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# Enhancing The Characteristic Performance of Squirrel – Cage Induction Motor Using Artificial Intelligence Techniques.

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***Abstract**. This paper is all about enhancing the characteristic performance of a three phase squirrel-cage induction motor using artificial intelligence network. The proposed method combines intelligent fuzzy logic and conventional PID controllers utilizing indirect field – oriented control technique to improve the speed response of the induction motor. The design of the intelligent fuzzy logic system consists of two input signals namely speed error and change in speed error each having seven fuzzy variables while the control action has nine fuzzy variables and fourty nine IF - - - THEN - - - rules that define the behavior of the motor. The hybrid controller output, observes the speed loop error signal and correspondingly changes the output by manipulating the stator frequency and voltage as well as the magnitude and phase angle of the stator current phasor so that the actual speed of the motor matches (tracks) the reference/desired/command speed of the motor. Matlab/Simulink software is employed in the implementation and simulation. Simulation results of the hybrid intelligent controller, is compared with that of the conventional PI controller in terms of performance significant measures such as rise time, settling time, maximum percent overshoot and steady – state error at various load conditions, variation in referencespeed as well as sudden load change. The results, proved the effectiveness of the proposed intelligent hybrid speed controller under different operating conditions and demonstrated performance enhancement in speed tracking and robustness of the system.*

***Keywords: Enhancing, Performance, Characteristic, SCIM, Artificial.***

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## I. Introduction

This paper presents the enhancement of the characteristic performance of squirrel – cage induction motor (SCIM) using artificial intelligence techniques. Artificial intelligence is defined as machine emulation of the human thinking processes[1]

Examples of artificial intelligence techniques includes but not limited to Genetic Algorithm (GA), Artificial Neural Network (ANN), Particle Swarm Optimization (PSO), Adaptive Neural - Fuzzy Inference System (ANFIS), Bacterial Foraging Optimization Algorithm (BFOA), Artificial Neural Multi-networks, Artificial Bee Colony (ABC),Fuzzy Logic Control (FLC), Expert Systems (ES) etc. Artificial intelligence – based techniques, when implemented in induction motor control, have shown improved performance [2]. Various researchers have over the years, used different artificial intelligence techniques to enhance the characteristic performance of the squirrel – cage induction motor.

Bacteria foraging optimization algorithm (BFOA) which is an intelligent bio – inspired optimization technique, was employed by [3] to enhance the characteristic performance of a three – phase squirrel – cage induction motor. This algorithm, is used for tuning the speed controller, flux controller and torque controller to achieve the described control performance. The directtorquecontrolled space vector modulated voltage source inverter (VSI) is fed with the induction machine to improve the performance of the system.Thus the close loop control of induction motor with BFOA technique, gives the minimum torque ripples and the motor can run at reference speed under different loading conditions.The authors [4],[5],[6],[7], *in their various works that centered on direct torque control (DTC) using artificial neural network (ANN) and adaptive neuralfuzzy inference system (ANFIS), for reduction of torque and flux ripples in transient and steady – state response for induction motor drive,showed the implementation of DTC system to optimize the flux and to improve the performance of fast*

*stator flux response in transient state. In this scheme, the proportional integral (PI) controller used in the conventional DTC arrangement, is replaced with the ANFIS – based speed controller.*
*[8], discussed new proportional-integral (PI) controller and ANN control system based on vector control scheme (PI-ANN). The controller was tested at different speed signals with less overshooting and fast response than the classical PI controller. The effectiveness of the controller was achieved by exposing the motor to external disturbances such as torque disturbances and speed variations during motor operation. In this work, the experimental results presented, agreed with the simulation results.*
*The successful application of the fuzzy logic controller(FLC) based on the indirect vector (field - oriented) control for normal speed control of induction motor drives, was investigated independently and at various times by [9],[10],[11],[12]. The results of their investigations, showed that the intelligence-based fuzzy logic controller (FLC), is insensitive to temperature changes, inertia variations and load torque disturbance and hence could be a suitable replacement for the conventional PI controller for high performance drive systems. The indirect vector control was employed to decouple the stator current into torque- and flux- producing components.*
*The author [13], had the main focus of his work on the direct vector (field - oriented) control of induction motor for high dynamic performance applications. In direct field-oriented control, the controlled variables are thestator currents that are transformed into reference currents in d-q coordinates. The control system investigates the reference currents from the motor torque,flux and the desired control speed. The direct vector control method, is however not without its demerits of hard physical implementation and switching complexity.*
*[14], presented a method of implementation of a rule-based fuzzy logic controller (FLC) for a constant speed operation of a three-phase induction motor. The control strategy is based on keeping the voltage-frequency ratio ($^V/_f$) constant and simulation results showed that the performance and speed response of the control method with FLC is better compared with that of a conventional PI controller as the overshoot and ripple is reduced substantially.*

*The enhancement methods and techniques so far stated, covered a wide spread of enhancing the characteristic performance of squirrel-cage induction motor using artificial intelligence. However, none of these methods represented a comprehensive analysis for squirrel-cage induction motor performance enhancement.*
*In this paper, a hybrid controller which combines a conventional proportional-integral-derivative (PID) controller and an artificial intelligence-based controller, FLC employing indirect vector (field-oriented) control technique is proposed*

## II. Electrical model of the squirrel – cage induction motor.

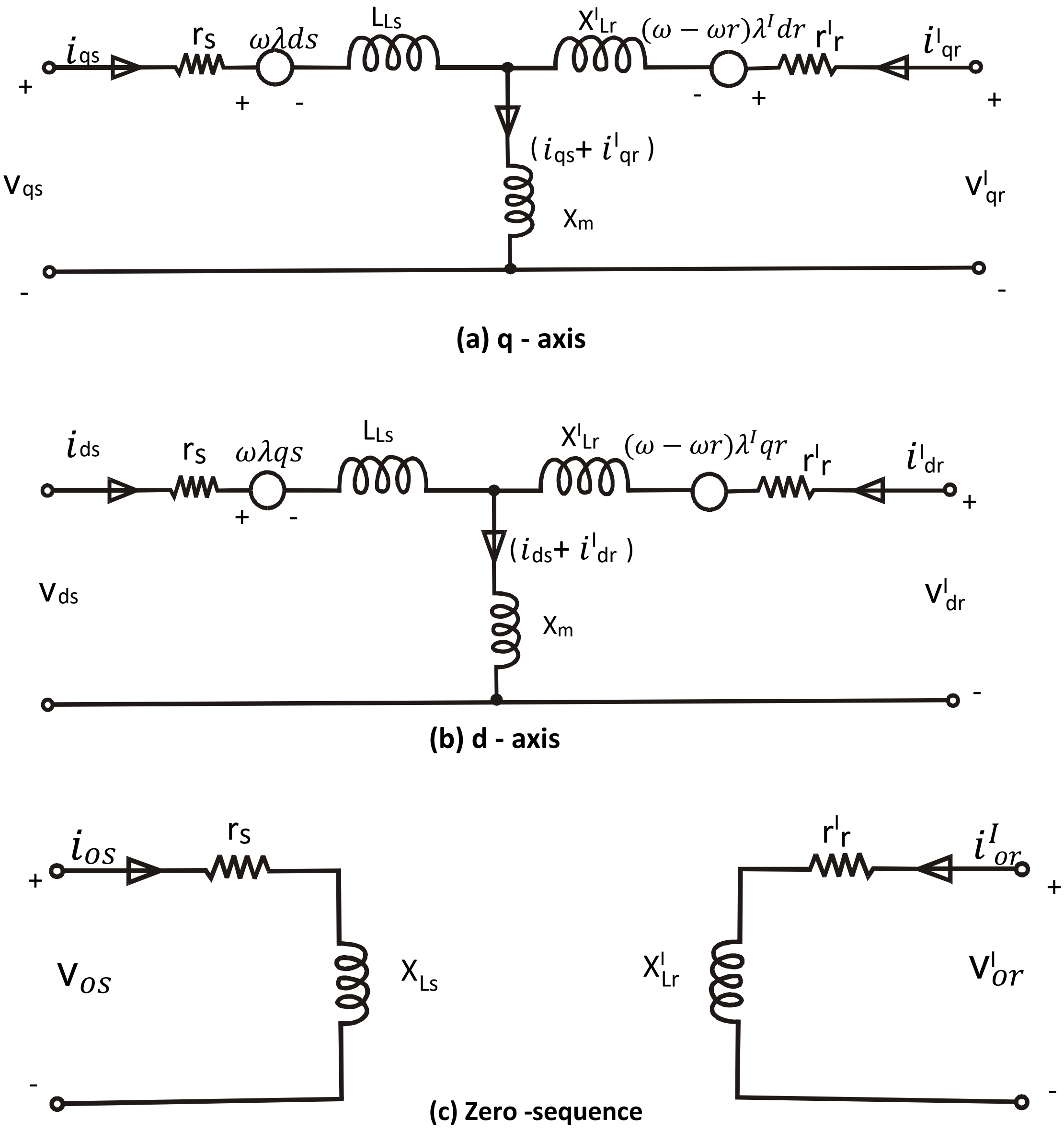
The stator and rotor voltage equations in the arbitrary reference frames are expressed as [16];

$$\left.\begin{aligned} V_{qs} &= r_s i_{qs} + P\lambda_{qs} +- \omega\lambda_{ds} \\ V_{ds} &= r_s i_{ds} + P\lambda_{ds} - \omega\lambda_{qs} \\ V_{os} &= r_s i_{ds} + P\lambda_{os} \\ V^I_{qr} &= r^I_{qr} i^I_{qr} + P\lambda^I_{qr} + (\omega - \omega_r)\lambda^I_{dr} \\ V^I_{dr} &= r^I_{dr} i^I_{dr} + P\lambda^I_{dr} - (\omega - \omega_r) \\ V^I_{or} &= r^I_r i^I_{or} + P\lambda^I_{or} \end{aligned}\right\} \quad (1)$$

