Research on Fault Signal Processing Method of New ANPC Inverter Circuit

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Abstract. Due to the good adaptability of wavelet theory in signal processing, its current application fields are very extensive. This paper first summarizes the application fields of current wavelet theory and analyzes the characteristics of wavelet analysis theory. Then, several methods for fault diagnosis of traditional inverter circuits are listed. The limitations of their fault diagnosis in new multi-level inverter circuits are analyzed. The wavelet analysis is applied to the fault diagnosis of multi-level inverter circuits. After analyzing the fault mode of the multi-level inverter circuit, the wavelet packet is used to extract the fault features, and then the support vector machine theory is combined to diagnose the fault. Finally, the method described in this paper is verified by Simulink simulation software, and the accuracy of the method is more than 90%. The method is feasible and effective.

1. Introduction
Wavelet analysis is an emerging discipline that uses wavelet transform to analyze signals. It has good localization properties in both time domain and frequency domain, and is the main means of time-frequency analysis. Since the wavelet transform has a rich wavelet base, wavelet analysis can adapt to signals with different characteristics. [1] The good adaptability of wavelet theory makes wavelet analysis widely used in various fields, shown as Table 1.

Table 1. Application areas of Wavelet analytical theory

| Application field       | Specific applications                                           |
|------------------------|-----------------------------------------------------------------|
| Image Processing       | Image compression coding, Image edge detection, Image filtering, Image fusion, Digital watermarking |
| Artificial Intelligence| Speech recognition, Text recognition, Face recognition         |
| Military field         | Fault diagnosis and navigation signal preprocessing of ordnance equipment |
| Aviation               | Engine blade flaw detection, Flight control system fault tolerance |
| The financial sector   | Stock price trend forecast                                      |
From the mathematical theory of wavelet transform, it is a generalization on the Fourier transform, which overcomes the shortcomings of the fixed Fourier transform time-frequency window, forming a window shape that can be changed, and both the time window and the frequency window can be changed. Time-frequency localization analysis method.[2] When the signal is processed, it has higher frequency resolution for the low frequency part of the signal, and has higher time resolution and lower frequency resolution in the high frequency part, which is very suitable for the inclusion of non-normal signals. The normal amount is described in detail, and the characteristics of the signal can be effectively extracted.

Compared with the traditional two-level inverter circuit, the current multi-level inverter circuit has the advantages of low output voltage harmonic content and high tracking precision, but the multi-level inverter circuit also contains many power switching tubes and nonlinear devices. In a two-level circuit, the overall failure rate of the circuit is thus greatly increased. The traditional fault diagnosis method that uses the voltage and current information to perform mathematical transformation to find the fault type is difficult to generalize to the multi-level inverter circuit with complex topology. The method of real-time monitoring of the status signal of each power tube in the inverter circuit to determine the fault location can quickly and accurately determine the fault location, but also does not apply to the multi-level complex topology due to the limitations of operation and maintenance costs and site factors. In the structure [3]. For multi-level inverter circuits with complex topologies, it is often used to detect the difference between the input and output characteristics during normal operation and fault, and to find the fault characteristics in order to determine the fault type and fault location. Literature [4] combines spectral estimation with neural network, uses spectral estimation equations to solve real-time residual estimates, and uses neural networks to classify and identify faults. However, the diagnosis process is affected by the neural network structure parameters and the spectrum selection during residual estimation. The algorithm is too complicated and is not suitable for multi-fault type inverter circuit diagnosis. [5-6]

In the means of extracting the fault characteristics of the inverter circuit, the wavelet transform is widely used in fault diagnosis because it can effectively detect the characteristics of the inverter circuit and the frequency signal, and reflect the occurrence time of the fault amount and the duration of the fault. [5]. The paper will use the wavelet packet to analyze the output characteristics of the inverter circuit, and combine the support vector machine to classify the fault features. The support vector machine method is based on the VC dimension theory and the structural risk minimum principle of statistical learning theory. The limited sample information seeks the best compromise between the complexity of the model (i.e., the learning accuracy of a particular training sample) and the ability to learn (i.e., the ability to identify any sample without error) in order to obtain the best generalization ability or generalization. The ability [6] can meet the needs of multi-level inverter circuit fault types and complex modes.

