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# PERFORMANCE IMPROVEMENT OF SPEED CONTROL FOR INDUCTION MOTOR BY USING INTELLIGENT OPTIMIZATION TECHNIQUE

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**ABSTRACT**

Induction motor is considered as one of the most motors that has many uses in the industrial applications in which requires rapid response and high accuracy of control for wide ranges of speed. In this paper, Field Oriented Control (FOC) method was utilized to achieve high performance of control by separating stator current into two components to control the torque and field, along with Space Vector Pulse Width Modulation (SVPWM) technique to reduce the harmonic of the output signal from the inverter and the best use of the DC voltage. The aim of this paper is to enhance the speed response during incurring of the motor for a sudden change of load torque or reference speed. The PSO technique was used to find the best parameters of the control unit in both the voltage and current controllers of the FOC system in order to improve the motor speed response using two objective functions of MAE and ME. The simulation results of PSO-PI controllers demonstrate the superiority over the trial and error PI controllers for enhancing steady state error, rise time and settling time.

**Keywords:** *Induction Motor, Indirect Vector Control, Space Vector Pulse Width Modulation, PI Controller, Particle Swarm Optimization*

## 1. INTRODUCTION

Induction motor of squirrel cage type is widely used in many industrial and domestic applications in which more than 50% of the produced energy is consumed by the motor. Moreover, most of the used motors are induction motors since they can be easily maintained, self-started, connected directly into AC current source, has strong structure, much cheaper compared with synchronous and direct machines for the same rated power, and can operate in polluted or explosive environment because they do not have carbonic brushes in their structures [1-3]. Despite that, the controlling process of the speed of induction motor is harder and more complex than controlling of the speed of DC motor [4]. The reason due to the high non-linear properties that result from intersection of the fields of stator and rotor [5].

Blaschke and Hasse invented a method to control AC machines that called vector control [6]. This method used when high performance of control is required [7]. In vector control, both field and torque are separately controlled by using the same controlling method of separately excited DC motor. At the latter motor, magnetic field resulted from the stator and field resulted from the rotor are perpendicular, which means there is no intersection between stator and rotor fields. This fixed ($90^{\circ}$) angle between fields is assured by the position of the carbonic brushes. The field of DC motor is controlled by controlling field current ($I_f$) for the stator. On the other side, when the torque control is required, the armature current ($I_a$) is controlled. This separation process of control for each of torque and field provides easiness and preciseness in controlling DC motor. In AC machines, the process is different. The magnetic field resulted from the stator intersects the field resulted from rotor since the angle between the two coils is not ($90^{\circ}$) and change with time [8]. To overcome this problem, vector control is used as a method to control the motor speed.

The vector control is classified into two methods. The first one is called Direct Torque Control (DTC) which invented by Blaschke in 1980 [8]. The second one is called Field Oriented Control (FOC) which invented by Hasse in 1970 [8]. The main difference between these two methods is how to find unite vector or flux angle [8]. The key of

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vector control method is to find out flux angle that used to convert the system from stationary reference frame into synchronous reference frame and vice versa [9]. In the direct torque control, the flux angle is calculated by sensors that placed inside the motor between the stator and the rotor to measure the flux at the air gap or by measuring both of the voltage and the current of the stator in which equations are used to calculate this angle [10]. Whereas, in FOC method the calculating ($\theta_e$) is achieved by measuring the rotor speed and calculating slip speed [8].

In this paper, FOC the most popular method is used due to its accuracy of control for wide ranges of speed change. Proportional –Integral (PI) controller is used extensively for systems that control the motor speed due to its low cost, simple at use, and easy at design. PI parameters have difficulty finding their best values. There are many methods used to find the PI parameters including conventional methods, such as Ziegler-Nichols and Cohen–Coon methods [11, 12]. However, these methods are difficult, have unsatisfactory results, and needs time since they mainly depend on knowing a mathematical model of plant and trial and error method [12]. Finding the parameters of the control unit by using trial and error method does not ensure that there is no more steady state error and settling time in the speed response. There are many smart techniques and random search methods used for improving the performance of the traditional controller of PI, such as fuzzy, neural network, and genetic algorithm (GA) [13]. However, these techniques have some limitations, for example fuzzy has a very difficult parameters modification process [13, 14]. GA has too many and complex calculations, as well as it has a premature convergence that reduce its performance for getting the best global solution while neural network did not have a common standard to confirm [12, 13]. In this paper, particle swarm optimization algorithm has been developed in order to improve the speed of the induction motor response by adjusting the PI parameters in both the voltage and current controllers of the FOC. PSO is one of the most popular intelligent optimization techniques that used for various engineering applications which are preferred to be used instead of other algorithms. This is due to its simplicity of implementation, quick convergence ability, and low computation cost [12]. The parameters of PSO-PI controllers are optimized so that to achieve a balanced improving response between settling time and steady state error based on objective function because it improved one of them may cause dropping for the other. The simulation results showed the success of the suggested PSO-PI method in regulating the speed of motor under different working conditions compared to the manual adjusting method.

