

# Swarm Intelligence Applications in Electric Machines

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## 1. Introduction

Particle Swarm Optimization (PSO) has potential applications in electric drives. The excellent characteristics of PSO may be successfully used to optimize the performance of electric machines in many aspects.

In this chapter, a field-oriented controller that is based on Particle Swarm Optimization is presented. In this system, the speed control of two asymmetrical windings induction motor is achieved while maintaining maximum efficiency of the motor. PSO selects the optimal rotor flux level at any operating point. In addition, the electromagnetic torque is also improved while maintaining a fast dynamic response. A novel approach is used to evaluate the optimal rotor flux level by using Particle Swarm Optimization. PSO method is a member of the wide category of Swarm Intelligence methods (SI). There are two speed control strategies will demonstrate in next sections. These are field-oriented controller (FOC), and FOC based on PSO. The strategies are implemented mathematically and experimental. The simulation and experimental results have demonstrated that the FOC based on PSO method saves more energy than the conventional FOC method.

In this chapter, another application of PSO for losses and operating cost minimization control is presented for the induction motor drives. Two strategies for induction motor speed control are proposed in this section. These strategies are based on PSO and called maximum efficiency strategy and minimum operating cost Strategy. The proposed technique is based on the principle that the flux level in a machine can be adjusted to give the minimum amount of losses and minimum operating cost for a given value of speed and load torque.

In the demonstrated systems, the flux and torque hysteresis bands are the only adjustable parameters to achieve direct torque control (DTC) of induction motors. Their selection greatly influences the inverter switching loss, motor harmonic loss and motor torque ripples, which are the major performance criteria. In this section, the effects of flux and torque hysteresis bands are investigated and optimized by the particle swarms optimization technique. A DTC control strategy with variable hysteresis bands, which improves the drive performance compared to the classical DTC, is presented.

Online Artificial Neural Networks (ANNs) could be also trained based on PSO optimized data. Here the fast response of ANN is used to optimize the operating conditions of the machine.

It is very important to note that, these applications were achieved without any additional hardware cost, because the PSO is a software scheme. Consequently, PSO has positive promises for a wide range of variable speed drive applications.

## 2. Losses Minimization of Two Asymmetrical Windings Induction Motor

In this section, applying field orientation based on Particle Swarm Optimization (PSO) controls the speed of two-asymmetrical windings induction motor is the first application of PSO. The maximum efficiency of the motor is obtained by the evaluation of optimal rotor flux at any operating point. In addition, the electro-magnetic torque is also improved while maintaining a fast dynamic response. In this section, a novel approach is used to evaluate the optimal rotor flux level. **This approach is based on Particle Swarm Optimization (PSO). This section presents two speed control strategies. These are field-oriented controller (FOC) and FOC based on PSO.** The strategies are implemented mathematically and experimental. The simulation and experimental results have demonstrated that the FOC based on PSO method saves more energy than the conventional FOC method.

The two asymmetrical windings induction motor is treated as a two-phase induction motor (TPIM). It is used in many low power applications, where three-phase supply is not readily available. This type of motor runs at an efficiency range of 50% to 65% at rated operating conditions [1, 2].

The conventional field-oriented controller normally operates at rated flux at any values with its torque range. When the load is reduced considerably, the core losses become so high causing poor efficiency. If significant energy savings are required, it is necessary to optimize the efficiency of the motor. The optimum efficiency is obtained by the evaluation of the optimal rotor flux level. This flux level is varied according to the torque and the speed of the operating point.

PSO is applied to evaluate the optimal flux. It has the straightforward goal of minimizing the total losses for a given load and speed. It is shown that the efficiency is reasonably close to optimal.

### 2.1 Mathematical Model of the Motor

The d-q model of an unsymmetrical windings induction motor in a stationary reference frame can be used for a dynamic analysis. This model can take in account the core losses. The d-q model as applied to TPIM is described in [1, 2]. The equivalent circuit is shown in fig. 1. The machine model may be expressed by the following voltage and flux linkage equations :

Voltage Equations:

$$v_{qs} = r_m i_{qs} + p\lambda_{qs} \quad (1)$$

$$v_{ds} = r_a i_{ds} + p\lambda_{ds} \quad (2)$$

$$0 = r_r i_{qr} - (1/k) * \omega_r \lambda_{dr} + p\lambda_{qr} \quad (3)$$

$$0 = r_R i_{ds} + k * \omega_r \lambda_{qr} + p \lambda_{dr} \tag{4}$$

$$0 = -i_{qfe} R_{qfe} + L_{mq} ( p i_{qs} + p i_{qr} - p i_{qfe} ) \tag{5}$$

$$0 = -i_{dfe} R_{dfe} + L_{md} ( p i_{ds} + p i_{dr} - p i_{dfe} ) \tag{6}$$

Flux Linkage Equations:

