A Survey of Fault Diagnosis Mothods for Multilevel Inverters Switching Tubes

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Abstract

With the development of power electronics technology, multi-level inverters have been widely used in industrial, military, aerospace and other important fields. However, the number of switching tubes increases because of the increases of inverters' level, which increases the probability of the inverters' fault. Therefore, it is necessary to adopt effective methods to diagnose the fault of switching tubes in multilevel inverters. This paper analyzes and discusses the existing open circuit fault diagnosis methods for multilevel inverters from qualitative and quantitative perspectives, summarizing the basic idea, research progress, applicable conditions, advantages and disadvantages of these techniques. Finally, the research direction and trend of open-circuit fault diagnosis techniques for switching tubes of multilevel inverters are further explained.

Keywords

Fault diagnosis, multilevel inverters, qualitative diagnosis, quantitative diagnosis.

1. Introduction

Multilevel inverters are new type of inverters, which can achieve high voltage and high power output by changing the topology. Compared with the traditional two-level circuit, multi-level inverters have the advantages of series voltage equalization of power devices, low switching loss, low harmonic content of output voltage, small influence of electromagnetic interference and high efficiency [1]. Therefore, they are widely used in medium and high voltage, power transmission and high power conversion systems. Meanwhile, as the central actuator of system control, the stability, reliability and maintainability of multi-level inverters are more important. However, with the increase of the inverters' level, the number of switches also increases, which increases the probability of the inverters' fault and seriously affects the safe and reliable operation of the system. Therefore, it is necessary to diagnose the fault of the switching tubes in multi-level inverters.

The fault of switching tubes in multilevel inverters can be divided into short-circuit fault and open-circuit fault. Because short-circuit fault of power devices usually occurs in a very short time and are difficult to detect, the diagnosis and protection of short-circuit faults are mostly solved by hardware circuit design. The short-circuit faults can also be transformed into open-circuit faults by connecting the fast fuse to the circuit [2, 3]. When open-circuit fault occurs, the system can continue to operate, resulting in non-fault power semiconductor devices flowing through greater current, reduced torque, heating and insulation damage, etc., which can cause the whole system paralysis in serious cases, resulting in huge economic losses. Therefore, the current research on fault diagnosis of multi-level inverters focuses on open-circuit fault of switching tubes.

According to traditional classification methods, fault diagnosis methods can be divided into analytical model-based methods, signal-based methods and knowledge-based methods [4]. In this paper, a new fault diagnosis classification method is proposed. The open circuit fault diagnosis methods of multi-level inverters are analyzed qualitatively and quantitatively. The basic ideas, research progress, applicable conditions, advantages and disadvantages of these methods are summarized. Finally, the future research directions and trends of open-circuit fault diagnosis methods for multi-level inverters are further explained.

2. Fault Classification and Diagnosis of NPC Three-Level Inverter

2.1 Classification of Open-circuit Faults of Switch Tubes

There are three main types of multilevel inverters: diode clamped, flying capacitor and cascade. As a typical multi-level inverters, Neutral point clamped (NPC) three-level inverters have been widely used in power transmission systems and high-power conversion systems. The topology is shown in Figure 1.

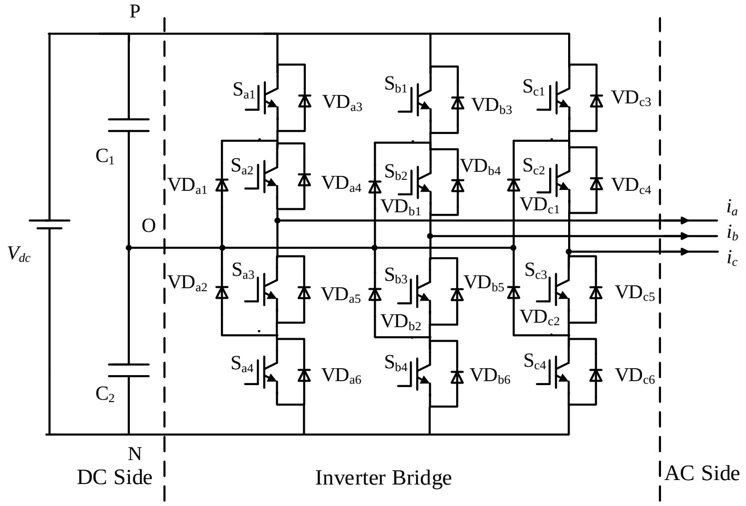

Fig. 1 Topology of NPC three-level inverter

NPC three-level inverters are composed of A, B and C three-phase bridge arms, each of which has the same structure. Each phase clamp diode is connected through the neutral point and connected to the neutral point on the DC side. Its function is to return the potentiometric clamp at the point connected to it on the bridge arm to the neutral point potential [5].

