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Strong inverter fault analysis and protection strategy based on advanced diagnostic technology

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Abstract. As a key equipment in the power electronic system, the stability and reliability of the strong inverter directly affects the operation efficiency of the whole power system. However, since the inverter is in the high-voltage and high-current working environment for a long time, fault problems occur frequently, how to effectively diagnose the faults and formulate a reasonable protection strategy has become an urgent technical problem to be solved. The purpose of this paper is to study the fault analysis and protection strategy of strong power inverter based on advanced diagnosis technology. Firstly, the common fault types and traditional diagnostic methods of strong power inverters are reviewed, and their limitations and shortcomings are analyzed. Subsequently, it focuses on the application of signal processing techniques, artificial intelligence algorithms and multi-source data fusion techniques in inverter fault diagnosis, and proposes a fault diagnosis framework that comprehensively utilizes these advanced techniques. Finally, based on the diagnostic results, this paper designs a set of intelligent protection strategies that can realize adaptive protection adjustment according to the fault types, thus improving the operation reliability of the inverter. The research results show that the fault analysis method and intelligent protection strategy based on advanced diagnostic techniques can effectively improve the fault detection accuracy and response speed of the strong power inverter, which provides a strong guarantee for the safe operation of the power system.

Keywords: strong inverter, fault diagnosis, protection strategy, signal processing techniques, artificial intelligence, multi-source data fusion.

1. Introduction

With the rapid development of power electronics technology, strong inverters play an increasingly important role in modern power systems and industrial applications. As the key equipment for converting DC power to AC power, inverters are widely used in solar power, wind power and electric vehicles[1]. However, inverters are prone to various faults in the high-voltage and high-current working environment, and these faults not only affect the normal operation of the equipment, but also may lead to safety hazards in the power system[2]. Therefore, timely and accurate diagnosis of inverter faults and effective protection measures are the key to ensure system stability.

Traditional inverter fault diagnosis methods mostly rely on experience and fixed rules, and these methods usually suffer from slow response speed and low diagnostic accuracy[3]. With the progress of technology, advanced diagnostic techniques, such as signal processing techniques, artificial intelligence algorithms and multi-source data fusion techniques, are gradually applied to inverter fault analysis. These techniques can improve the accuracy and real-time nature of fault diagnosis, which helps to warn of potential faults in advance and deal with them in a timely manner, thus reducing equipment damage and system downtime[4].

Advanced diagnostic techniques show significant advantages in inverter fault analysis, but how to effectively integrate these techniques into practical applications and formulate reasonable protection strategies based on the diagnostic results is still a challenging topic[5]. The purpose of this paper is to study the strong power inverter fault analysis and protection strategies based on advanced diagnostic techniques. Firstly, we will summarize the common fault types of strong power inverters and the shortcomings of their traditional diagnostic methods. Then, we will explore the application of signal processing techniques, artificial intelligence algorithms, and multi-source data fusion techniques in fault diagnosis, and propose a fault diagnosis framework that comprehensively utilizes these techniques[6]. Finally, based on the diagnosis results, intelligent protection strategies are designed to improve the operational reliability of the inverter. Through the research in this paper, it is hoped that new ideas and solutions can be provided for the fault diagnosis and protection of strong inverters, promote the development of related technologies, and provide strong support for the safe operation of power systems.

2. Strong inverter fault types and analysis methods

Strong inverters may experience a variety of faults during operation, and these faults can be categorized into several main types[7]. Common fault types include short-circuit faults, open-circuit faults, overload faults, and over-temperature faults. Short-circuit faults usually occur at the circuit connection points inside the inverter, resulting in an abnormal increase in current; open-circuit faults are caused by circuit breaks or poor connections, resulting in the inverter failing to work properly; overload faults refer to the inverter being subjected to loads exceeding its designed carrying capacity; and over-temperature faults are caused by poor heat dissipation or high ambient temperatures, resulting in the inverter's internal temperature exceeding the safe range[8]. These faults not only affect the performance of the equipment, but also may cause serious impact on the power system.The Fault Detection Threshold Calculation:

