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Multiple Open Circuit Fault Diagnosis in PWM Voltage Source Inverter for PMSM Drive System

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Abstract— In this paper, a simple and low-cost open-circuit fault detection and identification method for a pulse-width modulated (PWM) voltage-source inverter (VSI) employing a permanent magnet synchronous motor is proposed. An open-circuit fault of a power switch in the PWM VSI changes the corresponding terminal voltage and introduces the voltage distortions to each phase voltage. The proposed open-circuit fault diagnosis method employs the model reference adaptive system techniques and requires no additional sensors or electrical devices to detect the fault condition and identify the faulty switch. The proposed method has the features of fast diagnosis time, simple structure, and being easily inserted to the existing control algorithms as a subroutine without major modifications. The simulations and experiments are carried out and the results show the effectiveness of the proposed method.

Keywords : Fault detection, fault diagnosis, fault identification, model reference adaptive system (MRAS), multiple open-circuit fault, pulse-width modulated voltage-source inverter (PWM VSI).

I. INTRODUCTION

The permanent magnet synchronous motor (PMSM) is increasingly used in powered wheelchairs, electric vehicles, aerospace, medical and military applications, and nuclear power plants due to its advantages such as high power density, torque to inertia ratio, efficiency, and simple control [1]. In these applications, because an accident or fault can result in huge damages to the human life and environments, the reliability of the machine drives is one of the most important factors to guarantee the safe, continuous and high performance operation under even some accidents or faults. Generally, when an accident or fault occurs, the drive system has to be stopped for emergency or non programmed maintenance schedule. Due to the high cost of unexpected maintenance, the development of a reliable system is the area of interest.

A control system with minimum or zero effects from the faults is called a “fault-tolerant control system, and it performs the following three tasks [2]:

Fault detection;

Fault identification;

Remedial actions.

The fault detection is the process to determine whether the system is healthy or not. The fault identification is performed after the fault detection to identify the location, type, and nature of the fault. Finally, the remedial actions, also known as fault isolation, are the process to remove the faulty devices and reconfigure the system for a safe and continuous operation. Among these three tasks, the fault detection and fault identification are considered as a prime process for the practical implementation and are often called as a “fault diagnosis.”

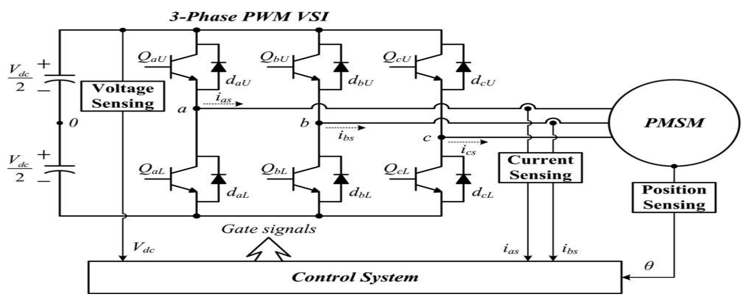

Fig. 1. General configuration of a PMSM drive system.

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Typically, the motor drive systems consist of a microcontroller unit (MCU) for implementing the control algorithms, a power electronic converter, i.e., pulse-width modulated voltage source inverter (PWM VSI), and a motor as shown in Fig. 1. In this figure, various types of faults can occur in the following components or subsystems such as:

Microcontroller unit (MCU);
Motor (PMSM);
Power converter (PWM VSI);
Sensors–voltage and current/position encoder;
Connectors and wires.

The MCU, connectors, and wires have very low failure rates compared to the remaining of the system. This is because the MCU is very reliable and does not involve high voltages or currents. The connectors and wires are static and have low failure rates if selected and installed properly. Some of the machine faults caused by the winding insulation failure due to the excessive voltage or current stress can practically be removed because the line voltage surges are absorbed at the input side of the power converter and the current stresses are limited by the over current protection of the power converter [3]. In recent years, the sensor faults have been increasingly concerned in the literature works. The sensor faults including biased signal, loss of signal, incorrect gain, and unresponsive signal are mainly due to the broken or bad connections, bad communications, or some hardware or software malfunction. Therefore, if the connectors and wires are installed correctly, the failure rates of the sensor faults can be lowered. For these reasons, those faults are not considered.

