Logic System Design for Fault Detection and Classification of Voltage Source Inverter Driving Induction Motor

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Abstract— Induction motors are commonly used in many different applications. The importance of these motors comes from their ruggedness, reliability, and low maintenance cost. Generally, the driving system of these motors can be vulnerable to injury of different types of faults during the operation, which leads to failure in continuous optimal operation of the system. This paper proposes a new simple algorithm to detect and classify the fault may occur in the driving system (in the Voltage Source Inverter VSI) of induction motor. The proposed method uses three parameters: First, the per phase average value of the stator current. Second, the Pulse Width Modulation (PWM) signal. Third, the switch voltage (drain to source voltage). The method is designed based on using the logic system. It is designed to decide whether the driving system is healthy or faulty. Moreover, the logic system can specify the fault location over the driving system. MATLAB 2020a is used to validate the results.

Keywords— Induction Motors, Short Circuit, Fault, Open Circuit, PWM, Logic system, Krause's Model.

I. Introduction

INDUCTION motors (asynchronous motors) are widely used in different applications due to their variable speed, reliability, efficiency, ruggedness, and low maintenance cost [1, 2]. The performance of the Induction Motor (IM) depends mainly on the reliability of the driving system. The rugged driving system can improve the efficiency of the induction motor and avoid any extra maintenance costs. Some failures in the motor may occur due to faults in the driving system. Faults in the induction motor can be divided into two types: First, faults that occur in the machine parts (Mechanical faults). Second, faults that occur in the driving system (Switching faults) [3].

Faults that occur in the induction motor itself such as eccentricity, rotor bar breaking and others. Whereas, the switching faults can be further divided into extra categories, such that: rectifier's diodes faults (diode shorted or opened), failure of DC link capacitors (fault at DC capacitors) and failure of switches (switches shorted or opened) [4, 5].

Induction motors able to operate under fault conditions but for short time. However, it commonly causes the motor to stop working. The cost of the work interruption in addition to the cost of maintenance increase the need to develop a fast and accurate fault detection techniques and diagnose the fault type and nature [2, 5].

The process of fault detection includes specifying the type and the severity of the fault. This requires an accurate mathematical model that describes the system under fault conditions. Different fault detection methods were proposed. Many of them have discussed different methods for fault identifications and some methods have been newly developed. All these methods are based on measuring some data from the IM model including stator or/and rotor current, stator voltage, temperature, vibration, and speed. These data have been analyzed to state whether the system is faulty or not and then specify the fault type [6-8].

Different methods are employed to detect the faults in the induction motors, in [9-12] the authors used smart algorithms to analyze the signals and diagnose the type of the faults in the induction motors.

Different methods are adopted by several publications in the process of fault diagnose and analyzing the fault signal [13-18]. Most of these works rely on monitoring and processing of different signals such that stator and rotor currents, torque, and other signals to get data of time or frequency and determine the fault nature and type. They emphasize on the advantages of using e.g., fuzzy logic, ANFIS system, Genetic algorithm in fault detection with acceptable degree of certainty. See Table 1.

This paper proposes a new fault detection and classification algorithm based on using simple logic system to inform the operator if the IM is healthy or not. The proposed method relies on three measured values. The first one is measuring the average of the stator current in the IM. Second one is measuring the PWM signal. Third, switches voltage (drain to source voltage) of the driving system. The logic system uses the if-then rules to decide about the fault type and its location in the driving system.

Table 1. Review of selected fault detection methods

Reference	Input Variables		IM model
[13]	Stator Currents	Stator and Rotor Speed	Symmetrical 3-phase model
[14]	Stator Currents		Symmetrical 3-phase model
[15]	Stator Current		Symmetrical 3-phase model
[16]	Stator Currents		Symmetrical 3-phase model
[17]	Stator Voltages and Currents		-
[18]	Load Torque and Stator Currents		Kraus's Model
This paper	Average stator current, PWM, switch voltage V_{ds}		Kraus's Model

The rest of the paper is organized as follow: Section 2 introduces the induction motor model based on Krause's model. The implementation of torque and speed equations are presented in Section 2. Section 3 discusses the induction motor controlled by open loop V/Hz method. Section 4 simulates the IM with driving system and implements the types of faults in the voltage source inverter. Moreover, Section 4 presents the proposed fault detection algorithm. Section 5 introduces the logic system for fault detection and classification. Finally, section 6 concludes the work.