$$\text{Threshold} = \mu + k \times \sigma \tag{1}$$

Traditional fault diagnosis methods rely heavily on experience and predefined rules. These methods include experience-based troubleshooting, routine testing and maintenance, and electrical parameter-based fault detection[9]. Empirical troubleshooting methods rely on maintenance personnel's experience with common faults and determine the cause of the fault through observation and manual testing. Routine testing and maintenance involves periodic inspection and replacement of critical inverter components[10]. Fault detection based on electrical parameters identifies anomalies by monitoring parameters such as the inverter's operating voltage, current and power. However, these methods often struggle to provide accurate diagnostic results when faced with complex faults or a mixture of faults.

With the development of technology, advanced diagnostic techniques are gradually being introduced to analyze the faults of strong inverters. These techniques include signal processing techniques, artificial intelligence (AI) and machine learning (ML) algorithms. Signal processing techniques are able to extract useful information and identify potential faults by analyzing the inverter operating signals in real time. Artificial intelligence techniques, especially machine learning and deep learning, are able to build accurate fault prediction models by training on large amounts of fault data. These technologies can handle complex fault patterns and improve diagnostic accuracy and real-time performance. In addition, multi-source data fusion technology combines information from different sensors and data sources to further enhance fault diagnosis. Root Mean Square (RMS) Value for Signal Analysis:

$$\text{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{2}$$

To improve the effectiveness of fault diagnosis, it is often necessary to combine traditional methods with advanced technologies. The integrated application includes the fusion of data-driven diagnostic models and rule engines. Higher diagnostic accuracy can be achieved by analyzing historical fault data, establishing a data-driven fault prediction model, and combining the traditional rule engine for fault determination. The multilevel fault analysis methodology not only considers the operating state of the inverter, but also integrates factors such as environmental conditions and load changes to provide more comprehensive fault analysis and prediction. This integrated application method provides effective support for the timely detection and treatment of strong inverter faults.

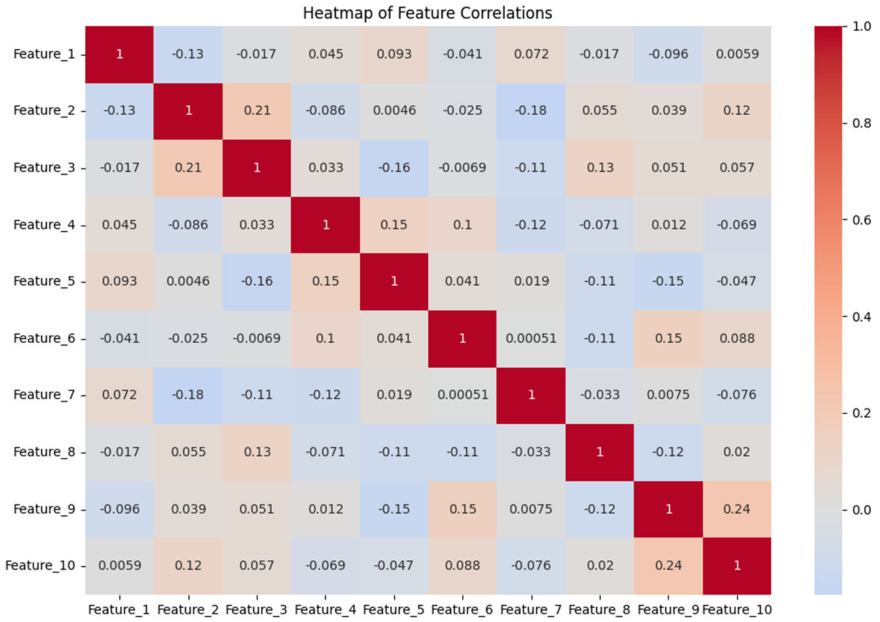
3. Application of advanced diagnostic techniques to inverter faults

