

Fault Diagnosis in Medium Voltage Drive Based on Combination of Wavelet Transform and Support Vector Machine

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Abstract

Nowadays, Medium Voltage Drive (MVD) has been widely applied in the field of high-powered motor speed-regulation. These types of converter use a lot of insulated gate bipolar translators (IGBTs). So it is very important to find an effective way to diagnose IGBT open-circuit faults. This study describes a method of diagnosis for IGBT open-circuit faults in MVD whose topology is cell series of multi-level. This method combines wavelet transform (WT) and support vector machine (SVM). The wavelet transform is used to extract fault features and SVM is used to classify the fault states of a single power unit. Then, the trained SVM classifier is used to scan all power units of MVD sequentially. Results of simulation on the platform of MATLAB/Simulink show that this method has a good diagnosis capability. It can diagnose the IGBT open-circuit faults of the whole inverter system, and diagnosis accuracy is up to 96%. So, this method has a good application prospect.

Keywords: Insulated gate bipolar transistors, multilevel systems, Support vector machines, Wavelet transforms

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1 Introduction

In recent years, MVD has been obtained large-scale application. It has the advantages of high output voltage, low content of harmonics, low switching frequency and so on. The three-phase voltage outputs of MVD are generated by series power modules. Every power module is composed of rectifier-bridge and H-bridge. One H-bridge is composed of four IGBTs. It means that there are a lot of IGBTs which are used in the inverter. But IGBT is the flimsiest component in a MVD system. So, it is very important to know if they have problem or not for MVD's reliability and power module replacement online technology. There always are open-circuit fault and short-circuit fault states when IGBTs are broken. As for short-circuit fault state, there is already proper way to diagnose. The voltage between collector and emitter of IGBT is often measured to figure out whether this kind of fault happened or not. But for IGBT open-circuit fault, its impact is not as big as the former. The motor may still run when IGBT open-circuit fault occur. However, the output wave of MVD will get distortion, and it will also introduce DC component and lead to increasing of harmonics, insulation failure, heating problem and so on. It even leads to some other bigger problem if this problem is not treated in a timely way [1]. There is still no proper way to deal with this kind of problem for MVD. So it is necessary to research some effective detection methods.

There are some methods such as expert system, neural networks, current measuring method and polarity detection method to diagnose IGBT open-circuit fault. Expert system method [2-3] is based on accumulation of experiences. It needs to list all possible fault states, summarize the rules and establish a knowledge database. When failures occur, it judges the fault state by querying the database. However, this method has some weakness. It is difficult to establish a complete database. Artificial neural net technique is used to identify fault state in the neural network method. It doesn't need the mathematical model of the diagnosis object, and it also has some other advantages such as powerful parallel processing ability, self-learning ability and good fault-tolerant ability [4]. But this method has blindness in its structure designing and fall into the local minimum point too easy [5]. Current measuring method is based on the analysis of system's output current. It derives average current park vector method [6-7], single

current transducer method [8], current slop method [9] and so on. However, these methods are sensitive to the load. Voltage current polarity judgment method is to use the polarity of PWM inverter's output to diagnose IGBT open-circuit fault. This method has the advantages of rapid diagnosis, high reliability. But, it is only applicable to the two-level or three-level inverter. For multi-level inverter, it is hard to identify fault states [10]. M. A. Rodríguez-Blanco and A. Vázquez-Pérez [11] proposed a fast fault detection scheme for IGBT open circuit using adaptive thresholds during the turn-on transient. This approach uses a lot of component for detection. So, it is not suited for medium voltage cascaded multilevel inverters. In [12], the author combined the wavelet analysis and the support vector to diagnose IGBT open-circuit fault. But they only analysed for two-level inverter, not for cascade multilevel converter.

In this paper, for cascade multilevel inverter system, wavelet transform is used to extract fault feature, multi-SVM is used to classify the states of IGBT fault. In time and frequency domain, the wavelet transform has good localization property. The frequency of converter's output is variable, that is to say, it's a non-stationary signal. So conventional Fourier transform is no longer suitable for spectrum analysis here. SVM is a kind of machine learning algorithms based on statistical theory. It can master the characteristics of the sample by studying the training data, and then classifies unknown samples. Multi-SVM is used in this paper to diagnose IGBT open-circuit fault.