2. Fault mode analysis of a new three-level ANPC inverter circuit
Most of the inverters are composed of two parts: the inverter main circuit and the control protection circuit. The failure of the inverter means that the inverter is in an abnormal working state, and each output performance index deviates from the specified allowable range. This paper mainly deals with the research of the main circuit topology of the inverter. The fault types of the new ANPC inverter...
circuit shown in Figure 1 mainly include power tube fault, drive signal fault and capacitor fault. The power tube fault is the most common fault of the inverter circuit. The damage of the power device causes the inverter to work in an abnormal state, which increases the voltage and current pressure of other power devices. If it is not diagnosed and eliminated in time, it will cause a secondary fault. Occurs, eventually leading to system downtime, causing great losses to industrial production [7]. Due to the large number of power tubes in the topology of the inverter circuit mentioned in the paper, short circuit or open circuit fault may occur in each power tube. Figure 2 shows several common modes of power tube faults in the inverter circuit.

Inverter power tube faults are divided into short circuit and open circuit. When an open circuit fault occurs, a large short circuit current will cause the overcurrent protector to cut off the short circuit part, thus converting the short circuit fault into an open circuit fault. Therefore, this article only discusses fault diagnosis in the case of open circuit faults. [8] In view of the small topology of the proposed topology, the impact of redundant bridge arm fault on the normal operation of the circuit is small. This paper will select the three-phase bridge arm as the fault diagnosis object to study the fault diagnosis method when the power tube is broken. Considering that the most likely type of fault in power tube faults other than the clamped power tube during actual operation is single-tube fault or double-tube fault, the probability of three-tube fault is small and if three or more tubes are present, When the tube is faulty, the probability that the circuit can achieve fault-tolerant operation is small, and it is not necessary to perform fault diagnosis. Therefore, this paper only considers the fault characteristics of
the circuit when the single-tube or double-tube faults other than the clamped power tube on the three-phase bridge arm side, and this is a troubleshooting study. [9]

The main purpose of this paper is to realize fault-tolerant operation of the inverter circuit. For the fault-tolerant topology conversion of the inverter circuit shown in Figure 1, the fault-tolerant function is mainly reflected in single-phase single-tube fault, multi-tube fault, and multiple identical-side power tube faults. Therefore, this chapter will take the phase A as an example. The types of faults studied are as follows:

1. A phase power tube fault on the A phase, including Sa1 and Sa2 single tube faults, and simultaneous faults;
2. The power phase fault of the lower phase of the A phase, including the single tube fault of Sa3 and Sa, and the simultaneous fault;
3. Simultaneous failure of two power tubes on the opposite side of phase A, including simultaneous failure of Sa1 and Sa3; simultaneous failure of Sa1 and Sa4; simultaneous failure of Sa2 and Sa3; and four cases of simultaneous failure of Sa2 and Sa4;
4. Two power tube faults on the upper two sides of A and B, including Sa1 and Sb1 faults at the same time; Sa1 and Sb2 faults at the same time, Sa2 and Sb1 faults at the same time; Sa2 and Sb2 faults at the same time;
5. Two power tube faults on the lower side of A and B phases, including simultaneous failure of Sa3 and Sb3; simultaneous failure of Sa3 and Sb4, simultaneous failure of Sa4 and Sb3; simultaneous failure of Sa4 and Sb4.
6. Three-phase normal operation

The above categories basically include single-tube and multi-tube faults that are more common in ANPC inverter circuits. At the same time, the fault types and diagnostic methods of other phases are similar to those of A.

3. Fault Diagnosis Based on Wavelet Packet Decomposition

Due to the complex topology of the new ANPC inverter circuit, it is difficult to implement fault detection and diagnosis by monitoring the working state of each power tube. In response to this situation, the detection signal output characteristic of the detection circuit is generally used to realize the detection of the fault. When the circuit is faulty, the output signal usually generates distortion, which causes a change in the signal energy of the same frequency band, and the signal is extracted by removing the noise of the signal. Feature, the fault type is determined by the fault feature.

For different types of signals, the methods used to process signals are also mainly spectrum analysis, wavelet analysis, time series method and FFT. Spectrum analysis, FFT, and time series methods are generally used for periodic signals, and FFT and wavelet analysis are generally used for fault signals. Compared with FFT wavelet analysis, it is more flexible due to the characteristics of “multi-scale analysis” and “multi-resolution analysis”. In this section, wavelet packet analysis technology is used to decompose the output voltage of various fault modes of the inverter circuit to extract fault characteristic information.

In the fault diagnosis process of the inverter circuit, it is divided into three stages: information acquisition, fault feature extraction and fault diagnosis [10]. In the event of a circuit failure, the fault signal is first collected by the detection system, and the fault signal collected is subjected to wavelet packet analysis to obtain the fault feature. The commonly used method is to extract the energy information represented by the signal. By decomposing the signals at different scales, the energy characterized in the different frequency bands is extracted. The specific process is shown in Figure 3 [11].

