ARTICLE IN PRESS
MR-12411; No of Pages 8
Microelectronics Reliability xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Microelectronics Reliability
journal homepage: www.elsevier.com/locate/microrel

Current similarity based open-circuit fault diagnosis for induction motor drives with discrete wavelet transform

Feng Wu, Yang Hao, Jin Zhao*, Yang Liu

Key Laboratory of Image Information Processing and Intelligent Control, Ministry of Education, School of Automation, Huazhong University of Science and Technology, Wuhan, China

ARTICLE INFO

Article history:
Received 17 December 2016
Received in revised form 17 March 2017
Accepted 25 May 2017
Available online xxxx

Keywords:
Euclidean distance
Discrete wavelet transform
Open-circuit
Fault diagnosis
Voltage-source inverter
Similarity analysis

ABSTRACT

Three-phase voltage-source inverters fed induction motor with space-vector controlled scheme are widely used in industrial applications. The suffered failures will degrade the system performance with output torque ripple and harmonic currents. In this paper, a novel diagnosis method is proposed to detect and locate the insulated gate bipolar translator open-circuit fault. Discrete wavelet transform is used as a pre-treatment technique for three-phase output currents, the approximate coefficients are applied to obtain energy vectors. Euclidean distance between every two of the energy vectors are calculated for measuring the current similarity to diagnose fault. When IGBTs occur open-circuit fault, the values of Euclidean distance will be smaller than that under normal conditions, then faults can be detected. Faults can also be located according to extracted features. Simulation and experimental results show high efficiency and merits of the proposed method.

1. Introduction

Two-level three-phase voltage-source inverters (2L-VSIs) fed induction motor (IM) are widely used in industry applications for their simple mechanical structure and superior control performance. The power converters play an important role in the control system, however, they frequently suffer failures including open-circuit and short-circuit fault, because of high dv/dt, thermal stress, overvoltage and others [1–3], resulting in degrading the system performance such as rippled torque and harmonic currents. Systems will be shut down or destroyed if no positive actions are taken, blind maintenance will increase the down time and cause economic loss. Hence, it is necessary to detect and identify the faults before their spread and simultaneously offer failure information for tolerant strategies or maintenance.

Semiconductors such as insulated gate bipolar translators (IGBTs) are the most fragile components in power converters [4]. The failures can be divided into three classes, short-circuit fault, open-circuit fault, and gate-misfiring fault [2]. Most of industrial products carry hardware and software protection strategies of short-circuit fault. IGBT short-circuit fault will cause overcurrent and immediately trigger the self-protection by cutting off the drive signals [5]. Gate-misfiring fault is caused by long cable or electromagnetic interference, the failure characteristics are similar to open-circuit fault. Open-circuit fault does not shut down the system immediately, however, the generated torque ripple will damage system mechanical structures and the unbalanced three-phase voltages or currents will be harmful to motors, which will induce secondary failure.

Timely detecting and identifying IGBT open-circuit fault can avoid secondary failures and offer information for maintenance. In recent years, lots of attentions have been attracted in this project. Generally, they can be divided as two kinds. Ones taken into IGBT parameters, lifetime models, environmental and operational stresses to predict the lifetime based on statistic tools with a confidence level (e.g., 90%) [4,6]. The other ones real-time diagnosed the IGBT by extracted signals, maybe from different sources, or with different pretreating or processing techniques. Refs. [7,8] analyzed the IGBT failure mechanism from micro-level with IGBT electrical model, based on the behavior of the gate-voltage during the turn-on transient. In these methods, every IGBT needed an extra detecting circuit, the system volume and cost were relatively high. Ref. [9] proposed to analyze the IGBT failures from system-level, based on currents or voltages of power converters.

A line-to-line voltage envelope function was proposed in Ref. [10] to generate voltage envelope and compared with preprocessed diagnosis eigenvalue to diagnosis IGBT open-circuit. Other voltage-based diagnosis methods were proposed by measuring the pole [11], phase [12] voltage, or residual errors between reference and

* Corresponding author.
E-mail address: jinzhao617@163.com (J. Zhao).

http://dx.doi.org/10.1016/j.microrel.2017.05.036
0026-2714/

Please cite this article as: F. Wu et al., Current similarity based open-circuit fault diagnosis for induction motor drives with discrete wavelet transform, Microelectronics Reliability (2017), http://dx.doi.org/10.1016/j.microrel.2017.05.036

measured voltages. These methods showed highly advantages in fast detection, robustness to transients at the expense of extra sensors or electrical circuits, Ref. [13] proposed a voltage-based diagnosis method with observer estimated voltage to replace the measured voltage. Economic cost and system volume would increase in most of these methods, even though, they had a previous application in medium- or high-power converters, which seriously required fast detection time.

