind power systems. These turbines are typically installed in remote areas such as mountainous regions, grasslands, Gobi deserts, and offshore locations with harsh natural conditions. Components including blades, gearboxes, generators, power electronic converters, and sensors are exposed to extreme environments characterized by high temperatures, humidity, vibrations, and electromagnetic interference. Such exposure makes them prone to damage and malfunctions, which can compromise other components, cause turbine shutdowns, reduce wind power generation, and disrupt stable grid operations.

Research [1,2] identifies three primary failure categories in wind power systems: mechanical components (45.5%), converter modules (25%), and sensors (14.1%). While mechanical failures account for 45.5% of total failures, converter and sensor malfunctions account for 25% and 14.1% respectively, with their downtime exceeding mechanical failures. Each component may experience simultaneous failures, resulting in complex fault patterns. Unlike mechanical failures requiring shutdowns for repairs, converter and sensor failures can be resolved through topology reset and controller reconfiguration without system shutdown. The effectiveness of these fault-tolerant control strategies depends on accurate diagnostic capabilities. By detecting faulty components through real-time monitoring data before severe damage occurs, operators can implement targeted fault-tolerant measures. This approach not only reduces economic losses from equipment outages but also provides actionable guidance for subsequent troubleshooting and maintenance, ultimately lowering operational costs for wind power systems.

2. Review of Domestic and Foreign Research Status

The classification of fault diagnosis research on converters and sensors of doubly-fed wind power generation systems by scholars at home and abroad is shown in Figure 1. It can be divided into three categories: model-driven, signal-driven and data-driven.

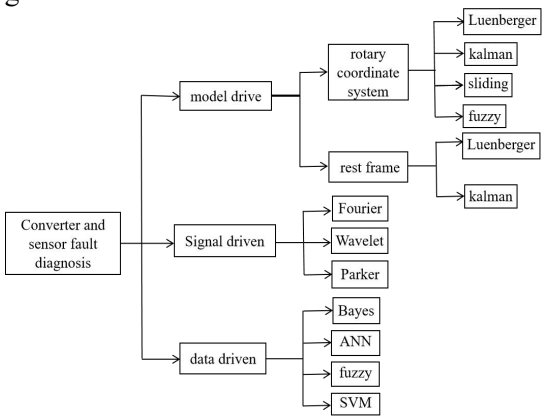

Figure 1. Classification of Fault Diagnosis Methods for Converters and Sensors in Doubly-Fed Wind Power Generation Systems

2.1 Converter Fault

In ack-to-back converters of doubly-fed wind power systems, the AC/DC converter and DC/AC converter are connected through a DC side. Open circuit and short circuit are two common fault types in switching devices. Short circuits trigger protective mechanisms in power electronic components, causing immediate shutdown of equipment. Current research primarily focuses on open-circuit faults in converter switching devices, including model-based approaches, signal analysis, and data-driven methodologies.

The model-driven approach utilizes object model knowledge for state observer design or parameter estimation, generating residual signals that characterize fault features for fault detection and identification. Literature [3] designed a Luenberger state observer based on an induction motor model, calculating residuals between estimated values and actual values, then comparing these residuals with preset thresholds to diagnose single and dual switching tube faults in three-phase inverters. To address the sensitivity of Luenberger observers to model parameter changes, literature [4] employed sliding mode observers to design current observers for induction motors. However, the introduction of sliding modes inevitably causes chattering phenomena, affecting both observer performance and diagnostic accuracy. In literature [3-4], observers were designed based on system models under a rotating coordinate frame, with observed quantities being DC current components. Literature [5] proposed a current observer using AC current signals in a stationary coordinate frame for open-circuit fault diagnosis in permanent magnet synchronous motor systems. Literature [6] applied bilinear observers to rotor-side converter faults in doubly-fed wind turbines, proposing adaptive threshold strategies to enhance algorithm adaptability across operating conditions. Literature [7] and [8] achieved three-phase converter fault diagnosis through feature parameter estimation and threshold comparison. While most works [3-8] focused on single-phase three-phase converter faults involving 6 switching tubes, literature [9] addressed open-circuit faults in 12-switching-tube back-to-back converters by designing state observers with adaptive threshold strategies.

The signal-driven method utilizes various signal processing techniques to extract fault characteristic information from measurement signals such as voltage, current, and rotational speed output by wind power generation systems, then compares these signals against thresholds to achieve fault diagnosis. Literature [10] employs the fast Fourier transform algorithm to perform spectral analysis on the DC-side voltage of three-phase inverters, combining rotor position information to identify faulty switching devices. Literature [11] measures DC-side current in inverters through wavelet packet decomposition, integrating three-phase current signals to diagnose open-circuit faults in converters. Literature [12] utilizes the Parker transform to extract characteristic variations in three-phase currents under faults. Literature analyzes normalized current average values after faults to detect open-circuit faults in back-to-back converters of doubly-fed wind power generation systems.

