Concurrent Detection and Classification of Faults in Matrix Converter using Trans-Conductance

Sarah Azimi*, Mehdi VejdaniAmiri**

* Departement of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran
** Departement of Electrical Engineering, University of Calgary, Alberta, Canada

ABSTRACT

This paper presents a fault diagnostic algorithm for detecting and locating open-circuit and short-circiut faults in switching components of matrix converters (MCs) which can be effectively used to drive a permanent magnet synchronous motor for research in critical applications. The proposed method is based on monitoring the voltages and currents of the switches. These measurements are used to evaluate the forward trans-conductance of each transistor for different values of switch voltages. These trans-conductance values are then compared to the nominal values. Under healthy conditions, the values obtained for the fault signal is less than the tolerable value. Under the open/short-circuit conditions, the fault signal exceeds the threshold, hence enables the matrix converter drive to detect and exactly identify the location of the faulty IGBT. The main advantages of this diagnostic method include fast detection and locating of the faulty IGBT, easiness of implementation and independency of the modulation strategy of the converter.

Corresponding Author:

Sarah Azimi,
Departement of Electrical and Computer Engineering,
Isfahan University of technology,
Isfahan, Iran.
Email: Sarah.Azimi88@gmail.com

1.   INTRODUCTION

Matrix converters have received considerable attention due to the recent uses in automotive, aerospace and military applications [1]-[2]. The commercialization, modulation technique and commutation issue of the matrix converter have been thoroughly investigated and have reached their maturity.

Matrix converter placed the traditional voltage source inventers and current source inverters by their effective advantages such asunity power factor, the lack of bulky capacitors, high number of voltage vectors available for modulation and sinusoidal input current [3], [5]. It has minimal energy storage requirement, which allows to get rid of bulky and lifetime, limited energy, storing capacitors frequency converters.

The matrix converter belongs to the direct conversion family since it directly connects the input ac lines to the output ac lines through bidirectional switches without the need for energy storage devices such as capacitors or inductors. As a consequence, their strengths are important weight/volume reduction and inherent four-quadrant operation, which are desirable features for transportation systems. The lack of energy storage devices does favor the possibility to arrange semiconductors in such a way that higher voltages and more voltage levels can be reached [4].

However, system reliability remains an open issue and has not received much attention. As a three phase matrix converter is an array of nine bidirectional power switches, if each switch is made of an anti-series connection of two standard IGBT's, there will be eighteen IGBTs per converter. The high number of

components increases the probability of occurrence of faults, giving additional importance to the diagnosis of faults in these systems.

There have been several methods investigating the detection and locating of switch faults in matrix converters. The first method of detecting open-circuit fault in switches of MC was proposed in [6] and developed in [7]-[9]. This method compares the measured value of the MC output voltage and the reference value acquired from the modulation algorithm. The proposed method in [12], uses the measured output currents, the reference angles of the input and output voltage vectors and the values of the duty-cycle of the switching state for detecting open-circuit faults when the optimum Alesina-Venturini modulation method is used. It is important to focus on the possibility of occurring faults in one or both transistors of bidirectional switches. The method proposed in [11] is based on discrete wavelet transform analysis of the measured output current waveform. This work has focused on the detecting of faults in only one or both transistors of a bidirectional switche. However, the existing studies have been mainly concerned with the detection of open-circuit fault, but the topic of short-circuit detection is relatively new and has received more isolated attention.

This paper presents a new method to detect and locate open-circuit and short-circuit faults in one or more transistors of matrix converters (MCs). In section II the possible faults that may occur in the MCs are presented. The proposed diagnosis method for these faults is then described in section III. Simulation results and the validation of the proposed method are presented in section IV.

2.   FAULTS IN MATRIX CONVERTERS

A three phase matrix converter consists of an array of three by three bidirectional switches. Usually constructed by two power transistors (IGBT) and two anti-parallel diodes, each bi-directional switch may have the common emitter or the common collector topology. When the gate is fired then depending on the switch voltage polarity, it will conduct in one of the two directions. Two major types of faults can appear in these IGBTs. These faults consist of open-circuit faults and short-circuit faults of one or more transistors. Possible causes of open-circuit faults include driver fault, a power transistor rupture caused by short-circuit or a soldering fault caused by high currents. The short-circuit fault of a power transistor may caused by an over-voltage, a temperature overshoot or a wrong voltage at the gate due to a driver fault, a DC supply fault or dv/dt disturbance.

