OPEN SWITCH FAULT DIAGNOSIS IN THREE PHASE INVERTER USING DIAGNOSTIC VARIABLE METHOD

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Abstract

The reliability of power electronics system such as three phase inverter is important in various applications. Different types of faults occur in it, which may influence the operation of system. Such faults require unexpected maintenance, which increases the cost of manufacturing. Therefore fault diagnosis of such devices plays vital role in industry. One possible fault that occurs in inverter is an open switch fault. This paper provides a new technique based on diagnostic variable which detects single as well as multiple open switch fault in three phase inverter. In this method, diagnostic variables are used to detect faulty phase. Along with these diagnostic variables, an average current of three phase inverter is used for the detection of single as well as multiple faulty switches.

Key Words: *Power electronics, open switch fault, diagnostic variables.*

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1. INTRODUCTION

The voltage source inverter (VSI) is one of the most used circuit configurations for speed control of three-phase induction motors. The main objective of inverter is to produce an ac output waveform from a dc power supply. A fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. Three phase inverter provides a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. The Pulse Width Modulation (PWM) is used to control the output voltage of inverter.

Three phase PWM inverter is used in many industrial applications such as electric motor drives, UPS, active power filters, etc. Different types of unexpected faults may occurs in it. These AC drives systems are sensitive to different types of fault occurring at the input rectifier, or at the power inverter stage, or at the control sub system. In general, when one of these faults occurs, system may damage. The cost of these steps can be high. These inverter faults may influence the operation of whole system. It is necessary to avoid this harmful influence and to enhance the reliability of the system. Therefore, fault detection and diagnosis are needed.

It is estimated that among all types of faults in variable-speed ac drives in industry, about 38% of the faults are due to failures of power devices [1]. Most of these inverters use insulated gate bipolar transistors (IGBTs) as the power device because of their high voltage and current ratings and ability to handle short-circuit currents for periods exceeding 10 µs. But they suffer failures due to excess electrical and thermal stress that are experienced in many applications.

IGBT failures can be broadly classified as open-circuit faults, short-circuit faults, and intermittent gate-misfiring faults. There are several methods are available for detection of inverter faults. In [2] and [3], the technique using Park's vector was proposed in which neural network is used for diagnosis. But this technique requires very complex pattern recognition algorithm. In [4] a fault detection using voltage sensors was proposed. This method is fast but it requires additional sensors. A method using a discrete Fourier transform (DFT) was proposed in [5]. In this method Fourier coefficients of current signal are used for fault diagnosis. In [6] and [7], neural network is used. This neural network is trained with the seven fault patterns which are calculated by average current Concordia vector trajectory.

Most methods are used to find single switch fault and not multiple switch faults. In this paper, open-circuit fault in inverter is discussed. Presented method is able to detect single as well as multiple open switch fault in three phase inverter. The average absolute values of current are used to calculate diagnostic variables. Some characteristics are obtained with these diagnostic variables and average current of inverter which are used to detect faulty phase and faulty switches. This method is more robust to false alarm.

2. THREE PHASE INVERTER

An inverter is an electronic device which converts Direct Current (DC) to Alternating Current (AC). This AC can be of any required voltage and frequency. The Variable Frequency Drive (VFD) mostly is of two types, Voltage Source Inverter (VSI) and Current Source Inverter (CSI).

VSI has advantages like higher efficiencies, minimizing installation timing, eliminating interconnect power cabling costs, and reducing building floor space. Efficiencies are

97% with high power factor through all load and speed ranges. Fig. 1 shows basic structure of a three phase voltage source inverter. In this model S1 to S6 are Insulated Gate Bipolar Transistors (IGBTs) which can be on or off Sinusoidal pulse width modulation (SPWM) is a common technique for controlling the switches. The average value of voltage fed to the load is controlled by turning the switch between supply and load on and off at a high frequency.

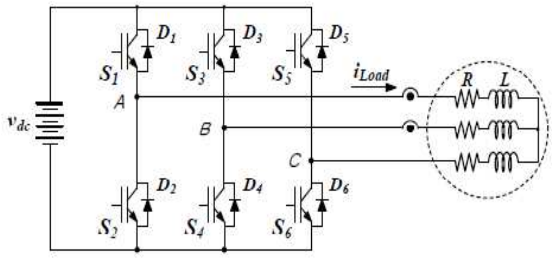


Fig -1: Three Phase PWM Inverter

The simplest way to generate a PWM signal is the intersective method, which requires a triangle waveform and a comparator. When the value of the reference signal is more than the modulation waveform, the PWM signal is in the high state, otherwise it is in the low state.

