# DSP Based Vector Control of Five-Phase Induction Motor Using Fuzzy Logic Control

**Z.M.S.El-Barbary ***
* *Department of electrical Engineering University of Kaferelsheihk1- Egypt, King Khalid university-KSA*

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**ABSTRACT**

This paper proposes an indirect field oriented controller for five-phase induction motor drives. The controller is based on fuzzy logic control technique. Simulation is carried out by using the Matlab/Simulink package. A complete control system experimentally implemented using digital signal processing (DSP) board. The performance of the proposed system is investigated at different operating conditions. The proposed controller is robust and suitable to high performance five-phase induction motor drives. Simulation and experimental results validate the proposed approaches.



***Corresponding Author:***

**Z.M.S.El-Barbary**
*University of Kaferelsheihk1- Egypt,*
*King Khalid university-KSA*
z_elbarbary@yahoo.com

## 1. INTRODUCTION

Over the years; induction motor (IM) has been utilized as a workhorse in the industry due to its easy build, high robustness, and generally satisfactory efficiency. Multi-phase machines have found wide applications in transport, textile manufacturing and aerospace since few years. In electrical drive applications, three-phase drives are widely used for their convenience. However, high-phase number drives possess several advantages over conventional three-phase drives such as: reducing the amplitude and increasing the frequency of torque pulsations, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, and lowering the dc-link current harmonics and higher reliability. By increasing the number of phases, it is also possible to increase the torque per rms ampere for the same machine volume [1-5].

Applications involving high power may require multiphase systems, in order to reduce stress on the switching devices. There are two approaches for supplying high power systems; one approach is the use of multilevel inverters supplying three-phase machines and the other approach is multi leg inverters supplying multiphase machines. Much more work has been done on multilevel inverters. It is interesting to note that the similarity in switching schemes between the two approaches: for the multilevel inverter the additional switching devices increase the number of voltage levels, while for the multi leg inverter, the additional number of switching devices increases the number of phases [6].The recent research works on

Multiphase machines can be categorized into multi-phase pulse width modulation (PWM) techniques for multiphase machines, harmonic injection to produce more torque and to achieve better stability, fault tolerant issues of multi-phase motor drives, series/ parallel connected multi-phase machines [6]. In Ref. [7], an n-phase space vector PWM (SVPWM) scheme can be described in terms of the applying times of available switching vectors on the basis of the space vector concept. However, the paper only focuses on how to realize a sinusoidal phase voltage. Much research on control method and running performance of five-phase drive with two-level inverter was made. Another research has been done on a multiphase two-level nonsinusoidal SVPWM [9].

The power rating of the converter should meet the required level for the machine and driven load. However, the converter ratings cannot be increased over a certain range due to the limitation of the power rating of semiconductor devices. One solution to this problem is using multi-level inverter, where switches of reduced rating are employed to develop high power level converters. The advent of inverter fed-motor drives also removed the limits of the number of motor phases. This fact made it possible to design machine with more than three phases and brought about the increasing investigation and applications of multi-phase motor drives [10].

The five-phase induction motor drives have many more space voltage vectors than the three-phase induction motor drives. The increased number of vectors allows the generation of a more elaborate switching vector table, in which the selection of the voltage vectors is made based on the real-time values of the stator flux and torque variations.

The objective of this paper is to design and implement a speed control scheme of 5-phase induction motor drive system using fuzzy logic controller (FLC). In a fuzzy logic controller (FLC), the system control parameters are adjusted by a fuzzy rule based system, which is a logical model of the human behavior for process control. The main advantages of FLC over the conventional controllers are that the design of FLC does not need the exact mathematical model of the system, and it can handle nonlinear functions of arbitrary complexity.