2. Problem Formulation

2.1. Fault Analysis of Cascade Multilevel Inverter Circuit

MVD is mainly composed of phase-shifting transformer and power modules. As is shown in Figure 1, it is the power modules connection model of MVD. The advantage of this structure is that it can avoid high voltage adding to IGBT. Figure 2 shows that the power module is composed of rectifier, filter and H Bridge. The connection port R, S and T which will be connected to the secondary winding of phase-shifting transformer are three phase inputs of power module, and the port U and V are outputs. U port of one power module is connected to V port of another power module. Finally, three phase high voltage output are formed in this way.

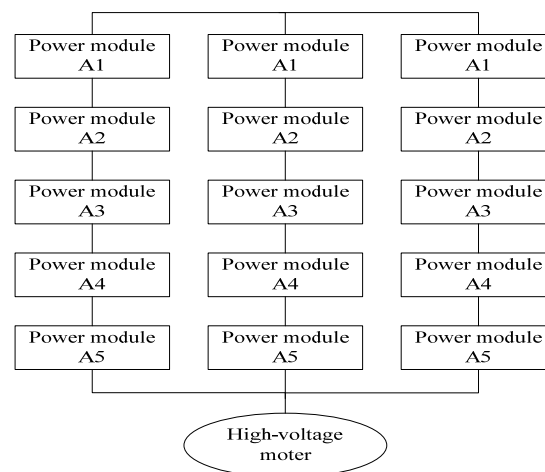


Figure 1. Power modules connection model of MVD

Single power module which is composed of 4 IGBTs is a two level inverter. As is shown in Figure 2, IGBT A+ and B-, B+ and A- switch on at the same time. The control signals of H Bridge are generated by the comparison of triangular wave and sinusoid. Sinusoid is called modulation wave and triangular wave is called carrier. Dead-time compensation is added to the up and down tube's control signal. We compare one modulation wave to other different carriers which have different phases to generate control signal. The difference of modulation wave among three phases is 120° .

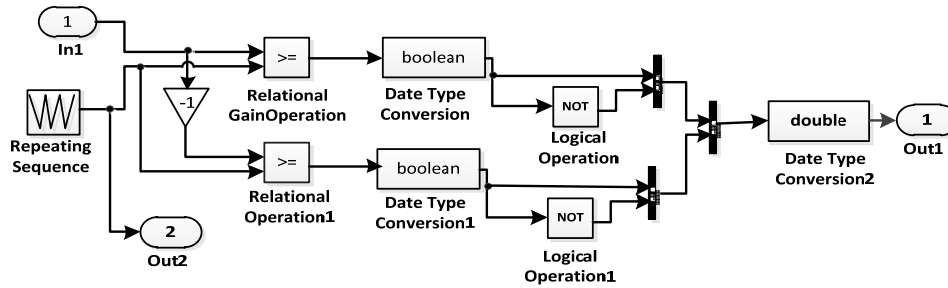


Figure 4. Model of SPWM waveform generator

2.2. Wavelet Transform of Power Module's Output Voltage

Wavelet transform is very sensitive to singular point of signal. The signal will show some features unlike noise's to some extent when the output wave distortion happens. So, waveform distortion could be detected in the strong noise background if we select proper wavelet basis and scale parameter. For noise, its maxima moduli of wavelet transform reduce rapidly. So, this could raise anti-jamming capability of fault diagnosis system.

A proper wavelet basis is needed to wavelet transform. There are some common used wavelet base functions such as Morlet, Mexico, Haar, DBN, Symlet and so on. They must meet some basic performance indicators, such as vanishing moment, regularity, compactly supported, symmetry. But it is conflict for vanishing moment and compactly supported. The high rank vanishing moment means that the value of wavelet function decays to zero quickly. This brings in a high resolution ratio, but lead to supporting length growing longer. So it needs to synthesize every kind of situation.