In open circuit fault condition, the IGBT falls in the off state and remains in this situation regardless of the gate voltage value. Open-circuit fault occurs due to lifting of bonding wires caused by thermic cycling. It may be caused by a driver fault or a short-circuit-fault-induced IGBT rupture. Open circuit faults generally do not cause system shutdown, but degrade its performance. Therefore, these diagnostic methods can be used in device-fault-tolerant systems.

3. FAULT DIAGNOSTIC METHOD:

3.1 Park's vector approach:

The Park's vector approach or dq transformation is mathematical transformation which simplifies three phase circuit. This method is used to transform three phase current of voltage source inverter (i_a,i_b,i_c) into two phase current (i_d,i_q). The Park's vector components are given by [1],

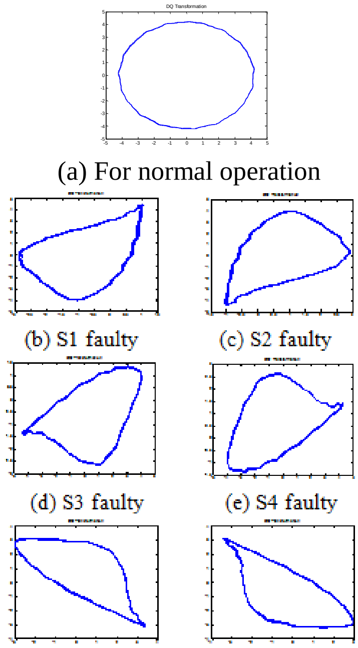
$$i_d = \sqrt{\frac{2}{3}} i_a - \frac{1}{\sqrt{6}} i_b - \frac{1}{\sqrt{6}} i_c \qquad (1)$$

$$i_q = \frac{1}{\sqrt{2}} (i_b - i_c) \qquad (2)$$

Using dq transformation the current patterns can be obtained which indicates faulty situation of inverter current. It gives different six patterns. A normal operation is represented by a circle. If an open switch fault has occurred, there is a change in the phase current value at the location of fault. Therefore, a change in the circle shape represents the occurrence of an open fault condition. When fault occurs, circle becomes semicircle. Fig.2 shows dq transformation for normal and faulty phase current of three phase inverter.

3.2 Normalization of currents:

The proposed method uses the dq transformation which transforms three phase current into two phase. This method requires only three phase currents as inputs and it does not require any extra sensors.



(a) For normal operation

(b) S1 faulty (c) S2 faulty

(d) S3 faulty (e) S4 faulty

(f) S5 faulty (g) S6 faulty

Fig -2: DQ transformation

Therefore, system complexity reduces. The normalization of measured current is used to overcome the problem of operating condition dependency and false diagnostics [8]. For normalization, dq transformation or Park's vector approach is used to calculate Park's vector modulus, given as

$$|\overline{is}| = \sqrt{i_d^2 + i_q^2} \qquad (3)$$

Where i_d and i_q are the Park's vector components. The normalization is done by dividing three phase current by Park's vector modulus. The normalized three phase current is given by,

$$i_{nN} = \frac{i_n}{|\overline{i_s}|} \qquad (4)$$

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

$$i_n = \begin{cases} i_a = I_m \sin(w_s t + \phi) \\ i_b = I_m \sin\left(w_s t - \frac{2\Pi}{3} + \phi\right) \\ i_c = I_m \sin\left(w_s t + \frac{2\Pi}{3} + \phi\right) \end{cases} \qquad (5)$$

where I_m is the currents maximum amplitude, w_s is the motor currents frequency, and φ is the initial phase angle. Because of this normalization process, the normalized motor phase currents will always take values within the range of

$\pm\sqrt{\frac{2}{3}}$, which is independent of the measured currents amplitude,

$$i_{nN} = \begin{cases} i_{aN} = \sqrt{\frac{2}{3}} \sin\left(w_s t + \phi\right) \\ i_{bN} = \sqrt{\frac{2}{3}} \sin\left(w_s t - \frac{2\Pi}{3} + \phi\right) \\ i_{cN} = \sqrt{\frac{2}{3}} \sin\left(w_s t + \frac{2\Pi}{3} + \phi\right) \end{cases} \quad (6)$$

3.3 Average absolute value of currents:

Average absolute values of three phase normalized currents $< |i_{nN}| >$ are given by,

$$\frac{w_s}{2\Pi} \int_0^{\frac{2\Pi}{w_s}} |i_{nN}| dt = \frac{1}{\Pi} \sqrt{\frac{8}{3}} \quad (7)$$