II. Induction Motor Model

Induction motors are simulated by a set of differential equations in the d-q coordination, and each part of the motor has its own equations. This dynamic modelling assumes that the Magnet-Motive Force (mmf) is sinusoidal dispersed over both stator and rotor parts due to the symmetry of their windings. One of the most popular induction motor models is called Krause's model and according to this model the differential equations are described as follows [19], starting with flux linkage equations:

$$\frac{dF_{qs}}{dt} = \omega_b\left(V_{qs} - \frac{\omega_e}{\omega_b}F_{ds} + \frac{R_s}{X_{ls}}\left(F_{mq} + F_{qs}\right)\right) \quad (1)$$

$$\frac{dF_{ds}}{dt} = \omega_b\left(V_{ds} - \frac{\omega_e}{\omega_b}F_{qs} + \frac{R_s}{X_{ls}}\left(F_{md} + F_{ds}\right)\right) \quad (2)$$

$$\frac{dF_{qr}}{dt} = \omega_b\left(V_{qr} - \frac{\omega_e-\omega_r}{\omega_b}F_{dr} + \frac{R_r}{X_{rl}}\left(F_{mq} + F_{qr}\right)\right) \quad (3)$$

$$\frac{dF_{dr}}{dt} = \omega_b\left(V_{dr} - \frac{\omega_e-\omega_r}{\omega_b}F_{qr} + \frac{R_r}{X_{rl}}\left(F_{md} + F_{dr}\right)\right) \quad (4)$$

ω_b, ω_r and ω_e are base, rotor and electrical speeds in rad/s respectively. F_{mq} and F_{md} are the magnetizing flux linkages in q and d axis, and given by:

$$F_{qm} = X_{ml}\left[\frac{F_{sq}}{X_{sl}} + \frac{F_{rq}}{X_{rl}}\right] \quad (5)$$

$$F_{dm} = X_{ml}\left[\frac{F_{sd}}{X_{sl}} + \frac{F_{rd}}{X_{rl}}\right] \quad (6)$$

The machine stator current is described by the following equations:

$$i_{qs} = \frac{1}{X_{ls}}\left(F_{qs} - F_{mq}\right) \quad (7)$$

$$i_{ds} = \frac{1}{X_{ls}}\left(F_{ds} - F_{md}\right) \quad (8)$$

$$i_{qr} = \frac{1}{X_{lr}}\left(F_{qr} - F_{mq}\right) \quad (9)$$

$$i_{dr} = \frac{1}{X_{lr}}\left(F_{dr} - F_{md}\right) \quad (10)$$

The electromagnetic torque on the machine shaft can be expressed as:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_b}\left(F_{ds}i_{sq} - F_{sq}i_{sd}\right) \quad (11)$$

$$T_e - T_l = \left(\frac{2}{J}\right)\left(\frac{1}{P}\right)\frac{d\omega}{dt} \quad (12)$$

The rotor speed of the shaft can be expressed as:

$$\omega_r(t) = \frac{P}{2J}\int\left(T_e - T_l\right).dt \quad (13)$$

III. Open Loop or V/f Control

Induction motor driving system (Fig. 1) mainly contains a diode bridge to rectify the AC voltage which comes from electrical power grid. Then, the DC voltage feeds an inverter to produce AC voltage to keep its airgap flux around the rated value of V/f ratio [1].

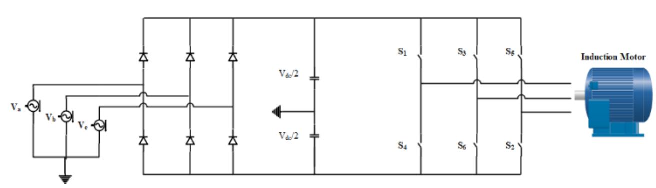

Figure 1. Induction Motor with driving system

To simplify the analysis in this paper the voltage per hertz open loop method is selected to control the induction motor. To generate the control signal of all inverter switches, three sinusoidal waves are compared with sawtooth signal. See Fig. 2.