An open-circuit fault results in a power failure at the motor drive. Short-circuit fault on the other hand may cause uncontrollable damage to the system due to the resulting high currents. Therefore, it is important to be able to timely detect the occurrence of faults.

3.   MC FAULT DIAGNOSIS BASED ON TRANS-CONDUCTANCE ESTIMATION

As explained before, open and short-circuit faults may cause considerable damages to the system. Hence fault diagnosis of MCs seems to be a necessary part of the system. In this section a novel technique to detect and locate a fault in these converters is explained.

The main idea of the proposed technique is to estimate the trans-conductance of the IGBTs at proper time i.e. when the IGBT is in its ON state. Using the estimated values of the trans-conductance during a gate pulse one can compare it to the nominal value to build a fault signal. A new fault signal is proposed in this paper to indicate healthy or faulty conditions.

To estimate the trans-conductance, it is necessary to measure the currents and the voltages of the switches and then deduce the IGBT voltages. In each switching period i.e. during a gate pulse, only three switches (six IGBTs) are selected by the control unit. Therefore, it is necessary to measure the currents and the voltages of these six IGBTs. The currents of theIGBTs are the same as the phase output currents which are measured during the velocity control process of the system. Hence, no additional measurements are made by considering these variables. To obtain the collector-emitter voltages of the IGBTs, one can read the measured values of the input and output phase voltages. The difference between these values can be considered as the collector emitter voltages of the active IGBTs. As a matter of fact, the voltage and the current of an IGBT are not constant during a gatepulse. As are shown in Figures 1 and 2 the measured voltage and current across an IGBT shows fluctuations. Accordingly, the trans-conductance of the IGBT can be estimated as the derivative of current with respect to the voltage:
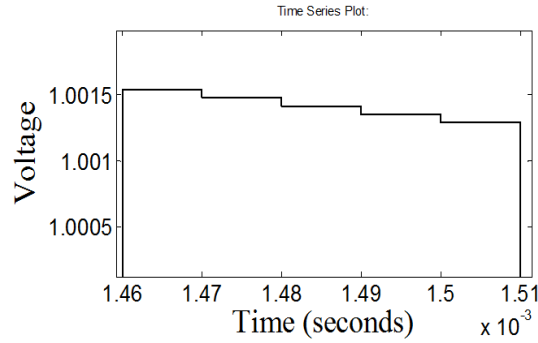
Figure 1. The behavior of the fault signal versus trans-conductance

$$G(n) = \frac{\Delta I(n)}{\Delta V(n)} = \frac{I(n) - I(n-1)}{V(n) - V(n-1)}$$

(1)

In which the first order derivative is implemented by finite differences. Depending on the sampling rate, the number of samples along a gate pulse is limited. To build a sensitive fault function, it may be necessary to interpolate the voltage-trans-conductance pairs to increase the number of samples. In this paper, using the linear interpolation, the number of points was increased to 50. Assuming that the tans-conductance in healthy conditions is denoted by G_0 then the fault signal was defined as below:

$$F = \frac{2E\left(\frac{G(n)}{G_0}\right)}{\left(1 + E\left(\frac{G(n)}{G_0}\right)\right)} - 1$$

(2)

In which $E(.)$ denotes the expectation operator and n represents the sample number. This fault signal has the property that for the open-circuit case i.e. $G(n) = 0$ will be -1 and in the case of short-circuit i.e. $G(n) = \infty$
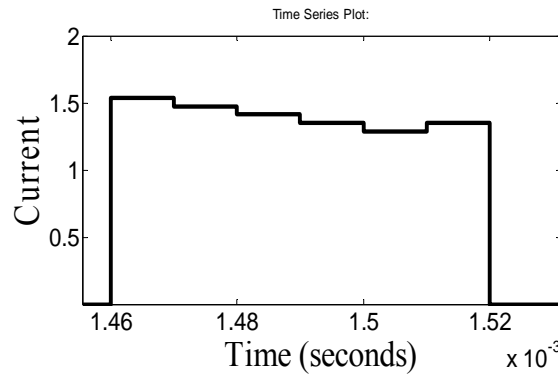

Figure 2. The measured current across an IGBT

Will take the $+1$ value and in the healthy condition i.e $G(n) = G_0$ will be zero.