The speed control algorithm is based on the indirect vector control. A specific FLC for 5-phase induction motor drive has been designed and successfully implemented in real time. The performance of the proposed fuzzy speed controller is investigated both theoretically and experimentally at different dynamic operating conditions. Simulation and experimental results are presented and discussed

## 2. MATHEMATICAL MODEL OF FIVE-PHASE INDUCTION MOTOR

Squirrel-cage five-phase induction motor is represented in its d-q synchronous reference frame. The winding axes of five-stator winding are displaced by 72 degrees. By increasing the number of phases, it is also possible to increase the torque per ampere for the same machine volume. In this analysis the iron saturation is neglected. The general equations of the five-phase induction motor can be introduced as follows:
The stator quadrature-axis voltage is given by:

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega\lambda_{ds} \quad (1)$$

The stator direct-axis voltage is given by:

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} + \omega\lambda_{qs} \quad (2)$$

For the stationary reference frame ω = 0, substitute into Equations (1) and (2) yields:

$$V_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \quad (3)$$

$$V_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \quad (4)$$

The stator q-axis flux linkage is given by:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \quad (5)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qr} + i_{qs}) \quad (6)$$

The stator d-axis flux linkage is given by:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \quad (7)$$

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{dr} + i_{ds}) \quad (8)$$

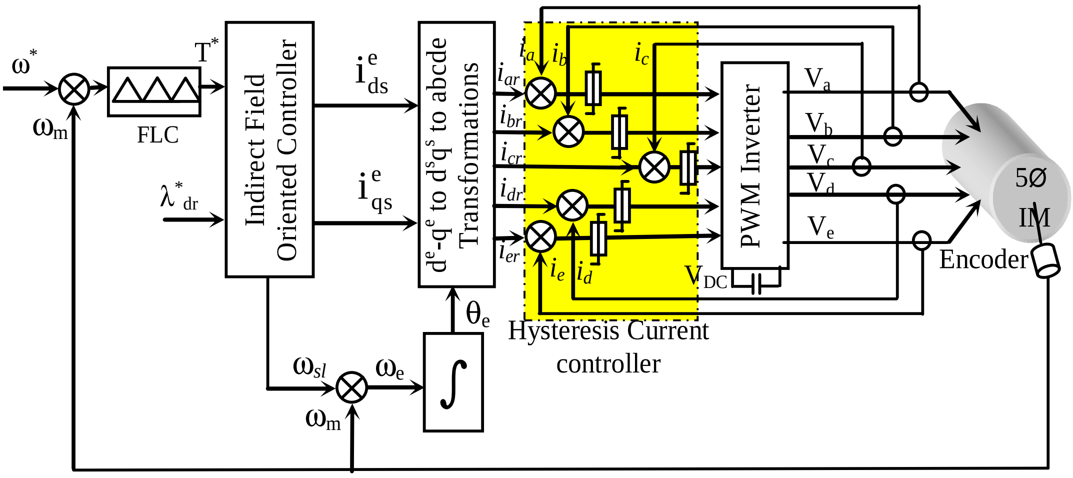



Fig. (1) Block Diagram of the Proposed Speed Control System

The electromagnetic torque is given by:

$$T_e = \frac{5}{2}\frac{p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (9)$$

$$T_e - T_l = j\frac{d\omega}{dt} + B\omega \quad (10)$$

Where, $I_{qs}$ , stator q- axiss current ,$I_{ds}$, stator d - axis current ,$I_{qr}$ , rotor q- axis current, $I_{dr}$ , rotor d-axis current ,$L_s$ , stator equivalent inductance, $L_{ls}$, stator leakage inductance ,$L_m$ , magnetizing inductance, $T_l$, load torque , J , inertia of motor and B, friction coefficient.

## 3. CONTROL SCHEME AND DESIGN OF FLC FOR FIVE-PHASE IM

### 3.1. Control scheme

The schematic diagram of the FLC-based indirect field oriented control is shown in Fig.1. The basic configuration of the drive consists of an IM fed by a current controlled 5-phase voltage source inverter. The block diagram of the fuzzy logic controller in this work is marked in Fig.1. In this FLC, the present sample of the speed error, and the present sample of the change of speed error, are the inputs while the present q-axis command current $i_q^*(n)$ is the output. The currents $i_q^*(n)$ and $i_d^*(n)$ are then transformed to a,b,c,d, and e current commands using inverse Park transform, the phase current commands $i_a^*, i_b^*, i_c^*, i_e^*$ and $i_d^*$ are then compared with the actual currents $i_a, i_b, i_c, i_e$ and $i_d$ to generate the PWM signals, which will fire the power semiconductor devices to produce the actual voltages for the motor