In the real operation, there are few simultaneous faults of three or more switches. The common open circuit faults of single and double switches are classified and described. The classification results are shown in Table1.

Table 1 Open circuit faults classification of NPC three-level inverter

Fault Classification	Fault Name	Fault Description
A	Normal Operation	No Fault
B	Single IGBT Open-circuit	One Fault in $S_{i1} \sim S_{i4}$, $i = a,b,c$,12 kinds in tatal
C	Two IGBT of The Same Bridge Arm Open-circuit	Two Faults in S_{im} and S_{in} , $i = a,b,c$, $m,n = 1,2,3$, $m \neq n$,18 kinds in tatal
D	Two IGBT of The Same Half-bridge Arm Overlapped Open-circuit	Two Faults in S_{ik} and S_{mn} , $i,m = a,b,c$, $i \neq m$ $k,n = 1,2,3,4$, $\lvert k-n \rvert \leq 1$, 24 kinds in tatal
E	Two IGBT of The Different Half-bridge Arm Overlapped Open-circuit	Two Faults in S_{ik} and S_{mn} , $i,m = a,b,c$, $i \neq m$ $k,n = 1,2,3,4$, $\lvert k-n \rvert > 1$, 24 kinds in tatal

2.2 Fault Diagnosis Method of Multilevel Inverter

By summarizing the existing research results, the existing software redundancy fault diagnosis methods are analyzed for the open-circuit fault of multi-level inverters. The current fault diagnosis methods of multi-level inverters are classified in qualitative and quantitative methods, and the quantitative diagnosis methods are subdivided according to the analytical model and data-driven layer by layer. The classification structure chart is shown in Figure 2.

