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Review of Diagnostic Methods for Open-Circuit Faults in Power Tubes of Three-Phase Inverters

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ABSTRACT
With the widespread application of three-phase inverters in new energy generation, motor drives, and other fields, open-circuit faults in power tubes can lead to system shutdowns, equipment damage, and safety hazards. Therefore, diagnosing faults in power tubes of three-phase inverters is of great significance. Derived from studies conducted by both local and international academics on methods of diagnosing inverter faults, this paper reviews the methods into three categories: signal analysis-based, model-driven, and data-driven. The principles, advantages and disadvantages, and applicable scenarios of each method are introduced. Finally, the current technical bottlenecks and future development trends are discussed.

KEYWORDS
nverter; Power Tube; Open-Circuit Fault; Fault Diagnosis

1 Introduction

As power electronics technology evolves swiftly, Inverters are widely used in various fields including industry,military, and aerospace. In new energy generation, if inverter faults cannot be detected, this will have a direct impact on the system's regular functioning and cause incalculable economic losses and safety hazards. Therefore, it is necessary to conduct research on inverter fault diagnosis methods. A three-phase inverter mainly consists of six switch tubes and six freewheeling diodes (as shown in Figure 1). Inverter faults are mostly caused by switch tube failures, with IGBT faults accounting for a large proportion. According to statistics, the fault probability of power tubes in power equipment is about 34% [1]; in AC speed regulation systems, the fault probability of power switching devices is 38% [2]. Fault varieties like short-circuit and open-circuit faults are mainly observed in inverter power tubes.Short-circuit faults occur in an extremely short time, and generally, a series fast fuse is used to convert power tube short-circuit faults into open-circuit faults, and then fault diagnosis is carried out. After an open-circuit fault occurs in the inverter power tube, Even though the circuit can operate for a short period, the problem continues to be promptly unsettled., a large current will flow through the circuit, causing secondary faults.

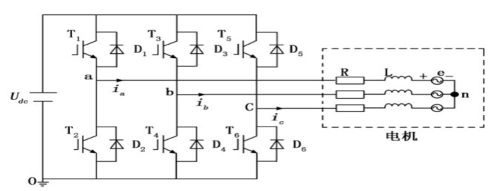

Figure 1

Currently, Techniques for fault diagnosis can be divided into signal analysis-based, model-driven, and data-driven methods (as shown in Figure 2) [3]. Model-based methods are suitable for systems where a mathematical model of the controlled object can be established. Signal processing and data-driven methods can collect physical quantities such as current, voltage, and power related to the circuit for fault diagnosis. Hybrid diagnosis is a combination of the above three methods. For inverter faults, this paper also reviews the fault diagnosis methods from these four aspects, specifically introduces the principles of various fault diagnosis methods, compares these methods from different aspects, and finally discusses the difficulties and future development directions of inverter fault diagnosis.

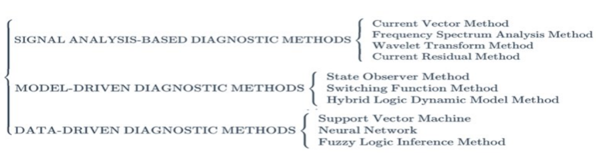

Figure 2

2 Signal Analysis-Based Diagnostic Methods for Power Tube Open-Circuit Faults

Signal analysis-based diagnostic methods for power tube open-circuit faults diagnose faults by analyzing the differences in electrical signal characteristics during system operation. This method mainly focuses on the real-time monitoring of inverter output current, voltage, or magnetic chain signals, extracts fault characteristics using signal processing technology, and completes the diagnosis through pattern recognition algorithms.

2.1 Current Vector Method

The current vector method samples and analyzes the output current signals of the inverter to segregate the amplitude and phase characteristics of the current vector, thereby determining whether a power tube open-circuit fault has occurred. Specifically, the current vector method first transforms the three-phase current through Clark transformation to obtain the current vector expression, and then converts signals from the three-phase stationary coordinate system into two-phase rotating coordinate system signals through Park transformation to obtain the amplitude and phase information of the current vector. In standard functioning circumstances, the amplitude and phase of the current vector have certain regularities, and the current vector trajectory in the coordinate system is circular. When a power tube open-circuit fault occurs, the amplitude and phase of the current vector will change significantly, and the current vector trajectory will present different forms of semicircles. Through contrasting the amplitude and phase traits of the present vector against those in standard operating conditions ,it is possible to determine whether a power tube open-circuit fault has occurred [4].

