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Fault Diagnosis of Power Converter for Switched Reluctance Motor based on Discrete Degree Analysis of Wavelet Packet Energy

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Abstract – Power converter plays a very important role in switched reluctance motor (SRM) systems, and it is also the easiest one to experience failures. Power converter faults will cause the motor to run in non equilibrium states, and a long time fault operation will lead to motor and other modules damaged, and make the system completely lose working stability. This paper uses an asymmetric bridge converter as the research object with three-phase SRM, employs the wavelet packet decomposition for the phase currents. It analyzes and studies the short circuit fault condition of IGBT, uses an energy discrete degree of the wavelet packet nodes as the fault characteristic, and conducts the corresponding experimental and simulation analysis to verify the effectiveness and practicality of the proposed method.

Keywords: Fault diagnosis, SRM, Power converter, Wavelet packet, Discrete degree

1. Introduction

Switched reluctance motor control system (SRD) is a typical electromechanical integration product, combining the electrical machinery, microelectronics, power electronics, control theory, to name but a few [1-4]. The power converter of SRM is a single polarity current converter, which is a very important part in the control system as the frequency converter to inverter-driven induction motor. It is also the most prone to the failure in the system. The power converter fault will destroy the equilibrium state of the drive system, which will produce torque gap even brake torque. Long-term fault operation will cause the entire system damaged. In this point of view it is very necessary to make fault diagnosis in the power converter implementation [5-6].

The fault diagnosis methods of power electronic devices are mainly classified as current test [7], voltage test [8-9], and pattern recognition methods [10]. The first two methods are to judge if the output signal exceeds the threshold value to find the fault directly, while the pattern recognition method is based on the fault current or voltage waveform mathematical transform to extract the fault characteristics and to realize fault diagnosis. The commonly used method is the Fourier transform and wavelet transform. Ref. [11-12] work on the fault diagnosis based on FFT, but FFT will inevitably produce frequency spectrum leakage and fence effect [14]. Ref. [15] studies the identification of defects inside a IGBT module. The diagnostic scheme is rapid, accurate and easy to implement, which has a good robustness for different transient disturbances. Ref. [15] presents a real-time implementation of an online protection technique for the induction motor fault detection and diagnosis. The protection system utilizes a wavelet packet transform (WPT)-based algorithm for detecting and diagnosing various disturbances occurred in three-phase induction motors. The diagnostic scheme is rapid, accurate and easy to implement. It has also a good robustness for different transient disturbances.

The wavelet transform is the local transform of the frequency and space which can effectively extract and analyze the sampling signal information. It makes multi-scale refinement analysis of the signal through the method of translation and expansion, which solves a lot of problems that Fourier transform can not solve. Using a three-phase power converter as the case study, it makes the wavelet packet decomposition into phase currents, extracts the energy of bottom nodes and defines discrete degree of nodes energy as fault characteristic features to realize fault diagnosis. The method can accurately judge the fault types and positions of the power converter. The simulation and experiment results verify the validity of the method.

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2. Power converter and its fault type

The asymmetric bridge converter uses only one chopping switch in every bridge arm as shown in Fig. 1. Each phase is independent of each other, so the system has strong stability, well fault tolerance and good performance.

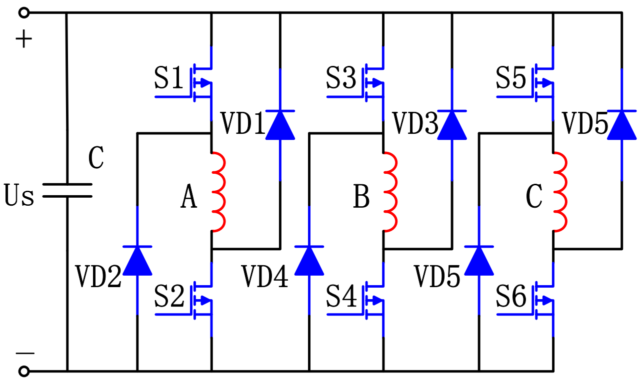


Fig. 1. Power converter

Power converter fault types include mainly short-circuit faults and open-circuit faults in various components. While the power switch is the core device of a power converter and the most vulnerable part. In this paper, different fault types of power switching devices are analyzed and diagnosed. Taking phase A fault as an example, if a short circuit fault occurs in the down switch S2 of phase A, S1 will implement a normal chopper control when phase A opens. S1 is closed when phase A closes, the winding current follows zero voltage through VD2. There still exist following current in the inductive drop stage, and generate braking torques, which will cause the reducing of system torques and increasing of torque ripples. When the short circuit of the top switch occurs, the winding is under the bus voltage directly in the opening interval of phase A, thus, it cannot carry out a chopping control. In the closing interval of phase A, S2 is closed, the winding current follows zero voltage through VD1, it still generates a braking torque, which will affect the normal operation of the system. When the open circuit of the up switch or down switch of phase A occurs, it will both cause the system running on the phase deficient state. For an open-loop system, a zero torque output of the fault-phase will directly impact on the system load capacity and torque ripple. For a close-loop system, although a good closed-loop control strategy can compensate the output capacity of the system, the torque gap still causes an increase of the torque ripple.