During the normal/steady state operation of the IM, the stator current has the path which illustrated in Fig. 3 (for instance). As seen in Fig. 3, and for simplicity, the current passes through the following path: $V_{dc}/2$, S_1, Z_s (stator impedance), S_6, $-V_{dc}/2$, then, to ground. The current equation is given by:

$$i_s(t) = \frac{V_{dc}}{Z_s} \tag{14}$$

Where V_{dc} is the rectified line voltage between A and B (for instance).

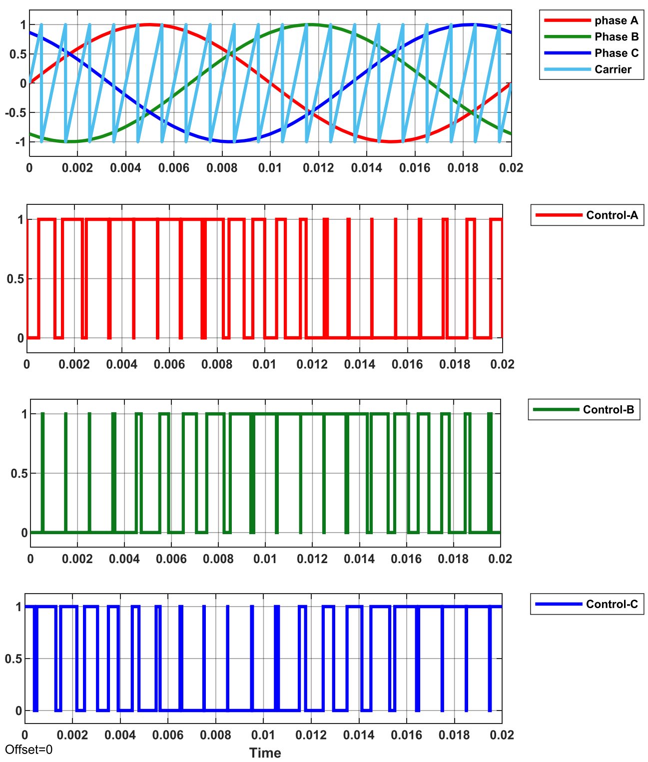

Figure 2. Control signal Generation of the driving system

The three phase stator currents of healthy IM are plotted in Fig.4. It is seen from Fig.4 the stator currents of IM are divided into two unequal periods. The first one is labeled by Transient period which represents the starting behavior of IM. The second one represents the steady state operation of IM. Moreover, to ensure the healthy operation of the IM, this condition must be satisfied:

The average value of the stator current over one switching period must be zero, this is given by:

$$I_{s_{dc}} = \frac{1}{T}\int_0^T i_s(t)dt \tag{15}$$

Where, T is switching time (or it is the full period of stator current $I_s(t)$).

In this paper and to make it simple, fault types are applied to S_1 (colored by oval cyan) in the driving system, see Fig. 3.

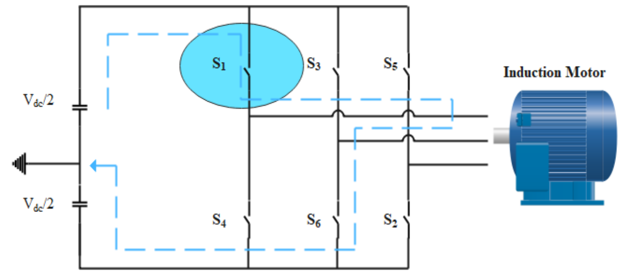

Figure 3. Stator Current Path in Healthy IM

IV. System Preparation and Fault Detection

A. System Preparation

The model of three phase induction motor driven by a conventional driving system. The driving system includes a three-phase voltage source with 400V rms line voltage, connected to three phase rectifiers, with DC capacitor of 100 uF. Six MOSFETs with freewheeling diodes are selected to build an inverter. The switching frequency of the inverter is set to 20 kHz. PWM stage is simulated based on an open loop control or constant V/Hz control. A 5.4 Hp, three phase squirrel-cage induction motor with rated phase voltage 230V rms, and rated speed 1430 rpm has two pairs pole, with stator and rotor resistors are 1.405 and 1.395 ohm, respectively. The stator and rotor leakage inductances are both set to 5.8 mH.