The advantage of the current vector method is that it has low hardware requirements and only needs to measure the filtered output current to achieve fault diagnosis. In addition, this method is simple to calculate and easy to implement in existing digital control systems. By reasonably designing the diagnostic algorithm, the current vector method can quickly and accurately detect and locate power tube open-circuit faults in three-phase inverters, providing a guarantee for the safe operation of equipment.

2.2 Frequency Spectrum Analysis Method

The frequency spectrum analysis method is a fault diagnosis method based on the frequency domain characteristics of signals. In the diagnosis of power tube open-circuit faults in three-phase inverters, the output signals of the inverter are subjected to frequency spectrum analysis to extract fault characteristics, thereby achieving the diagnosis of power tube open-circuit faults. When the inverter is operating normally, the output current or voltage signals have specific frequency spectrum characteristics. When a power tube open-circuit fault occurs, the output signals of the inverter will be distorted, and their frequency spectrum characteristics will also change accordingly. For example, the amplitude of certain harmonic components will increase or decrease significantly. By performing a Fourier transform on the output signals to convert them from the time domain to the frequency domain, these changes in frequency spectrum characteristics can be clearly observed. By comparing the frequency spectrum characteristics under fault conditions with those under normal conditions, setting thresholds or using pattern recognition algorithms, it is possible to determine whether a power tube open-circuit fault exists. The patterns of frequency spectrum characteristic changes may differ when different power tubes are open-circuited, and by analyzing these characteristics, the precise position of the fault line can be ascertained in greater detail [5].

2.3 Wavelet Transform Method

The wavelet transform method is a method for signal analysis and processing that analyzes the time-frequency characteristics of signals by decomposing them into different frequency bands. In the diagnosis of power tube open-circuit faults in three-phase inverters, the wavelet transform method first uses wavelet transform to decompose the output current signals of the three-phase inverter into low-frequency and high-frequency parts. The signal's primary trend data is housed in its low-frequency segment, and the high-frequency part contains the mutation and detail information of the signal. Then, the decomposed signals are analyzed to extract fault characteristics. When a power tube open-circuit fault occurs, the output current signals of the inverter will exhibit mutations and distortions, which will be reflected in the high-frequency part of the wavelet transform. By analyzing the wavelet coefficients of the high-frequency part, fault characteristics can be extracted. Then, the extracted fault characteristics are compared with the set threshold to determine whether a power tube open-circuit fault exists. If the wavelet coefficient exceeds the set threshold, it is considered that a power tube open-circuit fault exists. Finally, by further analyzing the distribution and changes of the wavelet coefficients, It's possible to pinpoint the exact position of the fault. For example, by comparing the wavelet coefficients of the current signals of different phases, it can be determined which phase's power tube has an open-circuit fault [6][7].

Formula Description: The formula for wavelet transform can be expressed as:

$$C_{m,n}=\frac{1}{a_0^m}\int_{-\infty}^{+\infty} f(t)\psi\left(\frac{t-nb_0}{a_0^m}\right)dt$$

Where:

· f(t) is the original signal, i.e., the output current signal of the inverter.

· $\psi(t)$ is the wavelet basis function.

· a_0 is the scaling factor, controlling the scale of the wavelet function.

· b_0 is the translation factor, controlling the position of the wavelet function.

· m and n are integers, representing the discrete values of scale and position, respectively.

· $C_{m,n}$ is the wavelet coefficient, representing the characteristics of the signal at a specific scale and position.

By calculating the wavelet coefficient $C_{m,n}$, the characteristics of the signal at different scales and positions can be analyzed, thereby extracting fault characteristics and performing fault diagnosis.