In the section "Application of Advanced Diagnostic Techniques in Inverter Faults", we will discuss the application of three key technologies, namely signal processing-based fault diagnosis, artificial intelligence-based fault diagnosis, and multi-source data fusion technology. Signal processing technology analyzes the electrical signal data of inverters to identify fault characteristics and extract relevant information; artificial intelligence technology uses machine learning and deep learning algorithms to train accurate fault prediction models from a large amount of historical data to improve the level of diagnostic intelligence; and multi-source data fusion technology integrates data from different sensors to provide a more comprehensive diagnostic result. The combined application of these three technologies makes inverter fault diagnosis more accurate, efficient, and adaptable to complex operating environments.

3.1 Fault diagnosis based on signal processing

Signal acquisition is the first step in signal processing-based fault diagnosis and involves obtaining raw current, voltage, and other operating signals from a strong inverter. Acquisition systems typically include sensors and data acquisition equipment that can record the dynamic behavior of the inverter in real time. The acquired signals often contain noise and interference, and thus require preprocessing to improve data quality and accuracy of analysis. The preprocessing steps include filtering and de-noising, data smoothing and signal normalization, etc., with the aim of eliminating external interference and system errors and ensuring the reliability of the subsequent analysis.

Time-domain feature analysis is a fundamental method in signal processing techniques to identify fault characteristics by directly analyzing the variation of signals over time. This involves real-time monitoring of inverter current and voltage waveforms to extract statistical features such as mean, variance, and peak values. Time-domain analysis is able to detect transient faults and periodic variations such as peak current anomalies caused by overload or short-circuit faults. By setting thresholds and anomaly detection algorithms, fault modes that are different from normal operating conditions can be recognized,showed in Figure 1 :



	Feature_1	Feature_2	Feature_3	Feature_4	Feature_5	Feature_6	Feature_7	Feature_8	Feature_9	Feature_10
Feature_1	1	-0.13	-0.017	0.045	0.093	-0.041	0.072	-0.017	-0.096	0.0059
Feature_2	-0.13	1	0.21	-0.086	0.0046	-0.025	-0.18	0.055	0.039	0.12
Feature_3	-0.017	0.21	1	0.033	-0.16	-0.0069	-0.11	0.13	0.051	0.057
Feature_4	0.045	-0.086	0.033	1	0.15	0.1	-0.12	-0.071	0.012	-0.069
Feature_5	0.093	0.0046	-0.16	0.15	1	0.041	0.019	-0.11	-0.15	-0.047
Feature_6	-0.041	-0.025	-0.0069	0.1	0.041	1	0.00051	-0.11	0.15	0.088
Feature_7	0.072	-0.18	-0.11	-0.12	0.019	0.00051	1	-0.033	0.0075	-0.076
Feature_8	-0.017	0.055	0.13	-0.071	-0.11	-0.11	-0.033	1	-0.12	0.02
Feature_9	-0.096	0.039	0.051	0.012	-0.15	0.15	0.0075	-0.12	1	0.24
Feature_10	0.0059	0.12	0.057	-0.069	-0.047	0.088	-0.076	0.02	0.24	1

Figure 1 Heatmap of Feature Correlations

Frequency domain analysis is able to identify periodic components and frequency anomalies in a signal by converting a time series signal into the frequency domain for analysis. This process is usually realized through a Fourier transform, which converts a time domain signal into a spectrogram. Frequency-domain analysis can reveal possible frequency-related faults in inverter operation, such as harmonic interference or frequency drift. By analyzing the amplitude and frequency distributions in the spectrum, potential sources of faults can be identified and diagnosed accordingly.

Joint time-frequency domain analysis combines the advantages of the time and frequency domains to provide a dual view of a signal in time and frequency by performing a time-frequency transform (e.g., wavelet transform) on the signal. This method is capable of handling complex non-stationary signals and revealing the characteristics of signal changes in different time periods and frequency ranges. Time-frequency domain analysis is particularly suitable for detecting complex failure modes, such as harmonic disturbances and transient faults in multiple frequency bands. By analyzing the time-frequency mapping, the dynamic behavior of the signal can be more comprehensively understood and the accuracy of fault diagnosis can be improved.