II. ANALYSIS OF THE OPEN-CIRCUIT FAULT IN THE PWM VSI

Fig. 2 shows the basic configuration of phase A leg of a three phase PWMVSI. When the system is under the normal condition as can be seen in Fig. 2(a), the terminal voltage of phase A, v_{a0} , is determined by the phase current i_{as} and the switching function S_a of Q_{aU} and Q_{aL} . If the switching function is 1, which means that Q_{aU} is turned ON and Q_{aL} is turned OFF, the terminal voltage of phase A is equal to $V_{dc}/2$, where V_{dc} is the dc-link voltage. If the switching function is 0, which means that Q_{aU} is turned OFF and Q_{aL} is turned ON, $v_{a0} = -V_{dc}/2$. The possible terminal voltages according to the switching function and the direction of phase current under the normal condition are

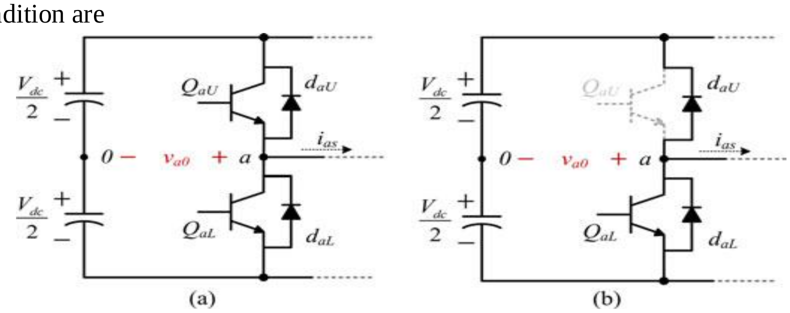

Fig. 2. Basic configuration of phase A leg of a three-phase PWM VSI.
(a) Normal condition. (b) Open-circuit fault in the upper switch Q_{aU}

TABLE I
TERMINAL VOLTAGES OF PHASE A UNDER THE NORMAL CONDITION

	$S_a = 1$	$S_a = 0$
$i_{as} \geq 0$	$v_{a0} = \frac{V_{dc}}{2}$	$v_{a0} = -\frac{V_{dc}}{2}$
$i_{as} < 0$	$v_{a0} = \frac{V_{dc}}{2}$	$v_{a0} = -\frac{V_{dc}}{2}$

TABLE II
TERMINAL VOLTAGES OF PHASE A UNDER THE OPEN-CIRCUIT FAULT CONDITION

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	$S_a = 1$	$S_a = 0$
$i_{as} \geq 0$	$v_{a0} = -\frac{V_{dc}}{2}$	$v_{a0} = -\frac{V_{dc}}{2}$
$i_{as} < 0$	$v_{a0} = \frac{V_{dc}}{2}$	$v_{a0} = -\frac{V_{dc}}{2}$

represented in Table I. Unlike the normal condition, however, an open-circuit fault in the upper switch *QaU* results in changing the corresponding terminal voltage when the phase current *ias* is positive and the switching function *Sa* is 1, since the upper switch *QaU* is not working properly. In this case, the terminal voltage of phase A is not equal to *Vdc* /2, but equal to−*Vdc* /2. The equivalent circuit after the open-circuit fault occurrence to the upper switch *QaU* is shown in Fig. 2(b), and the corresponding terminal voltages are represented in Table II. From the aforementioned analysis, it is obvious that the phase voltages may have the voltage deviations in the steady state after the fault occurrence from the normal condition. Based on this fact, the proposed fault diagnosis method indirectly observes these voltage deviations using the analytical model of the PWM VSI and the fault diagnosis can be achieved. To take a close look at the effect of the open-circuit fault of a switch on the phase voltages, the knowledge of the relationship between the terminal voltages and the phase voltages is required.

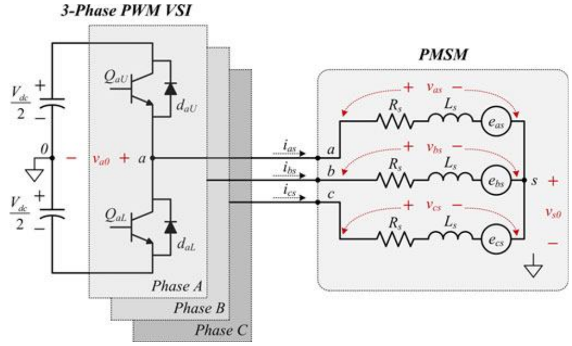

Fig. 3. Relationship between terminal voltages and phase voltages.

