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Fault Diagnostics in an Inverter Feeding an Induction Motor

KHATER, Faeka and ABU EL-SEBAH, Mohamed
Electronics Research Institute - Dokki, Cairo, Egypt

OSAMA, Mohamed
High Institute of Engineering – Six October City, Egypt

Abstract

This paper presents a fault diagnostics system for a three-phase voltage source inverter. The system is developed as a rule-based fuzzy logic system for fault cases of the inverter power semiconductor switches. Based on a time domain simulation model, the inverter different fault conditions are simulated with the resulting voltage spectrum providing the database for the fuzzy logic system. The developed fault diagnostics system is capable of identifying the type and location of the inverter fault.

Keywords: fault diagnostics, voltage source inverter, fuzzy logic

1 INTRODUCTION

Inverter use is popular in modern industrial, aerospace, traction, residential, etc.… systems and power plants in the present time. The induction motor (IM) is the most applicable motor type in variable speed AC drives, therefore reliability of the inverter feeding an induction motor is of great importance. To keep the inverter reliability at a high level, fault diagnostics is required to allow controlled shut down in order to reduce both outage time and damage of equipment, and to permit scheduling in preventive maintenance. Therefore, monitoring and control is not only required to switch off the drive system in a safe way, but detection of the fault location and seriousness enables use of standby equipment or modification of the operation strategy [1-3]. Online diagnostic techniques require the use of the available sensors in the drive system for economical reasons. Although several techniques have been developed for fault diagnostics (FD) and fault diagnostics model in the induction machine [4-7], very limited work has been carried out to investigate fault diagnostics in the inverter. This deficiency provides the interest to propose an adequate method to determine the fault type and its location in the inverter.

Detection techniques have previously been introduced for open-switch FD in the voltage source inverter (VSI) fed a synchronous machine drive system. The techniques utilize measurement of voltages at key points of the drive system and an analytical model [2]. Detection based on knowledge model is presented for a PWM inverter supplying a synchronous machine [8]. The diagnosis system used two approaches, the current-vector trajectory or the instantaneous frequency to detect and identify the fault of an open transistor in the inverter. A knowledge-based expert system approach has been presented for fault diagnosis of a 3-phase inverter except the fly wheeling diodes [9]. Such diagnosis was based on the most probable defect since the measurement information with Fourier analysis was not able to result explicit determination of the fault. In [10], an expert system based fault diagnosis for VSI fed ac motor was presented. The system defined only the fault type using a fault tree configuration of the VSI, motor and mechanical faults on-line or off-line (trouble shooting & repair). The on-line diagnosis is based on the input & output measurement of each device that results the type of fault.

Fault modes of VSI for IM drive were investigated for the key fault types [1]. A few selected fault types were mathematically analyzed and verified by simulation for open loop volts/hertz control of the drive. This study can be useful for prediction of post-fault operation and fault tolerance control. A survey on some diagnosis methods, for

VSI feeding IM drives, was presented with focus on function and properties of the diagnosis method [3]. This work covered the faults of the inverter components which still have promising investigation for future applications.

This paper presents a fault diagnostics system for a three-phase voltage source inverter. The system is developed as a rule-based fuzzy logic system for fault cases of the inverter power semiconductor switches. Based on a time domain simulation model, the inverter different fault conditions are simulated with the resulting voltage spectrum providing the database for the fuzzy logic system. The developed fault diagnostics system is capable of identifying the type and location of the inverter fault

2 INVERTER FAULTS

A three-phase voltage source inverter feeding an induction motor is shown in Fig. 1. The six power semiconductor switches $\left(S_a, \bar{S}_a, S_b, \bar{S}_b, S_c, \bar{S}_c\right)$ are usually selected as IGBTs. A Pulse Width Modulation (PWM) switching scheme is employed in order to shape and control the three-phase inverter output voltages in magnitude and frequency with a constant dc bus voltage [11].

Types of inverter faults can be classified as [1]:

- Switch gate drive open circuit.
- Short circuit in the switch.
- Line to line short circuit at the inverter output.
- Line to ground short circuit at the inverter output.
- DC bus short circuit.
- Earth fault on dc bus.

