

## Fuzzy-Logic-Controller-Based Fault Isolation in PWM VSI for Vector Controlled Induction Motor Drives

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**Abstract :** This paper presents a simple method for isolation of open circuit fault in pulse width modulated voltage source inverters (PWM VSIs) feeding vector controlled induction motor drives. The VSI operation process is repeated over the period of time. This repetitive operation is divided into six operating stages by certain rules depending upon the phase angle of one phase current. At each stage, only three power switches make vital influence and the other three perform negligible influence on the operation of VSI. The open circuit fault affects the operation and introduces the repetitive distortions in current waveforms. These distortions are observed at faulty stage and gets disappeared at healthy stage. Here, fuzzy logic controller is used for isolation of fault which shows its effectiveness in simulations and results.

**Keywords** – Fault detection, fault isolation, fuzzy logic controller, open circuit fault. PWM VSI.

### I. Introduction

The electric drive systems are used widely in the most of industrial manufacturing processes. Many times these drive systems are exposed to overloading or different environmental conditions, which result into aging process, to faults concern with induction motor or the inverter. These faults can be the reason for unpredicted downtime or damages to human life. Hence demand for maintainability and reliability is increasing largely.

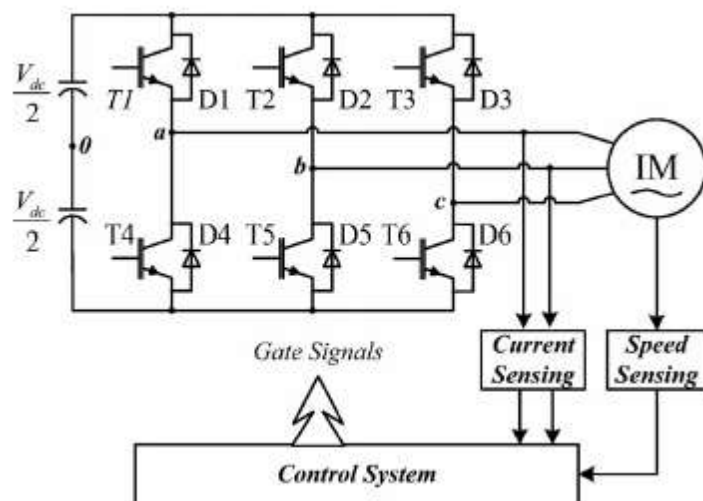


Fig.1. General configuration of an induction motor drive system

Generally, a motor drive system includes a microcontroller unit (MCU) for implementation of the control algorithms, a power electronic device such as pulse width modulated voltage source inverter (PWM VSI), and an induction motor as shown in Fig.1. Within this drive system, faults can occur in the inverter, dc bus, or in the motor itself. A voltage-source inverter is the most commonly used inverter topology in these systems and also in power quality applications. By considering their complexity, these power converters are found very susceptible in suffering critical failures. The fact is that about 38% of the failures in variable speed ac drives in industry are occurred in power electronics [1]. Recently, a survey of reliability in power electronic converters shows that semiconductor power device is the most fragile component, which is followed by capacitors and gate drives [2].

Now-a-days, the power converters designed for industrial use can be equipped with some diagnostic units to protect against disturbances and execute a shutdown in case of severe faults in order to avoid greater damages. It has become a standard feature for the inverters to protect against power transistor over current or short circuit by monitoring the transistor collector-emitter voltage but the open-circuit failures often cause slow

response. This type of fault may result the disconnection of the semiconductor due to lifting of bonding wires caused by thermic cycling or due to a problem in the gate control signal [3]. This kind of failure does not necessarily cause the system shutdown and can remain undetected for an extended period of time [4]. Since, it degrades the performance of the system by causing the operating topology imbalance, raising the current pressure of healthy transistors and thus a secondary fault may occur in the converter or in the remaining drive components which may result the total system shutdown and higher repairing costs, or even personal injury. So this paper introduces a simple and effective approach for detection of the open-circuit faults in inverter switches and isolation by using fuzzy logic controller.