2.4 Current Residual Method

The current residual method is a method for diagnosing power tube open-circuit faults in three-phase inverters. This method determines whether a power tube open-circuit fault has occurred through contrasting the variances between the three-phase command current and the actual output current. First, the current residual is extracted by taking the difference between the three-phase command current and the three-phase output current collected by the current sensor, resulting in the current residual Δik . Then, the normalized current residual Uk is calculated. Next, threshold judgment is performed by comparing the normalized current residual Uk with the set trigger threshold. If Uk exceeds the threshold, it is considered that a power tube open-circuit fault may exist. Then, logical judgment is carried out to determine the specific fault location. For example, when the current residual of a certain phase exceeds the threshold, it can be determined that the power tube of that phase may have an open-circuit fault. Finally, by comparing the magnitude and sign of the current residuals of each phase, the fault location can be determined, such as whether the fault occurred within the top or bottom bridge segment of a specific phase.

3 Model-Driven Diagnostic Methods for Power Tube Open-Circuit Faults

3.1 State Observer Method

The state observer method establishes a state observer model for the inverter and uses the state observer to estimate the state variables of the inverter in real-time. The error between the actual output and the estimated output, i.e., the observation error, is calculated. By setting a threshold, it is determined whether the observation error exceeds the threshold. If the threshold is exceeded, it is considered that a power tube open-circuit fault may exist. Then, the characteristics of the observation error are analyzed to determine the specific location of the fault [9][10].

Let the inverter system be represented as:

$$\begin{cases}\dot{x}(t)=Ax(t)+Bu(t)\\ y(t)=Cx(t)\end{cases}$$

The fault detection observation equation is:

$$\begin{cases}\dot{\hat{x}}(t)=A\hat{x}(t)+Bu(t)+D(y(t)-\hat{y}(t))\\ \hat{y}(t)=C\hat{x}(t)\end{cases}$$

Therefore, the state residual variable can be represented as:

$$e(t)=x(t)-\hat{x}(t)$$

The output residual variable can be represented as:

$$\varepsilon(t)=y(t)-\hat{y}(t)$$

Thus, the state error equation is:

$$\dot{e}(t)=\dot{x}(t)-\dot{\hat{x}}(t)=Ax(t)+Bu(t)-A\hat{x}(t)-Bu(t)-D\big(y(t)-\hat{y}(t)\big)=(A-DC)e(t)$$

The output error equation is:

$$\varepsilon(t)=y(t)-\hat{y}(t)=Ce(t)$$

After obtaining the output residual variable, a threshold (a constant value or a variable value) is set, and the residual is detected to determine whether the system has experienced a corresponding fault. Generally, when the system is fault-free, the residual is close to zero; In the event of a system fault, there will be a notable deviation of the residual from zero.

3.2 Switching Function Method

The switching function method establishes a switching function model for the inverter to describe the switching behavior of the inverter under normal and fault conditions. Then, the switching function model is analyzed to extract fault characteristics. Under normal operating conditions, the waveform of the switching function is a periodic square wave. When a power tube open-circuit fault occurs, the waveform of the switching function will become abnormal. Then, a threshold is set to determine whether the waveform of the switching function exceeds the normal range, thereby determining whether a power tube open-circuit fault exists. Finally, based on the changes in the waveform of the switching function and the circuit structure of the inverter, the specific location of the fault is determined [11][12].

This method assumes that the switch tube is an ideal switch and does not consider the switching dead zone between the two switch tubes of the same phase. The relationship between the voltage across the power tube and the switching function when the inverter is operating normally is established as:

$$\begin{cases} u_{T1} = (1 - s_a)U_{dc} \\ u_{T2} = s_a U_{dc} \\ u_{T3} = (1 - s_b)U_{dc} \\ u_{T4} = s_b U_{dc} \\ u_{T5} = (1 - s_c)U_{dc} \\ u_{T6} = s_c U_{dc} \end{cases}$$

Where, uT1,uT2,uT3,uT4,uT5,uT6 are the voltages across the power tubes, and Sa,Sb,Sc are the switching functions of the three-phase power tubes, which mean:

$$S_a = \begin{cases} 1 & \text{When power transistor T1 is on} \\ 0 & \text{When power transistor T1 is off} \end{cases}$$

$$S_b = \begin{cases} 1 & \text{When power transistor T2 is on} \\ 0 & \text{When power transistor T2 is off} \end{cases}$$

$$S_c = \begin{cases} 1 & \text{When power transistor T3 is on} \\ 0 & \text{When power transistor T3 is off} \end{cases}$$