### 3.2 Fuzzy logic PI controller

Traditional control systems are usually based on a definite mathematical model often represented by a set of differential equations which describe the relation between input and output variables as well as the system parameters. In contrast, fuzzy logic controller does not require such precise mathematical model [11]. A fuzzy logic controller consists typically of three stages or blocks namely, input block, processing block, and output block as illustrated by Fig. 2. The input block converts input signals into appropriate way to pertinence functions. The processing block invokes appropriate rules, generates a result for each rule, and combines the results of those rules. Finally, the output block transforms the combined result into a control signal.

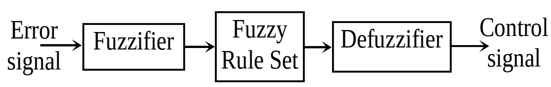



Fig. 2 Fuzzy Controller

The proposed fuzzy logic PI controller is illustrated in Fig.3, in which KP = Ku R(Kde) and KI = KuR(Ke) are the controller proportional and integral gains. The functions R(Kde) and R(Ke) are defined by the controller rule base which is summarized in Table (1). Initially the fuzzy input vector should be defined. It consists of two variables; the speed error $e(t)=\omega_r^*-\omega_r$ and its derivative $\frac{d}{dt}e(t)=\frac{d}{dt}(\omega_r^*-\omega_r)$

A fuzzy set for input and output variables is designed. Fig.5 and 6 show the five linguistic variables used for each fuzzy input variable, while the output variable fuzzy set is shown in Fig.6. The linguistic variables (LV's) used for inputs shown in Figs. 4&5 are PM (Positive Medium); PB (Positive Big); ZE (Zero); NB (Negative Big); and NM (Negative Medium). The same LV's are used for the output fuzzy set shown in Fig.6. A look-up table is required to develop the set of rules, in which the relation between the input variables, $e(t)$ and $\frac{de(t)}{dt}$ are defined and the output variable of fuzzy logic controller can be obtained. The look-up table used in the simulation program is given in Table (1). The output depends on the fuzzy rule expressed as follows;

If (Input1 AND Input2) THEN Output

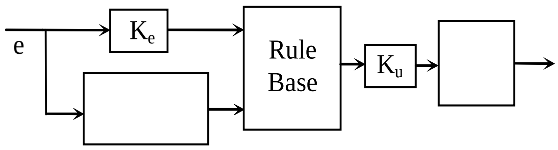



Fig. 3 Fuzzy Logic PI Controller

Table (1) Fuzzy rule

ERROR

| | | | | | | |
|---|---|---|---|---|---|---|
| PM | PB | ZE | NB | NM | | ERROR RATE OF CHANGE |
| ZE | NP | NM | NM | NM | NM | |
| PB | ZE | NB | NM | NM | NB | |
| PM | PB | ZE | NB | NM | ZE | |
| PM | PM | PB | ZE | NB | PB | |
| PM | PM | PM | PB | ZE | PM | |