This relationship can be represented as follows [1]:

$$\begin{bmatrix} (va0) \\ (vb0\,) \\ (vc0\,) \end{bmatrix} = \begin{bmatrix} (\,vas) \\ (\,vbs) \\ (vcs) \end{bmatrix} + vs0 \qquad (1)$$

where *vas*, *vbs* , and *vcs* are the phase voltages and *vs*0 is the neutral to center voltage, as shown in Fig. 3. In a three-phase three-wire system, the following condition by Kirchoff's law is satisfied as

$$ias + ibs + ics = 0. \qquad (2)$$

Also, the sum of each phase back EMF is equal to zero at any instant under the assumption that the air-gap magnetic flux distribution is a sinusoid. From (2) and this assumption, the following condition is satisfied for the PMSM as

$$vas + vbs + vcs = Rs\,(ias + ibs + ics) + Ls\,(d/dt)(ias+ibs+ics\,) + (eas + ebs + ecs) = 0 \qquad (3)$$

where *Rs* is a stator resistance, *Ls* is a stator inductance, and *eas, ebs* , and *ecs* represent the corresponding phase back EMFs, respectively. From (1) to (3), the neutral to center voltage *vs*0 becomes

$$vs0 = 1/3(va0 + vb0 + vc0\,). \qquad (4)$$

Therefore, the relationship between the terminal voltages and the phase voltages can be represented as follows:

$$\begin{bmatrix} vas\_f \\ vbs\_f \end{bmatrix} = 1/3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \end{bmatrix} \begin{bmatrix} va0 \\ vb0 \end{bmatrix} \qquad (5)$$

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vcs_f $-1\ -1\ \ 2$ $vb0$

On the other hand, the effect of an open-circuit fault on one of the switches can be represented by a deviation value from the terminal voltages of the PWMVSI. If $\Delta va0$ is considered as representing the voltage deviation due to an open-circuit fault in the upper switch QaU, the phase voltages after the open-circuit fault occurrence are represented as follows:

$$\begin{bmatrix} vas\_f \\ vbs\_f \\ vcs\_f \end{bmatrix} = 1/3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} va0 - \Delta va0 \\ vb0 \\ vb0 \end{bmatrix} \quad (6)$$

where $vas\ f$, $vbs\ f$, and $vcs\ f$ are the phase voltages after the open-circuit fault occurs to the upper switch QaU. After some calculations, (6) can be expressed as

$$\begin{bmatrix} vas\ f \\ vbs\ f \\ vcs\ f \end{bmatrix} = \begin{bmatrix} vas \\ vbs \\ vcs \end{bmatrix} + 1/3 \begin{bmatrix} -2\Delta va0 \\ \Delta va0 \\ \Delta va0 \end{bmatrix} = \begin{bmatrix} vas \\ vbs \\ vcs \end{bmatrix} + \begin{bmatrix} \Delta vas\ dist \\ \Delta vbs\ dist \\ \Delta vcs\ dist \end{bmatrix} \quad (7)$$

where$\Delta vas\ dist$,$\Delta vbs\ dist$, and$\Delta vcs\ dist$ are the phase voltage deviations introduced by the open-circuit fault occurred to the upper switch QaU . As can be seen in (7), the phase voltage after the open-circuit fault occurrence can be divided into two parts. The first term of (7), vks ($k = \{a, b, c\}$), are the normal phase voltages and the second term of (7),$\Delta vks\ dist$ ($k=\{a, b, c\}$), are the voltage deviations due to the open-circuit fault in the upper switch QaU . These phase voltage deviations can be considered as "*voltage distortions*" induced by the open-circuit fault and observed from the machine parameters, which is discussed in the following.

$$\begin{bmatrix} vq\ f \\ vd\ f \end{bmatrix} = T(\theta e) \begin{bmatrix} vas + \Delta vas\ dist \\ vbs + \Delta vbs\ dist \\ vcs + \Delta vcs\ dist \end{bmatrix} = \begin{bmatrix} vq \\ vd \end{bmatrix} + \begin{bmatrix} \Delta vq\_dist \\ \Delta vd\_dist \end{bmatrix} \quad (8)$$