$$\lambda_{qs} = L_{lm} i_{qs} + L_{mq} ( i_{qs} + i_{qr} - i_{qfe} ) \tag{7}$$

$$\lambda_{ds} = L_{la} i_{ds} + L_{md} ( i_{ds} + i_{dr} - i_{dfe} ) \tag{8}$$

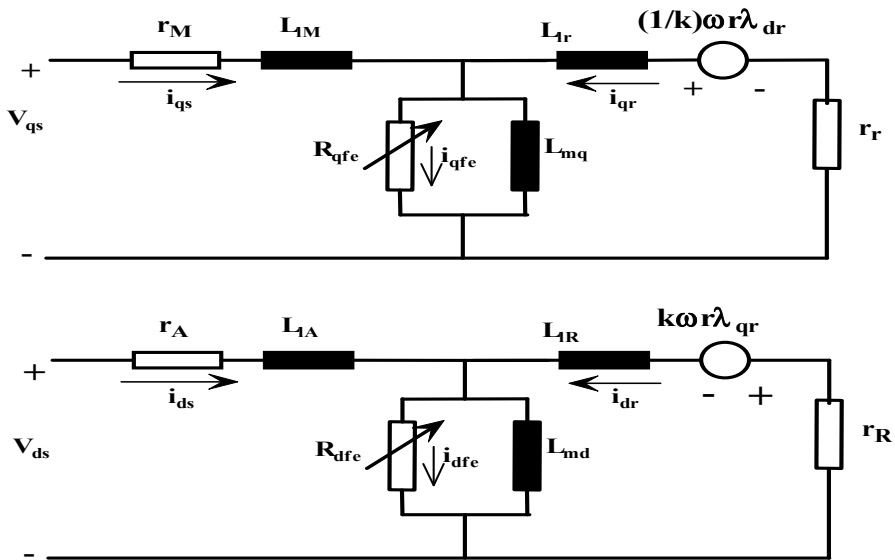


Figure 1. The d-q axes two-phase induction motor Equivalent circuit with iron losses [5]

$$\lambda_{qr} = L_{lr} i_{qr} + L_{mq} ( i_{qs} + i_{qr} - i_{qfe} ) \tag{9}$$

$$\lambda_{dr} = L_{lR} i_{dr} + L_{md} ( i_{ds} + i_{dr} - i_{dfe} ) \tag{10}$$

Electrical torque equation is expressed as:

$$Te = \frac{P}{2} ( k L_{mq} i_{dr} ( i_{qs} + i_{qr} - i_{qfe} ) - \frac{1}{k} L_{md} i_{qr} ( i_{ds} + i_{dr} - i_{dfe} ) ) \tag{11}$$

Dynamic equation is given as follows:

$$T_e - T_l = j_m p \omega_r + B_m \omega_r \quad (12)$$

## 2.2 Field-Oriented Controller [FOC]

The stator windings of the motor are unbalanced. The machine parameters differ from the d axis to the q axis. The waveform of the electromagnetic torque demonstrates the unbalance of the system. The torque in equation (11) contains an AC term; it can be observed that two values are presented for the referred magnetizing inductance. It is possible to eliminate the AC term of electro-magnetic torque by an appropriate control of the stator currents. However, these relations are valid only in linear conditions. Furthermore, the model is implemented using a non-referred equivalent circuit, which presumes some complicated measurement of the magnetizing mutual inductance of the stator and the rotor circuits [3]. The indirect field-oriented control scheme is the most popular scheme for field-oriented controllers. It provides decoupling between the torque of flux currents. The electric torque must be a function of the stator currents and rotor flux in synchronous reference frame [6]. Assuming that the stator currents can be imposed as:

$$i_{ds}^s = i_{ds1}^s \quad (13)$$

$$i_{qs}^s = k i_{qs1}^s \quad (14)$$

Where:  $k = M_{srd} / M_{srq}$

$$T_e = \frac{P}{2L_r} \left[ M_{sqr} i_{qs}^s \lambda_{dr}^s - M_{sdr} i_{ds}^s \lambda_{qr}^s \right] \quad (15)$$

By substituting the variables  $i_{ds}^s$  and  $i_{qs}^s$  by auxiliary variables  $i_{ds1}^s$  and  $i_{qs1}^s$  into (15) the torque can be expressed by

$$T_e = \frac{PM_{sdr}}{2L_r} \left[ i_{qs1}^s \lambda_{dr}^s - i_{ds1}^s \lambda_{qr}^s \right] \quad (16)$$

In synchronous reference frame, the electromagnetic torque is expressed as :

$$T_e = \frac{P M_{sdr}}{2 L_r} \left[ i_{qs1}^e \lambda_{dr}^e - i_{ds1}^e \lambda_{qr}^e \right] \quad (17)$$

$$T_e = \frac{P M_{sdr}}{2 L_r} \left[ i_{qs1}^e \lambda_{r}^e \right] \quad (18)$$

$$i^{e}_{ds1} = \frac{\lambda^{e}_r}{M_{sdr}} \quad (19)$$

$$\omega_e - \omega_r = \frac{M_{sdr}}{\tau_r * \lambda_r} i^{e}_{qs1} \quad (20)$$

