

# Digital Simulation of Fault Tolerant Inverter Fed Induction Motor with a Leg Swap Module

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## ABSTRACT:

Most of the industrial operations involve the use of induction motor drives. The operations of the drives are so crucial in some events that any fault in the operation of drive could result in serious loss to the industry in terms of capital and raw materials. Hence, it is necessary that an induction motor drive should be fault tolerant. This paper investigates the fault operation of a single phase open circuit fault in the drive by performing fault analysis on the harmonic spectrum of the current waveforms. A fault tolerant system is proposed which can operate even after occurrence of the fault in runtime. The simulation studies are done using MATLAB simulation tool and the results are presented.

**KEYWORDS:** Induction Motor, FFT Spectrum, Fault Analysis.

## 1. INTRODUCTION

Induction motor for many years has been regarded as the workhorse in industrial applications. In the last few decades, induction motor has evolved from being a constant speed motor to variable speed and variable torque machine. When the application requires large power and torque specifications, the usage of induction motor comes into demand. This results in application of an efficient machine which is stable during various fault conditions. Hence machine fault detection becomes an important factor of concern.

In past decades, a number of different incipient fault detection methods and schemes have been presented. Benbouzid M.E.H presents the idea of motor current signature analysis and its application as a medium for fault detection [1]. William Thomson and Mark Fenger explain in a concise manner the fundamental theory, main results, and practical applications of motor signature analysis for the detection and the localization of abnormal electrical and mechanical conditions that indicate, or may lead to, a failure of induction motors [2]. Biswas B. deals with harmonic analysis of motor current signatures under different fault conditions of medium and high power Variable Frequency Drive (VFD) systems. Computer simulation of a VSI fed induction motor based on constant voltage/frequency (V/f) operation is implemented using Powersim (PSIM) simulation software [3]. Bin Huo proposes a simple stator fault detector for Ac motors, based on the TMC320C243 DSP controller is presented. The detector provides

compensation of the constructional and supply voltage imbalances, and senses the ripple of the compensated instantaneous power [4]. Debmalaya Banerjee proposes a CSI-fed induction motor drive scheme where GTOs are replaced by thyristors in the CSI without any external circuit to assist the turning off of the thyristors [5].

Don-Ha Hwang describes the distribution characteristics of switching the surge voltage in the stator windings of an induction motor driven by IGBT PWM inverter [6]. Jee-Hoon Jung presents an online induction motor diagnosis system using the motor current signature analysis (MCSA) with advanced signal-and-data- processing algorithms. MCSA is a method for motor diagnosis with stator-current signals [7]. Luis Alberto Pereira presents the development and the practical implementation of a system for detection and diagnosis of interturn short-circuits in the stator windings of induction motors. [8]. Shi K. L. describes a generalized model of the three-phase induction motor and its computer simulation using MATLAB/SIMULINK. Constructional details of various sub-models for the induction motor are given, and their implementation in SIMULINK is outlined [9]. André M. S. Mendes, Xosé M. López-Fernández, and António J. Marques Cardoso present the thermal behavior of a three phase induction motor under direct torque control, when supplied by a three-phase voltage source inverter with fault tolerant capabilities [10]. Brian A. Welchko, Thomas A. Lipo, Thomas M. Jahns, and Steven E. Schulz presents behaviour of drives in fault tolerant operations and

presents different strategies for fault tolerant operations[11]. M.A. Rodriguez, A.Claudio, D.Theilliol proposed a fault tolerant strategy by replacing a damaged inverter leg with an auxiliary leg [12].

Fault Analysis of VSI fed Induction motor with leg swap module using MATLAB simulation is not present in the above literature. This paper proposes circuit model for VSI fed Induction motor drive and performs harmonic analysis on various fault conditions using MATLAB. It is followed by a “Fault tolerant inverter technique” adopted to analyze the fault in the inverter side of a three phase induction motor drive.