III. PROPOSED OPEN-CIRCUIT FAULT DIAGNOSIS ALGORITHMS

An open-circuit fault in the PWM VSI makes the current in that phase be zero for either the positive or negative half-cycle depending on whether it occurs to the upper or lower switch. If the open-circuit fault occurs to the upper switch QaU , for example, the positive half-cycle of phase A current is always zero. As a result, it causes a dc current offset in the faulty phase and this offset current is equally divided into the healthy phases. Therefore, the offset current gives the uneven current stress on the remaining switches of the PWM VSI, which may cause thermal defects [3]. To detect the open-circuit fault condition and identify the faulty switch, a simple and low-cost fault diagnosis algorithm is proposed. This proposed method is employing the model reference adaptive system (MRAS) techniques and does not require any additional hardware circuits such as voltage sensors. The voltage distortions caused by the open-circuit fault in the rotor reference frame are estimated by a voltage distortion observer which is based on the electrical model of the PMSM. And the estimated voltage distortions in the rotor reference frame are transformed to the *abc* frame for the error detection. By examining the error, the fault condition is determined by the time-based analysis and the faulty switch is also identified immediately according to the observed voltage distortions in the *abc* frame.

A. MRAS-Based Voltage Distortion Observer

The current dynamics of a PMSM including the voltage distortions caused by the open-circuit fault can be represented as follows [1]:

$$\begin{bmatrix} Diq/dt \\ Did/dt \end{bmatrix} = \begin{bmatrix} -Rs/Ls & -we \\ we & -Rs/Ls \end{bmatrix} \begin{bmatrix} iq \\ id \end{bmatrix} + 1/Ls0 \begin{bmatrix} Vq^* \\ Vd^* \end{bmatrix} + \begin{bmatrix} -\lambda m\omega e/Ls0 \\ 0 \end{bmatrix} \quad (10)$$

where iq and id are the q- and d-axis currents, ωe is the electrical rotor angular speed, and λm is the flux linkage established by the permanent magnet, respectively. As can be seen in (1), the motor currents are affected by the voltage distortions caused by the open-circuit fault.

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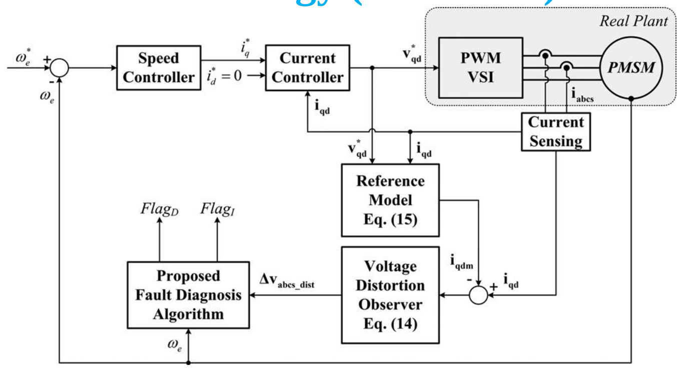

Fig. 4. Configuration of the proposed voltage distortion observer.

For the reference model of the MRAS, it is assumed that the voltage distortions due to the open-circuit fault are zero and the system is in the healthy mode. Under this condition, the calculated current dynamics using the nominal parameters can also be represented as follows:

$$\begin{pmatrix} Diqm/dt \\ Didm/dt \end{pmatrix} = \begin{bmatrix} -Rs0/Ls0 & -\omega e \\ \omega e & -Rs0/Ls0 \end{bmatrix} + \begin{bmatrix} iq \\ id \end{bmatrix} 1\ /Ls0 + \begin{bmatrix} Vq^* \\ Vd^* \end{bmatrix} \begin{bmatrix} -\lambda m0\omega e/Ls0 \\ 0 \end{bmatrix} \quad (11)$$

where $v\ q^*$ and vd^* are the *q*- and *d*-axis stator voltage commands, *iqm* and *idm* are the *q*- and *d*-axis currents of the model, respectively, and the subscript "0" represents the nominal value. From (11) and (12), the voltage distortions in the rotor reference frame caused by the open-circuit fault can be obtained as follows:

$$\Delta\ vq\_dist = Ls\ (\ diq/dt - diqm/dt\ )$$
$$\Delta\ vq\_dist = Ls\ (\ did/dt - didm/dt\ ) \quad (12)$$

where it is assumed that the nominal parameters *Rs*0, *Ls*0 , and $\lambda m0$ are identical to the real values *Rs*, *Ls* , and λm, respectively. Also, on the assumption that the switches in the PWM VSI are ideal, the voltage commands *vq** and *vd** are identical to the corresponding *q*- and *d*-axis voltages *vq* and *vd* . The average voltage distortions over the *k*th PWM step can be derived from (13) as follows:

$$\Delta\ vq\_dist\ (k) = Ls\ \{[iq(k) - iqm(k)]/Ts\}$$
$$\Delta\ vd\_dist\ (k) = Ls\ \{[id(k) - idm(k)]/Ts\} \quad (13)$$