3.3 Hybrid Logic Dynamic Model Method

The hybrid logic dynamic model method is a method for describing and analyzing hybrid systems. By introducing logical variables and auxiliary variables, the nonlinear system is transformed into a linear model form, which facilitates system analysis and control. In the diagnosis of power tube open-circuit faults in three-phase inverters, this technique initially sets up the inverter's hybrid logic dynamic model, representing the switching actions and fault states of the power tubes with logical variables. Different logical combinations correspond to normal operating states and open-circuit fault states. Then, the residual between the model prediction and the actual measurement is used for fault detection. When a power tube open-circuit fault occurs, the output current or voltage waveform of the inverter will show abnormal changes. By comparing the model-predicted output with the actual measured output and calculating the residual, if the residual exceeds the set threshold, it is judged as a fault state. Finally, based on the characteristics of the residual and the combination of logical variables, the specific location of the fault is determined [13][14].

4 Data-Driven Diagnostic Methods for Power Tube Open-Circuit Faults

4.1 Support Vector Machine

The support vector machine (SVM), rooted in statistical learning theory, is a prevalent machine learning technique employed in classification and regression functions. In the diagnosis of power tube open-circuit faults in three-phase inverters, the SVM constructs a classification model to achieve accurate diagnosis of power tube faults. In fault diagnosis, a set of training data containing normal and various fault states is first prepared. These data usually include characteristic signals such as the current and voltage of the inverter. Through feature extraction and selection, the raw data are transformed into feature vectors that can effectively represent the system state. Then, these feature vectors and their corresponding state labels (normal or fault) are used to train the SVM model. The goal of the SVM is to find an optimal hyperplane that correctly classifies the data points of different states into their respective categories as much as possible. After training, the trained SVM model is used to classify new test data. If the test data is classified as a fault state, it indicates that a power tube open-circuit fault may exist in the inverter. In this way, The SVM is capable of precisely identifying the open-circuit malfunction in the power tube, ensuring the inverter's safe functioning[15-16].

4.2 Neural Network

This neural network represents a computational simulation model emulating the configuration and operation of human brain neurons, consisting of a large number of nodes (neurons) and the weights connecting these nodes. It is widely used in pattern recognition, classification, and prediction. In the diagnosis of power tube open-circuit faults in three-phase inverters, the neural network achieves accurate diagnosis of power tube faults by learning the data characteristics under normal and fault conditions.

In fault diagnosis, a set of training data containing normal and various fault states is first prepared, which usually includes characteristic signals such as the current and voltage of the inverter. Then, through the learning algorithm of the neural network, such as the error backpropagation algorithm (BP algorithm), the weights and biases in the network are adjusted to enable the network to map the input characteristic data to the corresponding output state (normal or fault). After sufficient training, the neural network can recognize the characteristic patterns under different states. When new data is input, the neural network can determine whether a power tube open-circuit fault has occurred in the inverter based on its characteristic pattern and determine the specific location of the fault. For example, the method on the basis of the BP neural network extracts the characteristic values of the output signals of the inverter, such as the time-domain or frequency-domain characteristics of the current signal, constructs a fault characteristic vector, and then uses the trained BP neural network to classify these characteristic vectors, thereby achieving the diagnosis and location of the power tube open-circuit fault [17-19].