3.2 Artificial Intelligence Based Fault Diagnosis

Artificial Intelligence (AI) techniques play an increasingly important role in fault diagnosis, especially in fault detection and prediction of strong inverters.AI techniques include Machine Learning (ML) and Deep Learning (DL) algorithms, which are capable of learning from large amounts of historical data and building fault pattern recognition models. By automatically extracting features and learning fault characteristics, AI techniques can dramatically improve the accuracy and efficiency of diagnosis. Machine learning algorithms such as Support Vector Machines (SVMs), Decision Trees, and Random Forests, as well as deep learning algorithms such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are commonly used tools.

The core of AI fault diagnosis lies in high quality training data. Data collection includes obtaining operational data such as current, voltage, and temperature from the inverter's sensors and monitoring systems, and recording various fault types and their characteristics when they occur. Data processing includes steps such as data cleaning, feature extraction and data labeling to ensure the accuracy and validity of the data. The quality of the training data directly affects the performance of the AI model, so it needs to be rigorously preprocessed and labeled to improve the training effect of the model.

After the training data is prepared, the next step is to build and train the AI model. Machine learning algorithms identify failure modes and predict the probability of failure by performing classification or regression modeling on the training data. Deep learning algorithms automatically learn complex features and patterns from data by building neural network models. The training process includes selecting appropriate algorithms, tuning model parameters, and evaluating model performance. Through cross-validation and hyper-parameter optimization, the accuracy and generalization ability of the model can be improved so that it can be better applied to practical fault diagnosis.

After the AI model training is completed, it can be applied to real-time fault prediction and decision support. By predicting and analyzing real-time data, AI systems can detect potential failures in advance and provide early warning information. This prediction capability not only helps operations and maintenance personnel take measures in advance to reduce downtime, but also optimizes maintenance strategies and reduces operating costs.The decision support functions of AI technology include automatically generating fault reports, providing maintenance recommendations, and optimizing the troubleshooting process, thus improving the overall reliability and efficiency of the system.

3.3 Multi-source data fusion and fault diagnosis

Multi-source data fusion refers to the integration of multiple data types from different sources to provide more comprehensive and accurate analysis results. In fault diagnosis of strong inverters, it is often necessary to integrate data from current sensors, voltage sensors, temperature sensors, and other monitoring devices. Through data fusion, the measurement information from each sensor can be synthesized to improve the accuracy and reliability of fault diagnosis. This approach can compensate for the lack of information and measurement errors that may exist in a single data source, providing a more comprehensive view of the system state,showed in Figure 2 :