**2. VSI - FED INDUCTION MOTOR DRIVE**

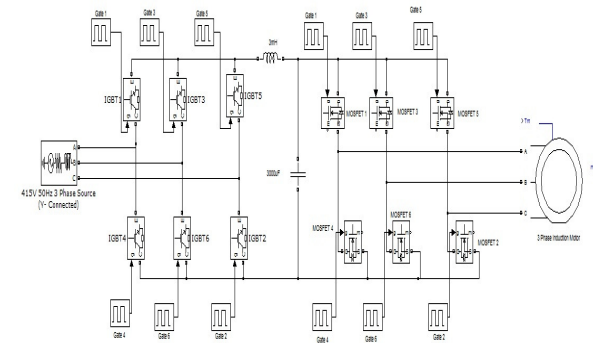
An inverter, in which the input voltage is maintained constant, is called as Voltage fed inverter. The variable frequency drives operate by converting a three-phase voltage source to DC using rectifier. After the power flows through the rectifiers it is stored on a DC bus. The DC bus contains capacitors to accept power from the rectifier, stores it, and later deliver that power through the inverter section. The inverter contains transistors that deliver power to the motor. The “Insulated Gate Bipolar Transistor” (IGBT) and MOSFET is a common choice in modern VFDs. These switches can switch on and off several thousand times per second and precisely control the power delivered to the motor. The MOSFET uses “pulse width modulation” (PWM) technique to supply a sine wave current at the desired frequency to the motor. A variable output voltage can be obtained by varying the input DC voltage and maintaining the gain of the inverter constant. On the other hand if the DC input voltage is not constant and is not controllable, a variable voltage can be obtained by varying the gain of the inverter by pulse-width modulation (PWM) control within the inverter.

In industrial complexes, many induction motors, may often be running at no load or partial load. Hence, Proper fault analysis is needed to obtain efficient results in the fault tolerant VSI fed induction motor analysis. This work is mainly concerned for harmonic analysis of motor current signatures for the following types of faults: open circuiting of one of the six MOSFETs gate, blowing off one MOSFET, short circuit of one MOSFET, line to ground fault at one of the motor phase terminals. Harmonic analysis is also performed on the rectifier side which has IGBT switches. The faults are being introduced in both inverter and rectifier module of the VSI fed induction motor drive.

**3. SIMULATION RESULTS**

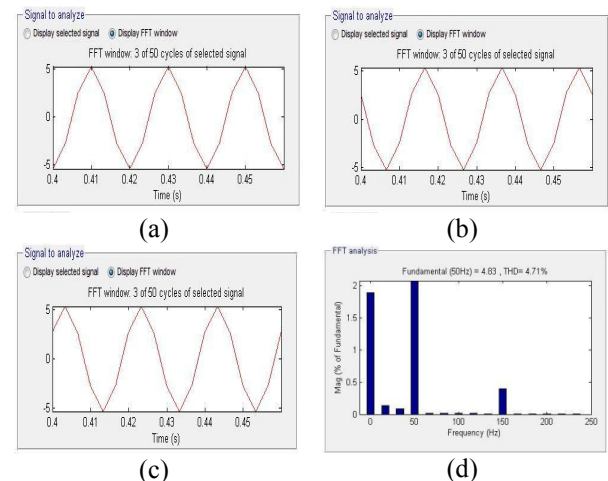
**3.1. Without fault**

Circuit for the Detection of faults for three phase induction motor is simulated by using MATLAB. The Simulink circuit is shown in Fig.1. The 415V AC voltage is applied to the induction motor.



**Fig. 1.** Simulink model of VSI-fed induction motor drive without fault

The waveforms of line Current Vs time of the three phases A, B & C respectively under the healthy condition are shown in Fig.2. It is observed that under healthy condition the current waveforms of phases A, B and C are symmetrical. The magnitude Currents in Phase A, Phase B and Phase C is 4.83 A.