While the stator and rotor flux linkages in the arbitrary reference frame are given as;

$$\left.\begin{aligned} \lambda_{qs} &= (L_{Ls} + L_m)i_{qs} + L_m i^1_{qr} \\ \lambda_{ds} &= (L_{Ls} + L_m)i_{ds} + L_m i^1_{dr} \\ \lambda_{os} &= L_{Ls} i_{os} \\ \lambda^1_{qr} &= (L^1_{Lr} + L_m)i^1_{qr} + L_m i_{qs} \\ \lambda^1_{dr} &= (L^1_{Lr} + L_m)i^1_{dr} + L_m i_{ds} \\ \lambda^1_{or} &= L^1_{Lr} i^1_{or} \end{aligned}\right\} \quad (2)$$

With equations (1) and (2), the dynamic equivalent circuits of an induction motor in the arbitrary reference frame is as shown in Figure (1).




**Figure(1). Dynamic equivalent circuit for a 3-phase SCIM in an arbitrary reference frame.**

Substituting the flux linkage values into the voltage equations, gives;

$$\left.\begin{aligned}
V_{qs} &= (r_s + L_s P)i_{qs} + \omega L_s i_{ds} + L_m P i^I_{qr} + \omega L_m i^I_{dr} \\
V_{ds} &= \omega L_s i_{qs} + (r_s + L_s P)i_{ds} - \omega L_m i^I_{qr} + L_M P i^I_{dr} \\
V_{os} &= (r_s + L_{ls} P)i_{os} \qquad\qquad (3) \\
V^I_{qr} &= L_m P i_{qs} + (\omega - \omega_r)L_m i_{ds} + (r^I_r + L^I_r P)i^I_{qr} + (\omega - \omega_r)L^I_r L^I_{dr} \\
V^I_{dr} &= (\omega - \omega_r)L_m i_{qs} + L_m P i_{ds} - (\omega - \omega_r)L^I_r i^I_{qr} + (r^I_r + L^I_r P)i^I_{dr} \\
V^I_{or} &= (r^I_r + L^I_{lr})i^I_{or}
\end{aligned}\right\}$$

Where;

$L_s = L_{Ls} + L_m$

$L_r^1 = L_{Lr}^1 + L_m$

$\omega_r$= Speed of the rotor in rad/sec

$\omega$= speed of the reference frame in rad /sec

The electromagnetic torque equation is expressed as [17];

$$T_{em} = \frac{3}{2}\frac{P}{2}L_m(i_{dr}^1 i_{qs} - i_{qr}^1 i_{ds}) \quad \text{N.m} \qquad (4)$$

While the electromechanical (rotor) dynamic equation is given by [18] as;

$$T_e = J\frac{d\omega_m}{dt} + T_L + B\omega_m \qquad (5)$$

Where;

J = moment of inertia of motor

$T_L$= Motor shaft load torque

B = friction coefficient of the load and motor

$\omega_m$ = mechanical rotor speed.

## III. Control strategy for characteristic performance enhancement of SCIM.

At the core of the induction motor control scheme aimed at enhancing its characteristic performance, lies the dynamic direct – quadrature axis model of the induction motor. Compared to the control of dc motors, the control of induction motors is difficult owing to the fact that the induction motor is a dynamic non – linear and highly coupled system. Also unpredictable disturbances such as noise and load changes and uncertainties in the machine parameters further complicate the control problem which affect the performance of squirrel – cage induction motor [2].
In this paper, the indirect field – oriented (vector) control which is one of the advanced control techniques, is adopted to reduce the complex non – linear nature of squirrel – cage induction motor with the sole aim of enhancing its performance.

### 3.1. Principle of field – oriented (vector) control

An ac induction motor requires a coordinated control of stator current magnitudes, frequencies and their phases because of the inherently coupling problem and this makes it a complex control. The requirement for the control of stator current magnitude, frequency and phase and hence the flux phasor, is made possible by inverter control. And this control is achieved in field coordinates hence the name field – oriented (vector) control. The field – oriented (vector) control scheme, made ac drives equivalent to dc drives in the independent control of flux and torques and superior to them in their performance [18]. The explanation of the principle of field – oriented (vector) control, centers on how a stator current phasor, $I_s$, is controlled in a synchronously rotating reference frame so that the expression of the electromagnetic torque,Te, of the smooth air – gap of the motor, resembles that of the torque in a separately excited dc motor.
In this technique, the motor terminal phase currents namely, $I_{as}$, $I_{bs}$ and $I_{cs}$, are converted to two – phase sinusoidal currents $I_{ds}$ and $I_{qs}$ in a stationary reference frame by Clarke's transformation . Finally the $I_{ds}$ and $I_{qs}$ , components are converted by Park's transformation into , $I_{ds}^e$ and $I_{qs}^e$ which represent the d- and q- axes currents in the synchronously rotating frame where they are now dc quantities [18].
Crucial to the implementation of the field-oriented (vector) control, is the field angle$\theta_f$(rotor flux vector position) which constitutes the necessary requirement for proper transformation from stationary reference frame to synchronously rotating reference frame and vice versa.

The indirect field – oriented (vector) control, is based on the calculation of the slip speed, $\omega$sl. The slip speed /frequency generated by a field – oriented controller is directly responsible for the vector position relationships of the rotor flux, $\lambda$r and stator current, $I_s$. And since torque is a vector product of these two terms, it is apparent that the terms of the field – oriented controller will determine the torque produced by the drive for any given stator current [20].

**3.2. Algorithm of indirect field-oriented control (IFOC):**

The algorithm of indirect field – oriented control is given asfollows:-

(1) The stator phase currents namely$I_{as}$, $I_{bs}$ and $I_{cs}$ are transformed into direct -and quadrature - axes stator currents in stationary reference frame using Clarke's transformation expressed as;

$$\begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos\theta_f & Cos(\theta_f - \frac{2\pi}{3}) & Cos(\theta_f + \frac{2\pi}{3}) \\ Sin\theta_f & Sin(\theta_f - \frac{2\pi}{3}) & Sin(\theta_f + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} (6)$$

(2) These $I_{qs}$ and $I_{ds}$ currents in the stationary reference frame, are converted into synchronously rotating reference frame using Park's transformation expressed as;

$$\begin{bmatrix} I_{qs}^e \\ I_{ds}^e \end{bmatrix} = \begin{bmatrix} Cos\theta_f & Sin\theta_f \\ -Sin\theta_f & Cos\theta_f \end{bmatrix}\begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} \quad (7)$$

(3) The rotor flux linkage phasor,$\lambda_r$, is obtained using the equation;

$$\lambda_r = \frac{L_m I_{ds}^e}{1+\tau_r} \quad (8)$$

Where;

$\tau_r$ = rotor time constant given as;

$$\tau_r = \frac{L_r}{R_r} \quad (9)$$

(4) The electrical field angle,$\theta_f$, is that of rotor flux vector and it is computed using the equation;

$$\theta_f = \int_0^t (\omega_r + \omega_{sl})dt = \int_0^t \omega_s dt (10)$$

(5) The required value of slip speed is calculated as [18][20];

$$\omega_{sl} = \frac{L_m}{L_r} * \frac{R_r}{\lambda_r} * I_{qs}^e \quad (11)$$

(6) The squirrel – cage induction motor speed,$\omega_r$ , is compared with the reference speed, $\omega_{ref}$ , and the speed error (difference) produced, is fed to the speed controller; and the output of the speed controller is the control / request / command value of the electromagnetic torque, $T_e^*$ .