The next step is to find a threshold to compare the fault signal with respect to it. To obtain a threshold, the sources of error in the system should be recognized first. There are two main types of error in the system. The first one is the sensor uncertainty or noise level which is represented by e. The other source of error may come from the tolerance of the trans-conductance which is called g. To set the threshold it is necessary to estimate the fault signal in the presence of these non-idealities. Assuming that the measured trans-conductance can be written as:

$$G(n) = G_0 + g + e \tag{3}$$

Then, the fault signal will take the following form:

$$F = \frac{2E\left(\frac{G_0 + g + e}{G_0}\right)}{\left(1 + E\left(\frac{G_0 + g + e}{G_0}\right)\right)} - 1 \tag{4}$$

This in turn can be written as follows:

$$F = \frac{2\left(1 + \frac{g}{G_0} + \frac{1}{G_0}E(e)\right)}{\left(2 + \frac{g}{G_0} + \frac{1}{G_0}E(e)\right)} - 1 = \frac{\frac{g}{G_0} + \frac{1}{G_0}E(e)}{\left(2 + \frac{g}{G_0} + \frac{1}{G_0}E(e)\right)} \tag{5}$$

Figure 2 depicts the behavior of fault signal versus different values of trans-conductance. As can be seen from this equation, if the number of samples during a gate pulse is high enough, then the measurement error effect will be negligible i.e. $E(e) = 0$. But in practice this depends on the sampling frequency. For higher sampling rates this error will have less effect on the estimation. However, due to the limited number of samples in the simulations performed in this paper, it is necessary to include the effect of this average. It is well-known [12] that the variance of the sample mean, for N as the number of samples used to estimate the sample mean of a white noise with standard deviation of σ, will be $\frac{\sigma^2}{N}$. Therefore, the standard deviation of sample mean will be $\frac{\sigma}{\sqrt{N}}$. Accordingly, the fault signal at k multiple of the standard deviation will be:

$$T = F(k\frac{\sigma}{\sqrt{N}}) = \frac{\frac{g}{G_0} + \frac{k}{G_0}\frac{\sigma}{\sqrt{N}}}{\left(2 + \frac{g}{G_0} + \frac{k}{G_0}\frac{\sigma}{\sqrt{N}}\right)} \tag{6}$$

Which in turn can be used as the threshold to maintain constant false alarm. This threshold is obtained at k standard deviation of the noise. One can trade off this value to reduce the false alarms. Accordingly, the probability of detection will degrade.

4.   PROBABILITY OF INCORRECT DETECTION

Since the voltage and current uncertainty or noise influence on the estimated trans-conductance, the effect of noise on the proposed detection method is investigated. n_a is the sample mean, for which N is the number of samples used to estimate. The variance of n_a is $\frac{\sigma}{\sqrt{N}}$.

$$n_a = E(e) \sim \left(0, \frac{\sigma}{\sqrt{N}}\right) \tag{7}$$

According to Equations (3) and (4), the fault signal will be:

$$F = \frac{\frac{1}{G_0}(g + n_a)}{2 + \frac{1}{G_0}(g + n_a)} = \frac{g + n_a}{2G_0 + g + n_a} \tag{8}$$

To obtain the probability of incorrect alarm when the IGBT is healthy, the distribution function of the fault signal should be considered. Since n_a has Gaussian distribution and fault signal is dependent of n_a

then, as it is well-known [10] for the probability density function (PDF) of a function of a random variable with known PDF, the PDF of the fault signal can be obtained:

$$f_F(F) = \frac{f_{n_a}(n_a)}{\left|\frac{df}{dn_a}\right|}$$

(9)

In which $f_{n_a}(n_a)$ is the probability distribution function of n_a. The derivative can be written as:

$$\frac{df}{dn_a} = \frac{2G_0 + g + n_a - (g + n_a)}{(2G_0 + g + n_a)^2}$$

(10)