## 2. MODEL OF INDUCTION MOTOR

The equations of three phase-induction motor in (d-q) axes is widely used in control applications in which it is possible to convert time-variable 3ph quantities into time-variable or constant 2ph quantities by using suitable reference frame. There are three reference frames that used to express motor equations [15].

1. Stationary reference frame.
2. Synchronous reference frame.
3. Rotor reference frame.

It is useful to build motor model in general reference frame. When the motor model is required to be used in the stationary reference frame, the speed value $\omega = 0$ must be adjusted, while if motor model is required to be used in the synchronous reference frame, the speed value $\omega = \omega e$ must be adjusted. However, in most cases, the motor model is represented in stationary, while the control system, especially the field oriented control, depends on the motor equations in synchronous.

From figures (1) and (2) the motor equations can be obtained in synchronous reference frame [14].

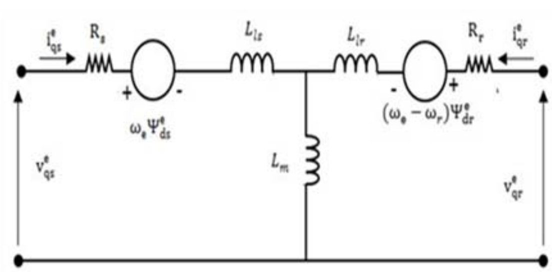


*Figure 1: Equivalent Circuit of IM in D-Axis*

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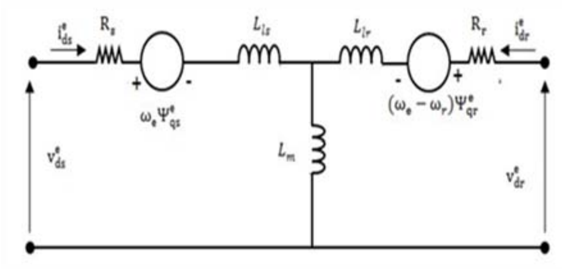

*Figure 2: Equivalent Circuit of IM in Q-Axis*

The relationship between $d^e - q^e$ two phase voltage and $abc$ three phase voltage is given by equation (1)

$$\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \\ v_{os}^e \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\,\theta_e & cos(\theta_e - \frac{2\pi}{3}) & cos(\theta_e + \frac{2\pi}{3}) \\ -sin\,\theta_e & -sin(\theta_e - \frac{2\pi}{3}) & -sin(\theta_e + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

Stator $d^e - q^e$ *axis* voltage equations:

$$v_{ds}^e = R_s\, i_{ds}^e + \frac{d\Psi_{ds}^e}{dt} - \omega_e \Psi_{qs}^e \quad (2)$$

$$v_{qs}^e = R_s\, i_{qs}^e + \frac{d\Psi_{qs}^e}{dt} + \omega_e \Psi_{ds}^e \quad (3)$$

Rotor $d^e - q^e$ *axis voltage* equation:

$$v_{dr}^e = R_r\, i_{dr}^e + \frac{d\Psi_{dr}^e}{dt} - (\omega_e - \omega_r)\Psi_{qr}^e \quad (4)$$

$$v_{qr}^e = R_r\, i_{qr}^e + \frac{d\Psi_{qr}^e}{dt} + (\omega_e - \omega_r)\Psi_{dr}^e \quad (5)$$

Stator $d^e - q^e$ axis flux equations:

$$\Psi_{ds}^e = (L_{ls} + L_m)\, i_{ds}^e + L_m\, i_{dr}^e = L_s\, i_{ds}^e + L_m i_{dr}^e \quad (6)$$

$$\Psi_{qs}^e = (L_{ls} + L_m)\, i_{qs}^e + L_m\, i_{qr}^e = L_s\, i_{qs}^e + L_m i_{qr}^e \quad (7)$$