The short circuit faults at the inverter output occur as short circuit at the machine terminals and thus protection system activates the circuit breaker but often fails to define faults in the power semiconductor switches (IGBTs). As a result, the faults considered in our study are in the IGBTs which are switch gate drive open circuit and switch short circuit. Different configurations are investigated by monitoring the inverter output voltage and current. The configuration of the faults in the inverter switches are selected as:

1. Open circuit faults in :
   a. One switch (upper or lower)
   b. Two switches for different phases (same side of dc bus)
   c. Two switches for different phases (different sides of dc bus)
2. Short circuit faults in :
   a. One switch (upper or lower)
   b. Two switches for different phases (same side of dc bus)
   c. Two switches for different phases (different sides of dc bus)

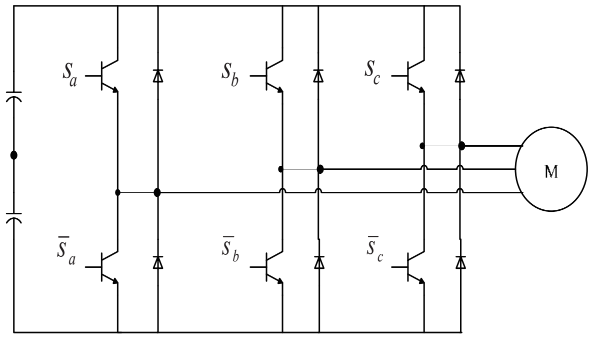


Figure 1. Inverter system with six power switches

3 SIMULATION MODELS OF THE INVERTER FAULTS

The inverter system is simulated for both healthy condition and for different fault condition configurations (both open and short circuit). The simulation is carried out for:

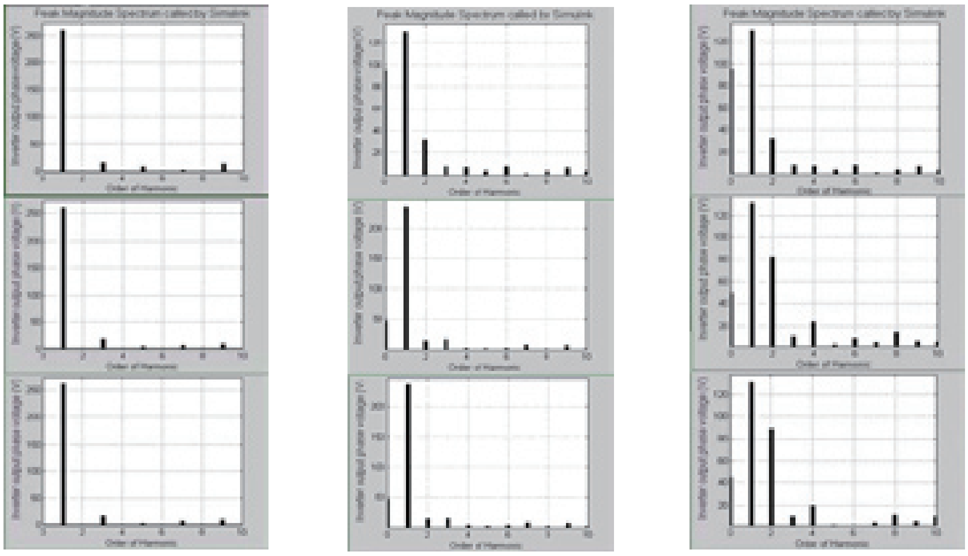
-Open circuit switch:

$S_a, \bar{S}_a, S_a \,\&\, S_b, \bar{S}_a \,\&\, \bar{S}_{b,} S_a \,\&\, \bar{S}_b, \bar{S}_a \,\&\, S_b$

- Short circuit switch:

$\bar{S}_a, S_a, \bar{S}_a \,\&\, \bar{S}_b, S_a \,\&\, S_{b,} \bar{S}_a \,\&\, S_b, S_a \,\&\, \bar{S}_b$