Knowing that:

$$n_a = \frac{2G_0 F}{1 - F} - g$$

(11)

Then, the distribution of F can be obtained as follows:

$$f_F(F) = \frac{\left(2G_0 + \frac{2G_0 F}{1 - F}\right)^2}{2G_0 \sigma} \sqrt{\frac{N}{2\pi}} e^{-\left(\frac{N}{2\sigma^2}\left(\frac{2G_0 F}{1-F} - g\right)^2\right)}$$

(12)

Considering *snr* as:

$$snr = 10^{SNR/20}$$

(13)

Where *SNR* is the signal to noise ratio for the transconductance signal. The the variance of noise will then be:

$$\sigma = \frac{G_0}{snr}$$

(14)

Consequently, the probability distribution function (PDF) can obtained as:

$$f_F(F) = \sqrt{\frac{2Nsnr^2}{\pi}} \frac{1}{(1-F)^2} e^{-\left(\frac{Nsnr^2}{2}\left(\frac{2F}{1-F} - \frac{g}{G_0}\right)^2\right)}$$

(15)

Having PDF, Prabability of the incorrect alarm can be determined.
       According to the Equation (6) the threshold is defined as:

$$T = \frac{g + k\frac{G_0}{\sqrt{Nsnr^2}}}{2G_0 + g + k\frac{G_0}{\sqrt{Nsnr^2}}} = \frac{\frac{g}{G_0} + k\frac{1}{\sqrt{Nsnr^2}}}{2 + \frac{g}{G_0} + k\frac{1}{\sqrt{Nsnr^2}}}$$

(16)

Then the probability of incorrect alarm for this threshold will be:

$$P_{fa} = \int_T^1 f_F(F)dF = \int_{\frac{\frac{g}{G_0}+k\frac{1}{\sqrt{Nsnr^2}}}{2+\frac{g}{G_0}+k\frac{1}{\sqrt{Nsnr^2}}}}^1 \sqrt{\frac{2Nsnr^2}{\pi}} \left(\frac{1}{1-F}\right)^2 e^{-\left(\frac{Nsnr^2}{2}\left(\frac{2F}{1-F} - \frac{g}{G_0}\right)^2\right)} dF$$

(17)

If the following deffinitions are applied to the integral:

$$\alpha = \sqrt{\frac{N}{2} snr^2}$$

$$\beta = \frac{g}{G_0}$$

$$u = \alpha \left(\frac{2F}{1-F} - \beta \right)$$

(18)

Then the parobabilityof incorrect alarm can be obtained by:

$$P_{fa} = \int_{\frac{k}{\sqrt{2}}}^{\infty} \frac{1}{\sqrt{\pi}} e^{-u^2} du = 0.5 \left[1 - \text{erf}\left(\frac{k}{\sqrt{2}} \right) \right]$$

(19)

In which, erf(.) denotes the error function. This equation, generally, shows that by using the threshold in (16), the probability of incorrect alarm will be independent of the noise statistics, sample size, SNR and will be constant.

5.   RESULT AND DISCUSSION
5.1. Simulation Model
Simulations of the proposed diagnostic approach have been carried out using a developed Matlab/Simulink model of an MC. The motor parameters are shown in table I. A direct torque control (DTC) is used to drive permanent magnet synchronous motor. DTC directly controls both the torque and flux of an electrical machine. The main advantages of this control strategy are its structure simplicity and robustness, since it does not depend on the motor parameters. The switching frequency of the DTC drive is a variable quantity that depends not only on the controller hysteresis bands but also on the slope of the developed torque.