(7) The quadrature stator current component reference,$I_{qs}^{e*}$, is calculated by [18] as;

$$I_{qs}^{e*} = (\frac{2}{3})(\frac{2}{P})(\frac{L_r}{L_m})(\frac{T_e^*}{\lambda_r}) \quad (12)$$

(8) The direct stator current component reference,$I_{ds}^{e*}$, is given as;

$$I_{ds}^{e*} = \frac{\lambda_r^*}{L_m} \quad (13)$$

(9) The direct and quadrature current references in the rotating reference frame namely, $I_{ds}^{e*}$ and $I_{qs}^{e*}$ , are converted into direct and quadrature current references in the stationary reference frame ( $I_{ds}^*$ and $I_{qs}^*$ ) using the Park's inverse transformation expressed as;

$$\begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} = \begin{bmatrix} Cos\theta_f & -Sin\theta_f \\ Sin\theta_f & Cos\theta_f \end{bmatrix} \begin{bmatrix} I_{qs}^e \\ I_{ds}^e \end{bmatrix} \quad (14)$$

(9) The direct – and quadrature - current references in the stationary reference frame ( $I_{ds}^*$ and $I_{qs}^*$ ), are converted into stator phase current references namely $I_{as}^*$, $I_{bs}^*$ and $I_{cs}^*$ by using the Clarke's inverse transformation given as;

$$\begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} = [T^{-1}] \begin{bmatrix} I_{qs} \\ I_{ds} \\ 0 \end{bmatrix} \quad (15)$$

Where;

$$[T^{-1}] = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \end{bmatrix} \quad (16)$$

These stator reference phase currents ($I_{as}^*$, $I_{bs}^*$,$I_{cs}^*$) , are fed tothe current regulator / controller. The current regulator / controller, then processes the actual stator phase currents ( $I_{as}$ ,$I_{bs}$ ,$I_{cs}$ ) and the stator reference phase currents ($I_{as}^*$,$I_{bs}^*$,$I_{cs}^*$) to produce the Pwm signals which will fire the power semiconductor devices of the three – phase inverter to produce the actual voltages to the motor[9],[21],[22].The algorithm for the indirect field – oriented control (IFOC) is reduced to a block diagram as shown in Figure (2).

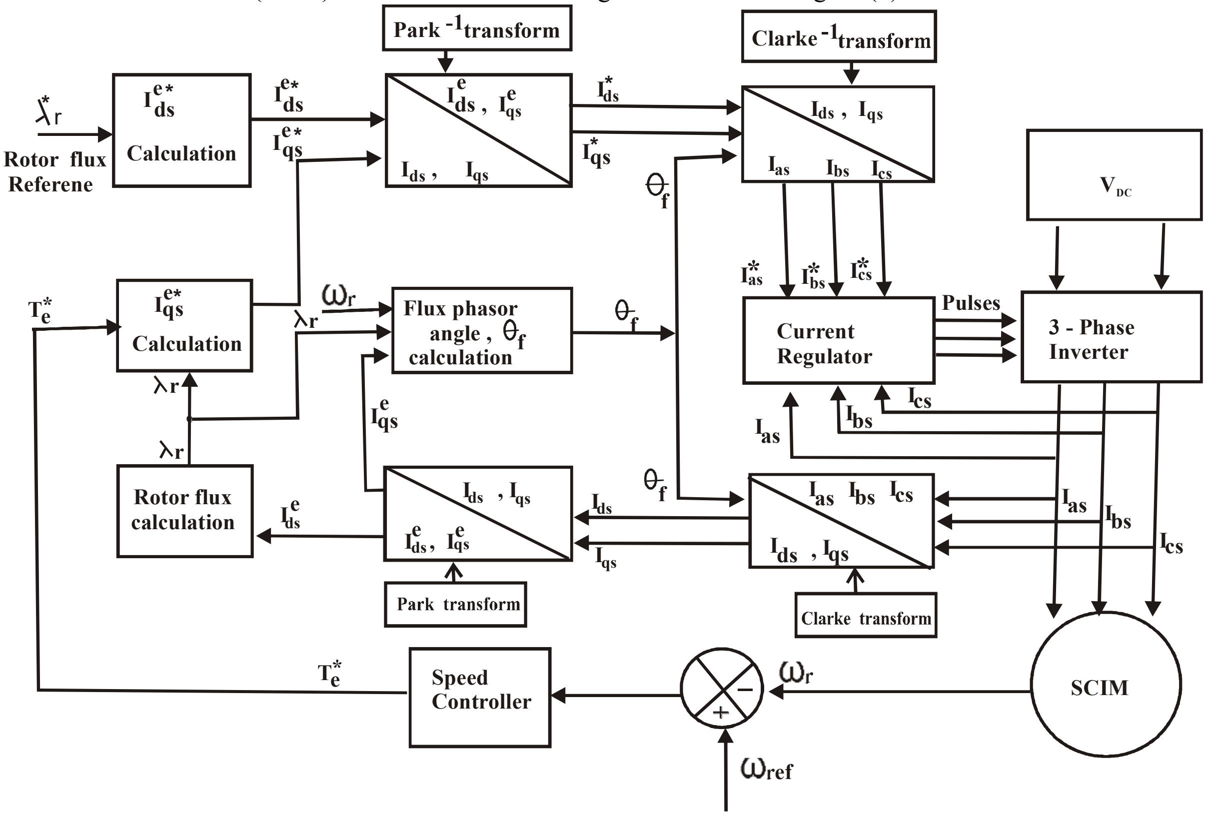



**Figure (2). Block diagram of indirect field – oriented (vector) control scheme.**

## IV. Speed Controllers

### 4.1. Proportional – Integral (PI) Controller

The proportional – integral (PI) controller is mostly adopted in industrial application due to its simple structure, easy to design as well as low cost. A PI controller responds to an error signal in a closed control loop and attempts to adjust the controlled quantity like speed, torque and flux to achieve the desired system response [7].

PI controllers produces the output control signal, U, that consists of the sum of error, E and the integral of that error. The error represents the difference between the reference (desired) rotor speed, $\omega_{ref}$ *and* the actual rotorspeed,$\omega_r$.

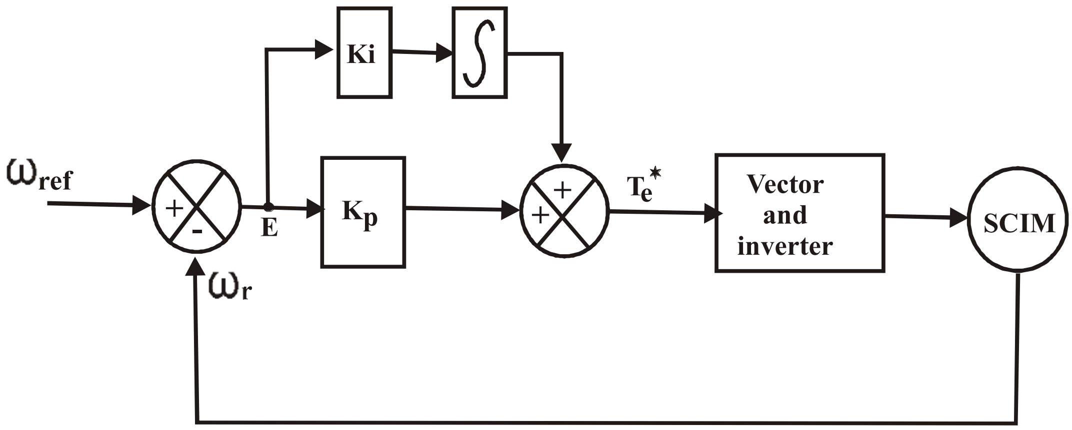



**Figure (3). Proportional–Integral (PI) controller block diagram with vector control.**

The error is mathematically expressed as;

$E = \omega_{ref} - \omega_r$. (17)

The transfer function for PI controller is expressed as [20];

$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s}$(18)

Where;

$K_p$ = proportional gain; $K_i$= integral gain; U(s) = output control signal

The output control signal, U(s), represents the reference (desired) torque,$T_e^*$, in vector control. From figure (4), the control signal,$T_e^*$, is proportional to the error signal, the integral of the error, the proportional gain, $K_p$ and the integral gain,$K_i$.

### 4.2. Proportional – Integral – Derivative (PID) controller.

Proportional–integral–derivative (PID) controller, is widely used in industrial control system. They remain a key component in industrial process control as over 90% of today's industrial processes are controlled by PID controllers [21]. The usefulness of PID control lies in their general applicability when the mathematical model of the system is not known and therefore analytical design methods cannot be used, PID controls prove to be most useful. The PID controller has the general form as [21];

$U(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt}$(19)

Where;

U(t) = system output; e(t) = system error;$K_p$= proportional gain

$K_i$= integral gain; $K_d$= derivative gain

The block diagram of a PID controller is as shown in Figure (4).