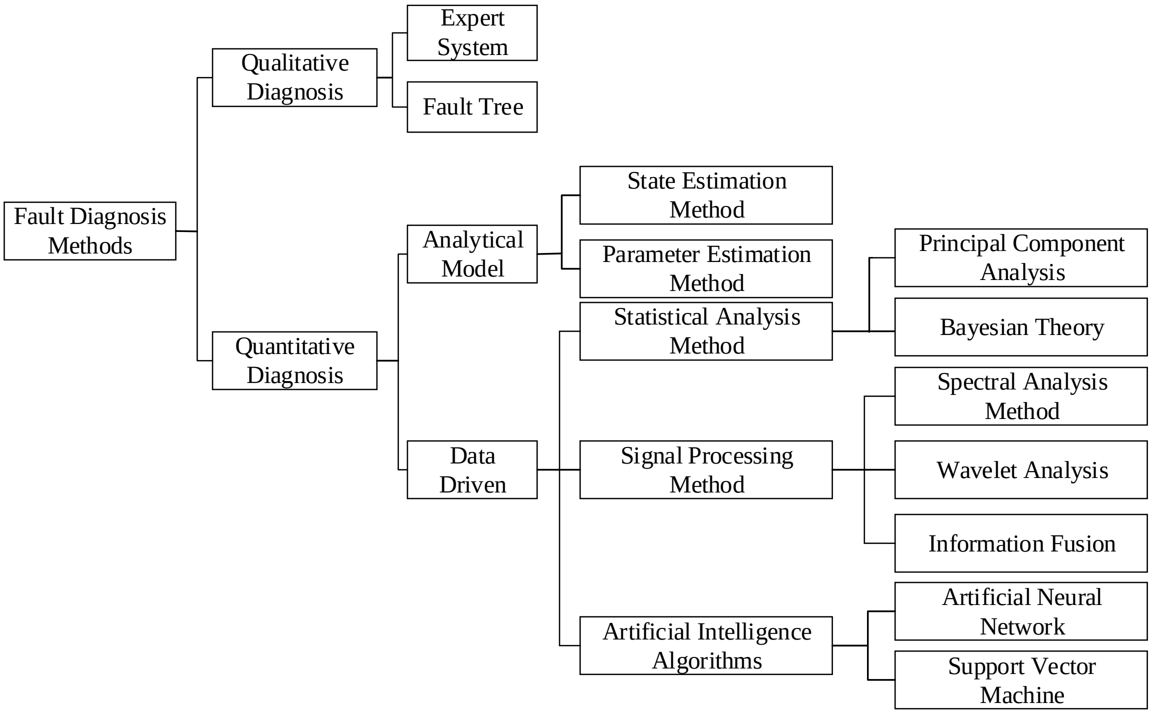

Fig. 2 Classification of fault diagnosis methods for multilevel inverters

3. Qualitative Fault Diagnosis Methods for Multilevel Inverters

Inverter fault diagnosis based on qualitative experience is to describe the functional structure of the system with incomplete prior knowledge, and establish qualitative model to realize fault diagnosis process. It mainly includes expert system (ES), fault tree analysis (FTA) and other methods.

3.1 Expert System

The basic idea of fault diagnosis method based on ES is to establish a knowledge base, Which through theoretical analysis according to the effective experience and professional knowledge accumulated by experts in the field of fault diagnosis, and to reasoning and decision-making fault information by computer simulation of expert thinking process to obtain the diagnosis results. A typical expert system for fault diagnosis of inverters is shown in Figure 3.

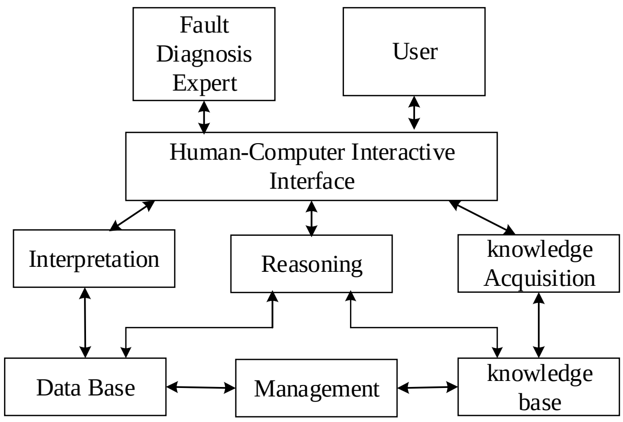

Fig. 3 Fault diagnosis of inverter based on expert system

Expert system provides a flexible man-machine interface, so the fault diagnosis results are intuitive and robust. Paper [6] studies the fault diagnosis method of wind power converter based on expert system theory. This method does not need to establish the system mathematical model, but extracts the effective fault diagnosis information from the converter fault knowledge obtained in advance, and then compares with the actual operation data of the converter, so as to realize the fault diagnosis of the system. ES is used to diagnose the fault of inverters. Compared with current and voltage measurement method, the practicability and accuracy of ES method are proved [7].

ES-based fault diagnosis of inverter switches does not require accurate mathematical models, and the diagnosis process and results are easy to understand. However, this method requires a lot of expert knowledge accumulation. Because ES method does not have the function of autonomous learning, the system will not be able to make judgments when the acquired knowledge is unknown or the threshold range exceeds the prediction. Therefore, more research focuses on the combination of expert system and artificial intelligence algorithm, such as D-S Fusion Expert system, neural network expert system and Bayesian network expert system [8, 9].

3.2 Fault Tree Analysis

FTA is a deductive analysis method based on fault tree logic diagram. It uses method to thin the system fault step by step from whole to part [10]. The fault tree diagnosis system is intuitive and logical. By combining with other algorithms, the fault diagnosis of multi-level inverters can be realized.

Based on bond graph model of three-phase voltage source PWM inverters, the open-circuit fault of the inverters is qualitatively analyzed by fault tree analysis method, which realizes the location of the fault source [11].It has the advantages of low accuracy requirement of the model and less calculation. Literature [12] realizes the fault diagnosis of inverters by combining fault tree and bidirectional associative memory neural network. Experiments show that the combination of the two methods improves the diagnostic ability, and shows good real-time and effectiveness.