Table 1. PMSM parameters

Output power	200w	Rated current	2A
Voltage	100v	l_d^s per phase	8.3 mH
Pole pairs	4	l_q^s per phase	6mH
Torque	0.64Nm	Rated speed	3000rpm
Stator resistance	2.5Ω	Maximum speed	4500rpm

5.2. Simulation Results
Using the simulation model described before, the matrix converter the fault signal of the specific IGBT in healthy condition is shown in Figure 4.
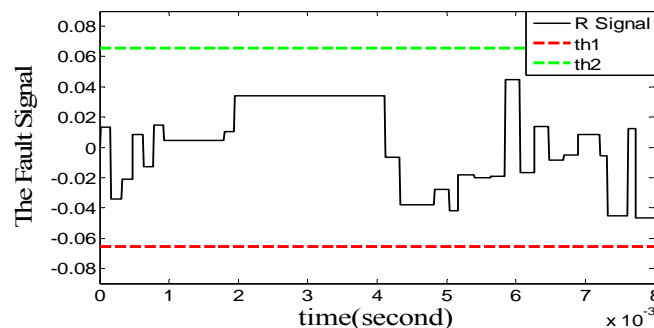

Figure 4. The fault signalunder healthy condistion

At t=1.3 ms, an open-circuit fault is introduced in IGBT number three, which connects the input phase C to the output phase A. This fault is simulatedas an increase in the resistance of the IGBT.

Figure 5 depicts the results obtained when open-circuit fault occurs. If the outputs phasevoltage changes, the collector-emitter voltage will increase. Therefore, the trans-conductance decreases from its nominal value and causes the fault signal exceed the threshold.
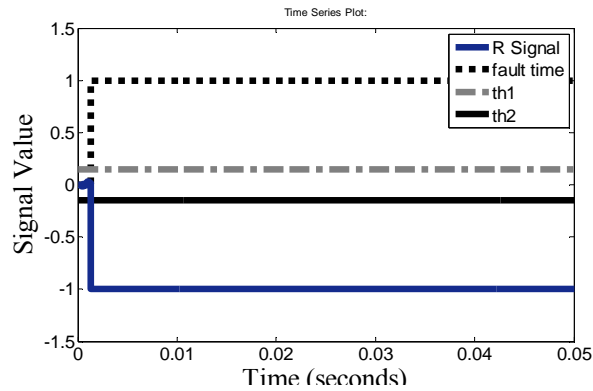

Figure 5. The fault signal under open-circuit condition

Figure 6 illustrates the fault signal in the case of a short-circuit fault occurring in to the IGBT number three. The collector current increase dramatically and accordingly, the trans-conductance increase from its nominal value and allows detecting the faulty IGBsT by exceeding the faulty signal from the threshold.

Using this diagnostic method, it is possible to detect faults in any transistor independently of the existence of faults in other IGBTs. Hence, allowing a fast and concurrent detection and identification of the faulty components. These results demonstrate the effectiveness of the proposed technique for detection of open-circuit and short-circuit faults in MC.
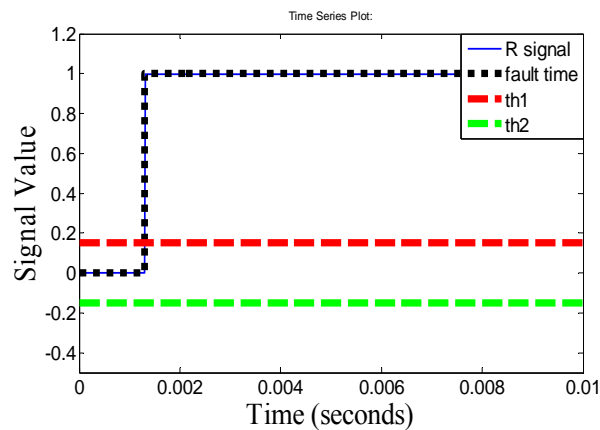

Figure 6. The fault signal under short-circuit condition

6. CONCLUSION

This paper present a new method for detecting and locating the faulty IGBT in bidirectional switches of matrix converter. The proposed method is based on monitoring the voltages and currents of IGBTs for appraising trans-conductance of each transistor. When any of the IGBTs causes open/short-circuit fault, the dedicated value of trans-conductance makes the fault signal of the faulty IGBT exceed from the threshold, which help the system identify a faulty IGBT and also the type of fault that happened. It's worth to say that the algorithm is based on divisions, sums and derivatives. Therefore, it is not computationally intensive. Using this algorithm, it is possible to detect the existence of more than one faulty transistor at the same time. Therefore, allows a fast and concurrent detection and identification of the faulty components.

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