**Fig. 2.** Line Current Waveforms under healthy condition (a) Phase A (b) Phase B (c) Phase C (d) Line spectrum under healthy condition

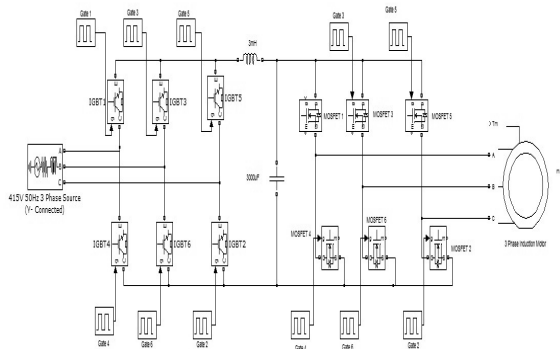
The Line spectrum under the healthy condition is shown in Fig. 2 Total Harmonic distortion of the phases is observed. It is also observed that third order harmonics are present along with the fundamental component. THD value in all the Phases is 4.71%.

**3.2. Fault analysis in inverter**

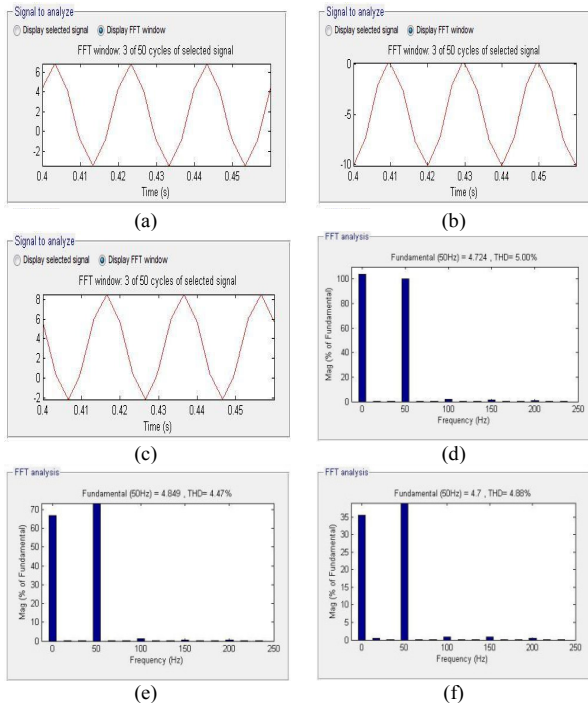
In this section various faults are introduced in the inverter of the VSI-fed drive.

**3.2.1. Open circuiting of one of the six MOSFETs gate terminal**

In this case, the upper leg Phase A MOSFET is grounded in the inverter module i.e. the pulse input to the MOSFET is absent. The Simulink circuit for this fault condition is shown in Fig. 3.



**Fig. 3.** Simulink model with Ph A MOSFET open circuited in inverter



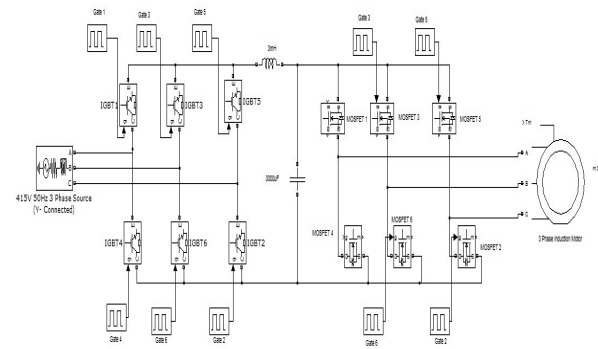
**Fig. 4.** Line Current Waveforms & Line Spectrum with Phase A MOSFET open circuited in inverter Line current waveform of (a) Phase A (b) Phase B (c) Phase C Line spectrum with Ph A MOSFET open circuited in inverter (d) Phase A (e) Phase B (f) Phase C.

The waveforms of line Current Vs time of the three phases A, B & C under the fault conditions are shown in Fig 4.a, 4.b&4.c respectively. It is observed that current direction gets reversed for Phase A. The Phase B&C waveforms are also distorted on introducing the fault. The magnitude of Current in Phase A is 4.724 A, Phase B is 4.849 A, and Phase C is 4.7A.

The line spectrum with Phase A MOSFET open circuited in inverter is shown in Figs. 4.d,4.e&4.f respectively. The presence of DC components is significant in this fault condition. THD value in Phase A is 5 % Phase B is 4.849 % and Phase C is 4.8 %.