Many faults may occur in the driving system during operation, and each type of fault has a particular impact on the overall system. Mainly, these faults are called switching faults, and they are classified as follows: 1. Rectifier Diode Open Circuit Fault. 2. Rectifier Diode Short Circuit Fault. 3. DC Bus Shorted to the earth Fault. 4. DC capacitor short Circuit Fault. 5. Power Switch Open Circuit Fault. 6.Power Switch Short Circuit Fault. 7. Loosing Gating Signals for Power Switch. This research focuses only on the short circuit faults that may occur over the controlled switches.

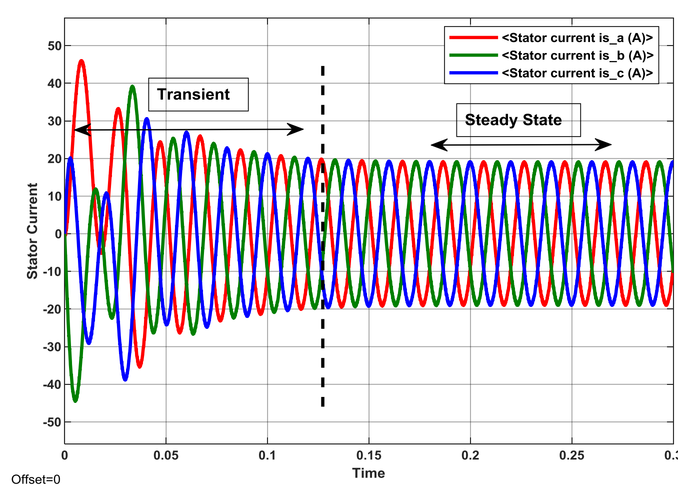

Figure 4. Stator current of Healthy IM

B. *Open Circuit Fault Analysis*

This fault is seen in the driving system *if one switch in the current path or more is disconnected*, see Fig. 5. If switch S_1 is opened, then, the stator current is almost zero. Fig. 6 shows the three-phase stator current. Due to power supply interruption, the phase A stator current (in red) shows a nearly zero peak.

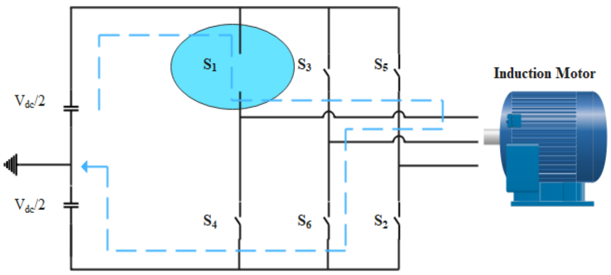

Figure 5. The equivalent circuit in case of open circuit fault

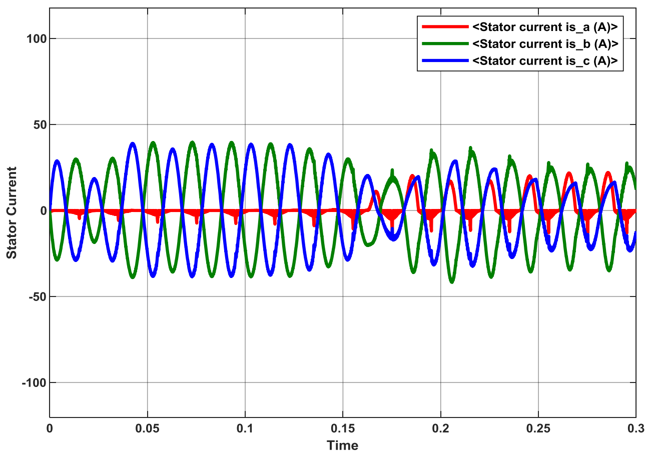

Fig. 6. Stator Current when S1 is opened

C. *Short Circuit Fault Analysis*

This fault is seen in the driving system *if one switch in current path or more is shorted out*. If switch S_1 is replaced by short circuit, then, the stator current is increased dramatically. See Fig. 7. The phase A stator current (in red, Fig. 8) shows a high average value when S_1 is shorted out.