Several papers and research works have been published and developed in the literature on the open-circuit fault diagnosis in the motor drive systems. Initially, a fault tolerant system was proposed for a brushless DC motor [4]. Further, the methods based on voltage, such as the error voltage method which compares the actual voltage with voltage command and lower switch voltage method [5], where the measurement of the voltages is used, show a fast diagnosis performance and thus reduce the time between the fault occurrence and diagnosis. But its major drawback is to increase system cost as it requires extra hardware equipments such as voltage sensors and electric circuits. The centroid determination method presented in [6] detects and identifies the faults in an inverter-fed induction motor from the centroid of the three-phase currents transformed from  $a - b - c$  to  $\alpha - \beta$  plane. In [7], two methods based on the analysis of these current vectors are proposed by the authors. The first one is known as slope method which uses the current vector trajectory in the Concordia plane to detect and localize faults on a PWM inverter. The second is called instantaneous frequency method that allows to detect an inverter fault, but not to identify the faulty switch. Moreover, the Park current vector method was introduced in [8], [9] by monitoring the average motor supply current trajectory to diagnose the faults in variable speed ac drives. The main drawback of all these earlier mentioned methods is the susceptibility to the load torque. In [9], the authors suggested the normalized direct component (DC) current method. To make the scheme independent from the load, the mean values of the three-phase currents are divided by the absolute value of its own first harmonic coefficients and by comparing with a threshold, faults are diagnosed. These suggested current-based methods have shown active performances in current open-loop control scheme such as scalar ( $V/f$ ) control, but are not seen quite effective in current closed-loop control scheme such as vector control [10].

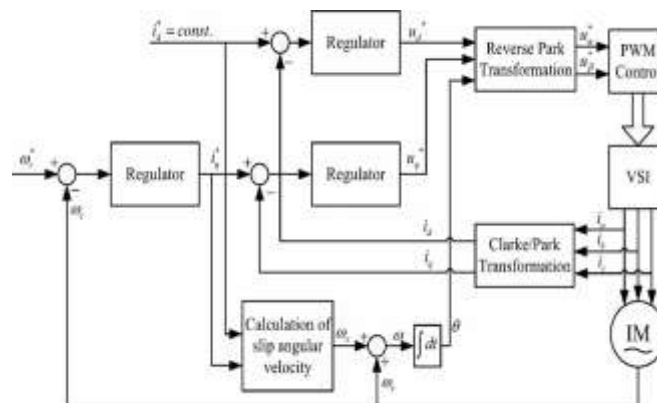


Fig.2. Ordinary indirect vector control system of an induction motor.

In this paper a simple method for detection and isolation of open-circuit faults of VSI feeding a vector-controlled induction motor drive by using fuzzy logic controller is presented. The principle of vector control gives a deep analysis and thus the relative features such as change in current distortions in faulty condition are obtained to detect and identify the faults. In this proposed scheme waveforms for three different conditions are observed: 1) Open loop response at normal stage, 2) open loop response with fault and 3) closed loop response with fault using controller. By introducing the fault in the circuit and setting required reference speed, the simulation results are obtained. These results are introduced with a distortion in current waveforms due to fault. In order to overcome this faulty stage, a fuzzy logic controller is used. The proposed fault isolation is configured without extra hardware equipment and excessive computational effort and thus allows to be embedded into an existing vector-controlled induction motor drive system. To test and validate the proposed method, open-circuit faults are introduced in the VSI for a vector-controlled induction motor drive. Simulation results show the validity of the proposed approach.

## II. Open-Circuit Fault Analysis In The VSI

When a transistor of an inverter does not work or turn on, the phase current of a machine are no longer sinusoidal. In a majority of fault detection methods, used for induction motor drives, three phase currents are

inputs for detection of faults. The ultimate purpose of vector control is to drive the induction motor as a shunt-wound dc motor which means to control the field excitation and the torque-generating current separately. Fig.2 shows an ordinary indirect vector control system of an induction motor drive without consideration of flux weakening. Here, the three phase currents are first transformed by using coordinate transformation into two synchronously rotating Cartesian vector components  $i_d$  and  $i_q$  which are controlled independently to control the rotor flux and torque respectively. It can be expressed by the set of equations with  $d-q$  frame with rotor-flux orientation.

$$T_e = \frac{n_p L_m}{L_r} \Psi_r i_q \tag{1}$$

$$\Psi_r = \frac{L_m}{R_r p + 1} i_d \tag{2}$$

where,  $i_d$  and  $i_q$  denote  $d$ - and  $q$ -axis rotor currents,  $\psi_r$  is the rotor flux in rotor reference frame,  $T_e$  stands for the electromagnetic torque,  $n_p$  is the number of pole pairs,  $L_m$  and  $L_r$  are the magnetizing inductance and rotor self-inductance, respectively,  $R_r$  is the rotor resistance, and  $p$  is the differential operator  $d/dt$ .