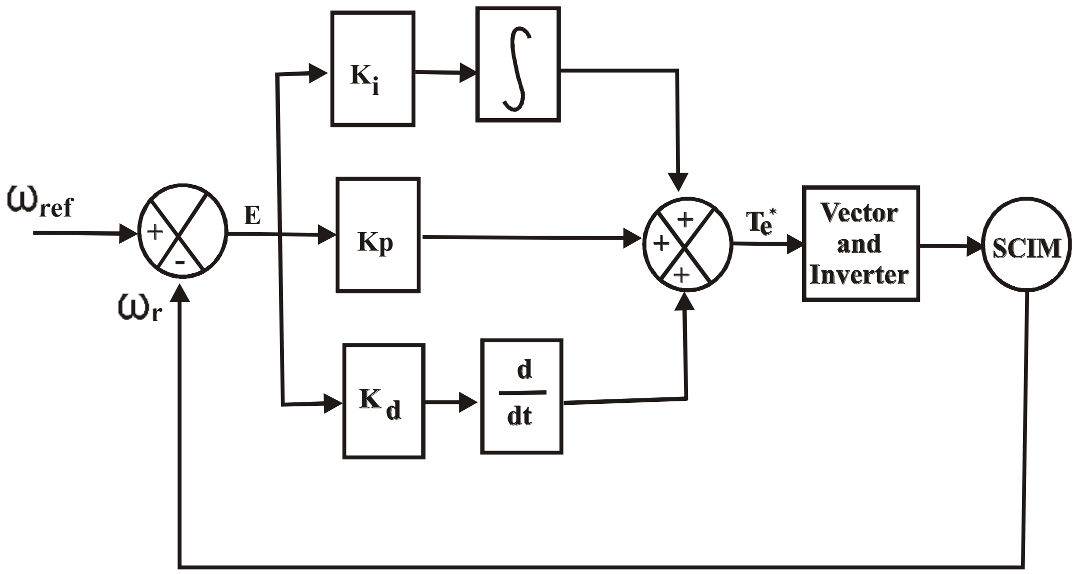



**Figure (4). Block diagram of PID controller with vector control**

The derivative mode of the controller, improves stability of the system and enables increase in proportional gain, $K_p$ which increases speed of the controller response [20]. The output of a PID controller consists of the error signal, the error integral and the error derivative. The transfer function of a PID controller is given as;

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{S} + K_d S \quad (20)$$

Where;

E (s) = error signal; U (s) = output control signal

While $K_p$ , $K_i$ and $K_d$ are as earlier defined in equation (18).

The output control Signal,U(s), represents the reference (desired) torque,$T_e^*$, in vector control. The PID controller combines the advantages of proportional, integral and derivative control action.

**4.3. Fuzzy logic Controller (FLC).**

**4.3.1. Fuzzy logic structure**

The basic structure of fuzzy logic controller consists of four main parts and it is as shown in Figure (5).

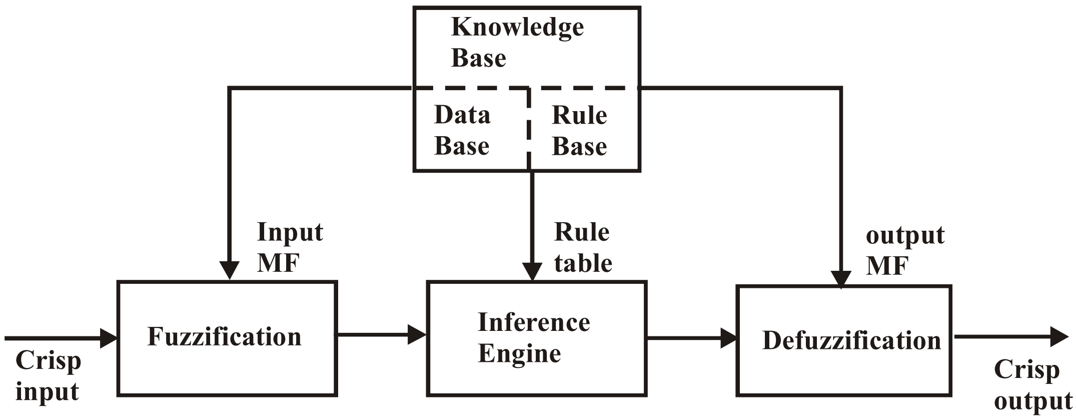



**Figure (5). Basic structure of fuzzy logic controller.**

**4.3.2.Input / output variables**

There are two input signals to the fuzzy logic controller (FLC) namely; the error signal, E(K) and the change in error signal, CE (K). The two input variables, are calculated at every instant as [22];

E (K) = $\omega_r^*(K)$ - $\omega_r(K)$(21)

CE (K) = E (K) – E(K-1) (22)

Where;

E (K) = speed error; $\omega_r^*(K)$ = reference (desired) speed of the motor

$\omega_r(K)$ = actual speed of the motor; E (K-1) = value of speed error at previous sampling time;K = sampling interval / time

The output variable of the fuzzy logic controller, is the variation of the command current, DU [$\Delta i_{qs}^{e*}(K)$]; and this signal when integrated, gives the reference (desired) current, $i_{qs}^{e*}$ , as expressed by [22];

U = $i_{qs}^{e*}(K)$ = $i_{qs}^{e*}(K-1) + \Delta i_{qs}^{e*}(K)$ (23)

The implementation of fuzzy logic controller in a vector controlled drive system is as shown in Figure (6).

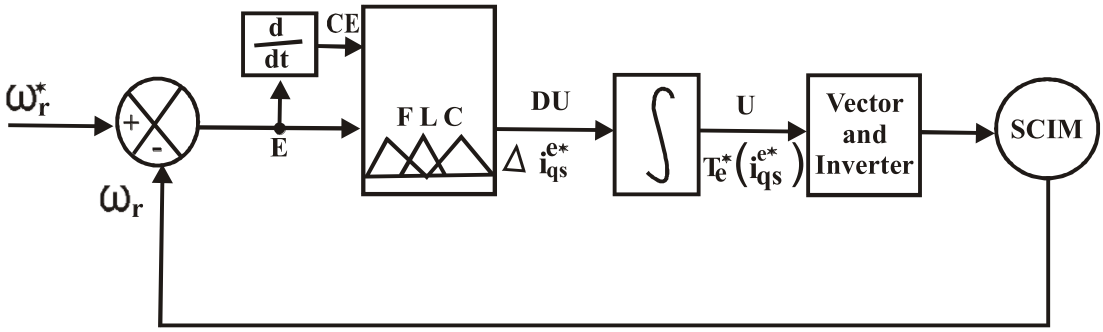



**Figure (6). Block diagram of application of FLC in SCIM**

The fuzzy logic controller (FLC), observes the speed loop error signal and correspondingly updates the controller output, DU [$\Delta i_{qs}^{e*}$], so that the actual speed of the motor, $\omega_r$ , matches the reference/command speed, $\omega_r^*$ .

**4.3.3. Fuzzification.**

The crisp input variables namely speed error, E (K) and change in speed error, CE (K) [ΔE(K)], are converted into fuzzy variables.

The proposed fuzzy sets for the speed controller, has linguistic variables as defined in table 1

**Table 1: Fuzzy sets definitions**

| S/NO | Fuzzy set | Definition |
|---|---|---|
| 1 | NVB | Negative very big |
| 2 | NB | Negative big |
| 3 | NM | Negative medium |
| 4 | NS | Negative small |
| 5 | ZE | Zero |
| 6 | PS | Positive small |
| 7 | PM | Positive medium |
| 8 | PB | Positive big |
| 9 | PVB | Positive very big |

Each of the input variable is divided into seven overlapping fuzzy sets given by linguistic terms namely NB, Nm, NS, ZE, PS, PM and PB.

The output variable is divided into nine overlapping fuzzy sets given by linguistic terms of NVB, NB, NM, NS, ZE, PS, PM, PB and PVB.