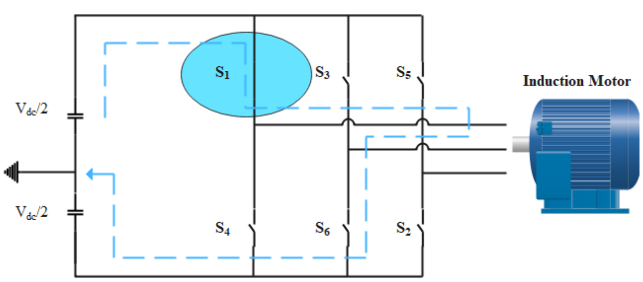

Figure 7. The equivalent circuit in case of short circuit fault

D. *Fault Detection Process*

The flowchart of the proposed fault detection method is illustrated in Figure 9. The process starts when the three-stator current average values are measured after steady-state operation.

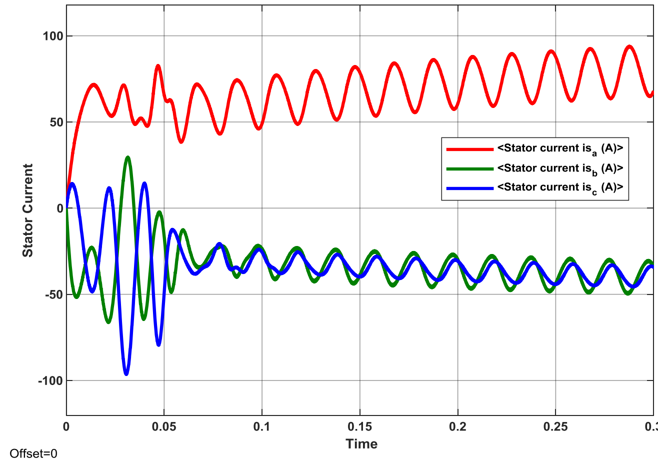

Figure 8. Stator Current when S1 is shorted out

The zero average value indicates that the IM is healthy. If the system gets a non-zero mean value of stator current, then, the next step starts.