The currents  $i_d$  and  $i_q$  in the  $d-q$  frame can be derived from the currents in the  $\alpha-\beta$  frame by Park transformation which is defined as

$$i_d = i_\alpha \cos \theta + i_\beta \sin \theta \tag{3}$$

$$i_q = -i_\alpha \sin \theta + i_\beta \cos \theta \tag{4}$$

where  $\theta$  is the rotor flux angle or transform angle, generated from the speed signal and slip signal and the currents  $i_\alpha$  and  $i_\beta$  in stationary frame are transformed by Clarke transformation defined as

$$i_\alpha = \frac{2}{3} \left( i_a - \frac{1}{2} i_b - \frac{1}{2} i_c \right) \tag{5}$$

$$i_\beta = \frac{2}{3} \left( \frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c \right) \tag{6}$$

where  $i_a$ ,  $i_b$  and  $i_c$  are the motor phase currents.

The vector control is based on projections which transform a three-phase time and speed dependent system into a two-coordinate ( $d$ - and  $q$ -coordinate) time invariant system and lead to a structure similar to a dc machine control. The vector control machine needs two variables as input references: the torque component ( $i_q^*$ ) and the flux component ( $i_d^*$ ). The vector control structure handles the instantaneous electrical quantities, as it is based on projections. This makes the control accurate in every working operation (steady states and transient) and independent of the limited bandwidth mathematical model. Without consideration of flux weakening, the amplitude of the rotor flux ( $\psi_r$ ) is maintained at a fixed value and thus there is a linear relationship between torque and torque component ( $i_q$ ). Thereby, the torque can be control by controlling the torque component of stator current vector. With regard to the current, the complex stator current vector is defined by

$$\vec{i}_s = i_a + \gamma i_b + \gamma^2 i_c = \vec{i}_d + \vec{i}_q = \vec{i}_\alpha + \vec{i}_\beta \tag{7}$$

where  $\gamma = e^{j2\pi/3}$  and  $\gamma^2 = e^{j4\pi/3}$  represent the spatial operator. Considering the  $d$ -axis aligned with the rotor flux, Fig. 3 shows the relationship between the  $\alpha-\beta$  reference frame and the  $d-q$  frame.

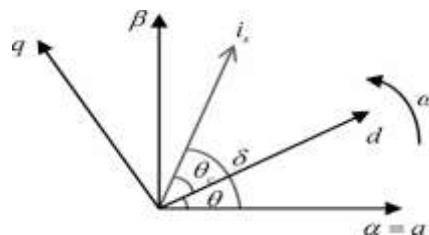


Fig.3. Current vector in the  $d-q$  frame and its relationship with the  $\alpha-\beta$  frame.

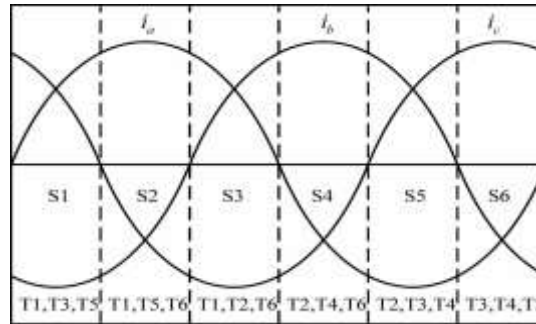


Fig.4. Three-phase currents distribution in the power switches

### III. Design Of Proposed FLC

The main reason for choosing a fuzzy approach is the very nature of the changes in the attributes. It is nonlinear, and in addition, it would be unreasonable to expect that each time the same level of a particular fault arises, the attributes would measure exactly the same values. The boundaries between two levels of a certain fault are not sharply defined, and therefore the use of a fuzzy logic control is appropriate. Membership functions and the degree of membership, rather than yes or no membership, give the opportunity, using previously acquired knowledge about the system attributes.

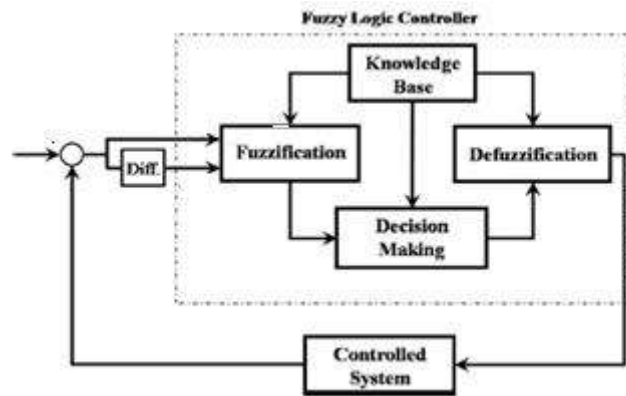


Fig.5. Structure of Proposed FLC

The input membership functions are usually a symmetric triangle with equal distribution over the universe of discourse. The formulation of membership functions of output variables show more variety frequently.