Lipschitz index α could be used to describe signal feature of partly singularity [13]. It must meet the following formula.

$$|f(x_0+h)-P_n(h)| \leq A|h|^\alpha \quad (1)$$

$$n < \alpha \leq n+1 \quad (2)$$

$$n \geq 0, n \in \mathbb{Z} \quad (3)$$

$$A \geq 0, A \in \mathbb{Z} \quad (4)$$

$$h_0 \geq 0, h_0 \in \mathbb{Z} \quad (5)$$

There is a theorem which states that wavelet transform can't detect singularity of signal if it just has n rank vanishing moment. So, the rank of wavelet basis must be high enough to get ability of detecting singularity of signal. Generally, to identify discontinuity of n th order derivative, we select at least n order disappeared regular wavelet. Some studies discover that Daubechies wavelet basis is suitable to process electronic circuit signal. Wavelet basis DB25 is selected to decompose fault signal into 8 levels. Mallat algorithm was selected to decompose the output wave of power module into 8 levels. One IGBT drive signal is disconnected at the output frequency of 50HZ.

2.3. Energy Eigenvalue of Wavelet Transform

First, evaluate energy value of wavelet decomposition coefficient. Then, put the evaluated value in a column vector which could be as eigenvector of a fault. The energy of wavelet is defined as follows:

$$EW_j = \int |S_j(t)|^2 d(t) = \sum_{k=1}^n |d_k^j|^2 \quad (6)$$

$S(t)$ is the function of a signal, and EW_j is the power of wavelet decomposition coefficient. Specific steps are as follows:

1. Decompose output voltage signal into 8 levels with wavelet transform.
2. Evaluate total energy of each band signal.

$$E(8, j) = \sum_{k=1}^n |x_{jk}|^2$$

If the power of $S(8, j)$ is $E(8, j)$ ($j=1,2,3,4,5,6,7,8$), then X_{jk} is the amplitude of recomposed signal.

3. Construct eigenvector based on energy of every band signal.

$$T1=[E(8,1)/E E(8,2)/E E(8,3)/E E(8,4)/E E(8,5)/E E(8,6)/E E(8,7)/E] \quad (7)$$

When some IGBTs open-circuit faults occur, there will be some changes of eigenvector. So, this eigenvector could be the input of SVM classifier.

3. Fault Diagnosis Based on Multi-SVM

SVM is a kind of machine learning algorithm which is based on statistic studying theory and structure risk minimizing principle. It has many advantages in solving small size sample, nonlinear and high dimensionality in pattern identification problems. It has a solid theoretical basis and simple mathematical model.

3.1. Principle of SVM's Multi-class Classification

The basic algorithm of SVM is to put linear inseparable problem be mapped into high-dimensional space by the kernel function.

If there are m samples as follows:

$$(x_1, y_1), (x_2, y_2), \dots, (x_m, y_m), x \in R^d, y \in \{+1, -1\} \quad (8)$$

In low dimensional space, linear discriminant function usually is expressed as follows:

$$g(x) = w * x + b \quad (9)$$

Equation of classification is as follows:

$$w * x + b = 0 \quad (10)$$

The condition of correct classification is that it must meet the following equation:

$$y_i (w * x_i + b) - 1 \geq 0 \quad (11)$$

The algorithm above just applies to binary classification problems. For this paper, we need to use multiclass classification method which is based on basic SVM above. There are two ways to construct multi-SVM classifier. One way is called direct method. It changes the objective function directly, incorporates multiple classification surface parameters into an optimization problem. It realizes multi-classification by solving the optimization problem. But this kind of method is complex and difficult to use. The other way is called indirect method. It gets the ability of multi-classification by combining multiple classifiers. This method is divided into two kinds. One is called one-versus-rest (OVR) SVMs. The other is called one-versus-one (OVO) SVMs. The basic method is to design a SVM binary classifier between any two samples. So samples of m category should be designed $m * (m - 1) / 2$ SVM binary classifiers. When we classify unknown samples, the number of one classification will be added one if it is corresponding category. Finally, the sample which has the maximum number will be recognized as the final classification result.

3.2. The Classification Method of IGBT Open-circuit Fault of MVD

As we can see from Figure 2 that four IGBTs are used in a power module. So, for a power module, there are 16 kinds of IGBT faults ($C_4^0 + C_4^1 + C_4^2 + C_4^3 + C_4^4 = 16$). Combining the above analysis, one to one classification algorithm (OVO SVMs) is more appropriate.