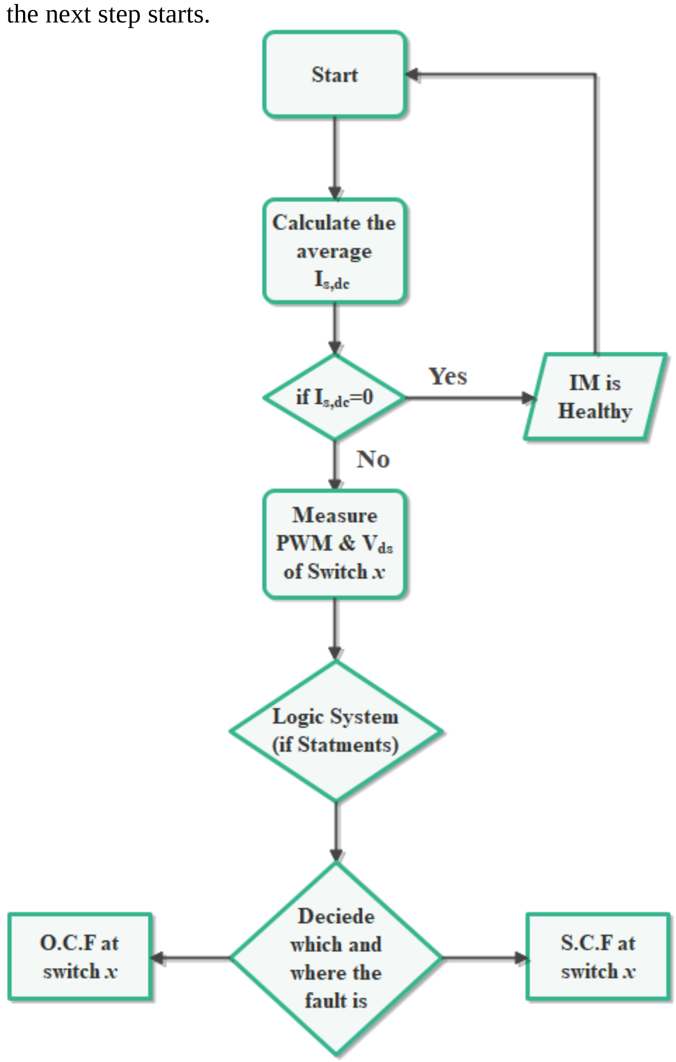

Figure 9. The proposed fault detection and classification method

The second level of the fault detection process depends on the PWM signal and MOSFET drain-source voltage in the driving system. The logic system takes these two variables and check the rule. For example, for $MOSFET_1$ in the driving system, the related rule should be (*if PWM_1 is Low and V_{ds1} is High THEN IM is HE*). Table 2 lists briefly the rules of the fuzzy system. Where, *x* is the number of switch and it's PWM in the driving system. H and F mean Healthy and Faulty, respectively. S.C.F and O.C.F mean Short Circuit Fault and Open Circuit Fault, respectively.

Table 2. If-then statements of logic system

Rule	If	And		IM	Fault	Which
	PWM_x	V_{dsx}		H or F	type	MOSFET
01	Low	High	**THEN**	HE	-	-
02	Low	Low		NHE	S.C.F	x
03	High	Low		HE	-	-
04	High	High		NHE	O.C.F	x

V. Logic System

To determine the fault type and the faulty switch, a combinational logic circuit is used. It consists of OR, AND, Not, NAND, NOR, XOR, and XNOR logic circuits. To design such circuit, it is necessary to build a truth table and minimize it using Karnaugh map method to get the logic function. The logic circuit can be built after that using the minimized output and target function. The table and figures for logic functions are shown in Table 3 and Figure 10.

Table 3. Logic gates truth table

X	Y	OR	AND	NAND	NOR	XOR	XNOR
0	0	0	0	1	1	0	1
0	1	1	0	1	0	1	0
1	0	1	0	1	0	1	0
1	1	1	1	0	0	0	1

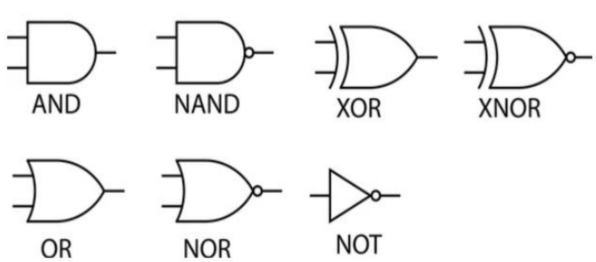

Figure 10. Logic circuits symbols

A. *Logic System Design and Implementation*

The block diagram of the proposed fault detection system is shown in Figure 11. It consists of induction motor, voltage source inverter fed induction motor, average current measurement for each phase, PWM signal for each switch, drain source voltage measurement for each switch, and logic circuit. Fault type and faulty switch can be determined based on the following parameters: 1) the average current of each phase 2) the driving VSI system parameters such as: PWM control signal voltage and drain source voltage of each switch for each phase current path. Following the flowchart of Fig. 9, the logic design circuit can be implemented based on Karnaugh map minimized table. The truth table and the minimized Karnaugh map table are shown in Table 4 and Table 5.