Model-based and data-driven approaches require prior knowledge such as models or signal patterns, whereas data-driven methods only need large amounts of historical data. Through artificial intelligence algorithms, these methods extract fault characteristics from historical data to achieve fault identification and classification. Researchers have adopted Bayesian networks, artificial neural networks [13], and fuzzy logic for diagnosing open-circuit faults in permanent

magnet synchronous motor inverters, full-power converters, and photovoltaic inverters.

2.2 Sensor Failure

Sensor failures cause measurement deviations from true values, degrade controller performance, and compromise the stability of closed-loop control systems. The complex structure of doubly-fed wind turbine measurement and control systems, combined with variable operating conditions under random wind speeds, makes sensor fault detection particularly challenging. Odgaard et al. developed a standardized wind turbine system for fault diagnosis testing, focusing specifically on sensor failures. Scholars worldwide have employed various methodologies including Kalman filters, fuzzy observers [14], Bayesian networks, and support vector machines to diagnose sensor failures in such systems. However, the turbine model in primarily considers mechanical components while simplifying both generator and converter models to first-order inertial links. By neglecting dynamic generator characteristics, the standard system only incorporates single-loop controllers instead of the classic multi-loop dual-loop vector controller under the rotating coordinate system, which deviates from practical engineering applications. The absence of detailed converter models prevents accurate simulation of power electronic switching tube dynamics and failure scenarios. Furthermore, the sensor failures in the standard system focus solely on rotational speed sensors, ignoring multiple voltage and current sensors utilized in vector control systems.

In sensor fault diagnosis for doubly-fed wind power generation systems, existing research has predominantly focused on motor and power electronics dynamics through observer-based model-driven approaches. Studies employed fuzzy observers and generalized observers to detect rotor current sensors failures while neglecting stator current sensors. References addressed both rotor and stator sensors simultaneously by developing parallel Luenberger observers for doubly-fed induction generator models, though their fixed threshold approach was vulnerable to operating point variations. Reference proposed an adaptive threshold strategy to enhance diagnostic accuracy. To mitigate the sensitivity of existing observers to model parameter changes, reference introduced an improved current observer using model-reference adaptive theory, yet only considered stator sensor failures. All observers in [15] were implemented in rotating coordinate frames, whereas references developed Kalman filters in static coordinate frames for permanent magnet synchronous motor system sensor fault diagnosis.

3. Analysis of Research Status

The following studies on fault diagnosis of converters and sensors in doubly-fed wind power generation systems by domestic and foreign scholars have the following limitations:

(1) In addressing converter failures, researchers typically focus exclusively on either the rotor-side or grid-side converters, with insufficient consideration given to their mutual interactions during simultaneous failures. Sensor malfunctions are generally analyzed through speed, rotor current, and stator current sensors, while voltage sensors and grid-side current sensors are often overlooked. Furthermore, existing studies rarely consider the interplay between converter and sensor failures, and testing procedures frequently disregard factors such as random wind speed variations and model parameter fluctuations. The current literature lacks comprehensive system-level models for doubly-fed wind power generation systems that holistically account for various converter failures, sensor malfunctions, and operational conditions.

(2) Current research primarily focuses on grid voltage balancing conditions, which represent an idealized scenario. In practical power systems, voltage imbalance often occurs due to factors such as unbalanced loads, single-phase renewable energy generation systems, and equipment defects. Under such operating conditions, doubly-fed wind turbines exhibit unbalanced voltage and current fluctuations that generate negative sequence components, leading to signal characteristic variations in converters and sensors under fault conditions. Notably, existing studies have yet to address fault diagnosis for doubly-fed wind power generation systems within unbalanced grid environments.

(3) The voltage and current signals output by doubly-fed wind turbines connected to the power grid are both AC signals. System disturbances caused by parameter variations and model deviations manifest as sinusoidal signals at the same frequency. The model-based methods mentioned in the aforementioned studies, including Luenberger observers, Kalman filters,

and sliding mode observers, are fundamentally proportional observers. These inherently fail to address state estimation challenges under sinusoidal interference conditions. Their inadequate resistance to sinusoidal disturbances ultimately compromises the accuracy of fault diagnosis algorithms.

(4) Both signal-driven and model-driven approaches involve comparing characteristic parameters with predefined thresholds to identify and classify faults through diagnostic logic. However, when dealing with variable operating points in doubly-fed wind power systems and complex fault types, designing appropriate thresholds and diagnostic algorithms becomes particularly challenging. Furthermore, the intricate measurement and control system architecture of doubly-fed turbines makes it difficult for signal-driven methods to effectively diagnose sensor failures.