**3.2.2. Open circuiting of one of the inverter legs**

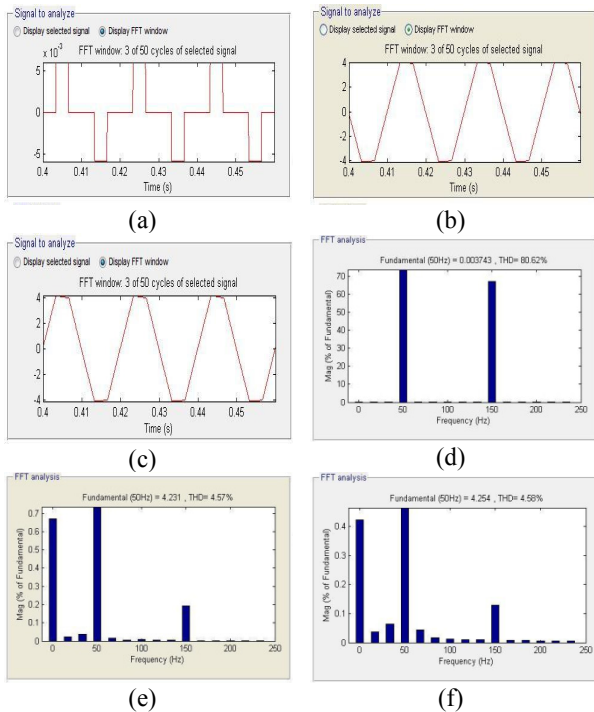
In this case, phase A leg is grounded in the inverter module i.e. the pulse generator input to the MOSFET is absent. The Simulink circuit for this fault condition is shown in Fig 5.



**Fig. 5.** Simulink model with Ph A leg open circuited in inverter

The waveforms of line Current Vs time of the three phases A, B & C under the fault conditions are shown in Figs 6.a, 6.b & 6.c respectively. It is observed that current direction gets reversed for Phase A. The Phase B&Phase C waveforms are also distorted on introducing fault. The magnitude of Currents in Phase A, Phase B and Phase C are 0.003743 A, 4.231 A, and 4.254A respectively.

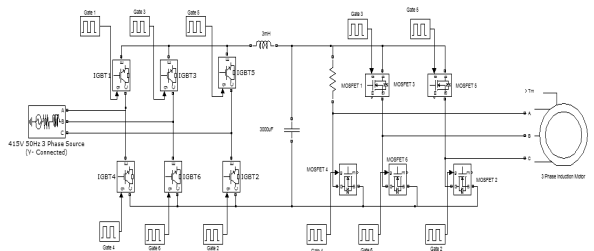
The Line spectrum for Ia, Ib &Ic with Phase A MOSFET open circuited in inverter is shown in Fig. 6.d, 6.e&6.f respectively. Phase A current becomes zero during this fault and the symmetry of other phases are affected. THD value in Phase A is 80.62 % Phase B is 4.57 % and Phase C is 4.58 %.



**Fig. 6.** Line Current Waveforms & Line Spectrum with Phase A leg open circuited in inverter (a) Phase A (b) Phase B (c) Phase C Line spectrum with Ph A MOSFET open circuited in inverter (d) Phase A (e) Phase B (f) Phase C

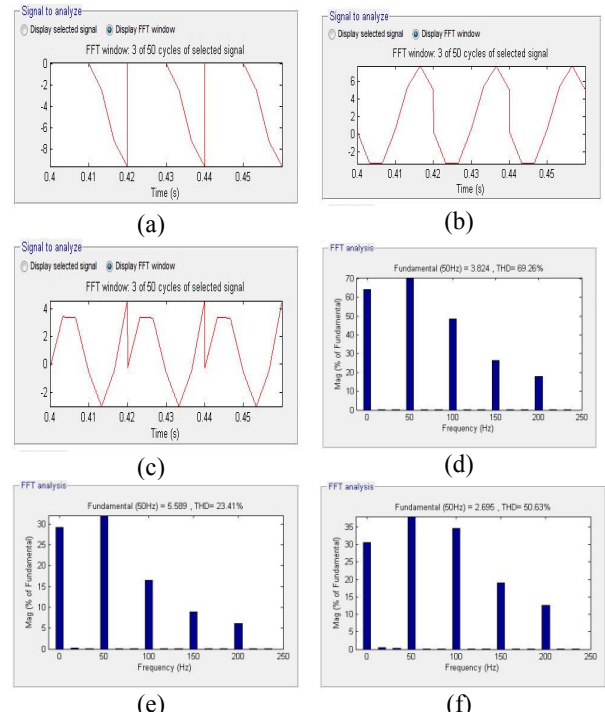
**3.2.3. Blowing off MOSFET in phase A**