Range of values were chosen for the input and output variables. For the speed error input variables, speed error range is taken as [-100, 100] rpm and the range for the change in error signal, is [-50, 50] rpm; while for the output signal, U, the range is designed for [-400, 400] N-m. The membership functions that define the fuzzy values of the controller inputs and outputs are defined on a normalized universe of discourse that usually coincide with the closed interval (-1,1),[19][23]. Thus the actual values of the controller inputs and controller output, are mapped unto normalized universe of discourse. The normalized speed error, $E_N$; normalized change in speed error $CE_N$ and normalized controller output $U_N$, are as given by [23], expressed as;

(a) $E_N = K_e E$ (24)

(b) $CE_N = K_{\dot{e}} CE$ (25)

(c) $U_N = K_u U$ (26)

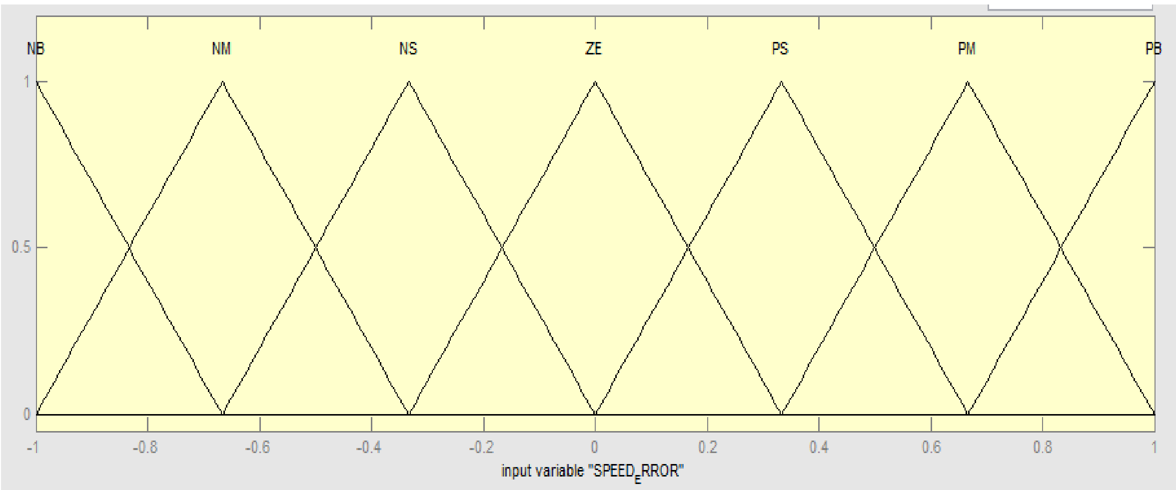
Where;

$E_N$ = normalized error signal; $K_e$ = scaling factor for error signal;E= error signal $CE_N$ = normalized change in error signal;$K_{\dot{e}}$= scaling factor for change in error signal ; CE = change in error signal; $U_N$ = normalized controller output

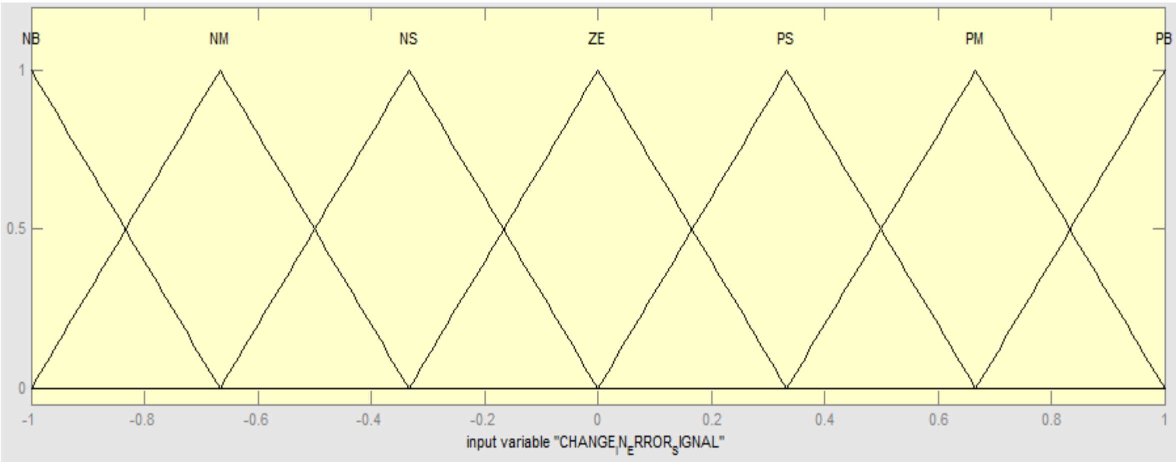
Ku = normalization factor; U = denormalized output

Given the range of values chosen for the speed error and change in speed error taking equations (24) and (25) into consideration, then the scaling factors will have derived values of Ke = 0.01 and $K_{\dot{e}}$= 0.02respectively while normalization factor will have a derived value of Ku = 0.0025.

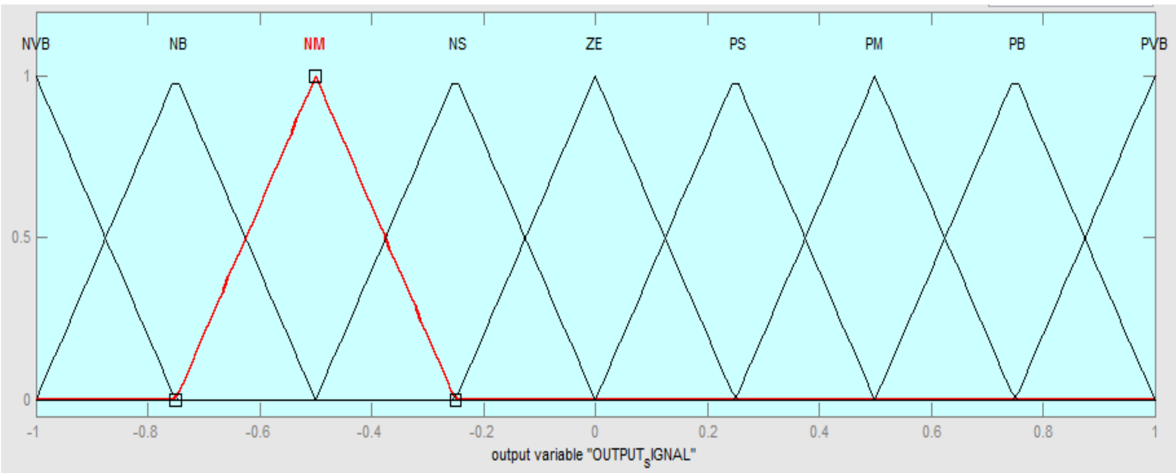
The fuzzification of inputs is done by representing them using triangular membership functions. The triangular membership functions is a good starting choice since apart from being the most known and frequently used, it makes the design and implementation process very simple and gives a good indication of the controller performance[23],[24]. The input and output membership functions for the fuzzy logic controller is as shown in Figure (7).




(a)Input Variable ‘$E_N$’




(b) Input Variable ‘$CE_N$’




(c) Output/control Variable ‘$U_N$’

**Figure (7). Membership functions for fuzzy speed controller for a normalized (a) Error (b) Change in error (c) Output/ Control signal.**

**4.3.4. Knowledge base and inference engine**

Knowledge base involves defining the rules represented as IF… THEN… statements governing the relationship in terms of membership functions. The input variables namely speed error, E and change in speed error, CE (ΔE), are processed by an inference engine that executes 49 rules. This mapping of inputs and outputs is done using fuzzy rule base which represents a crucial step in the design of fuzzy system. The rule base of the speed controller is shown in matrix form in table 2

**Table 2: Fuzzy rule base for speed control of SCIM**

| E | NB | NM | NS | ZE | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| CE | | | | | | | |
| NB | NVB | NVB | NVB | NB | NM | NS | ZE |
| NM | NVB | NVB | NB | NM | NS | ZE | PS |
| NS | NVB | NB | NM | NS | ZE | PS | PM |
| ZE | NB | NM | NS | ZE | PS | PM | PB |
| PS | NM | NS | ZE | PS | PM | PB | PVB |
| PM | NS | ZE | PS | PM | PB | PVB | PVB |
| PB | ZE | PS | PM | PB | PVB | PVB | PVB |

The top row of the matrix indicates the fuzzy sets of the speed error variable, E, while the left column indicates the change in speed error, CE.

The output control variable, U [$i_{qs}^{e*}(motor\ torque)$], is shown in the body of the matrix. The rules define the behavior of the motor. For illustration purpose, each rule is expressed in the following way;

IF the speed error, E, is positive small (PS) AND change in speed error, CE, is negative small (NS) THEN the output control signal U [$i_{qs}^{e*}(motor\ torque)$], is Zero (ZE). The fuzzy inference method used in this paper is the Mamdani method because it is found suitable for dc machine and induction machine models [15].

**4.3.5. Defuzzification**

A crisp value of the output variable of the FLC,$i_{qs}^{e*}(K)$, is obtained by using the height defuzzification method. In this method, the centroid of each output membership function for each rule is first evaluated. The final output is then

Calculated as the average of the individual centroid, weighted by their heights (degree of membership) as follows [1][22];

$$\mathrm{C}i_{qs}^{e*}(K) = \frac{\sum_{i=1}^{n} \mu[(ci_{qs}^{e*})i](ci_{qs}^{e*})i}{\sum_{i=1}^{n} \mu[(ci_{qs}^{e*})i]} \qquad (27)$$

Where;

i is the rule number

n is the total number of rules

($\mathrm{C}i_{qs}^{e*}$)i is the output fuzzy variable for the i[th] rule

**μ** [($\mathrm{C}i_{qs}^{e*}$)i] is the membership function of output fuzzy variable for the i[th] rule

The value of command current, $i_{qs}^{e*}(K)$, that is applied to vector control system is computed by equation (27). This computed C$i_{qs}^{e*}$ from equation (27), is the variation of torque-producing component of the stator current. When it is integrated, it produces the actual current, U [$i_{qs}^{e*}(T_e^*)$], which represents the reference (desired) torque – producing component of the stator current or commanded torque ( $T_e^*$ ) that is fed to the vector control.