In FLC design, one should identify the main control variables and determine the sets that describe the values of each linguistic variable. The specific structure of the FLC is shown in Fig.5. The input variables of the FLC are the reference speed and the change in the speed. The triangular membership functions are used for the FLC for easier computation. The Mamdani fuzzy inference method is used for the proposed FLC. In this controller, membership functions (N, Z, P) assigned with linguistic variables are used to fuzzify physical quantities. For inputs  $e(k)$  and  $e_0(k)$  we have  $(e.n, e.z, e.p)$  and  $(e_0.n, e_0.z, e_0.p)$ . For the output  $u(k)$ , we have  $(o.n, o.z, o.p)$ . The fuzzified inputs are inferred to a fuzzy rule base, which is used to characterize the relationship between fuzzy inputs and fuzzy outputs. In this study, the fuzzy rule base of the fuzzy logic controller is fixed. It consists of the following nine fuzzy rules:

1. If  $e(k)=N$  and  $e_0(k)=P$  then  $u(k)=Z$ .
2. If  $e(k)=Z$  and  $e_0(k)=P$  then  $u(k)=P$ .
3. If  $e(k)=P$  and  $e_0(k)=P$  then  $u(k)=P$ .
4. If  $e(k)=N$  and  $e_0(k)=Z$  then  $u(k)=N$ .
5. If  $e(k)=N$  and  $e_0(k)=N$  then  $u(k)=N$ .
6. If  $e(k)=P$  and  $e_0(k)=Z$  then  $u(k)=P$ .
7. If  $e(k)=Z$  and  $e_0(k)=N$  then  $u(k)=N$ .

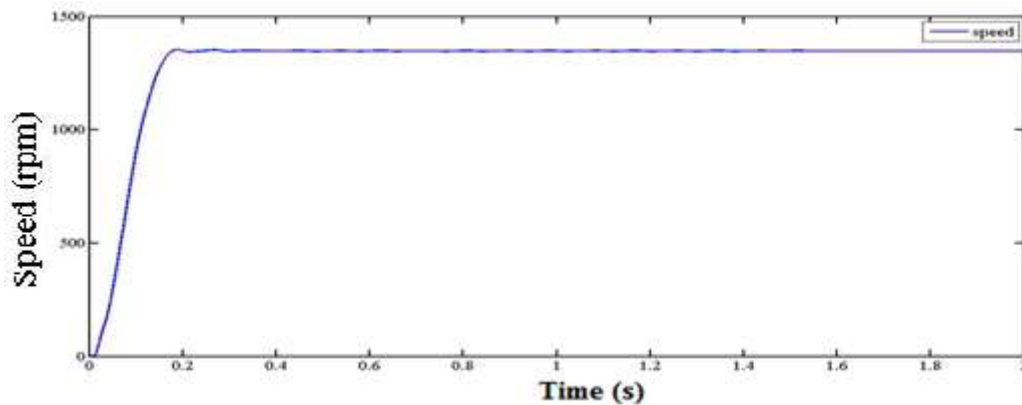
The response of each fuzzy rule is weighted according to the degree of membership of its input conditions. The inference engine provides a set of control actions according to fuzzified inputs. The commonly used inference engine is the MAX-MIN method and the centroid method is used for the defuzzification process.