The model currents *iqm* (*k*) and *idm* (*k*) in (14) can be obtained from the discrete form of (12) and these become as follows:

$$iqm\ (k) = iq\ (k-1) + Ts/Ls0\ [vq^*(k-1) - Rs0iq(k-1) - \omega eLs0\ id\ (k-1) \quad -\omega e\lambda m0\ ]$$
$$idm\ (k) = id\ (k-1) + Ts/Ls0\ [vd^*(k-1) - Rs0id(k-1) - \omega eLs0\ iq(k-1) \quad -\omega e\lambda m0\ ]$$

(14)

Fig. 4 shows the block diagram of the proposed voltage distortion observer. The observed voltage distortions from the plant and model currents are used for the fault diagnosis algorithm of the open-circuit fault in the PWM VSI. In this proposed fault diagnosis algorithm, two schemes, the error detection and fault detection time, are used for the robustness against the false fault diagnosis.

B. Fault Diagnosis Algorithm

By using the concept of the error detection and fault detection time , the algorithm for the fault detection is given by

$$Flag\ D = \begin{cases} 1, & te > T\ fault : \text{fault} \\ 0, & te < T\ fault : \text{normal} \end{cases} \quad (15)$$

where *te* is the elapsed time from the beginning of error detection to the arriving at the fault detection time *T fault* and *Flag D* is the fault detection flag indicating the fault condition. The error detection time *te* is reset to zero when the Boolean errors have the value

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of zero. For the fault detection, the error detection time *te* is compared with the fault detection time *T fault*

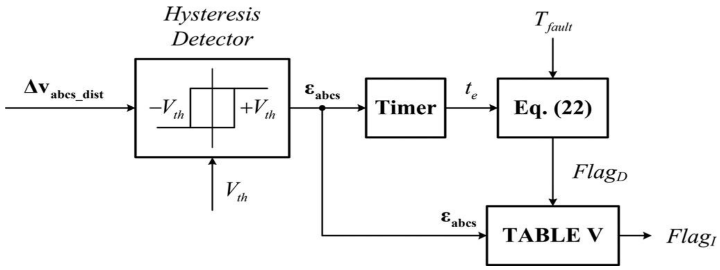

Fig. 5. Block diagram of the proposed fault diagnosis system.

and if $te \geq T\ fault$, the fault detection flag *FlagD* is set from low to high and the open-circuit fault is detected. The identification of the faulty switch is obtained just after the fault detection by the generated Boolean errors *εks* (*k = {a, b, c}*) from Table IV. According to the Boolean errors, the fault identification flag *FlagI* composed of three flags *FlagA*,
Flag B, and *Flag C* is defined as given in Table V and used to identify the faulty switch. Fig. 7 shows the block diagram of the proposed fault diagnosis algorithm. The fault diagnosis is accomplished in the following procedures:
observation of the voltage distortions;
Generation of the Boolean errors by the error detection;
Determination of the fault condition by the fault detection time;
Identification of the faulty switch.
Fig. 6 shows the process of the proposed fault diagnosis algorithm in the case of the fault occurrence to the upper switch *QaU* .When the open-circuit fault occurs to the upper switch *QaU* , the voltage distortion of phase A has a negative value. After the fault detection flag *FlagD* is set to high, the fault identification is obtained from Table V and the fault identification flag *FlagI* is set according to the faulty switch.

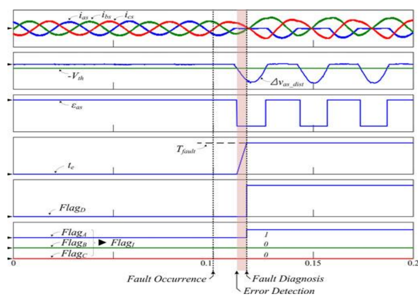

Fig. 6. Process of the proposed fault diagnosis algorithm when the open-circuit fault occurs.