3. Calculation of Nodes Energy Discrete Degree

The essence of the wavelet packet decomposition is to decompose a node into two nodes and to decompose step by step, i.e., subdivide the whole frequency band in order to observe each frequency component better and extract the fault characteristic value. If the decomposition layers are l, the number of nodes is 2l.

Using a five-layer wavelet packet decomposition for example, it analyzes the sampling signal, makes a five layers wavelet packet decomposition, and extracts all frequency components of the signal characteristics from the ith layer. S(i, j) stands for the jth node of the ith layer, where i=0,1,2,3,4,5; j=0,1,…31. S(5, j)(j=0,1,⋯31) corresponds to E(5, j) (j=0,1,⋯31), the function is given as

$$E(5,j)=\int\left|S(5,j)(t)\right|dt=\sum_{k=1}^{n}\left|d_{j,k}\right|^{2} \tag{1}$$

where dj,k(j=0,1,⋯31, k=1,2,⋯n) is the wavelet coefficient of S(5, j).

The discrete degree of the nodes energy is given by

$$\sigma=\{\sum_{n=1}^{k}[E(5,n)-E_{av}]^{2}/k\}^{1/2} \tag{2}$$

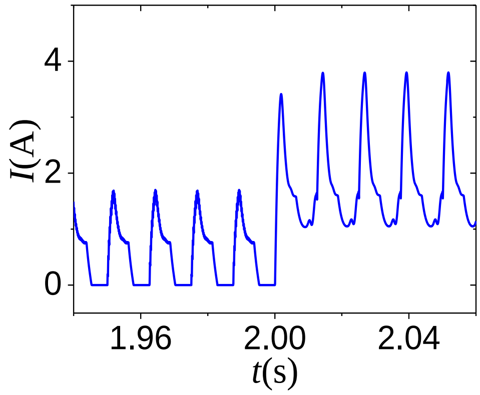
where the nodes energy average E_{av} is formalized as

$$E_{av}=\sum_{n=1}^{k}E(5,n)/k \tag{3}$$

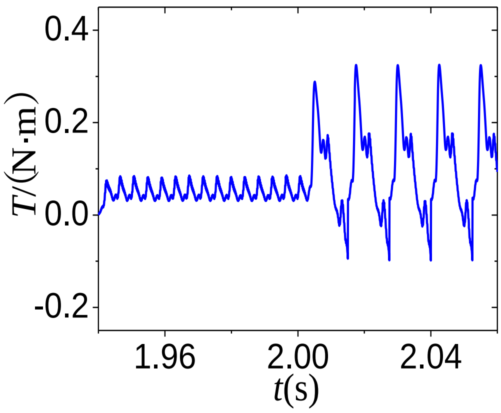
where $E(5,n)$ is the n^{th} node energy of the 5^{th} layer, k is the number of the nodes in the selection, E_{av} is the nodes energy average, σ is the discrete degree of the nodes energy.

4. Fault Simulation

Fig. 2 is the phase current and the total output of the torque when the short circuit fault in the down switch happens at 2s.When the fault happens, the fault phase is zero voltage of follow currents, the following current can not rapid feedback to the power supply. There still exists large follow currents in the dL/dθ<0 range, under the action of the induced electromotive force. According to the electromagnetic torque formula of SRM, it will inevitably produce the brake torque and torque ripple. The system runs in the phase-deficient state when the open-circuit fault happens. While it is possible to ensure that the output of the system capacity is under the good closed-loop control, it will still increase the torque ripple.



(a) Phase current



(b) Total torque

Fig. 2. Phase current and total torque of the short-fault

The paper uses db3 wavelet transform to make a five-layer wavelet packet decomposition for the current signal. Due to the large numbers of the nodes, it calculates and analyzes the previous eight nodes energy in order to reduce the computational complexity. Because the wavelet packet node will produce the band cross phenomenon, the actual order sort is not the nodes order. For a five layers of decomposition, the actual band sequence of the first eight nodes should be (5,0), (5,1), (5,3), (5,2), (5,6), (5,7), (5,5), (5,4). Using the above principle and method to calculate the underlying nodes energy, the average value and discrete degree of the nodes energy are shown in Table 1.