#### IV. Results And Simulation

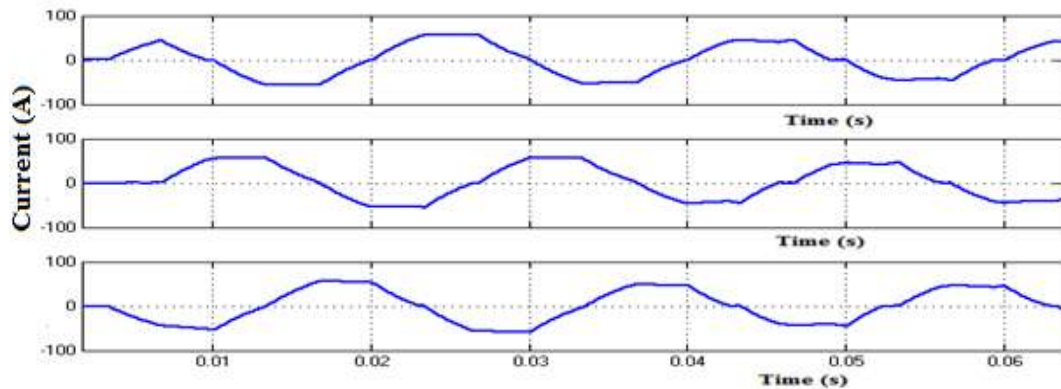
Simulation was applied on MATLAB/Simulink to the proposed fuzzy controller for the PWM VSI. The PI controller is selected for comparison because of its severe use in industry applications. The motor used in the simulation was a 5.5 kW squirrel cage motor with 400 V rated voltage, 12.5 A rated current and 1430 r/min rated speed. The PWM VSI was running with a switching frequency of 20 kHz.

##### 4.1 Open Loop Response At Normal Condition:

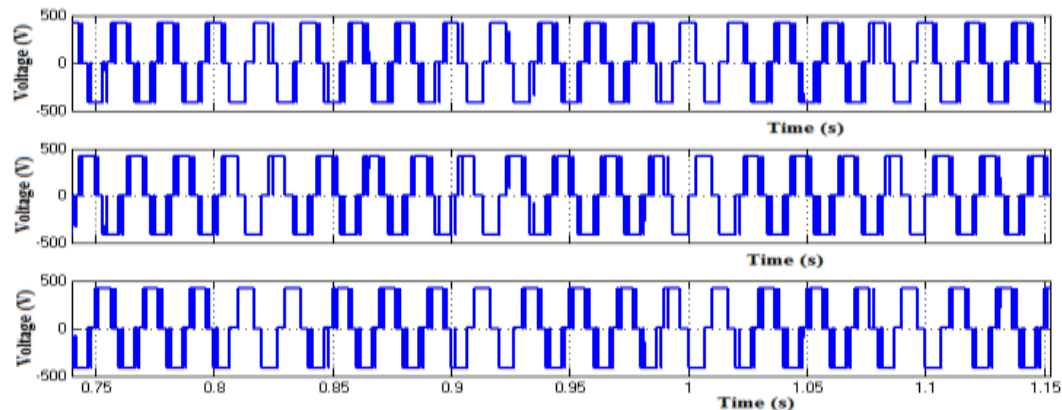
At normal and healthy condition i.e. when there is no fault in the inverter circuit, the current and voltage remain unchanged for it is the flux component of the stator current. The speed and torque are also continuous with time as motor is running smoothly. These all simulation results are shown below. It changes only when faults occur. So the current distortion is used to detect the occurrence of faults. When a fault occurs, both the current and voltage change abnormally and show repetitive waveforms. They distort at faulty stages where the faulty power switches make a vital influence and return to normal at healthy stages where the faulty power switches make a negligible influence.



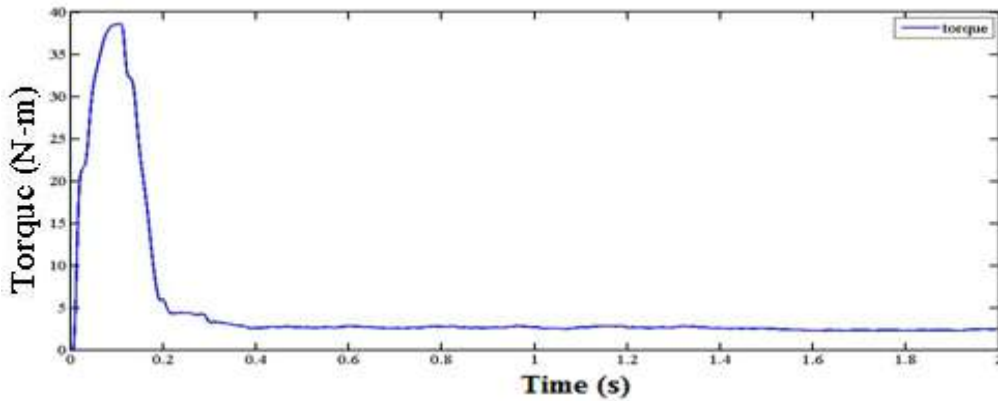
(1-a)



(1-b)



(1-c)