IV. PROPOSED FAULT DIAGNOSTIC METHOD

The proposed diagnostic method results from an improved version of the algorithm presented in [10], where the formulation of the diagnostic variables was improved and simplified. A block diagram of the new algorithm is shown in Fig. 1. The three motor phase currents are the unique inputs required by this technique since it is desirable that the fault diagnostic method utilizes variables already used by the main control, avoiding the use of extra sensors and the inherent increase of the system complexity.
To overcome the problems associated to the machine mechanical operating condition dependency and the issue of false diagnostics, the measured motor phase currents are normalized using the modulus of Park's vector, defined as

id =√2/ 3ia − 1/ √6ib − 1 /√6ic

iq = 1 /√2ib – 1/ √2ic

where id and iq are the Park's vector components and ia,ib,and ic the motor phase currents. The Park's vector modulus |is| is given by

|is |= √ [i d*2 + i q*2]

The normalization is performed by dividing the motor phase currents by Park's vector modulus. The obtained normalized motor

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phase currents inN are given by

$$i_{nN} = i_n / |i_s|$$

where n = a,b,c. Therefore, assuming that the motor is fed by a healthy inverter generating a perfectly balanced three-phase sinusoidal current system

$$i_n = \begin{cases} i_a = I_m \sin(\omega_s t + \varphi) \\ i_b = I_m \sin(\omega_s t - 2\pi/3 + \varphi) \\ i_c = I_m \sin(\omega_s t + 2\pi/3 + \varphi) \end{cases}$$

where Im is the currents maximum amplitude, ωs is the motor currents frequency, and φ is the initial phase angle, it can be proven that Park's vector modulus can be given by

$$|i_s| = I_m \sqrt{(3/2)}$$

As a consequence of this normalization process, the normalized motor phase currents will always take values within the range of $\pm\sqrt{2/3}$, independent of the measured motor phase currents amplitude, since

$$i_{nN} = \begin{cases} i_{aN} = \sqrt{2/3} \sin(\omega_s t + \varphi) \\ i_{bN} = \sqrt{2/3} (\sin \omega_s t - 2\pi\ 3 + \varphi) \\ i_{cN} = \sqrt{2/3} (\sin \omega_s t + 2\pi\ 3 + \varphi) \end{cases}$$

Finally, the three diagnostic variables en are obtained from the errors of the normalized currents' average absolute values, given by

$$e_n = \xi - \{|i_{nN}|\}$$

where ξ is a constant value equivalent to the average absolute value of the normalized motor phase currents under normal operating conditions given by (8), that is

$$\xi = 1/\pi(8/3) \approx 0.5198$$

The three diagnostic variables defined have specific characteristics which allow for the inverter fault diagnosis. When the drive is operating under normal operating conditions, all the diagnostic variables will take values near to zero. However, if an inverter open-circuit fault is introduced, at least one of the diagnostic variables will assume a distinct positive value. Consequently, the errors en can be effectively used to detect an anomalous inverter behavior.

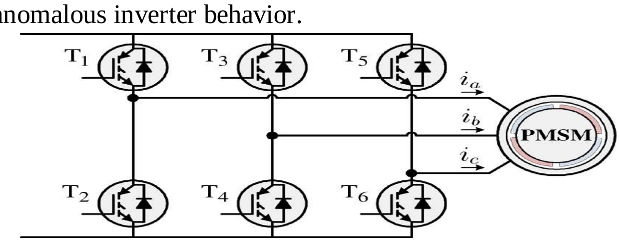
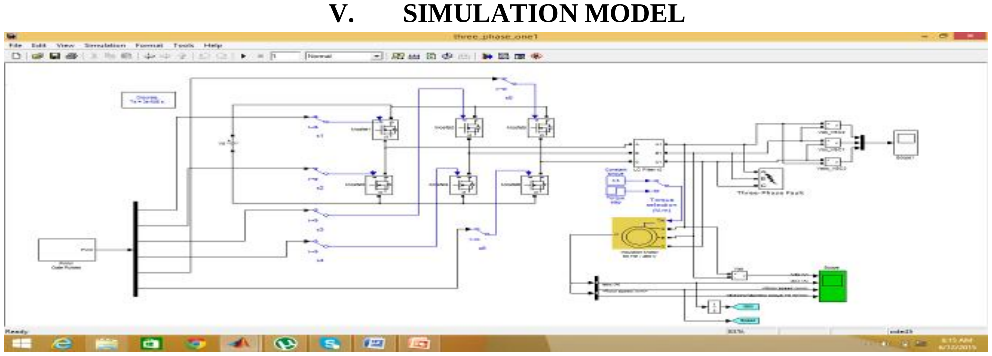


Fig.7. Diagram of a typical VSI feeding a PMSM.