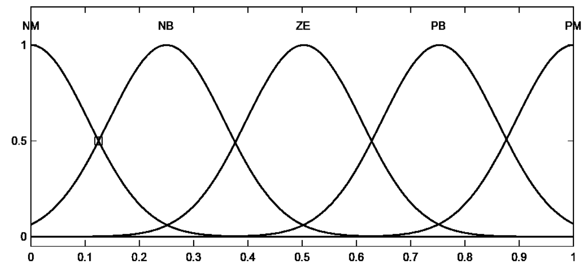



Fig. 4 Error Memberships

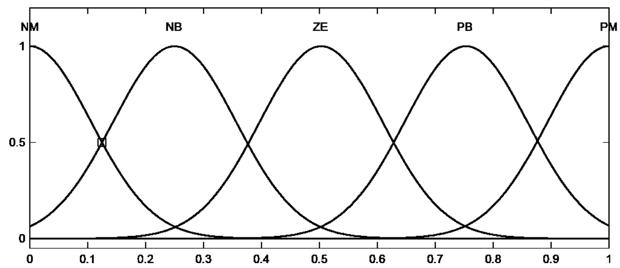



Fig. 5 Rate of Change of Error

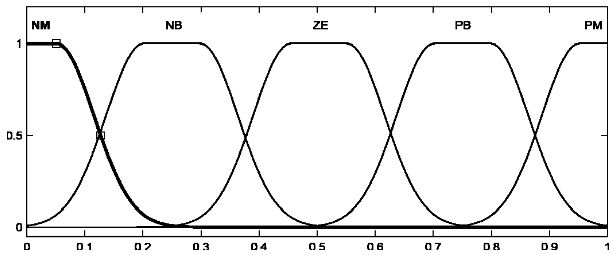



Fig. 6 Output membership

*The torque producing current component is calculated from:*

$$I_{qs}^{*} = \frac{1}{k_t}\frac{(\omega_r^{*}-\omega_r)}{\lambda_{dr}^{*}}\frac{K_{ps}[1+\tau_{cs}S]}{\tau_{cs}S} \quad (11)$$

$$I_{ds}^{e*} = \frac{1}{L_m}(1+\tau_r^{*}p)\lambda_{dr}^{e*} \quad (12)$$

The angular slip frequency command ( $\omega_{sl}^{*}$ ) is:

$$\omega_{sl}^{*} = \frac{L_m}{\tau_r^{*}}\cdot\frac{I_{qs}^{*}}{\lambda_{dr}^{*}} \quad (13)$$

Angular frequency is obtained as follows,

$$\omega_e^{*} = \omega_{sl}^{*} + \omega_m \quad (14)$$

$$\theta_e^{*} = \int \omega_e^{*}.dt \quad (15)$$

$$T_e = K_t \left|\lambda_{dr}^{e}\right| I_{qs}^{e} \quad (16)$$

Equation (16) is similar to that of the separately excited dc motor and denotes that the torque can initially proportional to the q-axis component of the stator current $I_{qs}^{*e}$ , if the $q^e$-axis component of the flux becomes zero ($d^e$-axis is aligned with the rotor flux axis), and the $d^e$-axis component $\lambda_{dr}^{*e}$ is kept constant. This is the philosophy of the vector control technique. The transformations used for the present system are expressed as follows;

$$q^e\text{-}d^e \rightarrow q^s\text{-}d^s \begin{Bmatrix} i_{qs}^{s*} = i_{qs}^{e*}\cos\theta_s + i_{ds}^{e*}\sin\theta_s \\ i_{ds}^{s*} = -i_{qs}^{e*}\sin\theta_s + i_{ds}^{e*}\cos\theta_s \end{Bmatrix} \quad (17)$$

Where $\theta_s$ represents the sum of the slip and rotor angles.

$$qd/abced \begin{Bmatrix} i_{as}^{s*} = i_{qs}^{s*}\cos(\theta) + i_{ds}^{s*}\sin(\theta) \\ i_{bs}^{s*} = i_{qs}^{s*}\cos(\theta - \frac{2\pi}{5}) + i_{ds}^{s*}\sin(\theta - \frac{2\pi}{5}) \\ i_{cs}^{s*} = i_{qs}^{s*}\cos(\theta - \frac{4\pi}{5}) + i_{ds}^{s*}\sin(\theta - \frac{4\pi}{5}) \\ i_{ds}^{s*} = i_{qs}^{s*}\cos(\theta + \frac{4\pi}{5}) + i_{ds}^{s*}\sin(\theta + \frac{4\pi}{5}) \\ i_{es}^{s*} = i_{qs}^{s*}\cos(\theta + \frac{2\pi}{5}) + i_{ds}^{s*}\sin(\theta + \frac{2\pi}{5}) \end{Bmatrix} \quad (18)$$

### 3.3 Five phase inverter

The modulated phases voltages of five phase inverter fed five phase induction motor are introduced as a function of switching logic NA, NB, NC,ND and NE of power switches by the following relations:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ds} \\ V_{es} \end{bmatrix} = \frac{V_{dc}}{5} \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & -1 & 4 & -1 & -1 \\ -1 & -1 & -1 & 4 & -1 \\ -1 & -1 & -1 & -1 & 4 \end{bmatrix} \begin{bmatrix} NA \\ NB \\ NC \\ NE \\ ND \end{bmatrix} \quad (19)$$

The per-phase switching state having a range of N = 0, 1.