3.4 Diagnostic variables:

The three diagnostic variables e_n(where n=a,b,c) are obtained from the errors of the normalized current's average absolute values, given by

$$e_n = \xi - \langle |i_{nN}| \rangle \quad (8)$$

Where ξ is a constant value equivalent to the average absolute value of the normalized motor phase currents under normal operating conditions given by (7), that is

$$\xi = \frac{1}{\Pi} \sqrt{\frac{8}{3}} \approx 0.5198 \quad (9)$$

The three diagnostic variables used for fault diagnosis because they have specific characteristics [9]. For normal operation, all the diagnostic variables will take values near to zero. If an inverter open-circuit fault is introduced, at least one of the diagnostic variables will takes positive value. But these variables only give the information about the faulty phase and not about faulty switches. Hence, along with diagnostic variables, current's average value is used to detect faulty switches.

$$E_n = \begin{cases} N \quad if\ e_n < 0 \\ 0 \quad if\ 0 \le e_n < k_f \\ P\ if\ k_f \le e_n < k_d \\ D\ if\ e_n \ge k_d \end{cases} \quad (9)$$

$$M_n = \begin{cases} L\ \ if\ \langle i_{nN} \rangle < 0 \\ H\ \ if\ \langle i_{nN} \rangle > 0 \end{cases} \quad (10)$$

The values of E_n and M_n are used to generate a distinct fault signature. The threshold value k_f is directly related to any fault detection, while k_d performs an important role in case of a double failure in the same inverter phase. Since the method is normalized, it is not required to adjust these values for each load and speed conditions. Table 1 gives different diagnostic signatures. Here, value of k_f and k_d are considered as 0.00006 and 0.1996 respectively.

4. ARCHITECTURE OF FAULT DIAGNOSIS

First step of fault diagnosis of three phase PWM inverter is to measure the three phase current and voltage. Measuring of current and voltage is done with different conditions. These measurements of current and signals are used for further processing.

Table -1: Diagnostic signatures for faulty switch detection

Faulty Switches	Ea	Eb	Ec	Ma	Mb	Mc
S1	P	N	N	L	-	-
S2	P	N	N	H	-	-
S3	N	P	N	-	L	-
S4	N	P	N	-	H	-
S5	N	N	P	-	-	L
S6	N	N	P	-	-	H
S1,S2	D	-	-	-	-	-
S3,S4	-	D	-	-	-	-
S5,S6	-	-	D	-	-	-
S1,S3	P	P	N	L	L	H
S2,S4	P	P	N	H	H	L
S3,S5	N	P	P	H	L	L
S4,S6	N	P	P	L	H	H
S1,S5	P	N	P	L	H	L
S2,S6	P	N	P	H	L	H

Data acquisition board is used to collect these signals and transfer them from analog to digital signals. Because signal processing can be done in digital domain. These signals then import in MATLAB. The diagnostic variable method can be applied on these signals to find whether inverter signals are faulty or not. If so, then it will calculate location of faulty switch. Fig. 3 shows fault diagnostic system for real time application.

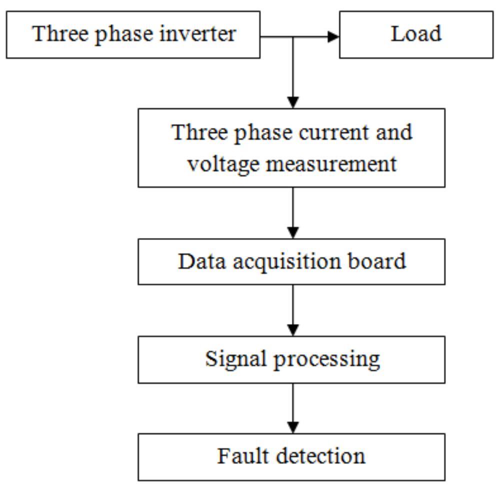


Fig -3: Fault detection system for real time application.

In this model, three phase inverter uses sinusoidal pulse width modulation technique. Input for inverter is 1 ph 40 V, 50 Hz. Output voltage of inverter is 0 to 25 AC. Load is resistive in star or delta. Output frequency is 0 to 50 Hz. Speed is controlled by frequency control. Data acquisition is the process of sampling signal that measure real world physical conditions and converting samples into digital numeric values that can be manipulated by a computer. It converts analog waveforms into digital values for processing. It includes sensors to convert physical parameter to electrical signal and signal conditioning circuitry to convert sensor signals into a form that can be converted to a digital form.