For simple systems, it is convenient to establish fault tree. However, with the increasing complexity of the system, the large scale of fault tree makes the fault diagnosis search process very difficult. Therefore, in order to better establish and maintain fault tree and achieve fast search and location of fault sources, fault tree diagnosis needs to cooperate with other statistical analysis methods or intelligent algorithms [13].

4. Quantitative Fault Diagnosis Methods for Multilevel Inverters

4.1 Method Based on Analytic Model

By comparing the measurable information of the diagnostic object with the prior information of the system expressed by the mathematical model, the residual is generated, and the residual is analyzed and processed to realize the fault identification and location [14]. According to the different ways of generating residual error, it can be divided into parameter estimation method and state estimation method. The basic principle of fault diagnosis based on analytical model is shown in Figure 4.

Paper [15] analyze the topological structure of voltage source inverters, and the concept of equipotential is proposed.Two functional models describing health and fault states are defined respectively Combining the residual between any two-phase functions and the topological structure of voltage source inverters, the fault location can be achieved accurately. By analyzing the mathematical model of voltage source inverter in PMSM drive system, an observer fault diagnosis algorithm based on adaptive threshold is proposed, which realizes the fault diagnosis of multiple IGBTs with short detection time [16]. Based on the calculated average bridge arm voltage and error adaptive threshold, the average bridge arm voltage deviation is used as the diagnostic variable for fault detection and identification to realize single and multi-switch open-circuit fault diagnosis of voltage source inverters [17].

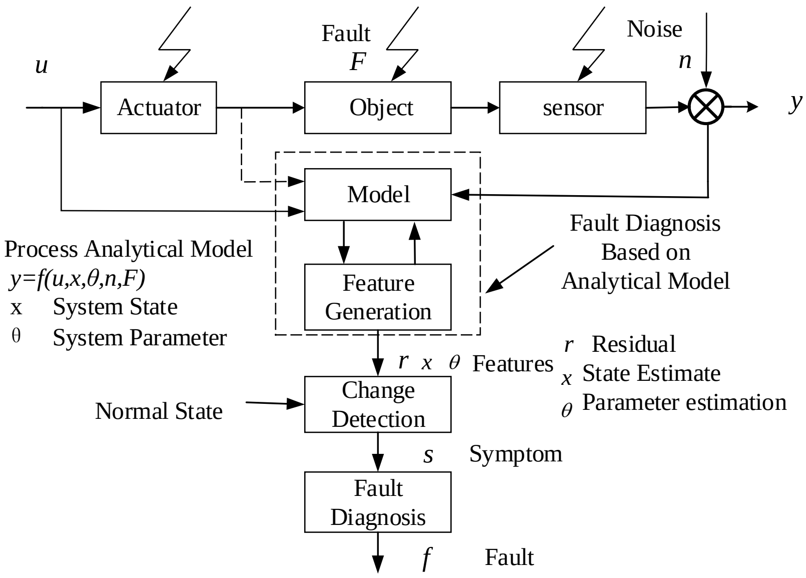

Fig. 4 Fault diagnosis principle based on analytic model

As a switching power converter, power electronic circuit is a typical Mixed Logical Dynamic (MLD) system [18, 19], whose discrete events interact with continuous dynamic characteristics. In recent years, fault diagnosis methods for Inverters Based on hybrid logic dynamic system model have been developed. Literature [20] establishes a hybrid logic dynamic model of power electronic circuits, and realizes circuit fault diagnosis based on fault event recognition vector. Finally, the effectiveness of the diagnosis method is verified by simulation and experiment of fault diagnosis of inverters. Literature [21] presents a new method for open-circuit fault diagnosis of single-phase PWM rectifier based on hybrid logic dynamic model and residual generation. By comparing the output of MLD model with that of actual system, residual is generated. Through residual analysis, fault diagnosis of rectifier is realized. Reference [22] establishes a hybrid logic dynamic model of three-level NPC converter, estimates the grid current, subtracts the estimated value from the measured current under different faults to produce residual, and then realizes fast detection and fault location of thyristors and diodes according to the characteristics of residual variation rate. The experimental results show that the fault diagnosis method has a short time and avoids secondary faults, and improves the reliability and efficiency of fault maintenance, and is also suitable for fault diagnosis of rectifiers and inverters.