V. SIMULATION MODEL



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VI. SIMULATION RESULT

A. Phase A Fault

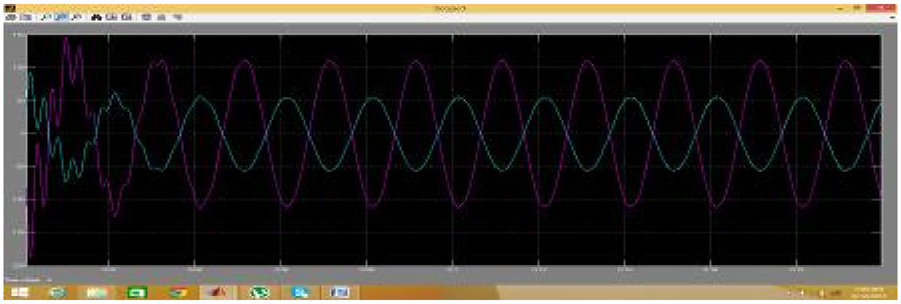

Fig 8. Voltage measurement when only phase A is Open Circuit fault.

Fig 9. Changes in motor current, voltage and speed when phase A is Open Circuit fault

B. Phase B Fault

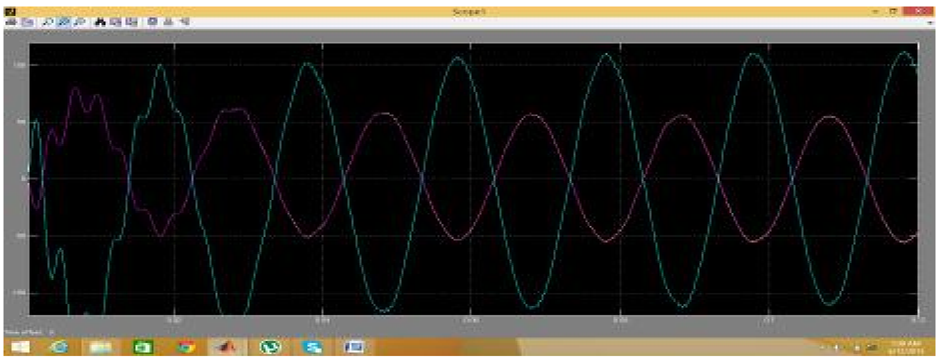

Fig 10. Voltage measurement when only phase B is Open Circuit fault.

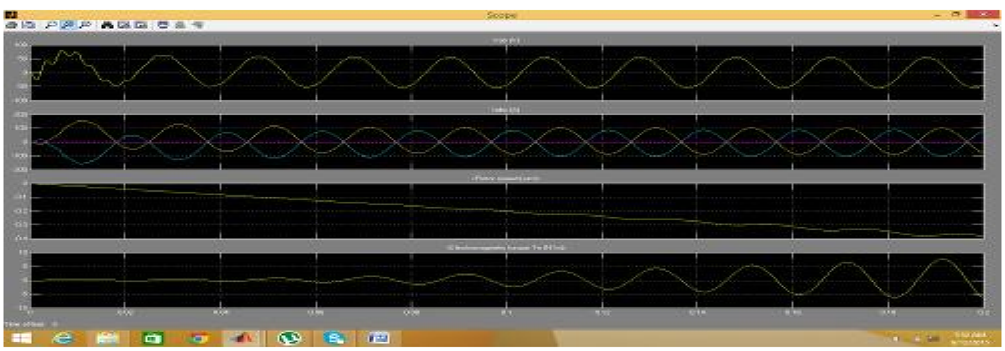

Fig 11. Changes in motor current, voltage and speed when phase B is Open Circuit fault.

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VII. CONCLUSION

The fault detection and identification is becoming more and more important for industrial applications. Therefore, it is increasingly required to improve the fault diagnosis capabilities. In this paper, a simple and low-cost open-circuit fault detection and identification method is presented. The types of fault diagnosis are achieved by the simple voltage distortion observer. Once the voltage distortions are estimated, these are compared with the threshold value to determine the fault condition. When the open-circuit fault occurs, the observed voltage distortions are bigger than the threshold value. By comparing these two values, the fault condition is decided. Also, the fault identification is achieved by using the observed voltage distortions, since the voltage distortions are different according to the faulty switch.