Simulation of the drive system for different fault types and conditions provides the waveform and spectrum of the output voltage & current after fault occurrence. Using the Fast Fourier Transform (FFT), it is found that each case of fault configuration has a salient waveform feature that distinguishes it from other faults. A detailed study of the FFT components concluded that only the fundamental component and dc component are sufficient to indicate the type and location of the fault. For example, Fig. 2 illustrates the voltage spectra of the inverter when it works at synchronous modulation (modulation ratio 21) and fundamental frequency 50 Hz. The healthy inverter case indicates no even harmonic components and no dc components. In Fig. 2-b, after fault occurrence of one switch (S_a) open, the voltage spectra has slight reduction in phases b & c for the fundamental component and almost dropped to half the value for phase a. A dc component exists in all phases with negative offset of phase since S_a is not active. Also, Fig. 2-b shows that even harmonic components appear in all phases in particular the second harmonic with the largest value occurs in phase a. After fault occurrence of one switch (S_a) shorted, as illustrated in Fig. 2-c, similar changes in the voltage spectra appear as for open switch except that the offset of voltage will be negative.



(a) (b) (c)

Figure 2. Inverter voltage spectra: (a) healthy case (b) one switch open (c) one switch short

4 FUZZY LOGIC BASED INVERTER FAULT DIAGNOSTICS

The results of the simulation model for different fault configurations provide the database that can be used in an online fuzzy logic based diagnostics system. Figure 3 illustrates the drive system with data monitoring and processing feeding the developed fault diagnostics (FD) system.

The following subsections will present the fuzzy input variables and the applied fuzzy sets. Fuzzy membership and scaling will also be introduced. The fuzzy inference is discussed with some If-Then rules of different fault conditions.

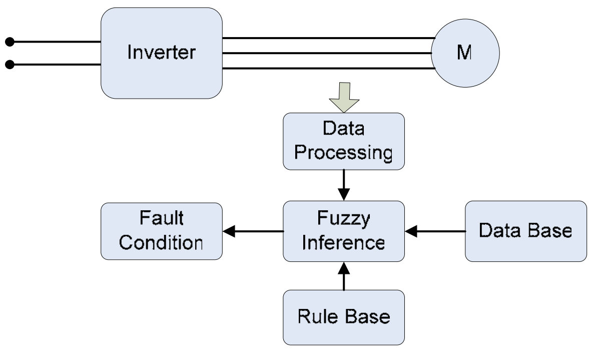


Figure 3. Fuzzy logic fault diagnostics system

4.1 Fuzzy System Input and Linguistic Variables

The input variables to the fuzzy system are the inverter output voltages. The considered variables are the fundamental component and the polarity of dc component obtained from FFT. Using the fuzzy set theory [12,13],

$$V_{a1} = \{\mu_{Va1}(v_{a1j}) \mid v_{a1j} \in V_{a1}\} \quad (1)$$

$$V_{b1} = \{\mu_{Vb1}(v_{b1j}) \mid v_{b1j} \in V_{b1}\} \quad (2)$$

$$V_{c1} = \{\mu_{Vc1}(v_{c1j}) \mid v_{c1j} \in V_{c1}\} \quad (3)$$

$$V_{a0} = \{\mu_{Va0}(v_{a0j}) \mid v_{a0j} \in V_{a0}\} \quad (4)$$

$$V_{b0} = \{\mu_{Vb0}(v_{b0j}) \mid v_{b0j} \in V_{b0}\} \quad (5)$$

$$V_{c0} = \{\mu_{Vc0}(v_{c0j}) \mid v_{c0j} \in V_{c0}\} \quad (6)$$

Where $v_{a1j}, v_{b1j}, v_{c1j}, v_{a0j}, v_{b0j}$ & v_{c0j} are the elements of the discrete universe of discourse (domain) $V_{a1}, V_{b1}, V_{c1}, V_{a0}, V_{b0}$ & V_{c0}. $\mu_{Va1}, \mu_{Vb1}, \mu_{Vc1}, \mu_{Va0}, \mu_{Vb0}$ & μ_{Vc0} are the corresponding membership functions. The input fuzzy variables are interpreted as linguistic variables in natural or artificial languages. Each fuzzy variable can be defined as X which has T(X) set of names of the linguistic values. The fuzzy sets are:

T(X) = {zero (Z), strongly very small (SVS), very small (VS), small (S), just small (JS), medium (M), just big (JB), big, (B), very big (VB), strongly very big (SVB)}

Where X = V_{a1}, V_{b1}, V_{c1}, V_{a0}, V_{b0} and V_{c0} respectively.