5. SIMULATION RESULTS

For simulation results, inverter should be simulated in MATLAB for every fault mode. In this paper three distinct faulty operations are considered, a single IGBT open-circuit fault, a single-phase open-circuit fault (double fault in the same inverter leg), and a double switch open-circuit fault. Open switch fault can be introduced by removing respective gate signal of switches.

a) Single IGBT open switch fault

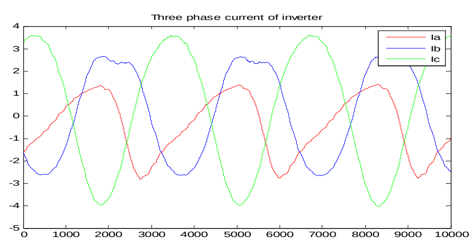
Fig. 4 shows the time-domain waveforms of the three phase inverter currents, the diagnostic variables and the normalized current's average values. An IGBT open-circuit fault in switch S1 is introduced by removing its gate signal. When the fault in IGBT S1 occurs, the diagnostic variable of the corresponding phase e_a immediately increases, converging to a value of 0.23. The other two remaining errors will decrease until they reach a value of approximately −0.08. S1 is upper switch of phase a, therefore the current flows through bottom IGBT switch which is large negative average value of current.

b) Single phase open circuit fault

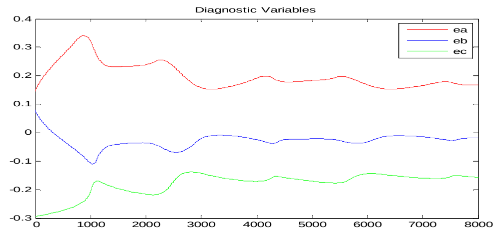
Fig. 5 shows simulation results for single phase open circuit fault in IGBT S1 and S2. In this case, the fault is introduced in S1 and S2 by removing corresponding gate signals. As a result, the diagnostic variable e_a will immediately increase to a final value of 0.51. Remaining two diagnostic variables will decreases, converging both to a value of about −0.18.

c) Double power switches open circuit fault

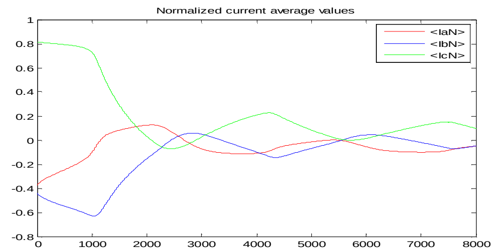
When the faults in transistors S1 and S3 are introduced, both the diagnostic variables e_a and e_b will increase and reach values higher than k_f. The diagnostic variable of the normal phase will decreases to negative value.



(a)

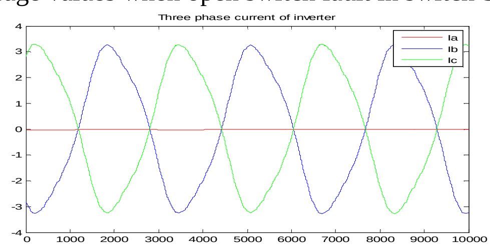


(b)

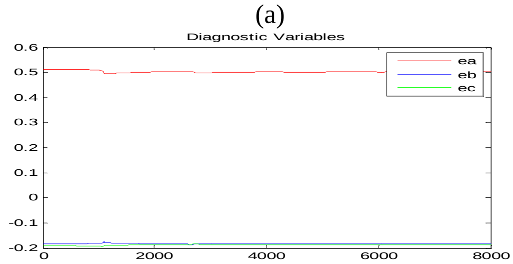


(c)

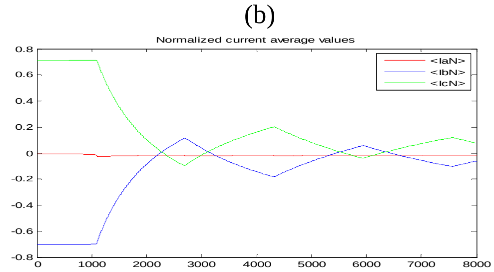
Fig -4: Simulation results of (a) inverter three phase current,(b) diagnostic variables and (c) normalized currents average values when open switch fault in switch S1.



(a)



(b)



(c)

Fig -5: Simulation results of (a) inverter three phase current,(b) diagnostic variables and (c) normalized currents average values when open switch fault introduced in switch S1 and S2.

CONCLUSION

In this paper, a new diagnosis scheme for three phase inverter IGBT open switch faults is presented. In proposed method, three phase current of inverter is used as input to diagnostic method. This method avoids extra sensors and therefore reduces cost of manufacturing. The diagnostic variables provide the information about faulty phase. Along with this, average normalized three phase current, faulty switches can be detected. This method gives detection of single as well as multiple faulty switches. Because of normalization method, this method becomes independent on load level or motor speed.

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