Current-based methods were most popular in recent years because no extra hardware or sensors were required by sharing the current sensors of controller in closed-loop strategies, such as field oriented control (FOC), direct torque control (DTC) and finite-control-set model predictive control (FCS-MPC) [14–16]. IGBT open-circuit will cause the voltages abnormal within a switching period, however, the currents need a longer time to be affected, usually relate to current fundamental period. Park's vector approaches [17] were proposed by identifying the normal or abnormal current trajectory in $\alpha\beta$-axis with motor rotating angle. Ref. [18] proposed to detect the fault by ripples in d-axis current component and identify the fault by the distorted current component in q-axis. Refs. [19,20] proposed to detect the fault by the percentage of zero-nearby samples and identify the fault by the polarity and other features extracted from three phase currents. Ref. [21] proposed to diagnosis the fault by the errors between reference and measured currents. The methods mentioned above showed high efficiency in low calculation consume. Current signal processing for feature extract without knowledge of model principles and pattern recognition for fault identification also attracted lots of attentions [22,23]. Generally, most of signal processing methods such as Fast Fourier Transform, Discrete Wavelet Transform (DWT), Empirical Mode Decomposition were proposed to extract features. Most of pattern recognition method such as Support Vector Machine, Bayes Networks, Neural Networks and Fuzzy System were proposed to identify the fault. These methods needed large amount of data to train the classifiers, and the calculation consume was relatively high, which limited their applications.

IGBT open-circuit fault will break the topology of 2L-VSI [24], the symmetry of topology can be described by three phase currents. In this paper, DWT are used as signal pre-treatment. Similarity analysis with Euclidean distance of three phase currents are used to identify fault. The proposed method need no knowledge of model principle and no data for training, and it can identify single and multiple faults on the same leg.

The structure of this paper is as following. Section 2 of this paper introduces the structure of VSI fed IM and the proposed fault diagnosis structure. Section 3 elaborates three phase current pre-treatment with DWT. Section 4 gives out the proposed diagnostic features, such as Euclidean distance and accumulated coefficients. Section 5 expresses the proposed fault diagnosis. Simulation and experimental results are showed in Section 6. A conclusion is made in Section 7.

2. 2L-VSI fed induction motor

Fig. 1 shows a vector controlled IM drive system fed by three-phase VSIs. It consists of a dc-link voltage source U_d, a 2L-VS and an IM. PWM signals generated by controlled system with control strategy of FOC. U_d is divided by capacities $C1$ and $C2$ equally. The invertor is composed of IGBTs and diodes, indicated by T1–T6 and D1–D6, respectively. Three phase currents i_a, i_b, i_c and speed n of the IM are used to generate PWM signals through vector-controlled system.

The proposed fault diagnosis structure is filled green and showed in Fig. 1. It includes three steps. Firstly, three-phase currents are pre-treated with DWT to reduce noise and the amount of data. Secondly, Euclidean distance are used to measure similarity between any two phase currents, contributing to describe the symmetry of 2L-VSI topology. Finally, the fault detection and identification are realized by looking up the diagnostic table designed by extracted features. The proposed fault diagnosis method does not need any extra sensors or electrical circuits, it can be inserted into the controller as a subroutine programme without major modification of original system.

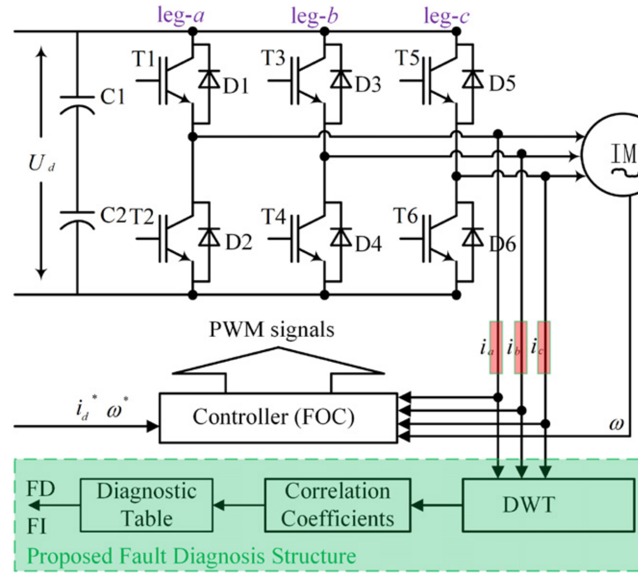

Fig. 1. Structure of 2L-VSI fed IM.

3. Current pre-treatment with DWT

The wavelet transform method can give information about the non-stationary signals generated in faulty condition both in frequency and time domains by correlating the function f of signal with wavelet $\phi_{u,s}(t)$ at scale s and position n continuously, shown as Eq. (1).

$$W_f(u,s) = \int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{s}}\phi\left(\frac{t-u}{s}\right)dt. \tag{1}$$

The discrete version of wavelet transform uses discrete scales and shift factors. In practical engineering, the sampled discrete signal is usually processed by high and low pass filters directly rather than the scale and shift function. Choosing of the wavelet basis translates to selecting of the filter coefficient correspondingly. The formulas of the decomposition algorithm are showed in Eq. (2).

$$\begin{aligned} A_{m+1}(n) &= \sum_{k=1}^{n} h(2n-k)A_m^{\cdot}(k) \\ D_{m+1}(n) &= \sum_{k=1}^{n} g(2n-k)A_m^{\cdot}(k) \end{aligned} \tag{2}$$

where, $h(n)$ and $g(n)$ are low and high pass filters, $A_0(n)$ is equal to the original signal series. The approximate signals $A_{m+1}(n)$ on behalf of the low frequency part and the detail signals $D_{m+1}(n)$ on behalf of the high frequency part can be calculated through the formula iteratively. The progress is shown in Fig. 2, where ↓ means an extraction operation saving data with an even index. Eliminating redundant arrays lose none information of the original signal according to the Nyquist probability rule.