Rotor $d^e - q^e$ axis flux equations:

$$\Psi_{dr}^e = (L_{lr} + L_m)\, i_{dr}^e + L_m\, i_{ds}^e = L_r\, i_{dr}^e + L_m i_{ds}^e \quad (8)$$

$$\Psi_{qr}^e = (L_{lr} + L_m)\, i_{qr}^e + L_m\, i_{qs}^e = L_r\, i_{qr}^e + L_m\, i_{qs}^e \quad (9)$$

Torque equation:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\Psi_{ds}^e\, i_{qs}^e - \Psi_{qs}^e\, i_{ds}^e\right) \quad (10)$$

Where:

$v_a, v_b$ and $v_c$= The input voltage for 3ph $(a, b, c)$.

$v_{ds}^e, v_{qs}^e, v_{dr}^e$ and $v_{qr}^e$= The stator and rotor component of the voltage in $(d^e$-$q^e)$ axis respectively in a synchronous reference frame.

$i_{ds}^e, i_{qs}^e, i_{dr}^e$ and $i_{qr}^e$= The stator and rotor component of the current in $(d^e$–$q^e)$ axis respectively in a synchronous reference frame.

$\Psi_{ds}^e, \Psi_{qs}^e, \Psi_{dr}^e$ and $\Psi_{qr}^e$= The stator and rotor component of the flux in $(d^e$–$q^e)$ axis respectively in a synchronous reference frame.

$\omega_e$ and $\omega_r$= Synchronous and rotor speed respectively.

$L_{ls}$ and $L_{lr}$= Stator and rotor leakage inductance respectively.

$L_s$ and $L_r$= Stator and rotor self- inductance respectively.

$L_m$= Mutual inductance.

$R_s$ and $R_r$= Stator and rotor resistance respectively.

$T_e$= Electromagnetic torque.

$P$= Number of pole pairs.

## 3. INDIRECT FIELD ORIENTED CONTROL (FOC)

In FOC, the stator current is divided into two separated components,($i_{ds}^e$) component which controls the flux and ($i_{qs}^e$) which controls the torque. Accordingly, FOC achieves a control over induction motor in similar way to the separately excited DC motor [9]. FOC method is not used only to control the speed, in fact it used to control both of flux and torque in the same time .The idea of this method is to keep the flux at a rated value that enables working at any reference speed within torque constant region. The FOC is classified at implementation into rotor flux orientation, stator flux orientation, and air gap flux orientation. The most used method in AC drive among all these methods is the rotor flux orientation method since it achieves a natural separation process and the unite vector is obtained by measuring the rotor speed and then calculating the slip speed [17, 18]. And from equations (4) and (5), we get

$$\frac{d\Psi_{dr}^e}{dt} + \frac{R_r}{L_r}\Psi_{dr}^e - \frac{L_m}{L_r}R_r\, i_{ds}^e - \omega_{sl}\Psi_{qr}^e = 0 \quad (11)$$

$$\frac{d\Psi_{qr}^e}{dt} + \frac{R_r}{L_r}\Psi_{qr}^e - \frac{L_m}{L_r}R_r i_{qs}^e + \omega_{sl}\Psi_{dr}^e = 0 \quad (12)$$

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For rotor flux orientation

$\Psi_{qr}^{e} = 0$ and $\Psi_{dr}^{e} = \Psi_{r}$

From equations (11) and (12) we get:

$$\frac{L_r}{R_r}\frac{d\Psi_{dr}^{e}}{dt} + \Psi_{dr}^{e} = L_m\, i_{ds}^{e} \quad (13)$$

At the case of steady state, $\frac{d\Psi_{dr}^{e}}{dt} = 0$

Therefore current can be calculated by equation (14):

$$i_{ds}^{*e} = \frac{\Psi_r}{L_m} \quad (14)$$

Slip speed can be calculated as:

$$\omega_{sl} = \frac{L_m}{\Psi_r}\frac{R_r}{L_r}\, i_{qs}^{e} \quad (15)$$

$$\theta_e = \int \omega_{\mathrm{e}}\, \mathrm{dt} = \int (\omega_r + \omega_{\mathrm{sl}})\, \mathrm{dt} \quad (16)$$