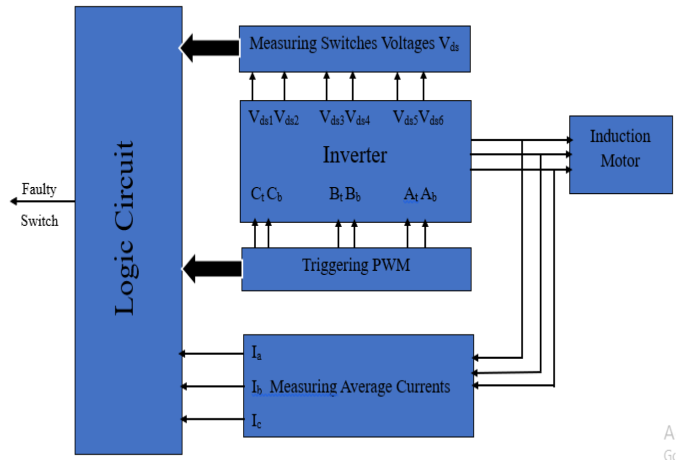

Figure 11. Proposed block diagram fault detection system

Table 4. Truth table for all parameters and motor status for phase x

I_{avx}	PWM_x	V_{dsx}	Output F	VSI status
0	0	0	1	HE
0	0	1	1	HE
0	1	0	1	HE
0	1	1	1	HE
1	0	0	0	S.C.F
1	0	1	1	HE
1	1	0	1	HE
1	1	1	0	O.C.F

Table 5. Minimized Karnaugh map truth table

PWM_X \ V_{dsX} / I_{avX}	00	01	11	10
0	1	1	1	1
1	0	1	0	1

Output:

$$F = \overline{I_{avX}} + \overline{PWM}_X\, V_{dsX} + \bar{V}_{dsX}\, PWM_X \quad (16)$$

$$F = \overline{I_{avX}} + V_{dsX}\ XOR\ PWM_X \quad (17)$$

The type of the fault when the output F is 0 can be determined by:

Open circuit fault O.C.F is

$$O.C.F\ output = PWM_X\ V_{dsX} \quad (18)$$

and the short circuit fault S.C.F is

$$S.C.F\ output = \overline{PWM}_X\ \bar{V}_{dsX} \quad (19)$$

Fig. 12 shows the combinational logic circuit for the VSI fed induction motor system.

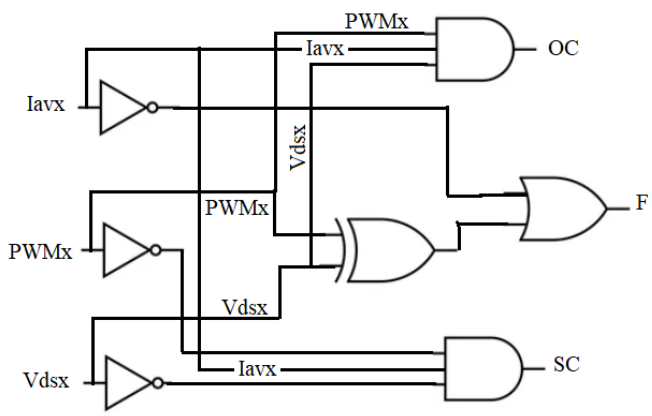

Figure 12. Combinational logic circuit for the system

From Fig. 12, the first the average current should be tested. If the average current is 0, then the motor is healthy. While, if the average current is 1, then the VSI parameters (PWM and V_{ds}) for the upper switch of the phase current path are checked. If the output F is 1, then the motor is healthy HE, otherwise it is not healthy (NHE). If the output F is 0, the motor is not healthy NHE, then based on (PWM and V_{ds}), it can be determined the type of fault and the faulty switch.

VI. Conclusion

In this paper, the fault in the Voltage Source Inverter (VSI) driving Induction Motor (IM) is detected, using a new simple method based on logic system design. The average current, PWM signal, and drain-source voltage of each switch, are used parameters to decide whether the system is healthy or not. A logic circuit is designed to analyze the fault type and detect the faulty switch. The simulation results using MATLAB 2020 are shown for open circuit and short circuit fault. In the future work, other methods can be used to detect the fault type and faulty switch using artificial intelligent methods such as: neural network, genetic algorithm, and fuzzy logic.

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