In this case the upper leg Phase A MOSFET has been replaced by a high resistance of 1Mega Ohm. The simulation circuit is shown in Fig.7.



**Fig. 7.** Simulink model with phase A IGBT blown off

The waveforms of line current Vs time of the three phases A, B & C under fault condition are shown in Figs 8.a, 8.b & 8.c respectively. It is observed that direction of current in the Phases A & B get reversed. The current of phase C waveform is also distorted on introducing the fault. The magnitude of Currents in Phase A, Phase B and Phase C are 3.824 A, 5.589 A, and 2.695A respectively.

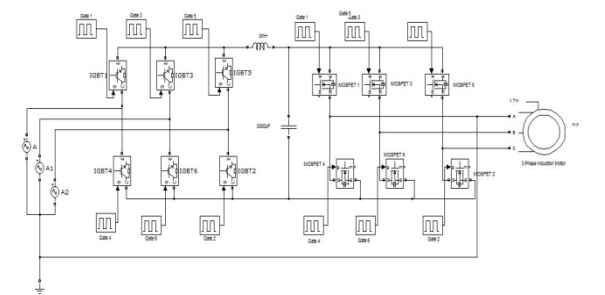


**Fig. 8.** Line Current Waveforms & Line Spectrum with phase A MOSFET blown off (a) Phase A (b) Phase B (c) Phase C Line spectrum with line to ground fault (d) Phase A (e) Phase B (f) Phase C

The Line spectrum with Phase A MOSFET blown off in inverter is shown in Fig. 8.d,8.e&8.f respectively. The presence of DC components in FFT analysis is significant in this fault condition. THD value in Phase A is 69.26% Phase B is 23.41 % and Phase C is 50.63%.

**3.2.4. Line to ground fault**

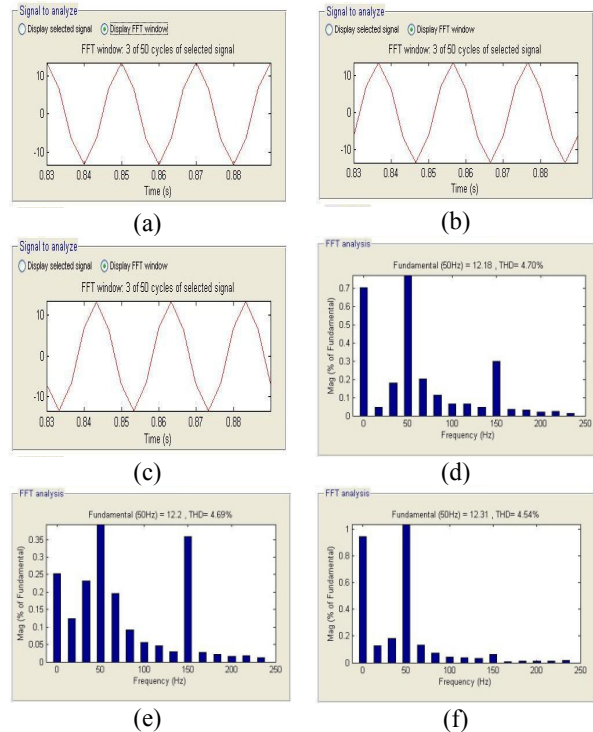
In this case the negative terminal of all the three single phase sources are connected together to form a neutral. From that neutral point connection is being made to the line of Phase A motor load. The Simulink circuit is shown in Fig. 9.