$$\omega_r = \frac{\mathrm{P}}{2}\, \omega_m \quad (17)$$

Where:
$\omega_r$= Rotor speed and *=reference value

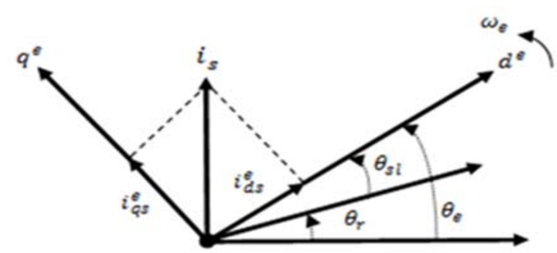

*Figure 3: Rotor Flux Orientation Phasor Diagram*

## 4. CONTROL SYSTEM

Figure (4), shows the feedback control system of three phase-induction motor which consists of two outer loop in feedback. The first loop is responsible on controlling ( $i_{ds}^{e}$) Component of the flux; the other is responsible on controlling ($i_{qs}^{e}$) component of the torque.

The ($i_{ds}^{*e}$) current is obtained from equation (14), while the ($i_{qs}^{*e}$) is obtained by comparing the real speed ($\omega_r$) and the reference speed ($\omega_r^{*}$). Then, the error is sent into the PI controller to produce ($i_{qs}^{*e}$) component. The ($i_{qs}^{*e}$) and ($i_{qs}^{e}$), also the ($i_{ds}^{*e}$) and ($i_{ds}^{e}$), are compared with each other. The resultant error from this comparison process is sent into PI in order to produce the voltage components of ($v_{ds}^{*e}$) and ($v_{qs}^{*e}$) in synchronous reference frame. After that, these quantities is converted into stationary reference frame ($v_{\alpha}, v_{\beta}$), and then sent into SVPWM to produce the suitable voltage and frequency for the motor.

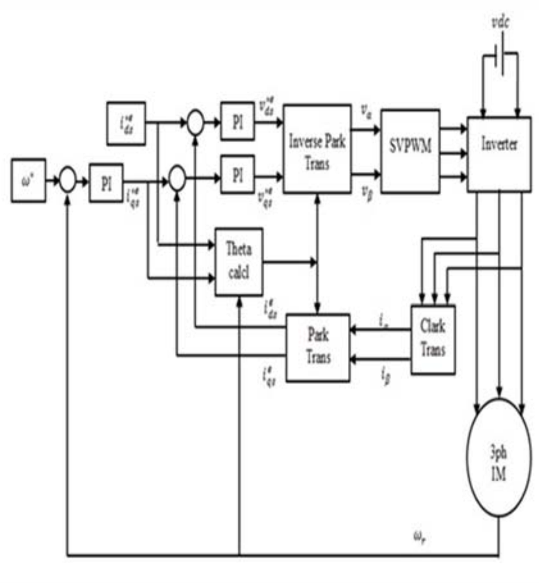


*Figure 4: Field Oriented Control Block Diagram*

## 5. PARTICLE SWARM OPTIMIZATION ALGORITHM (PSO)

The invention of the PSO algorithm backs to 1995 by Dr. Kennedy and Dr. Aberhart [1]. The idea of PSO is inspired by the social behavior of migratory birds and fish methods for food searching. A simulation of this behavior is used in some engineering applications to solve nonlinear and no differential problems. Each bird is introduced as a particle and all particles are represented as a swarm. Each particle has a velocity (v) and a position in the space (x) in which this position is considered as the solution of the problem. At each iteration, each one of these particles modify their velocity and position according to its own experience of flying and the experiences of its neighbors through a communication network between the swarm members to find the best solution. At each iteration, each one of these particles modify their velocity and position according to its own experience of

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flying and the experiences of its neighbors through a communication network between the swarm members to find the best solution. The velocity and the position of each particle are represented in $(n)$ number of iterations.

$$v_i(k) = [v_{i1}(k), v_{i2}(k) \dots \dots v_{in}(k)]^T \quad (18)$$

$$x_i(k) = [x_{i1}(k), x_{i2}(k) \dots \dots x_{in}(k)]^T \quad (19)$$

At each iteration, the particle rushes to get the local best position based on its own memory. This is what characterizes PSO algorithm from the other algorithms and can be represented at each iteration.

$$P_{best}(k) = \left[P_{best,i1}(k), P_{best,i2}(k) \dots P_{best,in}(k)\right] \quad (20)$$

The local best position at the swarm is called $G_{best}$ which represents the solution of the problem and can be represented at each iteration.