## 4. RESULTS And DISCUSSION

To verify the validity of the proposed system, an induction motor vector control system was constructed. Fig. 7 shows a block diagram of the experimental system, which was composed of a DSP board DSP 1104 which is based on 32-bit floating point DSP TI TMS32OC3I. The board is also equipped with a fixed point 16 bit TMS320P14 DSP which is used as a slave processor [12], Five phases currents $i_a, i_b, i_c, i_e$ and $i_d$ are sensed by Hall-effect current transducers. These signals are fed to the DSP through the signal conditioning circuit. Also the speed of the rotor is sensed by 2048 PPR incremental encoder for detecting the motor speed and fed to the encoder interface on the DSP board. The control algorithm is executed by 'simulink' and downloaded to the board through host computer. The outputs of the board are ten logic signals, which are fed to the, 5-phase inverter through driver isolation circuits. The sampling time for mental implementation is chosen as 100 sec. Also,The proposed control system shown in Fig. 1 is designed for a simulation investigation. Simulation is carried out using the general purpose simulation package Matlab/Simulink [13], Simulation and experimental results are presented to show the effectiveness of the proposed scheme at different operating conditions. These results are classified into two categories; the first represents start-up and steady-state while the second represents the dynamic performance.

### 4.1. Starting and steady state performance

Start-up and steady-state results are illustrated by Figures 8 and 9 .Figure 8 a and b shows the motor speed. Figures8a shows the speed signals obtained in real time, whares figure 8b shows the corresponding signals obtained from simulation. There is a good correlation between these signals, from start-up point up to the steady state value. Figure 9a shows the motor phase current obtained in real time. Whares, Figure 9b shows the corresponding signal obtained from simulation. In the two figures, the current signals are of sine wave profiles on which controller switching transients are shown.