There are two stages of this method. First, we should select the optimal parameters, train the multi-SVM classifier with the eigenvectors which are extracted from wavelet decomposition. Second, use trained classifier to classify test samples. Details are as follows:

1. Select the kernel function

According to the principle of the Hilbert - Schmidt, a function can be a kernel function as long as it satisfies the Mercer condition. Kernel functions which are usually used are as follows:

Linear inner product function

$$K(x, y) = x^T * y \quad (12)$$

Polynomial kernel function

$$K(x, y) = (x * y + 1)^d \quad (13)$$

RBF kernel function

$$K(x, y) = \exp \left\{ -r \|x - y\|^2 \right\} \quad (14)$$

In this paper, we select the RBF kernel function which can be carried out nonlinear mapping easily.

2. Pre-treatment of sample data and training classifier

First, we select the eigenvector which can reflect the feature of faults. Then, the faults which have the same characteristics are removed. The training samples are got by normalizing the feature vector.

3. Cyclical scan the output wave data of each power module with the trained classifier

In a complete cycle, all power modules could be diagnosed by the same classifier. Because control signals of IGBTs are generated by the compare of the same frequency modulation wave and the carrier. We use the classifier to cyclical scan all the power modules which we know their sequences. Then we know which IGBT and which power module occur the open-circuit fault. It is feasible to the real MVD, because every power module has a unit control board to control IGBT's operating states. This board is also can be used to gather the value of power module's output data and send it to the master controller which contains the classifier in it. Then IGBT open-circuit faults of the whole MVD system can be diagnosed by this classifier.

4. Simulation and Result Analysis

As is shown in Figure 3, it is a three-level MVD's simulation model. Every phase of the MVD is composed of three power modules. We open IGBT's driving signal to simulate its failure. Table 1 shows eigenvectors of energy value which are decomposed by wavelet transform when output frequency of MVD is 50HZ. The first column lists the IGBT states: "NO" means that there is no IGBT failure; "A+" means that IGBT A+ has open-circuit fault; "A+ A- B+ B-" means that all of them occur IGBT open-circuit fault. The second column lists labels of IGBT open-circuit fault. "E0" in the third column means wavelet transform's energy value of the eighth level in low frequency part. "E1" in the fourth column means wavelet transform's energy value of the eighth level in high frequency part. "E3" in the fifth column means wavelet transform's energy value of the seventh level and so on. From Table 1, we get information that the energy of power module's output is mainly focused on low frequency part. There also are some other information can be got that the first class and the forth class, the second class and the third class, the fifth class and the ninth class, the sixth class and the tenth class, the eleventh class and thirteenth class have nearly the same energy value of frequency band. So we merge the same two

classes into one class. As we can see from the following table, the most energy focuses on first four ranks. So, we select “E0”, “E1”, “E2” and “E3” as the eigenvector.

Table 1. wavelet transform’s energy value of one power module’s voltage output

Fault	Label	E0	E1	E2	E3	E4	E5	E6	E7	E8
NO	0	0.7184	0.0281	0.0186	0.1093	0.1188	0.0759	0.0544	0.0381	0.0318
A+	1	0.6882	0.0550	0.0767	0.1172	0.1058	0.0687	0.0504	0.0330	0.0277
A-	2	0.2902	0.0393	0.0799	0.1169	0.1088	0.0655	0.0492	0.0338	0.0284
B+	3	0.2367	0.0481	0.0657	0.0970	0.1041	0.0595	0.0456	0.0328	0.0275
B-	4	0.6883	0.0456	0.0883	0.1221	0.1037	0.0688	0.0494	0.0341	0.0284
A+A-	5	0.1978	0.0658	0.1138	0.1287	0.0864	0.0587	0.0440	0.0279	0.0226
A+B+	6	0.1087	0.0591	0.0811	0.1284	0.0905	0.6562	0.0433	0.0276	0.0241
A+B-	7	0.7391	0.0956	0.0562	0.0930	0.1019	0.0637	0.0463	0.0308	0.0254
A-B+	8	0.8619	0.0909	0.0588	0.0817	0.1009	0.0536	0.0410	0.0303	0.0251
A-B-	9	0.2061	0.0742	0.1332	0.1107	0.0814	0.0561	0.0400	0.0277	0.0234
B+B-	10	0.1097	0.0693	0.1250	0.1196	0.0828	0.0520	0.0387	0.0279	0.0223
A+A-	11	0.8382	0.1082	0.0915	0.1085	0.0626	0.0419	0.0319	0.0213	0.0178
B+										
A+A-	12	0.3393	0.1156	0.1149	0.1069	0.0711	0.0531	0.0357	0.0241	0.0215
B-										
A-B+	13	0.8389	0.1130	0.1307	0.0915	0.0614	0.0419	0.0283	0.0238	0.0212
B-										
A+B+	14	0.3025	0.1075	0.0902	0.0886	0.0603	0.0428	0.0324	0.0217	0.0178
B-										
A+A-	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
B+B-										