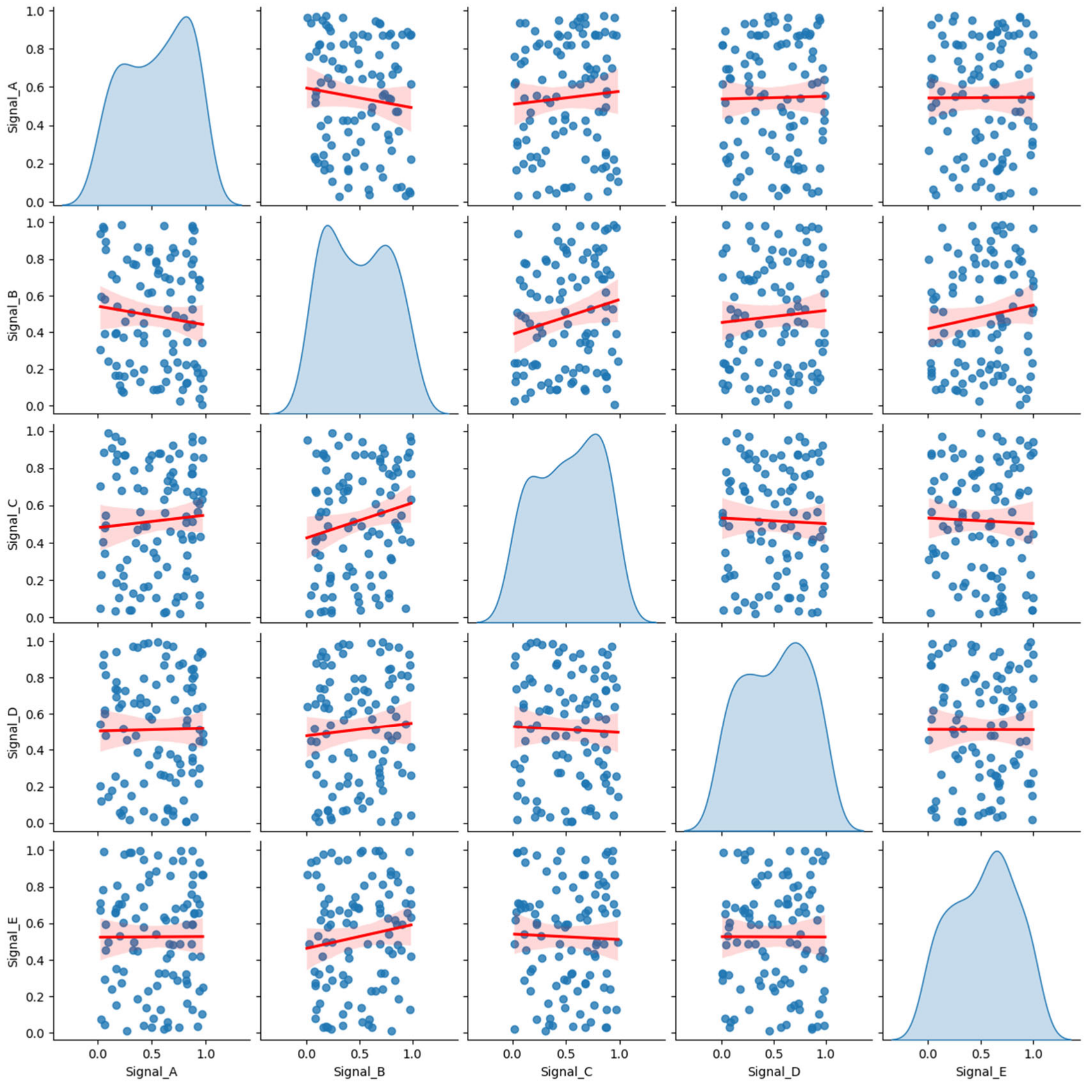


Figure 2 Pairplot of Different Signal Data

Methods to achieve multi-source data fusion include data-level fusion, feature-level fusion and decision-level fusion. Data-level fusion involves the direct integration of raw data from different sensors to form a unified dataset; feature-level fusion is the integration of features extracted from each data source to obtain more representative features; and decision-level fusion is the aggregation of independent diagnostic results to form a final fault judgment. Commonly used data fusion techniques include weighted averaging, principal component analysis (PCA), and Kalman filtering, which can deal with noise and inconsistency in the data and improve the accuracy of diagnostic results.

In the process of multi-source data fusion, data processing and analysis are key steps. The processing includes data cleaning, normalization and denoising to ensure compatibility and consistency across data sources. The analysis phase, on the other hand, extracts useful information from the fused data through the combined application of statistical analysis, pattern recognition and machine learning algorithms. Fused data can reveal fault patterns that are difficult to detect in a single data source and provide more accurate fault diagnosis and prediction results through comprehensive analysis.

In practical applications, multi-source data fusion technology has already achieved remarkable results in inverter fault diagnosis. For example, by fusing multiple data, such as current, voltage, and temperature, an assessment of the comprehensive health status of the inverter can be realized. Some case studies have shown that the application of data fusion techniques can significantly improve the early warning capability and diagnostic accuracy of fault detection, and reduce the false alarm and omission rates. By analyzing these successful cases, effective data fusion strategies can be summarized and provide reference and guidance for future fault diagnosis system design.