$$G_{best}(k) = \left[G_{best,i1}(k), G_{best,i2}(k), G_{best,in}(k)\right] \quad (21)$$

After finding the best $P_{best}$ and $G_{best}$, the particles modifies their positions and velocity according to the following equation [19]

$$v_{ij}(k+1) = w.v_{ij} + c_1\, r_{1,ij}\left(p_{best,ij}(k) - x_{,ij}(k)\right) + c_2\, r_{2,ij}\left(G_{best,ij}(k) - x_{,ij}(k)\right) \quad (22)$$

$$x_{ij}(k+1) = x_{ij}(k) + v_{ij}(k+1) \quad (23)$$

The equation of velocity has three components:

1. Inertia component: This component provides a memory for the particle to rush into the current direction and prevent it from drastic changing of direction.
2. Cognitive component: it is a measure of the performance for the particle between the current and the previous position, i.e. individual memory that leads the particle into the local best position that is obtained at each iteration.
3. Social component: it is a measure of the performance for the particle relative to the all particles in the swarm and this component drives each particle towards the best position in the swarm.

The efficiency of the PSO in finding the best solution of the problem essentially depends on adjusting its parameters in which some of them which have a significant impact and some of them have a small impact. Some of these parameters are the number of particles, the number of iteration, and $c_1$, $c_2$, $w$, $r_1$, $r_2$ [20].

The particles number is chosen to fit the problem size, also to cover the largest possible area of the search and therefore less number of iteration to get the best solution is required. The largest number of particles needs a longer time to finish the search process. During experiments, it was found that the appropriate number of particles in the search was (20-60). Number of iterations is also depends on the size of problem. The greater number of iterations may result in ending the search before getting the best solution. $r_1$, $r_2$ are random numbers (0-1). $c_1$ is called social rate in which it expresses how confidence of the particle with itself. $c_2$ is called cognitive rate in which it expresses how confidence of the particle with its neighbors [20]. $w$ is called inertia weight which has a value between (0-0.9). Its greatest value enables it to determine global and its smallest value enabling local discovery [21]. At this paper, PSO is used to determine best parameters of ($K_P$, $K_I$) based on objective function mean error (ME), and mean absolute error (MAE).

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n} e \quad (24)$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |e| \quad (25)$$

## 6. RESULTS AND DISCUSSION

This test was performed by using MATLAB program version (2015) on three phase-induction motor with parameters shown in table (1). Figure (4) illustrates FOC circuit that includes three PI controllers to produce the components ($v_{ds}^{*e}$, $v_{qs}^{*e}$, $i_{qs}^{*e}$). Two methods were used to determine PI parameters. The first one is offline-PSO with ME and MAE , Table 2 shows the final choice of the control parameters PSO algorithm that is considered the optimal choice in this paper, while the second is trial and error. This test was carried out in two steps. The first one was by changing the load torque and fixing the speed. The second one was by changing the speed and fixing the load torque. These tests were achieved to evaluate the performance of the various control units. The results showed the efficiency of the PSO-PI control unit in assigning strong controllers for the sudden changes of the applied torque and reference speed that made the control system more robust to regulate the speed of the motor.

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*Table 1: Induction Motor Parameters [22].*

| N0. | Induction Motor Parameters | |
|---|---|---|
| | Parameters | Values |
| 1 | Rated power | 2.2 KW |
| 2 | Frequency | 50 HZ |
| 3 | Line to line Voltage | 380 V |
| 4 | Number of poles | 4 |
| 5 | Stator resistance | 3.3 Ω |
| 6 | Rotor resistance | 2.2 Ω |
| 7 | Stator inductance | 0.3 H |
| 8 | Rotor inductance | 0.3 H |
| 9 | Mutual inductance | 0.2864 H |
| 10 | Damping factor | 0.01 NM/(rad/sec) |
| 11 | Inertia | 0.05 $\mathrm{kg.m^2}$ |
| 12 | Rated speed | 1415 RPM |
| 13 | Maximum load torque | 14.8 NM |

*Table 2: PSO parameters.*

| N0. | PSO Parameters | |
|---|---|---|
| | Parameters | Values |
| 1 | Particle size (n) | 20 |
| 2 | Maximum iteration (k) | 100 |
| 3 | Cognitive rate ($c_1$) | 2 |
| 4 | Social rate ($c_2$) | 1.9 |
| 5 | Inertia weight (w) | 0.9 |

1. Changing load torque: at this test, the load torque is gradually changed while the speed is fixed at rated value (148.1 rad/s), while motor without load until time 0.3s, quarter load is exerted until time 0.4s, Half load is exerted until time 0.5s, three quarters of load is exerted until time 0.6s, Full load is exerted until time 1s. The table shows the results of this test.