The output frequency of MVD was changed from 10HZ to 70HZ. So, there are 71 samples for every type of IGBT faults. We selected the sample data of one power module as the SVM’s training data. The data of other power modules were diagnosed by this trained SVM.

The SVM’s parameters were optimized with grid-research method. Finally, the value of penalty factor was set to 32768. The parameter g was set to 0.5. The final result of IGBT open-circuit fault classification in power module whose accuracy is 96.9262% is shown as Figure 5.

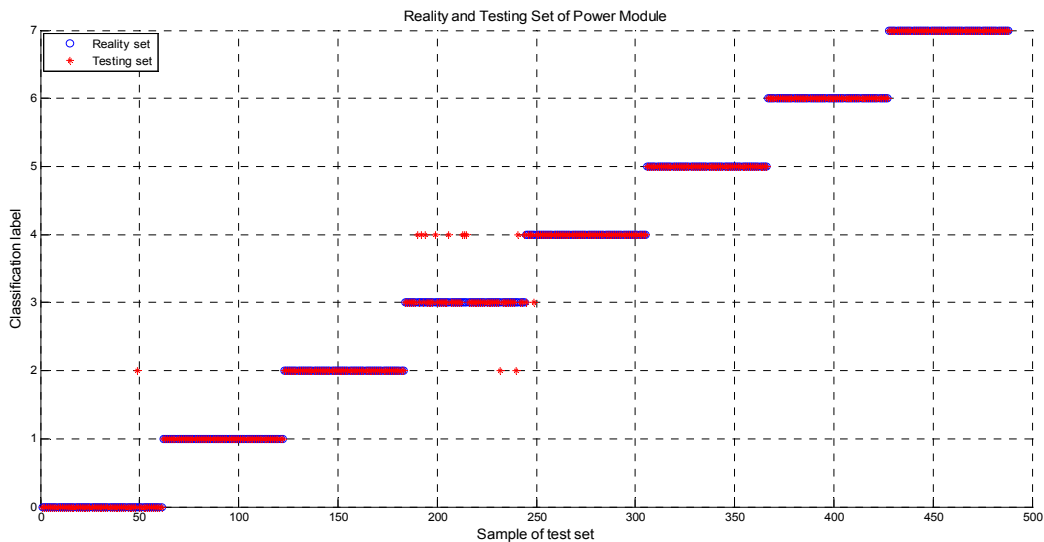


Figure 5. Diagnosis result of IGBT open-circuit fault

The final diagnosis of the whole MVD is finished by this SVM classifier diagnosing all the power modules in turn. The accuracy of the remaining power modules are 96.9508%, 96.9305%, 96.7754%, 96.8433% and 96.7205%. It can be seen that the accuracy of all the power modules are high enough.

5. Conclusion

This paper proposes a method for IGBT open-circuit fault detection in Medium Voltage Drive whose topology is cell series multilevel. The proposed method combined WT analysis and SVM classifier. The basic parameters of WT are obtained by analysing output of power modules in MVD and multi-SVM classifiers are trained by the eigenvectors of this output. The remaining power modules are diagnosed by the trained multi-SVM classifier one by one. The simulation results demonstrate the possibility and effectiveness with this method to detect IGBT open-circuit faults in MVD. It is also adaptable for some MVDs which have different control algorithms such as vector control and voltage to frequency control, if we put the related samples to train the multi-SVM classifier.

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