(5) The data-driven approach suffers from inadequate fault feature extraction and pattern recognition capabilities. Both methods require signal preprocessing to select fault-sensitive signals for feature extraction, which compromises information integrity. Moreover, the limited data processing capacity of algorithms ultimately results in insufficient accuracy of fault diagnosis outcomes. Additionally, data-based approaches are prone to fluctuations in model parameters, demonstrating poor robustness.

4. Research Meaning

Given the limitations in existing domestic and international research, this paper aims to study fault diagnosis algorithms for doubly-fed wind power generation systems under grid voltage balancing and imbalance conditions. The research will address system model uncertainties when multiple types of complex faults occur in converters and sensors. To achieve these objectives, the paper applicant has conducted extensive preparatory work. In literature, a Kalman filter-based fault diagnosis method was proposed for voltage and current sensor failures in doubly-fed wind power systems. To address the sensitivity of Kalman filters to model deviations, literature proposed an improved two-stage Kalman filter algorithm considering model uncertainties. Literature [16] introduced a robust fault-tolerant control strategy for doubly-fed wind turbines using proportional resonance controllers. Meanwhile, literature and employed deep neural networks and random forest methods to diagnose faults in standard wind turbine models, with comparative analyses conducted against other data-driven algorithms.

Traditional model-driven fault diagnosis methods, developed over decades, have established a comprehensive theoretical framework that accounts for model uncertainties. However, these methods fail to account for the common sinusoidal disturbance signals in AC systems during design. Moreover, as the number of faulty components increases and operating conditions become more complex and variable, traditional model-based approaches struggle to achieve accurate fault detection. Data-driven deep learning algorithms can effectively identify and classify complex faults, yet they are vulnerable to uncertainties such as parameter variations and model deviations, resulting in insufficient robustness. Additionally, proportional resonant controllers, by incorporating resonance mechanisms, can effectively suppress sinusoidal interference at specific frequencies in AC systems, making them widely adopted in power electronic renewable energy generation systems.

This research holds significant practical value for enhancing the safety and reliability of doubly-fed wind power systems while reducing operational and maintenance costs. It also provides innovative approaches for state monitoring of wind power systems, robust fault observer design, and complex system fault diagnosis.

5. Fault Diagnosis Scheme

5.1 Hybrid Model and Data Driven

Based on the model knowledge and data information, a fault diagnosis method with robustness to uncertain disturbance of communication system model and excellent feature extraction and pattern recognition ability can be explored.

In AC systems, all output signals are sinusoidal alternating currents. System uncertainties such as parameter variations and model deviations manifest as sinusoidal disturbances of the same frequency, which degrade the estimation performance of AC system observers. The proportional-resonance controller introduces a resonant component (also known as a generalized AC signal integrator), enabling zero-gain tracking of sinusoidal reference signals at

resonant frequencies and demonstrating strong robustness against AC system sinusoidal disturbances. Building on the design philosophy of proportional-resonance controllers, this study improves traditional state observers to develop a novel proportional-resonance observer theory. As shown in Figure 2, the proposed structure enhances the observer's suppression capability for sinusoidal disturbances and improves its estimation performance for sinusoidal AC signals by incorporating a resonant element into the proportional link of the state observer. The research explores the structural design, robustness, stability, and parameter optimization methods of the proportional-resonance observer.

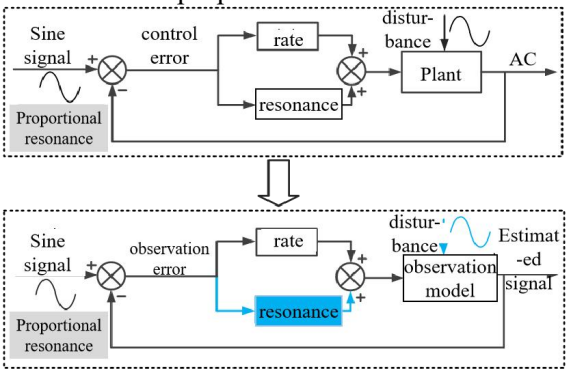

Figure 2. Principle of Proportional Resonator Observer

The model-driven proportional resonant observer incorporates system uncertainties by calculating robust residual signals from the estimated state of the observer output, which can characterize fault characteristics for fault diagnosis. However, when operating conditions change, more components fail, or faults interact with each other, this model-based approach struggles to achieve accurate fault detection. Data-driven deep neural networks, which require no prior knowledge of system models, possess enhanced feature learning and pattern recognition capabilities, enabling identification and classification of various complex faults as a fully data-driven diagnostic method. Nevertheless, performance of data-driven approaches is susceptible to parameter variations and demonstrates poor robustness against model uncertainty disturbances. Therefore, by leveraging the strong robustness of observer-based model methods and the learning capabilities of deep learning data-driven approaches, we explore a hybrid model-data driven fault diagnosis method as shown in Figure 3. For actuator and sensor failures in AC closed-loop control systems, this study investigates feature extraction and utilization based on robust observers, along with network training and testing combining observers and deep neural networks.