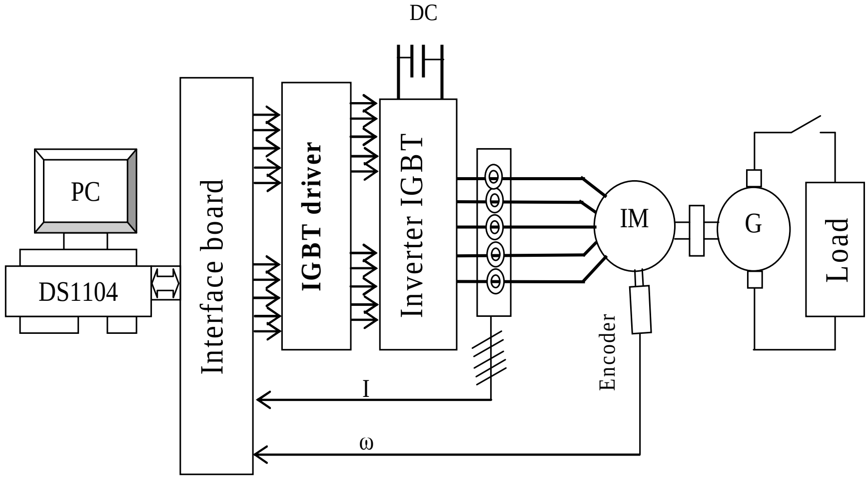


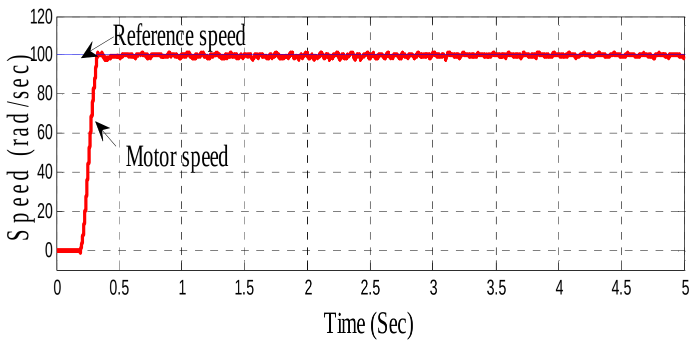

Fig 7 Experimental set-up for DSP-based control of induction motor

### 4.2. Dynamic performance

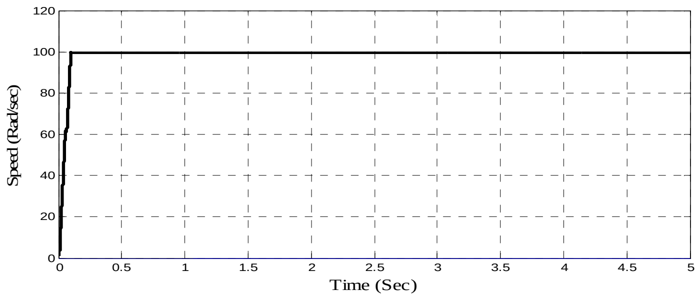
For studying the dynamic performances of proposed system, a series of measurements and simulations have been carried out. In this respect, the dynamic response of the proposed algorithm is studied under speed step change.

To study the dynamic response of the control system due to a step changes in the command of speed, the motor is subjected to step changes in the speed command at no load to evaluate its performance. At t=1 second .The motor speed command is changed from 120 rad/sec to 150 rad/sec and return back to 120 rad/sec after 2.5 sec. Figure 10 a and b shows the motor speed signals corresponding to these step changes. It can be seen that the motor speed is accelerated and decelerated smoothly to follow its reference value with nearly zero steady state error. Figure 10.a shows the speed signal obtained in real time. Figure 10.b shows the corresponding signal obtained from simulation. These results show a good correlation between these speed signals. Phase current corresponding to this speed step changes are shown in Figs. 11 a and b respectively. Figure 11a represents the phase current these results ensure the effectiveness of the proposed controller and shows good behaviour of its dynamic response.

To study the response of the control system under load condition, at t=0.75 second the speed command is changed from 120 rad/sec to 150 rad/sec at full load. Figure 12 a and b shows the motor speed signals corresponding to these step change. It can be seen that the motor speed is accelerated smoothly to follow its reference value with nearly zero steady state error. These results show a good correlation between these speed signals. Phase current corresponding to this speed step change are shown in Figs. 13 a and b respectively.

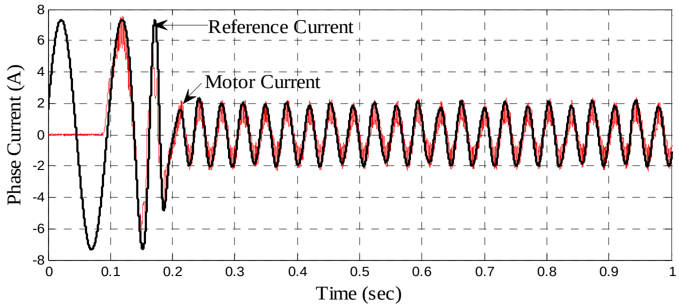



(a)

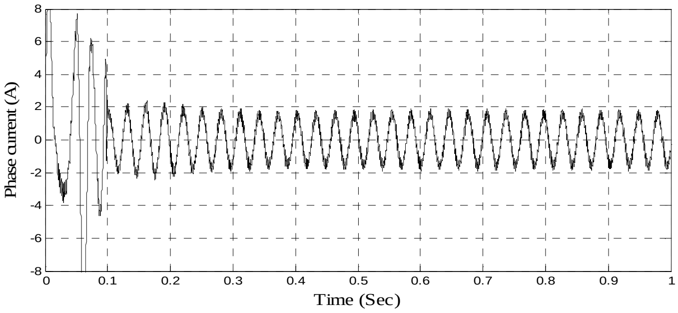



(b)