*Table 3: Speed Response of Changing Load Torque with Objective Function (ME) and Trial and Error PI Conventional.*

| Load Torque | Controller | Settling Time | Steady State Error |
|---|---|---|---|
| No Load | PI | 0.036 | 1.171 |
| | PSO-PI | 0.022 | 0.091 |
| 1/4 Load | PI | 0.009 | 1.092 |
| | PSO-PI | 0.004 | 0.093 |
| 1/2 Load | PI | 0.005 | 0.915 |
| | PSO-PI | 0.005 | 0.198 |
| 3/4 Load | PI | 0.016 | 0.814 |
| | PSO-PI | 0.006 | 0.286 |
| Full Load | PI | 0.017 | 0.713 |
| | PSO-PI | 0.007 | 0.373 |

*Table 4: Speed Response of Changing Load Torque with Objective Function (MAE) and Trial and Error PI Conventional*

| Load Torque | Controller | Settling Time | Steady State Error |
|---|---|---|---|
| No Load | PI | 0.036 | 1.171 |
| | PSO-PI | 0.026 | 0.824 |
| 1/4 Load | PI | 0.009 | 1.092 |
| | PSO-PI | 0.016 | 0.696 |
| 1/2 Load | PI | 0.005 | 0.915 |
| | PSO-PI | 0.008 | 0.585 |
| 3/4 Load | PI | 0.016 | 0.814 |
| | PSO-PI | 0.005 | 0.417 |
| Full Load | PI | 0.017 | 0.713 |
| | PSO-PI | 0.001 | 0.373 |

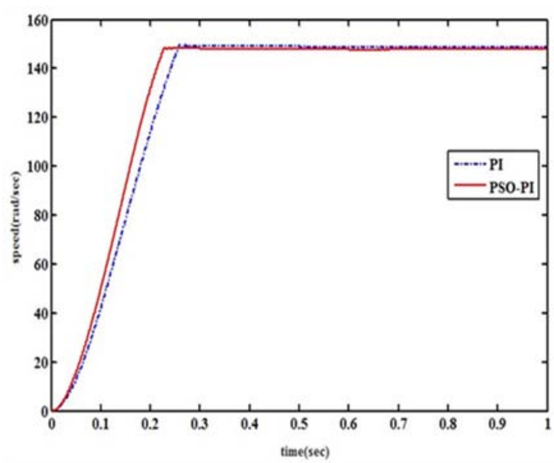


*Figure 5: Speed Response of Changing Load Torque for Conventional PI & PSO-PI with Objective Function ME*

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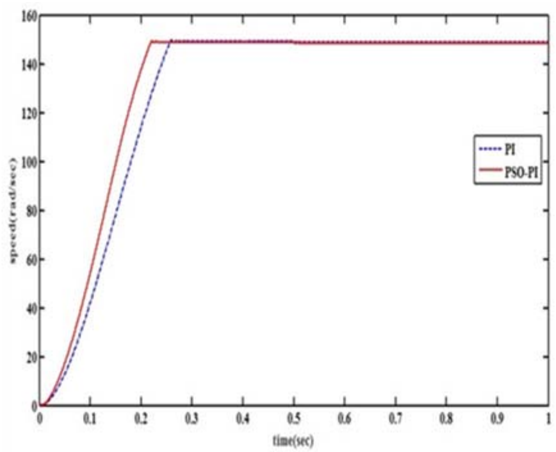


*Figure 6: Speed Response of Changing Load Torque for Conventional PI & PSO-PI with Objective Function MAE*

2. Changing of reference speed: in this test, reference speed is gradually changed at no load. Motor at rated speed (148.1 rad/sec) until 0.3s, changing of the reference speed to (120 rad/sec) until 0.4s ,changing of the reference speed to (100 rad/sec) until 0.5s, changing of the reference speed to (80 rad/sec) until 0.6s, changing of the reference speed to (60 rad/sec) until 1s. The table shows the results of this test.