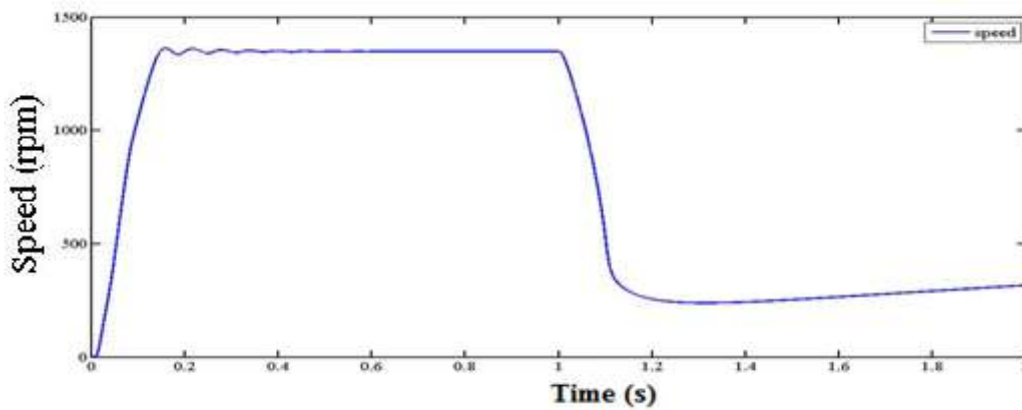


(1-d)

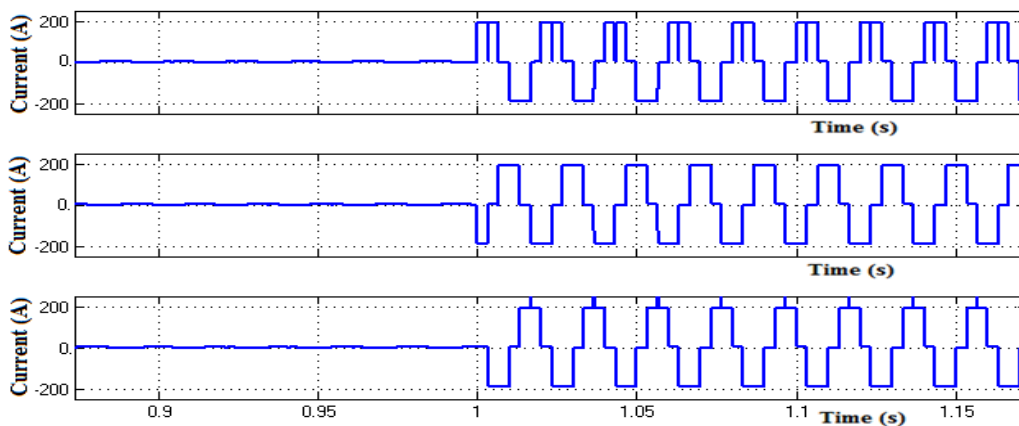
Fig.6. Simulation results in normal condition without fault: (1-a) Motor speed; (1-b) Output current;(1-c) Output voltage; (1-d) Load torque.

**4.2 Open Loop Response At Faulty Condition:**

When the fault occurs in the VSI circuit, step change is introduced in switching pulse and the other parameters get disturbed wiz. Speed of the motor decreases and continues at low speed till the fault isn't isolated. In case of current and voltage the waveforms gets distorted means the waveforms shows repetitive distortions until the fault isolation. The torque also changes at the instant of fault occurrence then continues to normal.



(2-a)



(2-b)