The proposed method can be well combined with the post fault actions which are the reconfigurations of the whole drive system to operate safely and continuously. In comparison with the previous existing fault diagnosis, the proposed method has simple structure and fast fault detection time. Also, it can be implemented without any extra devices such as voltage sensors and the computing effort is very small. The execution of the algorithm can be easily embedded in the existing systems without major modifications. To show the effectiveness of the proposed method, the simulations and experiments are carried out for the digitally controlled PMSM drive system. The simulation and experimental results verify the validity of the proposed method and show that the proposed method gives the good performance and practical value

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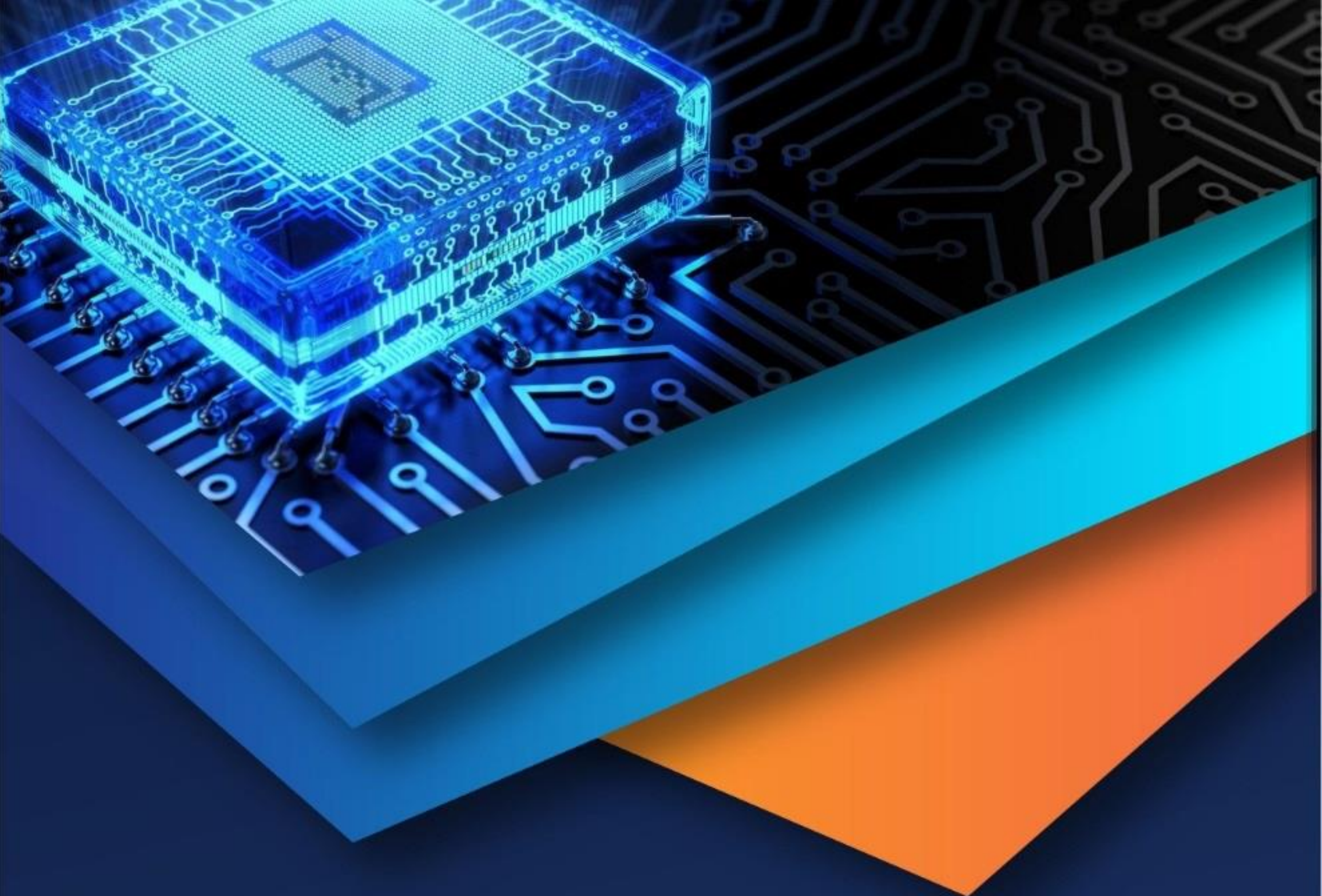

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