### 4.3.6. Hybrid controller

A conventional fuzzy logic in conjunction with a conventional proportional – integral – derivative (PID) controller to function as one controller is proposed in this work. It is known as PID type FLC (FZ - PID) controller [21]. It is a hybrid controller because it combines an artificial intelligence – based controller (FLC) with a conventional PID controller. This hybrid controller, combines the advantages of both fuzzy logic controller and proportional – integral – derivative controller employing

indirect field-oriented (vector) control to control the speed of squirrel-cage induction motor for enhanced performance.

For the hybrid controller, the inputs still remain the speed error, E (K) and the derivative of the speed error ( $\frac{dE}{dt}$) which is referred to as change in speed error, CE(K) [ΔE(K)]. The block diagram for the hybrid speed controller to drive squirrel – cage induction motor with the use of vector control is as shown in Figure (8).

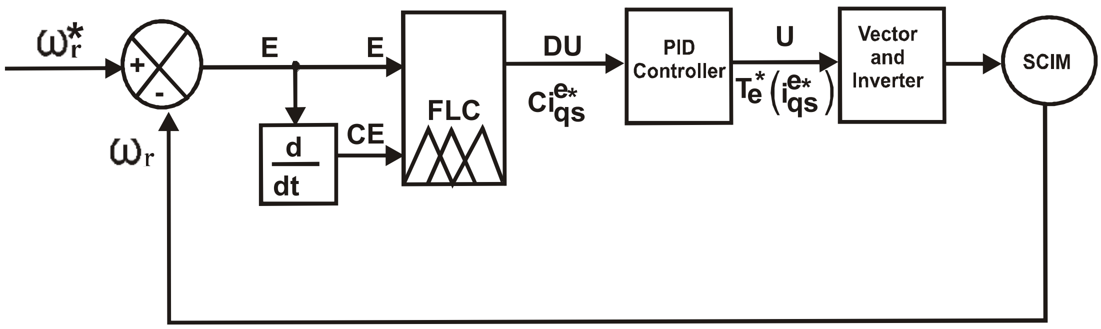



**Figure (8). Hybrid (FZ - PID) controller to drive SCIM with the use of vector control.**

The hybrid controller output, U [$T_e^*(i_{qs}^{e*})$], is the command torque producing component of the stator current, $i_{qs}^{e*}$, which represents the torque reference/command value, $T_e^*$ , for indirect field – oriented control. The hybrid controller output, observes the speed loop error signal and correspondingly changes the output so that the actual speed of the motor, $\omega_r$, matches the reference/desired speed, $\omega_r^*$ .

The Simulink model of the indirect field-oriented control algorithm and the hybrid controller for the squirrel-cage induction motor, is as shown in figure(9).

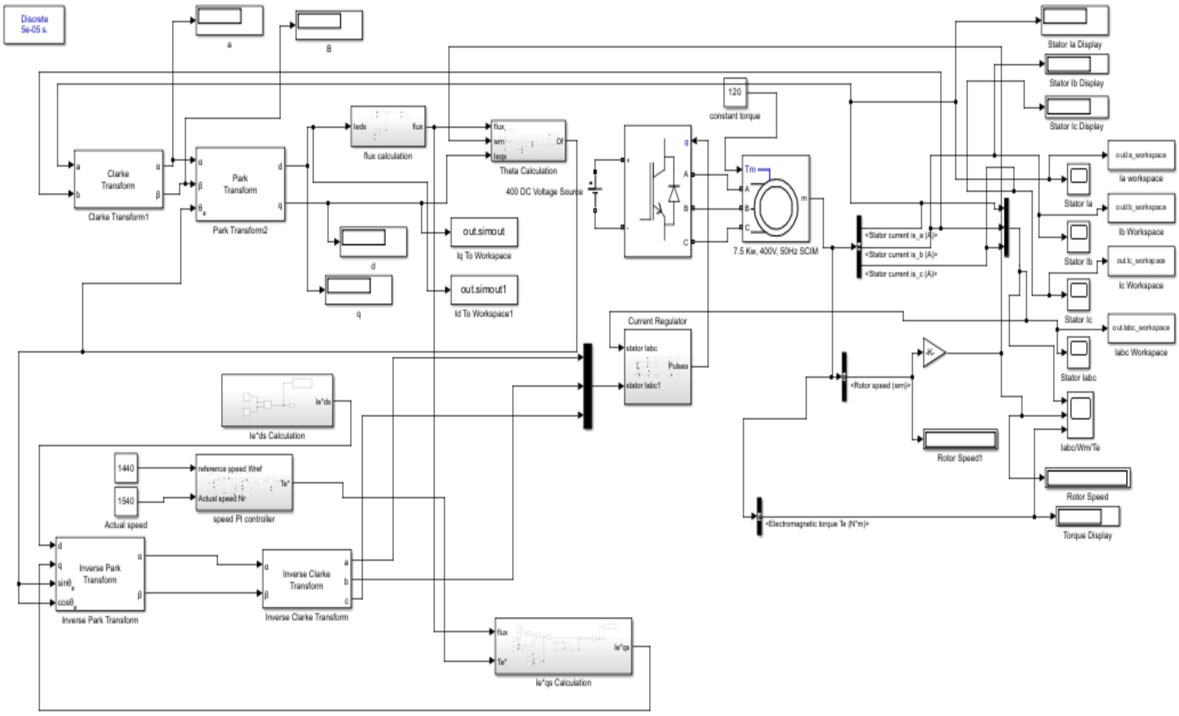



**Figure (9). Simulink model of the IFOC algorithm and hybrid controller for the SCIM.**

## V. Simulation and discussion of simulation results.

The simulation is implemented using a 7.5 Kw, 400-V, 50 Hz, 3-phase squirrel-cage induction motor whose parameters are as displayed in appendix 1.

**Simulation 1: Fixed reference speed and load torque variations for both controllers.**

In this simulation, the reference speed for the conventional PI controller and FZ - PID (Proposed method) was fixed at 1440 rpm (151 rad/sec) while the load torque was varied from 0 N-m to 240 N- m at 60 N-m steps. The simulation time for each of the controllers is 7 seconds. The speed response curves for the conventional PI controller and FZ - PID speed controller of squirrel-cage induction motor (SCIM) at 60 N-m load torque and reference speed of 1440 rpm are as shown in Figure(10) and Figure(11) respectively.

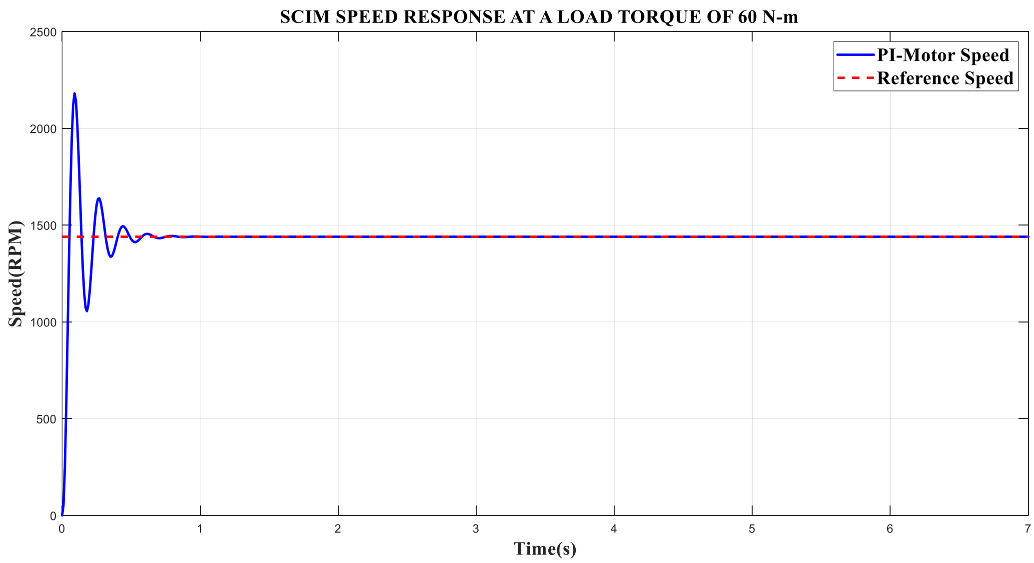
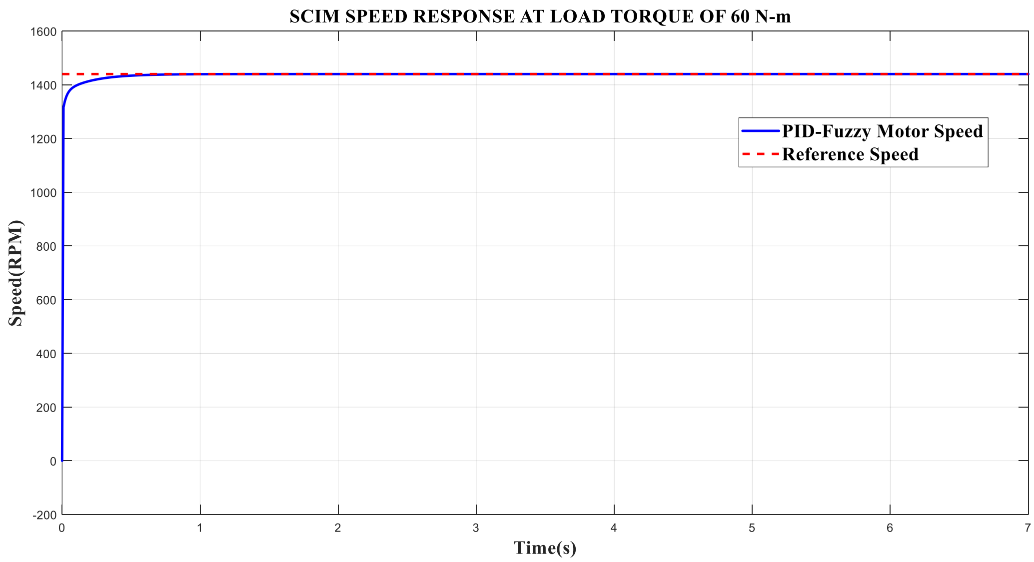