![Figure 3. Fault feature vector extraction step](image-url)
(1) Wavelet packet decomposition: Select the wavelet packet basis function and the decomposition scale j, that is, the number of decomposition layers, and perform wavelet packet decomposition on the output voltage of the inverter circuit. According to the voltage output characteristics of the inverter circuit, the db wavelet is generally selected to decompose the signal. As shown in Figure 3, if the number of decomposition layers is j, there will be a spectral component.

(2) Extracting energy values: The energy values of the respective bands are solved according to the equation (1).

\[ E_{jk} = \sum_{m=0}^{N} |x_{jm}|^2 \]  

The j is the number of wavelet packet decomposition layers, and k is the number of bands, which is the wavelet coefficient.

(3) Normalization processing: When analyzing the wavelet packet decomposition result, the specific energy of each frequency band is usually solved, so the energy is normalized. The heavy energy is obtained by the formula (2).

\[ E_j = \sum_{k=0}^{2^j-1} E_{jk} \]  

(4) Extract the fault feature vector: Solve the weight of each band energy as the feature vector of the fault, as shown in equation (3)

\[ T = \left[ \frac{E_{j0}}{E_j}, \frac{E_{jk}}{E_j}, \frac{E_{j\beta}}{E_j}, \ldots, \frac{E_{j(2^j-1)}}{E_j} \right] \]  

The paper will use the db4 wavelet to perform 3-layer wavelet packet decomposition on the output voltage (ie, j=3). According to the above steps, the fault feature vector of the signal is solved.

4. Multi-classification problem based on support vector machine

From the basic principle of support vector machine, it can be seen that the classification of support vector machine is actually a two-class problem, but in practical problems, the types of data are often more than two. Therefore, there are two main methods when constructing SVM multi-class classifiers: First, the modification is directly performed on the objective function, and the parameter solutions of multiple classification surfaces are combined into one optimization problem, and the multi-class classification is realized at one time by solving the optimization problem. [12] This method is more complicated to calculate and difficult to implement, and is only suitable for small and medium-sized problems. The second is the indirect method, which is realized by combining multiple two classifiers. The common one is one-to-many and many-to-one.

1) One-to-many method

In the training, the samples of a certain category are classified into one class, and the other remaining samples are classified into one class, so that k categories constitute k SVM classifiers.

2) One-to-one method

Design an SVM between any two samples, so k categories of samples need to design k(k-1)/2 SVMs. When classifying an unknown sample, the classification with the most votes last is the classification of the unknown sample.

3) Hierarchical Support Vector Machines (H-SVMs).

Hierarchical taxonomy first divides all categories into two subclasses, then further subclasses into two subclasses, and so on, until a separate category is obtained.

4) Other multi-classification

In addition to the above methods, there are error correction coding SVMs for acyclic graph SVM and binary encoding of classes.

In the above classification method, the one-to-many method is very suitable for the fault diagnosis of the inverter circuit because of its simple algorithm and short training time. [13] Therefore, this
chapter uses the one-to-many SVM to identify the fault eigenvectors after wavelet packet decomposition.

5. Simulation verification

Based on Matlab/SIMULINK, the circuit topology shown in Figure 1 is built. The finite set model predictive control is used to control the circuit. The simulation parameters are as follows: Vdc=270V, filter inductor L=2mH, filter capacitor C=40μF, rated frequency 400Hz. The circuit load is a 400Ω resistive load and the system sampling period is Ts=10μs.

5.1. Circuit Fault Waveform Analysis

Taking the single-tube fault of the A-phase circuit as an example, Figure 4 and Figure 5 are the three-phase output voltage waveforms of the A-phase upper power tube and the lower power tube respectively.

![Figure 4. A phase circuit upper side power tube fault voltage output waveform](image)

Since the Sa1 single-tube fault and the Sa2 single-tube fault are the same as the circuit reconstruction scheme after the Sa1 and Sa2 faults at the same time, the output waveforms are the same when three faults occur, and the Sa1 and Sa2 single-tube faults and the double-tube simultaneous faults can be classified into one class. That is, the upper power tube of the A phase is faulty.

![Figure 5. A phase circuit underside fault voltage output waveform](image)

Because Sa3 single-tube fault and Sa4 single-tube fault are the same as the circuit reconstruction scheme after Sa3 and Sa4 fail at the same time, the output waveforms are the same when three kinds of faults occur, and Sa3 and Sa4 single-tube faults and double-tube simultaneous faults can be classified into one class. That is, the power phase of the lower side of the A phase is faulty.

Due to the space limited, the rest fault voltage output waveform are not introduced.

5.2. Fault energy feature extraction

The output voltage data in the fault mode listed in 4.1 is decomposed by three-layer wavelet packet using db4 wavelet to extract its energy characteristics.