In summary, the fault diagnosis based on analytical model needs to fully understand the operating mechanism of the system, and the ideal fault detection and location can be achieved only on the basis of building a suitable mathematical model. Therefore, this method is suitable for systems that can establish accurate mathematical models. However, the whole system of multi-level inverters is a complex non-linear system, and there are grid disturbances and load disturbances. It is difficult to establish an accurate mathematical model. Therefore, the fault diagnosis of multi-level inverters based on analytical model has limitations.

4.2 Data-Driven Method

Data-driven diagnosis method refers to the method of analyzing and processing process running data, learning and reasoning by a series of methods such as mathematical method or intelligent algorithm, so as to realize the fault diagnosis of the system. There are three kinds of methods: method based on statistical analysis, method based on signal processing and method based on artificial intelligence quantitative algorithm.

4.2.1 Method Based on Statistical Analysis

The method based on statistical analysis refers to the use of basic mathematical theory and methods to statistics and analysis of system operation data, so as to achieve fault diagnosis of the system. Principal Component Analysis (PCA) and Bayesian Network (BN) are the main statistical methods for fault diagnosis of multilevel inverters.

(1)PCA

Principal Component Analysis (PCA) is a commonly used multivariate statistical analysis method. By reducing the dimensions, the multivariate data can be transformed into a small number of indicators that can reflect the characteristics of things, so as to analyze the main influencing factors from the multivariate things. PCA is mainly used for feature vector dimension reduction and fault identification in fault diagnosis of multilevel inverters [23].

Literature [24] presents a fault diagnosis technique based on principal component analysis and multi-classification correlation vector machine. Firstly, the characteristic signal is preprocessed by fast Fourier transform. Secondly, PCA is used to extract the fault signal features and reduce the sample dimension. Finally, multi-class support vector machine is used to realize the fault diagnosis of cascaded H-bridge multi-level inverters. In reference [25], the fault detection and diagnosis of three-phase voltage source inverters are studied, and a principal component analysis algorithm based on the output current of the inverters is proposed. The feasibility of the algorithm is verified by simulation.

PCA is mainly used for dimensionality reduction of fault signal characteristics of multilevel inverters, and can process multivariate correlated data with measurement noise, error and even data missing. By combining PCA with other methods, the fault detection and diagnosis of multilevel inverters can be realized.

(2)BN

Bayesian network is a statistical model decision-making method which uses probabilistic reasoning technology to estimate some unknown states under the condition of uncertain and incomplete information, and then updates the probabilistic information with Bayesian formula for diagnostic decision-making [26].

A fault diagnosis method for NPC three-level inverters based on multi-resolution wavelet and Bayesian classifier is proposed [27]. The fault signal is decomposed into multi-scale by wavelet analysis, and the fault features are established, which can be used as input of Bayesian classifier for fault identification. Literature [28] presents a fault diagnosis method for three-phase inverters based on FFT-PCA-BN. Fast Fourier transform is used to extract signal features, principal component analysis is used to reduce the dimension of samples, and Bayesian network is used to detect and diagnose system faults. Experiments show that the data-driven fault diagnosis method based on Bayesian theory has better tolerance to sensor noise and bias.

The construction of Bayesian network requires experts and engineers in relevant fields to collect relevant information extensively and synthesize their various detection data and fault symptoms, so as to obtain more comprehensive fault sets and symptoms, as a result to improve the accuracy of diagnosis results.

4.2.2 Method Based on Signal Processing

The fault diagnosis method based on signal processing is to detect and locate faults directly by using the time domain and frequency domain characteristics of the measured signal. In the process of sensor fault, fault information exists in the measured signal, and the fault diagnosis of the system is realized by comparing these fault features with the corresponding characteristics of the normal system. Signal processing is usually the first step in other fault diagnosis methods. The fault diagnosis methods of multi-level inverters based on signal processing mainly include spectrum analysis, wavelet analysis and information fusion technology.