4. Strong inverter fault protection strategy

The first step of the fault protection strategy of the strong inverter is to establish an effective fault detection and alarm mechanism. Through real-time monitoring of the operating status of the inverter, the system is able to quickly identify abnormal changes in parameters such as current, voltage and temperature. Once an abnormality is detected, the system will immediately trigger the alarm mechanism to notify the maintenance personnel for inspection and treatment. The alarm mechanism can be set to multiple levels of alerts, including warning, warning and emergency alarms, so that different countermeasures can be taken according to the severity of the fault. The design of the fault detection and alarm mechanism needs to take into account the operating environment and fault characteristics of the equipment to ensure an accurate and timely response to potential problems.

In inverter fault protection, the configuration of protection devices is crucial. These devices include overload protection, short-circuit protection, over-temperature protection, etc. They are able to automatically disconnect the circuit when an abnormality occurs in the inverter to prevent the fault from expanding. The automatic switching function, on the other hand, is able to switch the load to the backup equipment or backup power supply when a fault is detected, ensuring the continuous operation and stability of the system. By setting reasonable protection parameters and selecting appropriate protection devices, equipment damage and system shutdown can be effectively prevented, ensuring the safety and reliability of the power system.

Fault recovery and repair is an important part of the inverter protection strategy. Fault recovery involves repairing and reconfiguring the inverter to restore its normal operating condition. After fault detection and alarm, maintenance personnel need to conduct a detailed inspection of the inverter to determine the cause of the fault and repair it accordingly. The repair process includes replacing damaged components, adjusting system parameters and optimizing operating conditions. After restoration, the system also needs to be functionally tested to ensure that the repair work is effective and the inverter is restored to its normal operating condition.

Regular maintenance and preventive measures are essential in order to improve the long-term stability of the inverter and reduce the incidence of malfunctions. Maintenance measures include regular inspection, cleaning and calibration of inverters and their protection devices to ensure proper operation of the equipment. Meanwhile, preventive measures include monitoring the operational status of the equipment, analyzing fault data and trends, and developing reasonable maintenance plans and contingency plans. By implementing a comprehensive maintenance and prevention strategy, potential problems can be detected in advance, the frequency of failures can be reduced, and the overall reliability and service life of the inverter can be improved.

5. Conclusion

Advanced technologies and methods play a crucial role in fault diagnosis and protection strategies for strong inverters. In this paper, we systematically discuss the application of signal processing techniques, artificial intelligence techniques and multi-source data fusion techniques in inverter fault diagnosis, as well as the measures required to implement effective fault protection strategies.

Signal processing technology provides a reliable tool for fault diagnosis through time-domain analysis, frequency-domain analysis and joint time-frequency domain analysis, and can accurately identify transient faults and complex fault patterns. Artificial intelligence technology utilizes machine learning and deep learning algorithms to extract fault characteristics from a large amount of historical data to achieve efficient fault prediction and intelligent diagnosis. Multi-source data fusion technology improves the accuracy and comprehensiveness of fault diagnosis by integrating data from different sensors and enhances the system's ability to handle complex problems.

In terms of fault protection, the establishment of effective fault detection and alarm mechanisms, the configuration of appropriate protection devices and automatic switching functions, and the implementation of comprehensive fault recovery and maintenance strategies are all key measures to ensure the safe operation of inverters. These strategies not only reduce the risk of faults occurring, but also improve the reliability and operational efficiency of the system. Combining signal processing, artificial intelligence and data fusion technologies, as well as sound protection strategies, can significantly improve the fault diagnosis capability and system safety of strong inverters. In the future, with the continuous progress of technology and the accumulation of application experience, the field of inverter fault diagnosis and protection will usher in a wider range of innovations and developments, providing a stronger guarantee for the stable operation of power systems.

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