4.3 Fuzzy Logic Inference Method

The fuzzy logic inference method is a reasoning method on the basis of fuzzy logic and is used to deal with uncertain and fuzzy information. In the diagnosis of power tube open-circuit faults in three-phase inverters, this method achieves accurate diagnosis of faults through fuzzification, fuzzy inference, and defuzzification. In fault diagnosis, the characteristic data of the inverter, such as the root mean square value and average value of the three-phase current, are first extracted. These data are used as inputs and are converted into fuzzy quantities through the fuzzification process, i. e., the membership degrees of each input data in different fuzzy sets are determined. For example, the average value of the current can be fuzzified into fuzzy sets such as "negative large," "negative medium," "zero," "positive medium," and "positive large," each with corresponding membership functions. Next, fuzzy inference is carried out according to the pre-established fuzzy rules. Fuzzy rules are formulated based on expert experience and historical data, describing the fuzzy relationship between input characteristics and fault types. For example, if the average value of phase A current is "negative large," and the average values of phases B and C current are "positive small," it can be inferred that a certain power tube has an open-circuit fault. Finally, the fuzzy inference result is converted into a specific fault type through the defuzzification process. Common defuzzification methods include the maximum membership method and the centroid method. For example, the centroid method can be used to calculate the precise value of the fault type, thereby determining the specific fault location. The advantage of the fuzzy logic inference method is that it can deal with uncertain and fuzzy information without the need for an accurate mathematical model and complex calculations. By reasonably designing fuzzy rules and membership functions, this method can quickly and accurately diagnose the open-circuit fault of the power tube in the three-phase inverter and provide a guarantee for the safe operation of the equipment [20].

5 Technical Bottlenecks and Future Development

The diagnosis of power tube open-circuit faults in three-phase inverters faces some technical bottlenecks. First, the difficulty of fault feature extraction is high. The traits of power tube open-circuit faults are closely related to load conditions and inverter topology, making fault feature extraction difficult. Second, the complexity of the model is high. Model-based fault diagnosis methods require the establishment of an accurate mathematical model, but there are nonlinearity, time-varying, and parameter uncertainty in actual inverter systems, making the model complex and difficult to accurately describe system behavior. In addition, the limitations of data-driven methods are also obvious. Data-driven methods base on a large amount of historical data for training, but in actual applications, the acquisition of fault data is often difficult, and the data quality is uneven, affecting the generalization ability and diagnostic accuracy of the model. At the same time, the challenge of diagnosing multiple fault types is also great. There may be multiple fault types in the inverter, and the characteristics of these faults are similar and coupled, posing a great challenge to fault diagnosis. Finally, real-time and computational resource limitations are also a bottleneck. Some advanced diagnostic methods have high computational complexity and cannot meet the real-time requirements of actual applications.

In the future, the diagnosis of power tube open-circuit faults in three-phase inverters will develop towards intelligence, multi-method integration, and real-time. Intelligent diagnostic methods will become the mainstream. As advances in artificial intelligence and machine learning technologies, intelligent diagnostic methods can improve diagnostic accuracy and robustness through automatic feature extraction and learning. Multi-method integration will also be a future development trend. Combining signal analysis, model prediction, and data-driven methods can fully utilize their respective advantages and improve the comprehensive performance of fault diagnosis. Real-time and online diagnosis will receive more attention. To meet the real-time requirements of actual applications, research will focus more on the development of online diagnostic methods. The collaborative optimization of hardware and algorithms will also become a research focus. By accelerating hardware and optimizing algorithms, computational complexity can be reduced, and diagnostic efficiency can be improved. Finally, the development of multi-physics field coupling analysis methods will receive more attention to more comprehensively understand and diagnose faults.

6 Conclusion

The diagnosis of power tube open-circuit faults in three-phase inverters is important for ensuring the safe operation of power electronic equipment. This paper reviews the current main diagnostic methods, including signal analysis-based, model-driven, and data-driven technologies, and analyzes their principles, advantages and disadvantages, and applicable scenarios. Although these methods still face some technical bottlenecks in fault feature extraction, model complexity, and data dependency, the future development trend is very clear with the constant progress of science and technology.

The rise of intelligent diagnostic methods, especially the broad utilization of artificial intelligence and machine learning technologies, will significantly improve diagnostic accuracy and robustness. The strategy of multi-method integration, combining signal analysis, model prediction, and data-driven methods, is expected to give full play to their respective advantages and further enhance the comprehensive performance of fault diagnosis. The development of real-time and online diagnosis technologies will better meet the needs of actual applications and guarantee the stable operation of the system under various working conditions. The collaborative optimization of hardware and algorithms, as well as the exploration of multi-physics field coupling analysis methods, will also bring new breakthroughs to fault diagnosis technologies.

In short, the research on the diagnosis of power tube open-circuit faults in three-phase inverters has important theoretical and practical application value. Through continuous research and innovation, future diagnostic technologies will be more intelligent, efficient, and reliable, offering a firmer assurance for the safe operation of power electronic equipment.

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