Spectrum analysis method

Spectrum analysis refers to the transformation of fault signals from time-domain information into frequency-domain, and then analyse the power spectrum, cepstrum or higher-order spectrum. By extracting the fault characteristics of different spectrum performance, the fault diagnosis of the system can be realized [29]. The spectrum analysis method used in multi-level inverters mainly refers to Fourier transform method.

A fault detection and diagnosis method for Inverters Based on Fourier transform and neural network is proposed. The windowed Fourier transform is used to extract the positive sequence symmetric components of the output signal of inverters, and the concepts of spectral residual and relative spectral residual are proposed. The basic residual is used to realize the fault detection of inverters [30]. Aiming at the open circuit fault of the inverter switch in the variable frequency drive system, the double Fourier transform technique of the switching function is applied to realize the fault diagnosis of the inverter by detecting whether the low frequency of the DC side current spectrum contains modulation signal [31].

The fault feature extraction method based on Fourier transform is simple and suitable for the processing of stationary signals. However, the signal in three-phase voltage of multi-level inverters contains non-stationary or time-varying information, so it is difficult to extract fault features effectively. Moreover, after Fourier transform, the original fault signal undergoes a process of global change, which abandons the time-domain characteristics and can not be used for local analysis. Based on the above shortcomings, the spectrum analysis method is gradually replaced by the wavelet analysis method.

Wavelet analysis

Wavelet analysis is a localized analysis of time and space frequency. It refines the signal step by step through scaling and translation operations, and ultimately realizes time subdivision at high frequency and frequency subdivision at low frequency, thus focusing on any details of the signal. At present, the main wavelet analysis methods used in fault diagnosis of multi-level inverters are wavelet transform, wavelet packet transform and wavelet multi-resolution analysis [32].

Reference [33] presents a method of fault feature extraction for inverters based on wavelet transform and Concordia transform, and is used for fault diagnosis and location of power transistors in open-loop control inverters. Literature [34] proposes a fault diagnosis method for three-level converter based on wavelet packet analysis and probabilistic neural network. The feature vectors are extracted by wavelet packet analysis, and then the feature vectors are dimensionally reduced by kernel principal component analysis. Finally, the probabilistic neural network is used to establish fault classifier to improve the robustness of the diagnosis method.

Compared with the spectrum analysis method, the wavelet analysis method can effectively deal with unsteady and non-linear signals. It has many excellent characteristics such as multi-resolution analysis, time-frequency localization and so on. Therefore, it is an effective tool to analyze and process the fault information of multi-level inverters. By combining with other mathematical analysis methods and intelligent algorithms, the reliability of fault diagnosis can be further improved. However, this method also has some shortcomings, such as weak adaptive ability, difficult selection of wavelet basis function, energy leakage caused by the interaction of time-frequency resolution of wavelet spectrum, and so on.

Information Fusion Technology

When there is a large disturbance or noise in the actual system, the uncertainty of fault information will reduce the reliability of the diagnosis system. If only the DC side voltage or AC side phase current is extracted as the fault eigenvector. The idea of fault diagnosis method based on information fusion technology is to analyze and synthesize multiple information sources by utilizing the complementary and redundant relationship between different sensor information, to overcome the problem of fault diagnosis errors caused by uncertainty of fault information using single data source information, so as to achieve accurate fault location.

Information fusion can be divided into data level fusion, feature level fusion and decision level fusion according to the abstract level of information fusion. Data level fusion is usually realized by collecting fault information from multi-source sensors. The information fusion technology applied to fault diagnosis of multi-level inverters is mainly feature level fusion and decision level fusion. Its diagnosis structure is shown in Fig. 5 and Fig. 6 respectively [35].