Fig.8 Start-up and steady-state,Motor Speed
(a) Experimental (b) Simulation



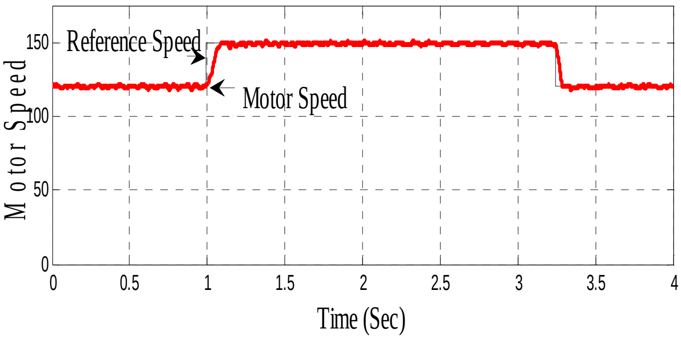

*(a)*



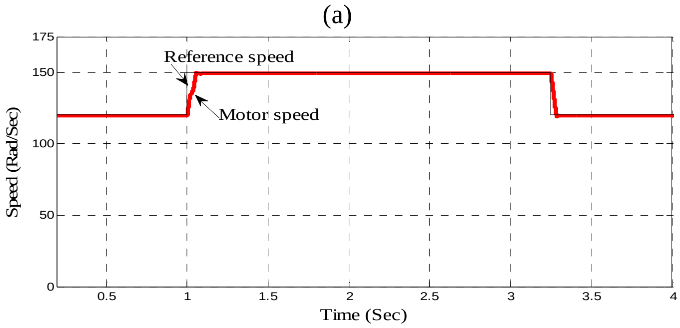

*(b)*

*Fig.9 Start-up and steady-state, Motor Phase-a current*

*(a) Experimental (b) Simulation*

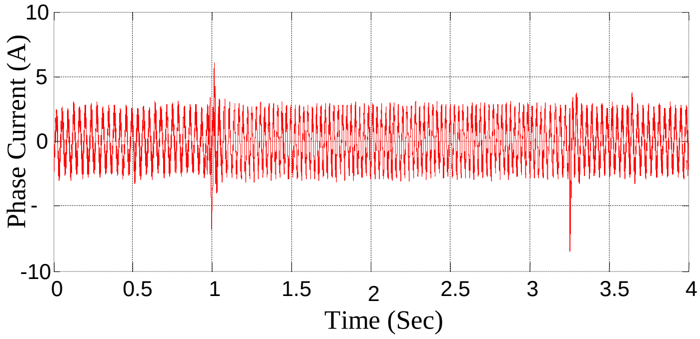



(a)

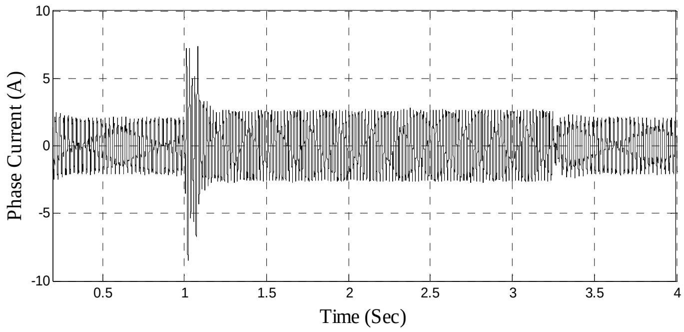



(b)

Fig.10 Speed step up and step down changes ,Motor Speed
(a) Experimental (b) Simulation