Table 1. Average value discrete degree of nodes energy

Speed (r/min)	Average value E_{av}		Discrete degree σ	
	Normal	Fault	Normal	Fault
400	12.2036	12.2403	24.8088	28.9210
500	12.1371	12.2215	21.7379	28.2889
600	12.0871	12.1603	19.2245	27.3287
700	11.9985	12.0808	18.2729	27.5968
800	11.9457	12.1603	17.5129	27.3287
900	11.8964	12.0040	17.3018	27.5484
1000	11.7319	11.9300	17.4341	27.3608
1100	11.7262	11.9206	17.6262	27.5981

The nodes energy average Eav does not change significantly before and after the short-circuit fault of the down switch, but the discrete degree changes a lot. When the phase A open-circuit fault happens, the phase A current drops to zero, and the discrete degree σ becomes zero. So using the discrete degree of the node energy as the fault characteristics can accurately distinguish short-circuit faults and open circuit faults of the power converter.

5. Fault Experiment

The experimental system uses an asymmetric bridge converter, and the DC bus voltage is 12V. The control mode is PWM voltage regulation control, and the speed closed-loop is the fuzzy control. The main control chip is DSP TMS320F2812 with high speed logic circuits, and the experiment platform is shown in Fig. 3. Motor parameters are shown in Table 2.

Table 2. Motor parameters

Parameters	Value
Phase number	3
Stator poles	12
Rotor poles	8
Rated speed/(r/min)	1500
Rated power/(W)	100

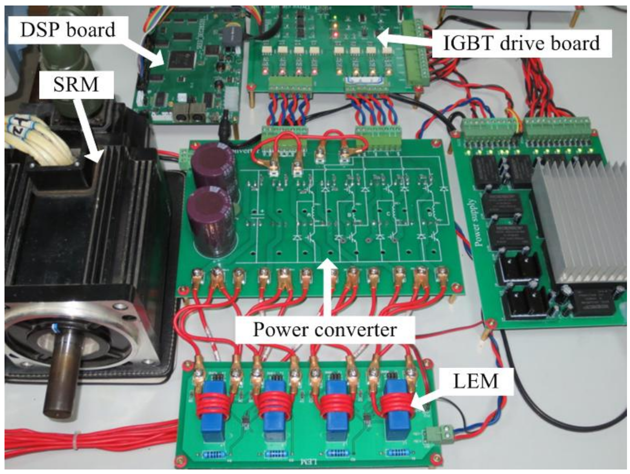
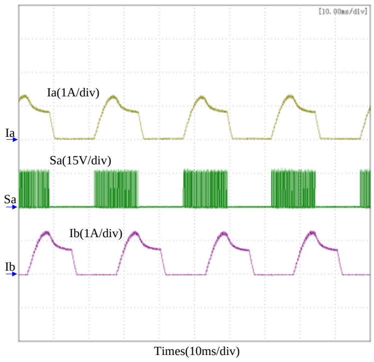
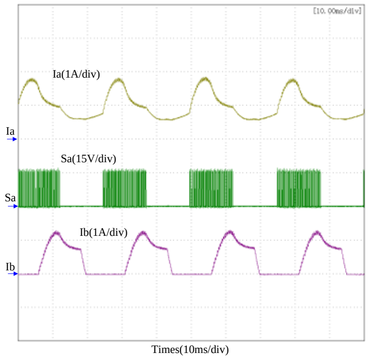


Fig. 3. Experiment system

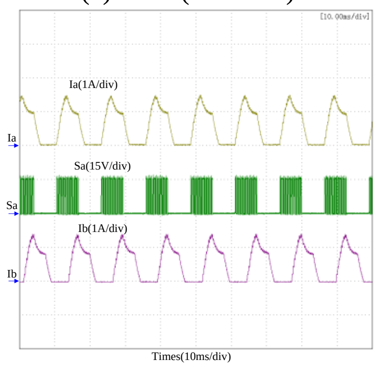
The phase current before and after the short fault of the down switch is shown in Fig. 4. Phase A is for the experimental phase, Sa is the driving signal of phase A, phase B is the normal phase. The current sampling frequency is set to 10k HZ, the phase current is sampled before and after the fault between speed of 400r/min and 1100 r/min, and the wavelet packet decomposition is made to sampling current, as shown in Table 3 and Fig. 5. The energy concentrates mainly in the first eight nodes, and the rest of the nodes energy is very small which can be ignored. The fault characteristics are calculated and extracted from the first eight nodes in this paper.