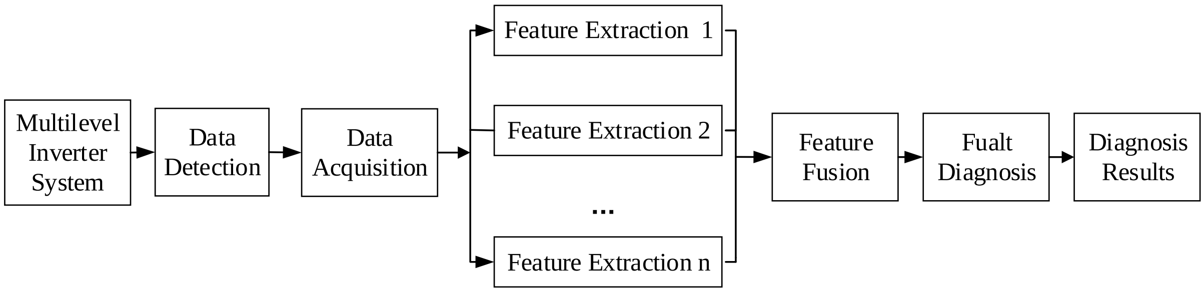

Fig. 5 Fault diagnosis structure of multi-level inverter based on feature level fusion

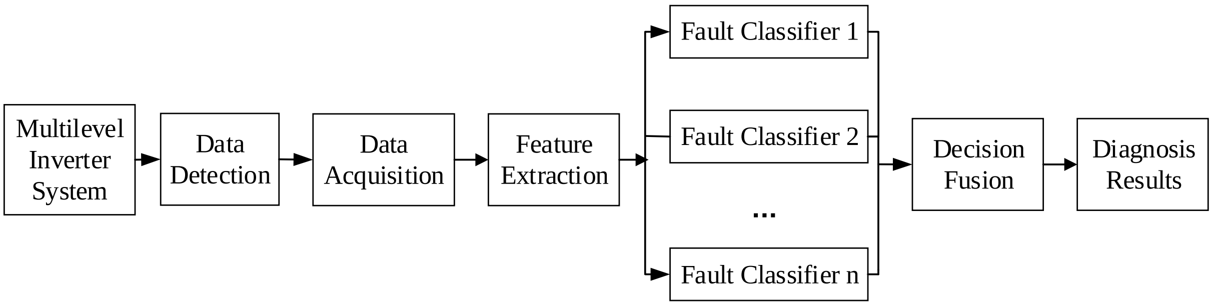

Fig. 6 Fault diagnosis structure of multi-level inverter based on decision-making level fusion

Multi-source information feature fusion is applied to the fault diagnosis of grid-connected photovoltaic inverters [36]. Current on the grid side and voltage on the important bridge arm are selected as the fusion objects. Wavelet transform is used to preprocess and extract the data. Neural network is used to train the eigenvalues, which effectively improves the accuracy of fault diagnosis of grid-connected photovoltaic inverters. The voltage and current signals of the circuit to be tested are pretreated and extracted by wavelet transform and principal component analysis, and the voltage and current characteristic vectors are combined to form the characteristic vectors by interval crossover. The fault diagnosis is realized by inferring the joint characteristic vectors by neural network [37].

Information fusion fault diagnosis technology makes full use of the fault information of the system, so as to achieve fault location accurately. With the development of information fusion technology, the method of multi-feature extraction and multi-classifier fusion decision-making in fault diagnosis will further improve the accuracy and reliability of fault diagnosis. At present, the core and difficulty of information fusion technology is how to select appropriate fusion algorithm and establish fault diagnosis rules, which is the direction of further research.

4.2.3 Method Based on Quantitative Algorithms of Artificial Intelligence

Quantitative algorithm of artificial intelligence is an important component of the fault diagnosis method of inverters. By combining the intelligent algorithm with the idea of fault diagnosis, the fault detection and location of the system can be realized. It mainly includes Artificial Neural Network (ANN), Support Vector Machines (SVM) and so on.

ANN

ANN is a quantitative artificial intelligence algorithm with good generalization ability, self-learning, self-organization, parallelism and strong associative memory. Therefore, it is increasingly used in fault diagnosis of multi-level inverters. Neural network is generally composed of input layer, hidden layer and output layer.

The fault diagnosis method based on neural network is to train a large number of known fault data samples, adjust the weights and thresholds constantly through data learning, so as to establish the mapping relationship between fault information and fault types, and then input the fault information to the trained neural network, so as to realize the fault diagnosis of the system.