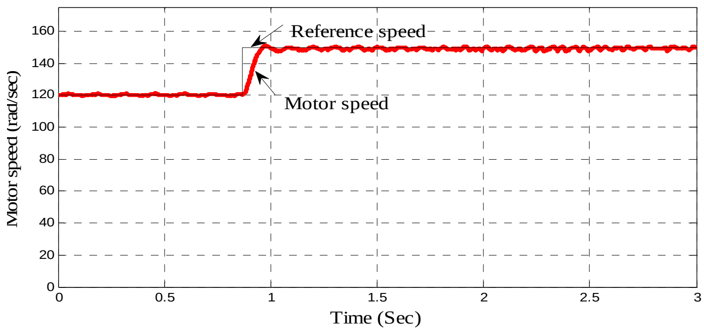

**(a)**



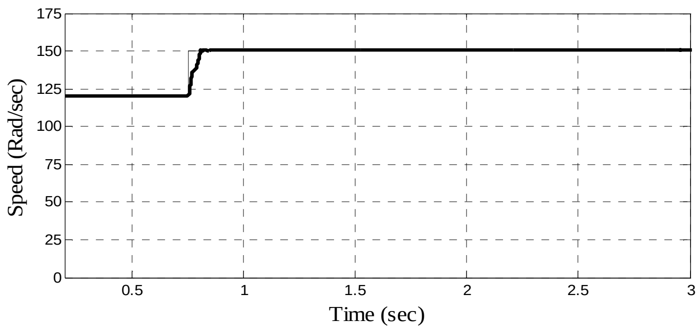

*(b)*

*Fig.11 Speed step up and step down changes, , Motor Phase-a current*

*(a) Experimental (b) Simulation*

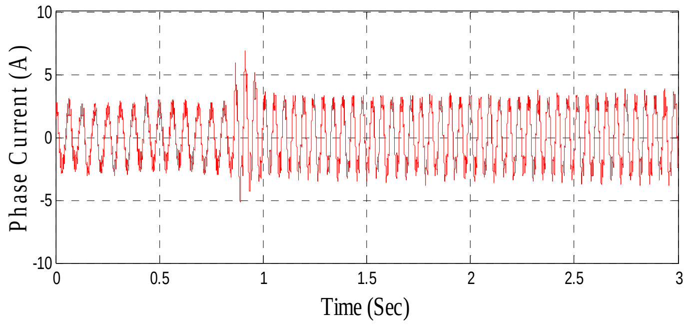



*(a)*

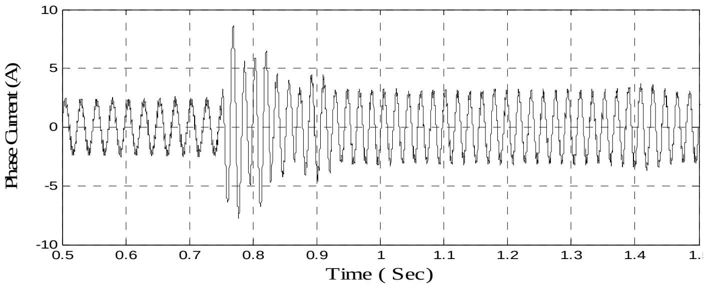



*(b)*

*Fig.12 Speed step up change,Motor Speed: (a) Experimental (b) Simulation*




*(a)*




*(b)*

*Fig.13 Speed step up change, , Motor Phase-a current*

*(a) Experimental (b) Simulation*

## 5. CONCLUSIONS:

The paper demonstrates the versatile application of fuzzy theory for the control of five-phase induction motor drive system. A simple structure of fuzzy logic controller has been proposed. This structure has been derived from the dynamic model of five-phase induction motor drive system using the vector control technique. The effectiveness of the fuzzy logic controller has been established by performance prediction of an experimental and simulation of five-phase induction motor drive over a wide range operating conditions. The proposed fuzzy logic controller based drive system has been successfully implemented in the real time for the laboratory five-phase induction motor. Simulation and experimental results have confirmed the expected performance of the fuzzy logic controller. The results show that the effectiveness and robustness of the proposed speed control method.

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**Appendix**

*Motor Parameter*

| | |
|---|---|
| *No. of poles* | *4* |
| *Stator resistance* | *7.4826 ohm* |
| *Rotor resistance* | *3.6840 ohm* |
| *Rotor leakage inductance* | *0.0221 H* |
| *Stator leakage inductance* | *0.0221 H* |
| *Mutual inductance* | *0.4114 H* |
| *Supply frequency* | *50 Hz* |
| *Motor speed* | *1500 r.p.m.* |
| *Supply voltage* | *380 volts* |
| *Inertia* | *0.02 kg.m2* |

**Dr. Z. M. Elbarbary:** was born in Kaferelsheihk, Egypt, in 1971. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Menoufiya University, Shebin El-Kom, Egypt, in 1994, 2002, and 2007, respectively. In 2009, he joined Kaferelsheihk University as an Assistant Professor. His fields of interests are ac motor drives ; power electronics and Solar energy.