(1) Analysis of wavelet packet energy spectrum under normal conditions

The wavelet coefficients of each node of the A, B, and C three-phase voltages under normal conditions are shown in Figure 6.
In the second part, we get the fault eigenvectors of six different types of faults, and we usually normalize the data before using the data for machine learning. Generally, the energy values of a phase are obtained through wavelet packet decomposition. Therefore, the fault feature vector is as shown in equation (4).

\[ T_i = [E_{a30}, E_{a31}, E_{a32}, E_{b30}, E_{b31}, E_{b32}, E_{c30}, E_{c31}, E_{c32}] \] (4)

Where \( i = 1, 2, 3, 4, 5, 6 \) represent the fault type, which \( E_{a30} \) respectively represent the (3.0) value of a phase.

According to the extraction requirements of the fault energy coefficients in the six failure modes solved, it is necessary to use the three-phase voltage wavelet packet energy of A, B and C to characterize a fault mode. Therefore, the fault feature vector is as shown in equation (4).

Due to the space limited, the rest fault energy are not introduced.

According to the wavelet packet decomposition energy table in the six failure modes solved, the energy of the frequency band obtained by wavelet packet decomposition under normal conditions, and the corresponding nodes are shown in Table 2.

Table 2. Wavelet packet decomposition energy under normal conditions

| Wavelet packet energy | (3.0) | (3.1) | (3.2) | (3.3) | (3.4) | (3.5) | (3.6) | (3.7) |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Phase A | 2507.5994 | 5323.7982 | 649.13877 | 1807.7012 | 41.6688 | 0.00893 | 0.12617 | 0.06527 | 0.11186 |
| Phase B | 2508.3719 | 9744.8982 | 116.4750 | 0.84350 | 0.00579 | 0.12420 | 0.04504 | 0.07928 | 4893.5897 |
| Phase C | 2507.7487 | 1827.9928 | 126.5300 | 0.78179 | 0.00494 | 0.13902 | 0.05143 | 0.07290 | 7777.5515 |

The energy of each frequency band obtained by wavelet packet decomposition under normal conditions, and the corresponding nodes are shown in Table 2.
meaning, and the weight needs to be set according to the actual situation. The energy of the band is normalized. The normalization method is as shown in equation (5).

\[ t_i = \left[ \frac{E_{a30}}{H}, \frac{E_{a31}}{P}, \frac{E_{a32}}{P}, \frac{E_{b30}}{H}, \frac{E_{b31}}{P}, \frac{E_{b32}}{P}, \frac{E_{c30}}{H}, \frac{E_{c31}}{P}, \frac{E_{c32}}{P} \right] \]  \tag{5}

among them:

- “i” is the type of failure;
- \( H = 3(E_{a30} + E_{b30} + E_{c30}) \);
- \( P = 3(E_{a31} + E_{a32} + E_{b31} + E_{b32} + E_{c31} + E_{c32}) \);

Normalize all the data to get a data set, one data set contains 6 fault vectors.

Select the radial basis kernel function for machine learning, as shown in equation (6)

\[ h(x_i, x_j) = \exp(-\gamma \|x_i - x_j\|^2), \gamma > 0 \] \tag{6}

After selecting the kernel function, the penalty coefficient \( C \) and the penalty coefficient selected by the kernel function coefficient are set. In this test, \( C = 1 \).

For 6 different fault types, we collected fault experimental data under different load conditions, a total of 30 data sets, 15 sets of data for data learning, and the remaining 15 groups for testing. The test results are shown in Table 3.

**Table 3. SVM classification test results**

| Fault type                                      | Accuracy |
|------------------------------------------------|----------|
| Normal circumstances                            | 100%     |
| Single-phase upper power tube failure           | 100%     |
| Single-phase lower side power tube failure      | 93.3%    |
| Single-phase power tube failure                 | 93.3%    |
| Two-phase upper side power tube failure         | 93.3%    |
| Two-phase lower side power tube failure         | 100%     |

In order to verify the influence of external interference on the diagnosis result, 10% white noise is added to the voltage output. The classification diagnosis result is shown in Table 4 below.

**Table 4. SVM classification test results when there is noise**

| Fault type                                      | Accuracy |
|------------------------------------------------|----------|
| Normal circumstances                            | 100%     |
| Single-phase upper power tube failure           | 93.3%    |
| Single-phase lower side power tube failure      | 93.3%    |
| Single-phase power tube failure                 | 93.3%    |
| Two-phase upper side power tube failure         | 93.3%    |
| Two-phase lower side power tube failure         | 93.3%    |

6. Conclusions
It can be seen from the experimental results shown in Table 3 and Table 4. The accuracy of the diagnostic results is above 90%. At the same time, the method requires less sample size and can better solve the problem of insufficient sample size in machine learning.
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