**Fig. 9.** Simulink model with Line to Ground Fault

The corresponding waveforms of Line Current Vs Time of the three phases A, B & C respectively under the fault conditions are shown in Fig.10.a,10.b&10.c respectively. The magnitude of Current in Phase A is

12.18A, Phase B is 12.2A, and Phase C is 12.32 A.



**Fig. 10.** Line Current Waveforms with Line to Ground fault (a) Phase A (b) Phase B (c) Phase C Line spectrum with line to ground fault (d) Phase A (e) Phase B (f) Phase C

The Line spectrums for  $I_a$ ,  $I_b$  &  $I_c$  with Phase A MOSFET open circuited in inverter are shown in Fig. 10.d, 10.e&10.f respectively. The current drawn by the motor rises during this fault condition.

**Table 1.** Summary of FFT Analysis

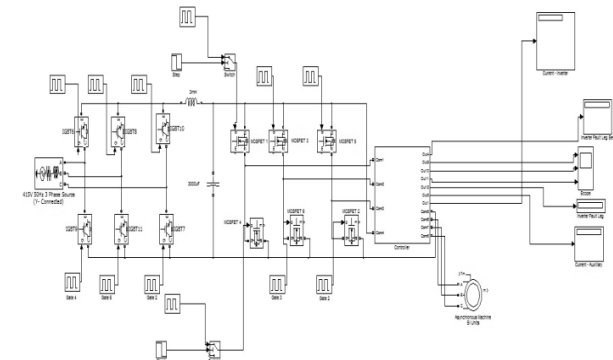
SCENARIO	PHASE		
	A	B	C
HEALTHY			
Current	4.83	4.831	4.882
THD(%)	4.71	4.71	4.52
PHASE A MOSFET OPEN CIRCUIT			
Current	4.724	4.849	4.7
THD(%)	5.00	4.849	4.88
Single Phase Open Circuit			
Current	0.003743	4.231	4.254
THD(%)	80.62	4.57	4.58
PHASE A MOSFET BLOWN OFF			
Current	3.824	5.589	2.695
THD(%)	69.29	23.41	50.63
L G FAULT			
Current	12.18	12.2	12.31
THD(%)	4.70	4.69	4.54

The summary of THD for various faults is given in Table1. From the table1 it is observed that for single phase open circuit fault and Phase A MOSFET blown off fault THD increases to high value. This will degrade

the performance of the induction motor. Where as for rest of the fault there is no significant change in THD but the symmetry of the current wave form is disturbed.

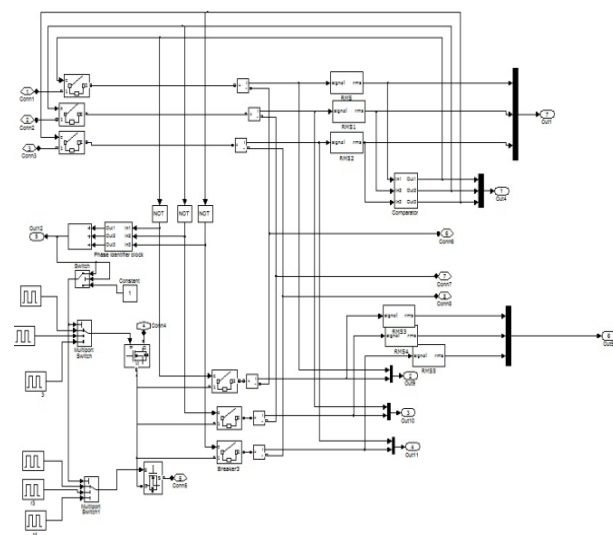
### 3.3. Fault tolerant VSI FED induction motor drive with leg swap module

A Fault tolerant design is proposed and it is capable of operating even after the occurrence of fault. The simulation circuit is given in Fig 11.