**Figure (10). Speed response curve of SCIM at 60 N-m load torque and 1440 rpm reference speed using conventional PI controller.**




**Figure(11). Speed response curve of SCIM at 60 N-m load torque and 1440 rpm reference speed using FZ - PID (Proposed method) controller.**

The values of the different performance significant measures such as rise time (tr) in seconds, settling time (ts) in seconds, maximum overshoot (Mo) in percentage and steady – state error (Ess) in percentage for the various load torques for both controllers, is as displayed in table 3

**Table 3: Performance analysis of both speed controllers for SCIM at reference speed of 1440 rpm (151 rad/sec) and different load torques in N-m.**

| Load torque (N - m) | Controller | Rise time, $t_r$ (sec) | Settling time, $t_s$ (sec) | Maximum Overshoot $M_o$ (%) | Steady – state error $E_{ss}$(%) |
|---|---|---|---|---|---|
| 60 | PI<br>FZ – PID | 0.0339<br>0.0036 | 0.4705<br>0.1764 | 51.37<br>0.0 | 0.90<br>0.50 |
| 120 | PI | 0.0226 | 0.7438 | 70.41 | 1.00 |

| | | | | | |
|---|---|---|---|---|---|
| | FZ - PID | 0.0008 | 0.0614 | 0.0 | 0.15 |
| 180 | PI<br>FZ - PID | 0.0180<br>0.0005 | 1.2160<br>0.0296 | 82.29<br>0.0 | 1.80<br>0.05 |
| 240 | PI<br>FZ - PID | 0.0154<br>0.0004 | 3.0792<br>0.0150 | 90.96<br>0.0 | 4.5<br>0.10 |

From table (3), it is seen that the proposed method (FZ-PID controller), has best values for the different performance significant measures for the squirrel – cage induction motor (SCIM) as compared to the conventional PI method.

**Simulation 2: Fixed load torque with step change in reference speed.**

In this simulation, the dynamic performances of the PI and FZ - PID controllers are performed by applying a 120 N-m load torque while the reference speed undergoes a step change from 720 rpm (75.5 rad/sec) to 1440 rpm (151 rad/sec).

For the conventional PI controller, this performance produced an overshoot of 56.7% followed by an oscillation that lasted for 0.5 seconds before settling at a reference speed of 720 rpm. The rise time is 0.0207Secs; settling time of 0.3469 Secs and steady – state error of 0.6 %. But a step change in reference speed (From 720 rpm to 1440 rpm) is applied to the motor at 3.5 second time interval. This resulted in another overshoot and oscillation of the same magnitude as the first one before settling at the reference speed of 1440 rpm.This dynamic performance of the conventional PI controller is as shown in Figure(12).The simulation time is 10 seconds.

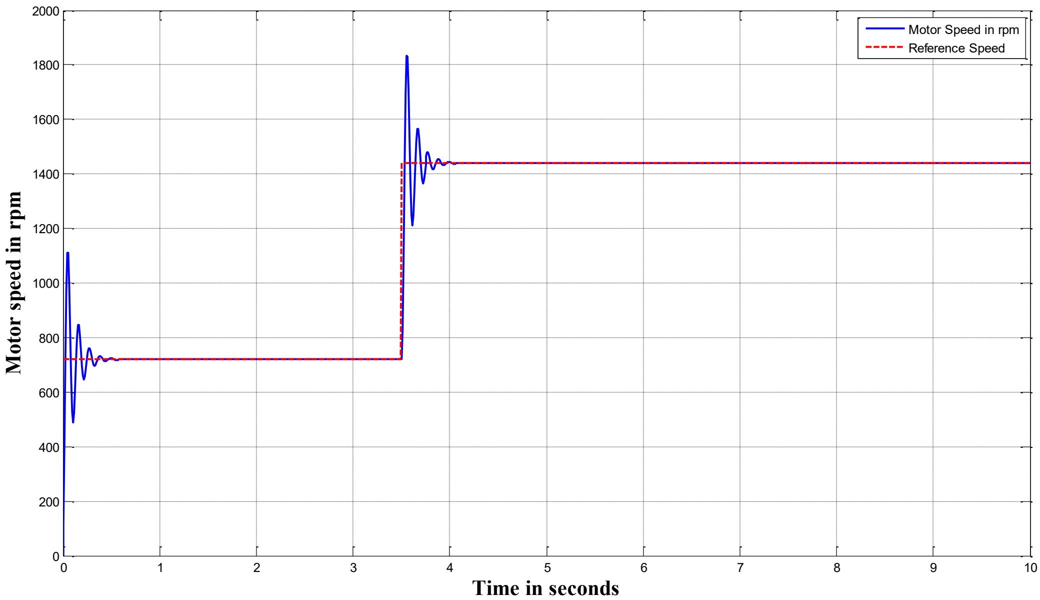



**Figure (12). Speed response curve of SCIM at 120 N - m load torque and 720 rpm to1440 rpm step change in reference speed using conventional PI controller**

On the other hand, the dynamic performance of the FZ -PID controller on the SCIM, produced no overshoot and oscillation, had faster rise and settling times of **0.0007**seconds and 0.0068 seconds respectively and steady state error of 0.12 %**.**

This dynamic performance of the proposed method is as shown in Figure(13). The simulation time is 10 seconds.

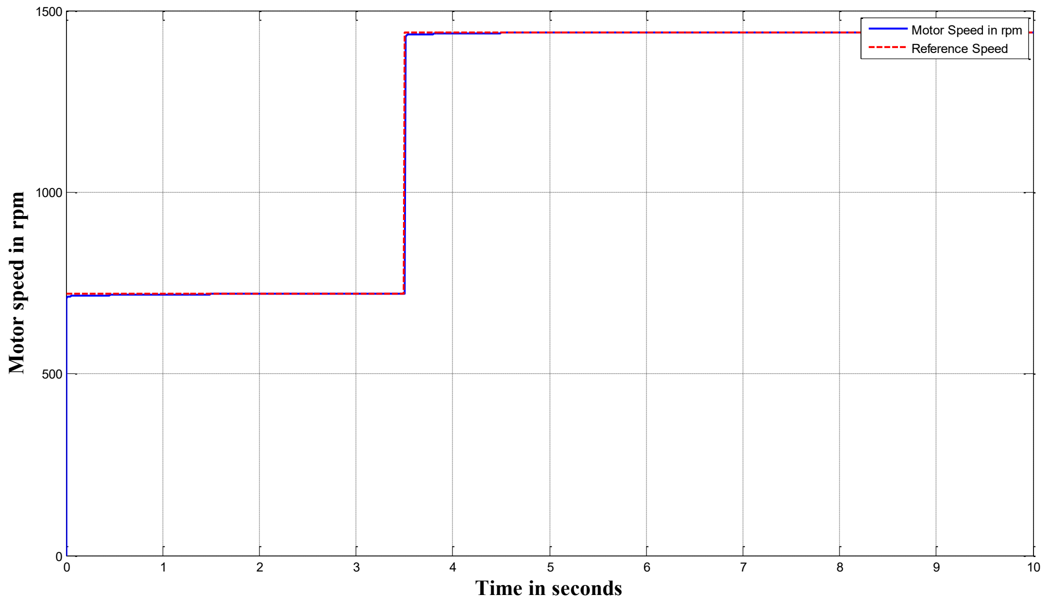



Figure (13). Speed response curve of SCIM at 120 N – m load torque and 720 rpm – 1440 rpm step change in reference speed using FZ-PID controller.