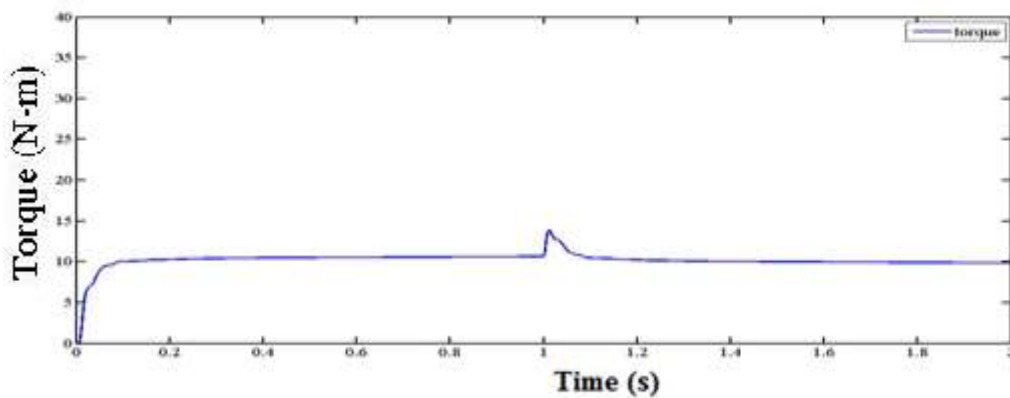
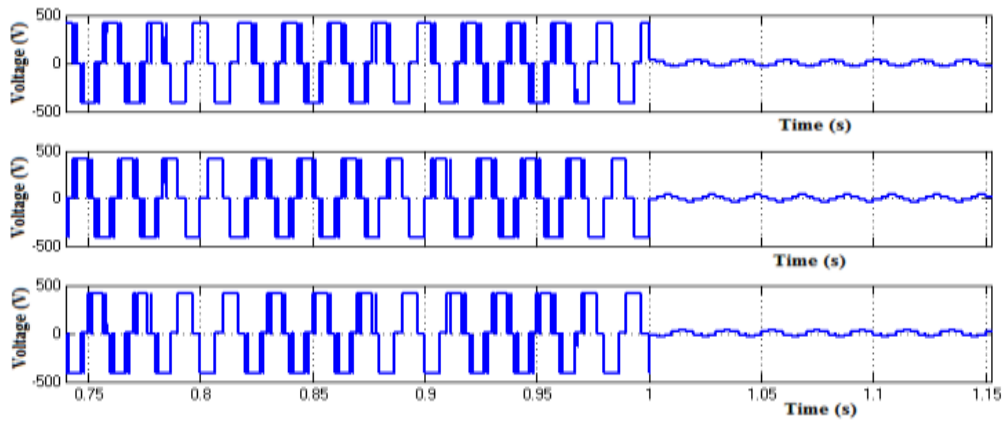
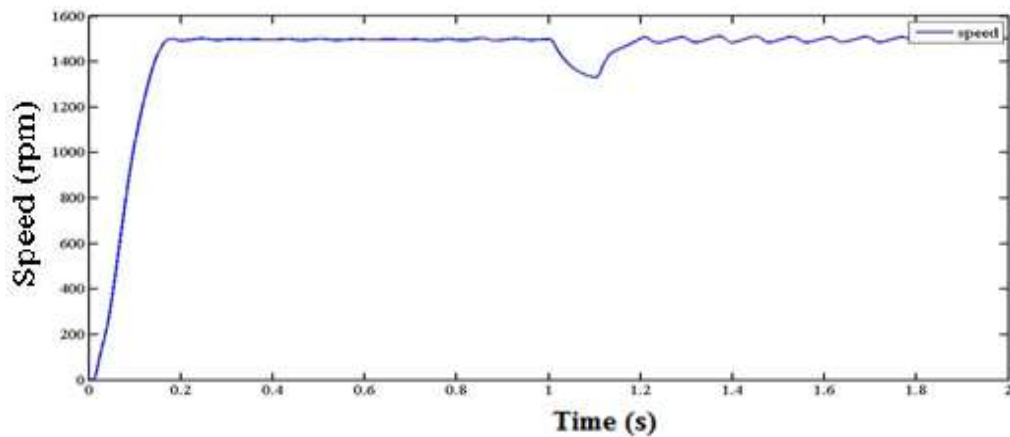


Fig.7. Simulation results in normal condition without fault: (2-a) Motor speed; (2-b) Output current; (2-c) Output voltage; (2-d) Load torque.

### 4.3 Closed Loop Response With Fuzzy Logic Controller:

In order to overcome above results due to fault a fuzzy logic controller is used. With the help of this controller fault is isolated and the motor runs in normal condition. This is observed in below simulational results. As the fuzzy logic controller is more improved than a conventional PI controller, it gives the accurate and results.