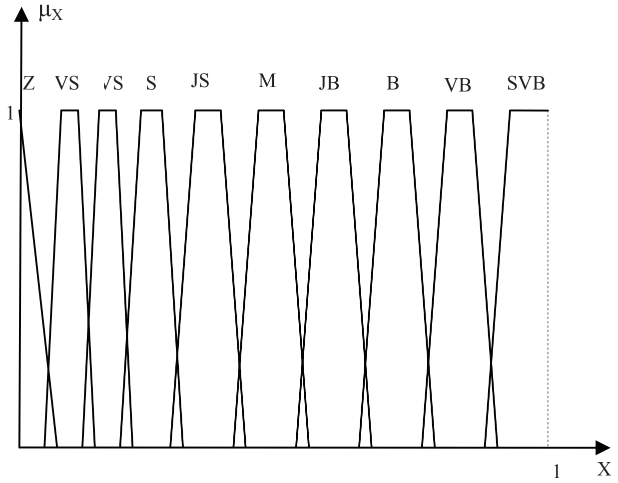


Figure4. Fuzzy membership function of input variables

4.2 Fuzzy Membership Functions and Scaling

The normalized membership functions are defined according to the predicted inverter voltage for each faulty case. Fine scaling of the fuzzy variables is carried out to cover the normalized domain (0,1) of the fundamental components of voltage signals. Fig. 4 illustrates the membership function of the used fuzzy sets. The dc components of the voltages can also be defined as linguistic variables in a normalized domain (-1, 1). However, the rule-based proposal to implement fault diagnostics requires only the sign of the dc component, so {negative (N), zero (Z), positive (P)} are the adequate fuzzy sets.

4.3 Fuzzy Inference

Fuzzy inference is emulating the human thought and skills as a real-time expert system that has the engineer FD experience in the form of action rules. Individual rule-based inference is preferred since it provides very efficient computation and results in saving in the memory usage.

The rule base provides diagnostic rules that support the fuzzy inference engine, while the database provides the corresponding input membership functions [12,13]. Some rules for the FD system in the form of If-Then are:

(A) If V_{a1} is JB and V_{b1} is SVB and V_{c1} is SVB then a switch of phase a (S_a or $\overline{S}_a$) is open.
If V_{a0} is N and V_{b0} & V_{c0} are P, then S_a is open.
Else, if V_{a0} is P and V_{b0} & V_{c0} are N, then $\overline{S}_a$ is open.

(B) If $V_{a1}$is JB and V_{b1} is JB and V_{c1} is JB, then a switch of phase a (S_a or $\overline{S}_a$) is short
If V_{a0} is P and V_{b0} & V_{c0} are N, then S_a is short.
Else, if V_{a0} is N and V_{b0} & V_{c0} are P, then $\overline{S}_a$ is short.

Notice that the (A) or (B) rules must be applied in consequent steps with inputs as linguistic variables, but outputs identify the type of fault (open or short) and the location of the fault exactly.

Table 1. Fault diagnostics matrix

		$V_{ph}(V_{a1}, V_{b1}, V_{c1})$					
		JB, SVB, SVB	JS, JS, B	B, B, VB	JB, JB, JB	Vs, VS, S	M, M, VS
(V_{a0}, V_{b0}, V_{c0})	N, P, P	S_a : *Open*			$\overline{S}_a$: *Short*		
	P, N, N	$\overline{S}_a$: *Open*			S_a : *Short*		
	N, N, P		S_a : *Open* S_b : *Open*			$\overline{S}_a$: *Short* $\overline{S}_b$: *Short*	
	P, P, N		$\overline{S}_a$: *Open* $\overline{S}_b$: *Open*			S_a : *Short* S_b : *Short*	
	N, P, Z			S_a : *Open* $\overline{S}_b$: *Open*			$\overline{S}_a$: *Short* S_b : *Short*
	P, N, Z			$\overline{S}_a$: *Open* S_b : *Open*			S_a : *Short* $\overline{S}_b$: *Short*