**Simulation 3: Fixed reference speed and sudden change in load torque**

In this simulation, the dynamic performances of PI and FZ - PID Controllers, are analyzed. This is done by having a fixed reference speed of 1440 rpm (151 rad/sec) with initial load torque of 60 N-m. Then at 3.5 seconds interval time, the load torque is increased to 240 N-m.

With the conventional PI controller, the motor speed response curve initially showed an overshoot of 82.2%, oscillated briefly before settling at the reference speed but at the instant of the load torque changing to 240 N-m, a drop in motor speed(undershoot) occurred and lasted for 0.9886 seconds before settling. The rise time is 0.0142 sec; settling time is 0.9886 sec and steady – state error is 1.4 %. This is as shown in Figure (14). The simulation time for each of the controllers is 10 seconds.

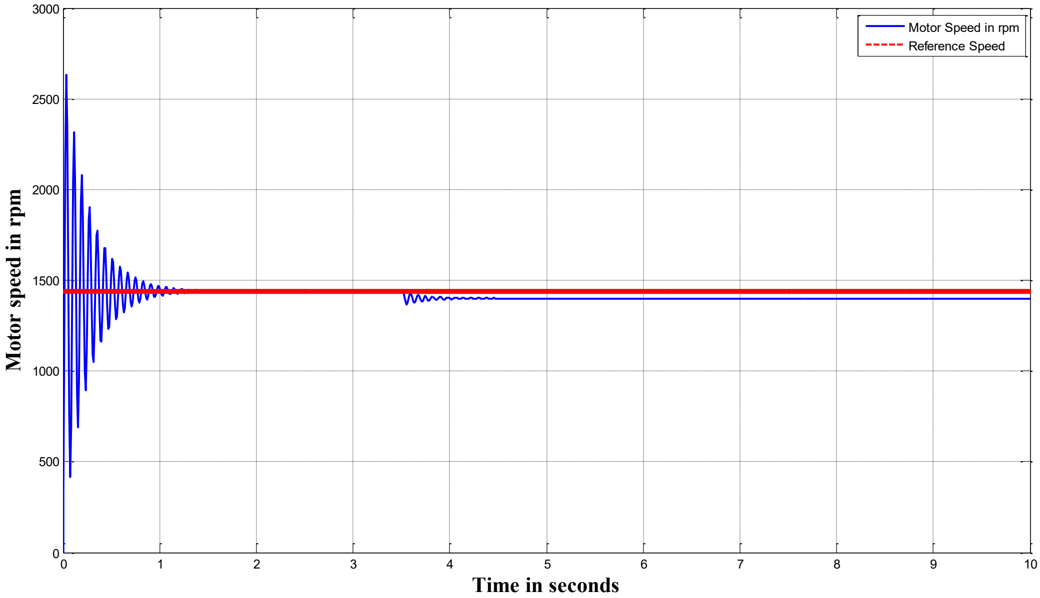
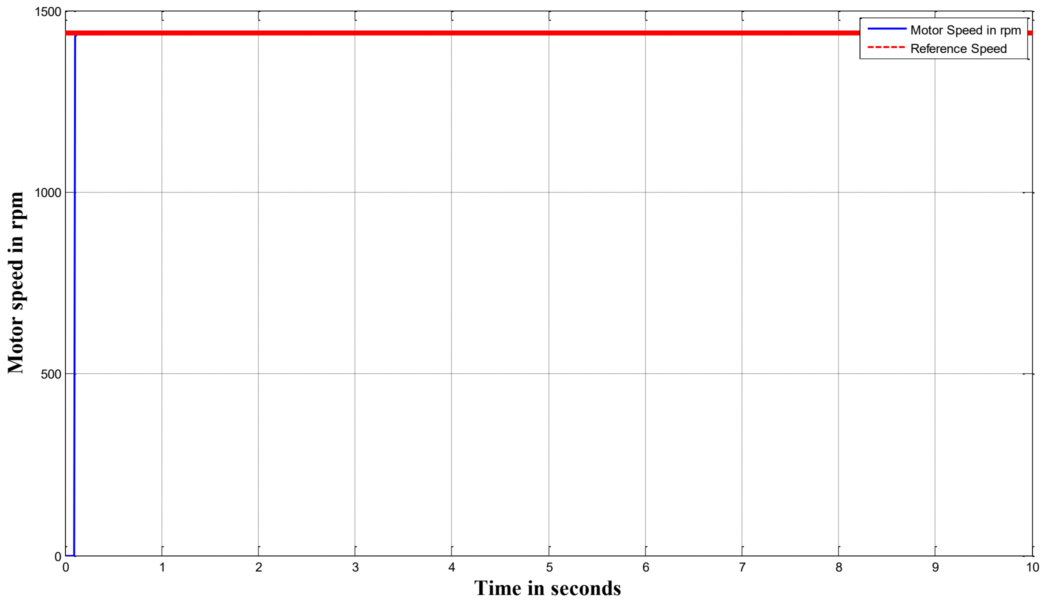



Figure (14). Speed response curve of SCIM at reference speed of 1440 rpm and sudden increase in load torque from 60 N - m to 240 N – m using PI controller.

But with the proposed method (FZ - PID controller), there is no drop in motor speed response (undershoot), rather the actual speed of the squirrel – cage induction motor, faithfully tracked the reference/desired speed giving rise to an improved speed response that produced an enhanced performance significant measures as can be seen from the 0.0003 seconds for rise time, 0.0008 seconds for settling time, zero (0) overshoot and steady – state error of 0.025 %. This is as shown in Figure (15).




Figure(15). Speed response curve of SCIM at a reference speed of 1440 rpm and sudden change in load torque from 60 N - m to 240 N- m using FZ - PID.

## VI. Conclusion

This paper has successfully presented a hybrid (FZ -PID) controller for controlling a three – phase squirrel – cage induction motor (SCIM) to enhance its characteristic performance. To achieve this, a conventional PID controller and an artificial intelligence – based fuzzy logic controller (FLC), is used as a single controller. This proposed hybrid controller, employed the indirect field – oriented control (IFOC) to decouple the stator current phasor into torque – producing and flux – producing components thereby solving the induction motor coupling effects problem that not only makes the motor speed response sluggish but can also lead to instability.

The conventional PI controller and the proposed hybrid controller, were designed and simulated in matlab/Simulink software package. The performance significant measures such as rise time $(t_r)$ in seconds, settling time $(t_s)$ in seconds, percentage maximum overshoot $(m_o)$ and percentage steady – state error $(E_{ss})$ of the proposed method, were compared with the conventional PI controller and the comparative study, showed enhanced performance with the proposed method.

The dynamic response characteristics with the proposed method, showed high level of robustness as the motor speed was able to track the reference/desired motor speed despite disturbances such as step change in reference speed and sudden change in load torque compared with the conventional PI controller.

In conclusion, the proposed hybrid speed controller for closed loop operation of the squirrel-cage induction motor drive system, has demonstrated enhanced performance over the conventional PI controller as it gives better speed response combined with high level of robustness in tracking the reference/desired motor speed.

**APPENDIX 1**

**SCIM parameters with values based on predefined model in matlab**

| S/NO. | Parameters | Values | Unit |
|---|---|---|---|
| 1 | Stator resistance, Rs | 0.7384 | Ω |
| 2 | Rotor resistance, Rr | 0.7402 | Ω |
| 3 | Stator inductance, Ls | 3.045 | mH |
| 4 | Rotor inductance, Lr | 3.045 | mH |
| 5 | Mutual inductance, Lm | 124.1 | mH |

| | | | |
|---|---|---|---|
| 6 | Moment of inertia, J | 0.0343 | Kg-$m^2$ |
| **7** | **Viscous friction factor B** | **0.000503** | **Nms** |
| 8 | No of poles | **4** | **--** |

**APPENDIX 2**

Equivalence of Simulink Symbols/Expressions for the indirect field- oriented control (IFOC).

| S/NO | Simulink symbol/Expression | Equivalent symbol/Expression used in the work |
|---|---|---|
| 1 | $I_\alpha$ | $I_{ds}$ |
| 2 | $I_\beta$ | $I_{qs}$ |
| 3 | $I_d$ | $I_{ds}^e$ |
| 4 | $I_q$ | $I_{qs}^e$ |
| 5 | $I_d^*$ | $I_{ds}^{e*}$ |
| 6 | $I_q^*$ | $I_{qs}^{e*}$ |
| 7 | $I_\alpha^*$ | $I_{ds}^*$ |
| 8 | $I_\beta^*$ | $I_{qs}^*$ |
| 9 | $T_e^*$ | $T_e^*$ |
| 10 | Theta,$\theta$ | $\theta_f$ |
| 11 | Flux | $\lambda_r$ |
| 12 | $Flux^*$ | $\lambda_r^*$ |

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