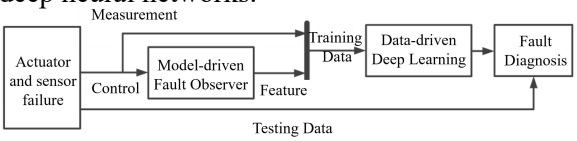

Figure 3. Structure of Fault Diagnosis Method Driven by Model and Data Mixture

5.2 Fault Diagnosis of Wind Turbine

Based on the fault diagnosis method studied, considering the condition of voltage balance and imbalance in the power grid, the robustness and accurate diagnosis of multiple types of complex faults of converters and sensors in the doubly-fed wind power generation system can be realized.

First, based on the proportional resonant observer theory explored, we design a fault observer for doubly-fed wind turbines (DFIG-WT) considering both balanced and unbalanced grid conditions. In the static coordinate system, the voltage and current signals output by DFIG-WT are sinusoidal AC quantities, where parameter variations and model deviations manifest as in-phase sinusoidal disturbances. Under the rotating coordinate system, the electrical signals from DFIG-WT operating in balanced grid conditions exhibit DC components. However, when connected to unbalanced grids, DFIG-WT systems generate additional second harmonic negative sequence components, with corresponding model disturbances appearing as second harmonic sinusoidal variations. To address converter and sensor faults in doubly-fed wind power systems under both balanced and unbalanced grid conditions, we utilize DFIG-WT models in both static and rotating coordinate systems to develop proportional resonant observer-based fault observer designs. This approach enables accurate system state estimation by suppressing sinusoidal disturbances, as illustrated in Figure 4.

Secondly, building upon the model-data hybrid-driven methodology outlined, this study investigates multi-type complex robust fault diagnosis for converters and sensors in doubly-fed wind power systems. As shown in Figure 5, the closed-loop control system architecture of the doubly-fed wind turbine is analyzed to examine the interaction between converter and sensor failures, characterize system output

signals under different fault scenarios, and assess the impact of disturbances including grid voltage imbalance, wind speed variations, and model parameter changes on fault signatures. Crucially, converter and sensor failures directly affect turbine models and measurement values, thereby compromising the estimator's performance. To address this, the study develops a data-driven deep neural network that leverages fault signature extraction from proportional resonance fault estimators, demonstrating the effectiveness of model-data hybrid-driven algorithms in doubly-fed wind power system fault diagnosis.

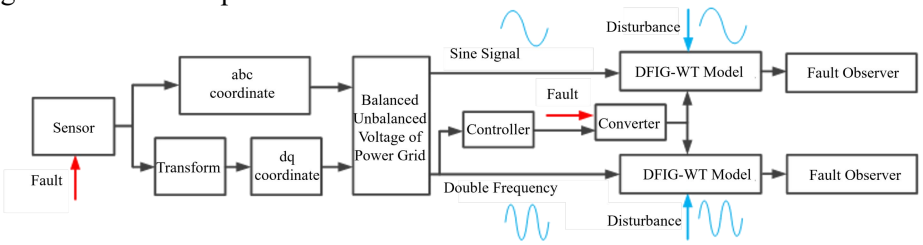

Figure 4. Design Principle of Fault Observer for Doubly-fed wind Power Generation System under Grid Voltage Balance and Imbalance Conditions

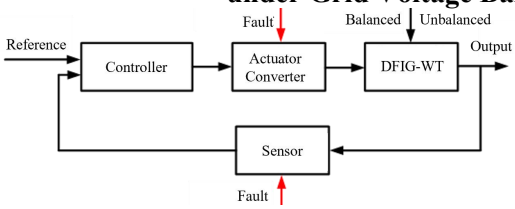

Figure 5. Structure of Doubly Fed Wind Power Generation System under Fault and Disturbance

6. Conclusion

By integrating traditional state observer theory with proportional resonant control theory, robust state estimation under sinusoidal disturbances can be achieved for fault feature extraction in AC systems. When model-driven and data-driven approaches are combined to complement each other's strengths, robust and accurate diagnosis of various complex faults becomes feasible. This paper explores the integration of these theories and methods, proposing a proportional resonant observer and a hybrid model-data driven algorithm. These innovations could subsequently be applied to fault diagnosis of converters and sensors in doubly-fed wind power systems under balanced and unbalanced grid conditions. The research holds significant practical value for enhancing the safety and reliability of doubly-fed wind power systems while reducing operational and maintenance costs.

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