5 FAULT DIAGNOSTICS AND RULE-BASED GROUPS

In the previous section the sample of if-then rules was performed in a multistage form to get a defined fault condition. All the fault case of the inverter switches (S_a, S_b, S_c, $\bar{S}_a$, $\bar{S}_b$ and $\bar{S}_c$) are considered in a universal form of rule-based fuzzy system. Fault diagnostics could be developed as groups in a matrix form given in Table 1. Each cell in the matrix provides the fault condition that occurs if the input variables (V_{a1}, V_{b1} and V_{c1}) satisfy the linguistic values in the upper raw and at the same time the variables (V_{a0}, V_{b0} and V_{c0}) have the polarity given in the left column. As an example, if (V_{a1}, V_{b1} and V_{c1}) are (B, B, VB) and (V_{a0}, V_{b0} and V_{c0}) are (NPZ), then switch S_a and $\bar{S}_b$ are open circuit. Notice that rule-based matrix has empty cells which is common case in practical system and leads to save in memory and fast acting performance [13]. The developed rule-based fuzzy system matrix can be used in an on-line fault diagnostic for IM drive system. In such a system the input variables are monitored by sensors. Data processing is applied through DSP and on line FFT to obtain the spectra of the signals which defines the peak values of the fundamental phase voltage and the dc component.

6 CONCLUSION

A fault diagnostics system has been proposed for a three phase voltage source inverter. The system has been developed as a rule-based fuzzy logic system for fault cases of inverter power semiconductor switches. Based on a time domain simulation model, the inverter different fault conditions have been simulated with the resulting voltage spectra providing the developed for the fuzzy logic system. The proposed fault diagnostics system has resulted in a matrix that provides the fault condition according to the data base status. The developed system is capable of identifying the type of and location of the faulty inverter switches. In addition, it is adequate for use in an on-line fault diagnostics system in induction motor drives.

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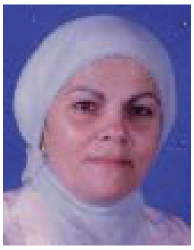

Faeka Khater (IEEE SM) received the B.S., M.S. and Ph.D. degrees in electrical engineering from Cairo University, Cairo, Egypt, in 1967, 1976 and 1982, respectively. From 1984 to 1987 she was an honorary fellow in the ECE Department at the University of Wisconsin, Madison, USA. Since graduation she has been working for the Electronics Research Institute (ERI) as, RA (1967-1982), Assistant Professor (1982-1987), and Associate Professor (1987-1992). Since 1992, Dr. Khater She has been a Professor in the Department of Power Electronics & Energy Conversion, ERI, in which she was Department Chair from 2001 to 2006. She was a visiting Professor at the Institute of Power Electronics & Electric Drives, Aachen, Germany (May/June 2001). Prof. Khater interests include electric machines, electric drives system control, power electronics converters, digital electronic control, renewable energy, and energy efficient techniques.

Mohamed I. Abu El-Sebah received the B.S, M.S and Ph.D. degrees in electrical engineering from Cairo University in 1990, 1996 and 2003 respectively. Since graduation he has been with the Electronics Research Institute (ERI), Cairo, Egypt. In 2003 he became an Assistant Professor in ERI. His research interests are electric drives, power electronics and digital control.

Mohamed Osama received the B.S. degree in electrical power engineering from Cairo University, Giza, Egypt, in 1991 and the M.S. and Ph.D. degrees in electrical engineering from the University of Wisconsin, Madison, USA in 1994 and 1997, respectively. From 1997 to 2005, Dr Osama was with the Corporate Research & Development Center, General Electric Company (GE-GRC), Niskayuna, NY, USA where he led and executed R&D projects in motors, generators and electrical drives technology. Since Jan. 2005, Dr Osama has been an assistant professor at the High Institute of Engineering, 6th of October City, Egypt. Dr Osama is currently, the vice-president of EGWEA (Egyptian Wind Energy Association). Dr Osama is a senior member of the IEEE. He is the author of eleven IEEE published technical papers including three Journal (IAS transactions) papers. Dr. Osama holds nine issued US patents.