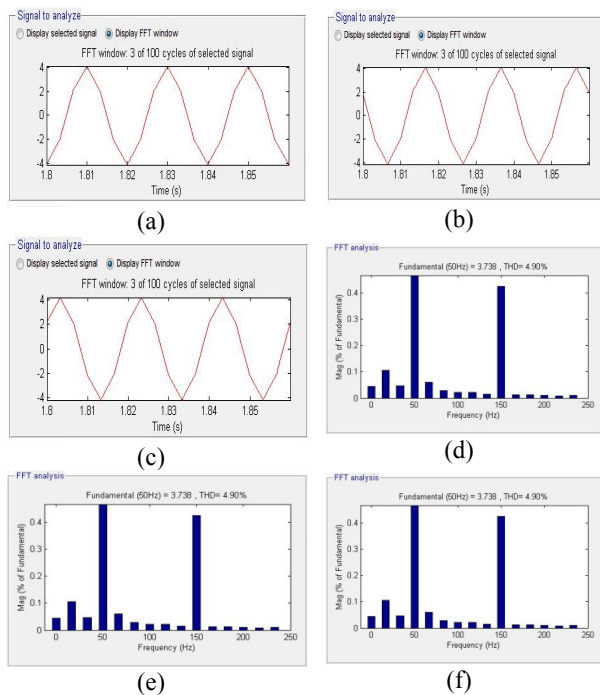


**Fig. 11.** Simulink model for fault tolerant VSI fed induction motor drive

The above Simulink model includes a leg swap module which contains the auxiliary leg. The logical operator in leg swap module senses the fault current. The corresponding fault phase is identified by Phase identifier. Thus the fault Phase is isolated and replaced by auxiliary leg. The swapping is done by means of breaker. The leg swap module is presented in Fig.12. The 415V AC voltage is applied to induction motor. In healthy condition, the performance of the fault tolerant inverter was similar to the healthy VSI system shown in Fig.12.



**Fig. 12.** Leg swap module used in fault tolerant inverter



**Fig. 13.** Line Current Waveforms in healthy operation of fault tolerant inverter (a) Phase A (b) Phase B (c) Phase C Line spectrum of healthy operation of fault tolerant inverter (d) Phase A (e) Phase B (f) Phase C

The waveforms of line currents during single phase open circuit fault in phase A is presented in Fig 13.a,13.b&13.c respectively. The magnitude of current in all the Phases is 3.7 A.

The Line spectrum for  $I_a$ ,  $I_b$  &  $I_c$  under the healthy condition is shown in Fig. 13.d,13.e&13.f respectively. Total Harmonic distortion of the phases is observed. It is also observed that third order harmonics are present along with the fundamental component. THD values in Phase A, Phase B and Phase C is 4.9 %.The comparison of VSI and fault tolerant inverter with Phase A open circuit Fault is given in Table2.

**Table 2.** A comparison of fault operation of voltage source inverter and fault tolerant inverter

PHASE	HEALTHY VSI		DURING FAULT OPERATION (Fault in Phase A)			
			VOLTAGE SOURCE INVERTER		FAULT TOLERANT VOLTAGE SOURCE INVERTER	
	CURRENT (A)	THD (%)	CURRENT (A)	THD (%)	CURRENT (A)	THD (%)
A	3.7	4.9	0.038	80.4	3.7	4.9
B	3.7	4.9	3.3	4.6	3.7	4.9
C	3.7	4.9	3.3	4.7	3.7	4.9

From the tabulations, it is inferred that during the single phase open circuit fault, the fault tolerant inverter was able to replicate the performance of a healthy VSI. The performance of the fault tolerant inverter was similar when the single phase open circuit fault occurs either in phase B or phase C.

#### 4. CONCLUSION

In this paper fault tolerant inverter is proposed for VSI fed induction motor drive. The harmonic spectrum analysis for single phase open circuit fault of VSI fed-drive is presented. From simulation it is seen that there is an increase in the harmonic distortion due to faults. The current harmonics get introduced upon introduction of faults in inverter module. The contribution of this work is the development of Simulink model for fault tolerant inverter system. The simulation study indicates that fault tolerant operation of the system was similar to the healthy operation of VSI-fed drive. The scope of this work is design and simulation of fault tolerant inverter fed induction motor drive. Future scope of this work includes hardware implementation of the fault tolerant system.

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