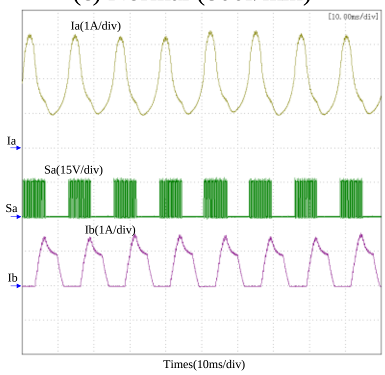
(a) Normal (400r/min)



(b) Fault (400r/min)



(c) Normal (800r/min)



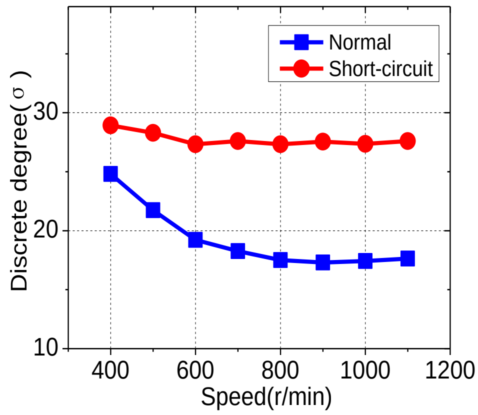
(d) Fault (800r/min)

Fig. 4. Phase current before and after the fault

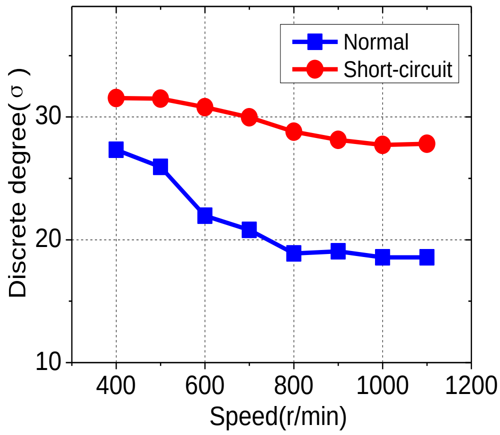
Under normal circumstances, with the increase of the rotational speed, the node energy of (5, 0) is on the decline, and the nodes energy of (5,1), (5,2), (5,6), (5,4) falls after the rise, and the nodes energy of (5,3), (5,7), (5,5) is on the rise. Compared to the same speed, the nodes energy changes a lot before and after the short-circuit fault. The node energy of (5,0) increases significantly, and the nodes energy of (5,1) to (5,7) reduces significantly. Average and discrete degree of nodes energy is shown in Table 3 and Fig. 5.

Table 3. Average value discrete degree of the nodes energy

Speed (r/min)	Average value E_{av}		Discrete degree σ	
	Normal	Fault	Normal	Fault
400	12.4387	12.4723	27.3313	31.5366
500	12.4123	12.4797	25.9382	31.4893
600	12.4031	12.4789	21.9511	30.8003
700	12.4060	12.4817	20.7941	29.9744
800	12.3618	12.4809	18.8774	28.8022
900	12.3684	12.4806	19.0554	28.1371
1000	12.3286	12.4788	18.5680	27.7155
1100	12.3446	12.4773	18.5676	27.8211



(a) Simulation



(b) Experiment

Fig. 5. Value of σ before and after the fault

The experimental results show good agreements with the simulation ones. It is revealed that:

1) The average value of nodes energy E_{av} changes little after the short-circuit fault, but the discrete degree σ changes obviously. The value of σ declines rapidly as the speed increases in normal, and it falls flat after short circuit. However it increases significantly. Using σ as the fault characteristics can accurately determine the working state of the power switches.

2) Although the distinction of the discrete degree of nodes energy σ is not big at low speeds than at high speeds, the value still increases obviously after the failure, and it does not affect the accuracy of the diagnosis. As long as it detects that a phase current discrete degree σ of nodes energy increases suddenly, it can determine the phase short-circuit fault, regardless of the motor is in steady state or in the process of accelerations.

3) When an open-circuit fault happens, the motor is in phase-deficient operation state. The fault phase current drops to zero directly. The energy of each node is zero, and the value of the discrete degree σ is zero. It can be used to diagnose the open circuit fault by judging whether the value of the discrete degree σ is zero.

4) Wavelet packet decomposition mainly involves two aspects, which are the selection of decomposition layers and the number of nodes. The more decomposition layers, the more you will get the nodes. Although the frequency band partition is finer, the DSP has greater pressures. The studies show that, it can both reduce the computing complexity and guarantee the quickness and accuracy of the fault diagnosis to extract fault characteristic value of the former eight nodes.

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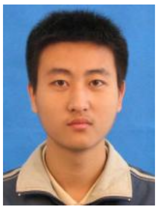

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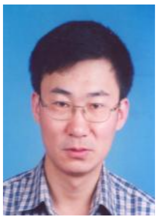

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