Artificial neural network is applied to the fault diagnosis of multilevel inverters. By applying genetic algorithm to principal component analysis, the dimensionality reduction of fault information and fault feature extraction are realized. This method not only improves the fault diagnosis performance of the system, but also greatly reduces the training time of the neural network [38]. Literature [39] extracts harmonic amplitude and phase of bridge arm voltage from spectrum analysis as fault feature information, and applies multi-neural network to fault diagnosis of power devices of three-level inverters, realizing multi-fault mode diagnosis of single device and multiple devices open at the same time. Experiments show that the method has the advantages of high accuracy of diagnosis results and strong anti-interference ability.

ANN has high non-linear fitting ability, robustness and fault-tolerance, and does not need to consider the internal structure of the system. It overcomes the shortcomings of establishing accurate models to understand the analytical model, so it is widely used in fault diagnosis of multi-level inverters. However, network learning requires a large number of fault samples, so ensuring the integrity and typicality of fault samples is the key to accurately realize system fault detection and location. Secondly, ANN has poor interpretability of learning and diagnosis results. It can integrate neural network with other intelligent algorithms and construct mapping relationship with ANN, so as to find rules that can make the knowledge contained in ANN expressed in language and enhance the interpretability of fault diagnosis.

SVM

SVM is a quantitative intelligent algorithm based on statistical learning theory and structural risk minimization principle, which has strong classification ability. SVM has complete mathematical form, intuitive geometric interpretation and good generalization ability. It is a powerful tool for dealing with small sample, high dimension and non-linear problems.

Literature [40] proposes a fault diagnosis strategy based on PCA-SVM model for cascaded H-bridge multilevel inverters. The fault signals are preprocessed and feature vectors are extracted by fast Fourier transform and principal component analysis. Finally, training and fault diagnosis are carried out by SVM. Experiments show that the diagnostic accuracy of this method is as high as 98%, and the computational efficiency is high. Reference [41] presents a fault diagnosis method for three-phase inverters based on adaptive noise and support vector machine. Experiments show that the method has higher diagnostic accuracy and better anti-interference ability.

SVM is suitable for learning and diagnosing fault features of small sample systems, and overcomes the shortcomings of building neural network mapping relationships requiring a large number of known fault samples. However, SVM parameters and the completeness and representativeness of samples have a great impact on the accuracy of fault diagnosis results, and SVM only diagnoses faults from the perspective of classification, and does not excavate the structural information of data in depth. Therefore, SVM is usually combined with other methods to improve the accuracy of diagnosis results.

5. Conclusion

Method based on qualitative fault diagnosis, which the function structure of the system is described by incomplete prior knowledge, the fault diagnosis of the system is realized by establishing qualitative model. This method needs abundant experience knowledge as support, and does not have the ability of self-learning. When the system is too complex, qualitative fault diagnosis method is difficult to accurately implement. Therefore, for the research of qualitative fault diagnosis method, more emphasis is put on the combination of artificial intelligence algorithm and qualitative fault diagnosis method to achieve system fault diagnosis. Quantitative fault diagnosis methods are mainly based on analytical models and data-driven methods. Multilevel inverters are a non-linear discrete system, so it is difficult to establish an accurate mathematical model. Therefore, the fault diagnosis method based on analytical model is greatly limited. In recent years, with the Deep learning of information processing technology and artificial intelligence algorithm, the fault diagnosis method based on data-driven has been further developed. The extraction, processing and decision-making of system fault features are gradually tending to multi-information fusion, which greatly improves the accuracy and reliability of fault diagnosis. Therefore, the fault diagnosis of multi-level inverters will gradually become a research hotspot in the future by combining various technical methods and making use of the advantages and disadvantages to realize the fault diagnosis of multi-level inverters. Especially, when the number of inverters increases or the structure of the system is complex, the fault state of the system will multiply. How to select and collect appropriate fault information and conduct accurate fault diagnosis is also a direction worthy of study.

In industrial production, if the inverters fail to take timely measures to deal with them, the system will be shut down and the output will be affected, and the major economic loss or catastrophic accident will be brought to industrial production. Therefore, on the basis of the existing fault diagnosis technology, it has broad prospects and application value to carry out in-depth research on multi-level inverters' fault state early warning and equipment operation life prediction, as well as fault tolerant control after fault.

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