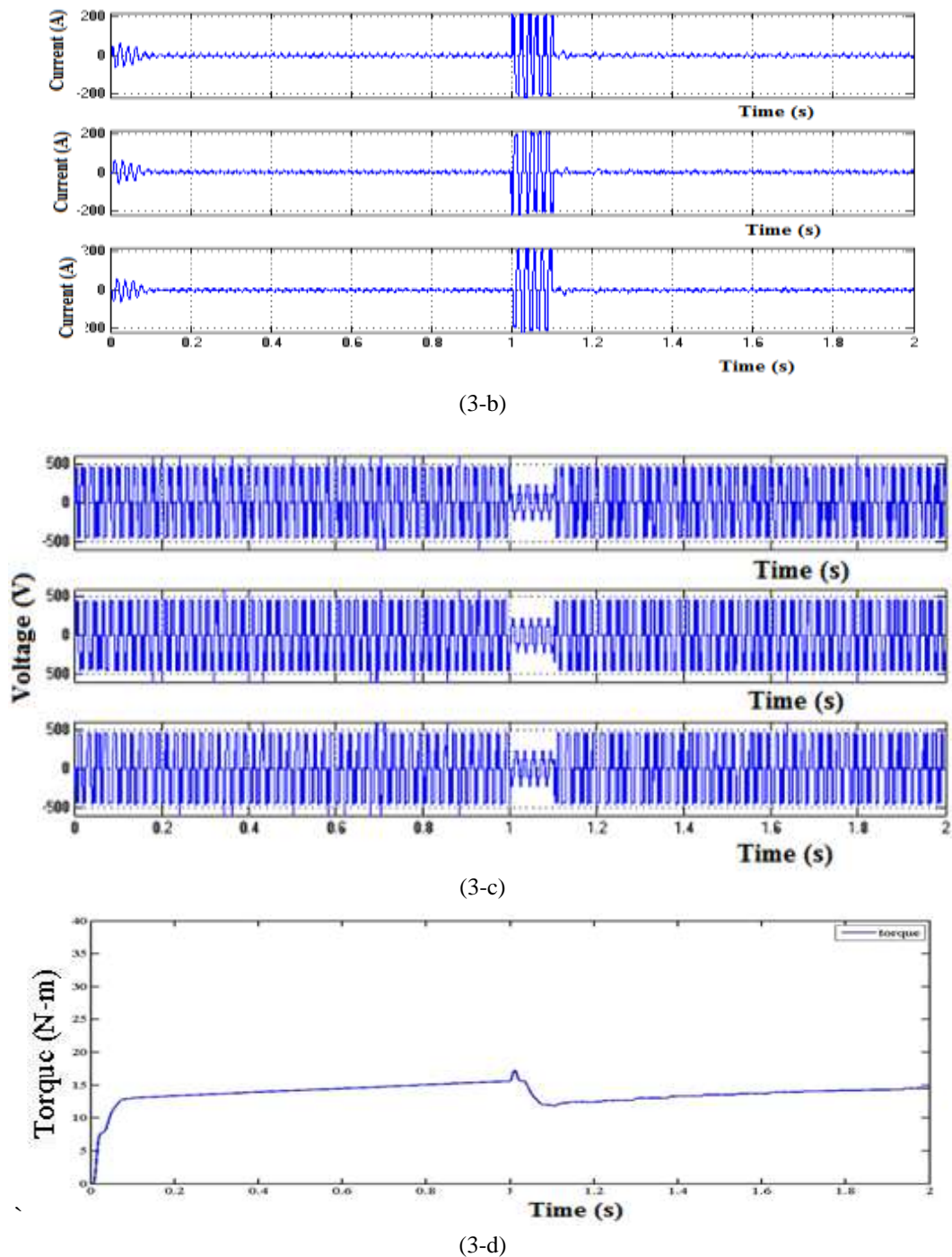


Fig.8. Simulation results in normal condition without fault: (3-a) Motor speed; (3-b) Output current; (3-c) Output voltage; (3-d) Load torque.

## V. Conclusion

This paper has presented Fault Isolation in PWM Voltage-Source Inverters for Vector controlled Induction Motor Drives using Fuzzy logic controller. Simulation results are obtained showing a good agreement with the theoretical analysis. This method uses just as inputs the three-phase currents which are already available for the main control system, avoiding the use of extra sensors and the subsequent increase of the system complexity and costs. Comparing with previously published methods, the original method relies on the stage conversion. An open-circuit fault of power switches in the VSI changes the corresponding phase currents and introduces the periodic current distortions. When the fault occurs, the distortions are estimated. In order to overcome these estimated distortions, the fuzzy logic controller is used in the circuit. This controller shows the



more accuracy than the conventional PI controller. Moreover, this method can be embedded into the existing vector-controlled induction motor drive software as a subsystem without excessive complications.

The Basic circuit and modified circuit elements are designed using relevant equations. The simulation circuits are developed using elements of simulink library. The Simulation is successfully done and open loop / closed loop simulation results are presented. The Simulation results coincide with the theoretical results.

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