*Table 5: Speed Response of Changing Reference Speed for Conventional PI & PSO-PI with Objective Function $ME$.*

| Load Torque | Controller | Settling Time | Steady State Error |
|---|---|---|---|
| 148.1 Rad/Sec | PI | 0.036 | 1.171 |
| | PSO-PI | 0.022 | 0.091 |
| 120 Rad/Sec | PI | 0.055 | 1.294 |
| | PSO-PI | 0.03 | 0.208 |
| 100 Rad/Sec | PI | 0.055 | 1.306 |
| | PSO-PI | 0.031 | 0.281 |
| 80 Rad/Sec | PI | 0.051 | 1.478 |
| | PSO-PI | 0.026 | 0.429 |
| 60 Rad/Sec | PI | 0.048 | 1.578 |
| | PSO-PI | 0.036 | 0.593 |

*Table 6: Speed Response of Changing Reference Speed for Conventional PI & PSO-PI with Objective Function $MAE$.*

| Load Torque | Controller | Settling Time | Steady State Error |
|---|---|---|---|
| 148.1 Rad/Sec | PI | 0.036 | 1.171 |
| | PSO-PI | 0.026 | 0.824 |
| 120 Rad/Sec | PI | 0.055 | 1.294 |
| | PSO-PI | 0.041 | 0.897 |
| 100 Rad/Sec | PI | 0.055 | 1.306 |
| | PSO-PI | 0.026 | 0.946 |
| 80 Rad/Sec | PI | 0.051 | 1.478 |
| | PSO-PI | 0.034 | 1.088 |
| 60 Rad/Sec | PI | 0.048 | 1.578 |
| | PSO-PI | 0.034 | 1.183 |

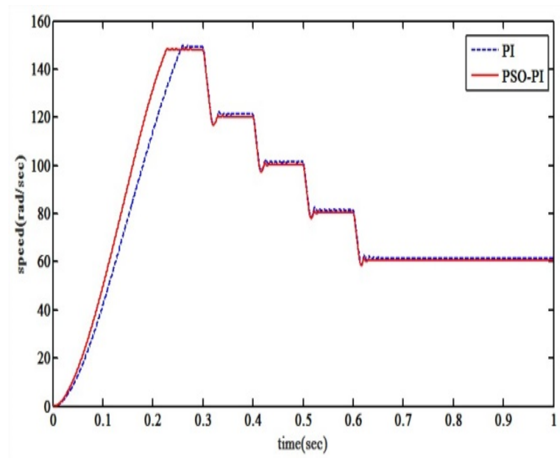


*Figure 7: Speed Response of Changing Reference Speed for Conventional PI & PSO-PI with Objective Function $ME$*

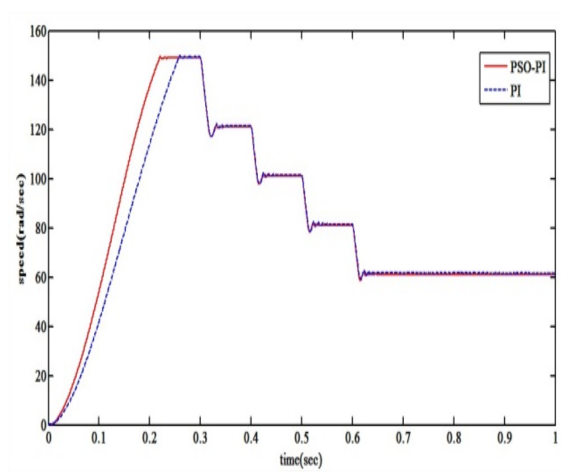


*Figure 8: Speed Response of Changing Reference Speed for Conventional PI & PSO-PI with Objective Function $MAE$*

## 7. CONCLUSION

In this paper, the PSO algorithm was used to determine the best parameters for three PI controllers for producing the voltage component $(v_q, v_d)$ and the current component $i_q$ in the FOC to improve the speed response of the induction motor. Testing the complete system was achieved under different working conditions to evaluate the performance of the PSO-PI based controllers and compared with the PI controller based on manual adjustment. The simulation results showed an improvement in the speed response with the PSO-PI controller as the rotor speed follows the reference speed with less steady state error and settling time compared with the PI manual adjustment method which showed the largest settling time and steady state error. The performance of the PSO-PI controller was very satisfactory in both steady state and transient modes. PSO reduced the time period for getting the best PI parameters, and the best performance of this algorithm was achieved with objective function ME where a good speed response with less settling time and steady state error (close to zero). A conclusion can be made from this work that the PSO-PI controller is suitable for improving the performance of the induction motor.

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