### 2.3 Model with the Losses of two asymmetrical windings induction motor

Finding the losses expression for the two asymmetrical windings induction motor with losses model is a very complex. In this section, a simplified induction motor model with iron losses will be developed [4]. For this purpose, it is necessary to transform all machine variables to the synchronous reference frame. The voltage equations are written in expanded form as follows:

$$v_{qs}^e = r_m i_{qs}^e + L_{lm} \frac{di_{qs}^e}{dt} + L_{mq} \frac{di_{qm}^e}{dt} + \omega_e (L_{la} i_{ds}^e + L_{md} i_{dm}^e) \quad (21)$$

$$v_{ds}^e = r_a i_{ds}^e + L_{la} \frac{di_{ds}^e}{dt} + L_{md} \frac{di_{dm}^e}{dt} - \omega_e (L_{lm} i_{qs}^e + L_{mq} i_{qm}^e) \quad (22)$$

$$0 = r_r i_{qr}^e + L_{lr} \frac{di_{qr}^e}{dt} + L_{mq} \frac{di_{qm}^e}{dt} + \frac{\omega_{sl}}{k} (L_{lr} i_{dr}^e + L_{md} i_{dm}^e) \quad (23)$$

$$0 = r_R i_{dr}^e + L_{lR} \frac{di_{dr}^e}{dt} + L_{md} \frac{di_{dm}^e}{dt} - k * \omega_{sl} (L_{lr} i_{qr}^e + L_{mq} i_{qm}^e) \quad (24)$$

$$i_{qs}^e + i_{qr}^e = i_{qfe}^e + i_{qm}^e \quad (25)$$

$$i_{ds}^e + i_{dr}^e = i_{dfe}^e + i_{dm}^e \quad (26)$$

Where:

$$i_{dfe}^e = \frac{v_{qm}^e}{R_{qfe}} ; i_{dfe}^e = \frac{v_{dm}^e}{R_{dfe}}$$

$$v_{dm}^e = - \frac{\omega_e L_{lr} L_{mqs}}{L_r} i_{qs}^e \quad (27)$$

$$v_{qm}^e = \omega_e L_{m ds} i_{ds}^e \quad (28)$$

The losses in the motor are mainly:

- Stator copper losses,
- Rotor copper losses,
- Core losses, and
- Friction losses.

The total electrical losses can be expressed as follows

$$P_{losses} = P_{cu1} + P_{cu2} + P_{cor} \quad (29)$$

Where:

- $P_{cu1}$ : Stator copper losses  
 $P_{cu2}$ : Rotor copper losses  
 $P_{core}$ : Core losses

The stator copper losses of the two asymmetrical windings induction motor are caused by electric currents flowing through the stator windings. The core losses of the motor due to hysteresis and eddy currents in the stator. The total electrical losses of motor can be rewritten as:

$$P_{losses} = r_m i_{qs}^e + r_a i_{ds}^e + r_r i_{qr}^e + r_R i_{dr}^e + \frac{v_{qm}^e{}^2}{R_{qfe}} + \frac{v_{dm}^e{}^2}{R_{dfe}} \quad (30)$$

The total electrical losses are obtained as follows:

$$P_{losses} = \left[ r_m + \frac{r_r L_{mqs}^2}{L_r^2} + \frac{\omega_e^2 L_r^2 L_{mqs}^2}{L_r^2 R_{dfe}} \right] \left[ \frac{T_e^2 L_r^2}{P^2 \left( \frac{L_{m ds}}{K} \right)^2 \lambda_r^2} \right] + \left( r_a + \frac{\omega_e^2 L_{m ds}^2}{R_{qfe}} \right) \frac{\lambda_r^2}{L_{m ds}^2} \quad (31)$$

Where:

$\omega_e = \omega_r + \omega_{sl}$ , and  $\omega_{sl}$  is the slip speed r/sec.

$$\omega_{sl} = \frac{2 T_e * r_r}{P * \lambda_r^2} \quad (32)$$

Equation (31) is the electrical losses formula, which depends on rotor flux ( $\lambda_r$ ) according to operating point (speed and load torque).

$$\begin{aligned} \text{Total } P_{losses} (TP_{losses}) &= P_{losses} + \text{friction power losses} \\ &= P_{in} - P_{out} \end{aligned}$$

$$\text{Efficiency } (\eta) = P_o / (P_o + \text{Total } P_{losses}) \quad (33)$$

Where:

Friction power losses =  $F * \omega_r^2$ , and

Output power ( $P_o$ ) =  $T_L * \omega_r$ .

The equation (31) is the cost function, which depends on rotor flux ( $\lambda_r$ ) according to the operating point. Figure 2 presents the distribution of losses in motor and its variation with the flux. As the flux reduces from the rated value, the core losses decrease, but the motor copper losses increase. However, the total losses decrease to a minimum value and then increase again. It is desirable to set the rotor flux at the optimal value, so that the efficiency is optimum.

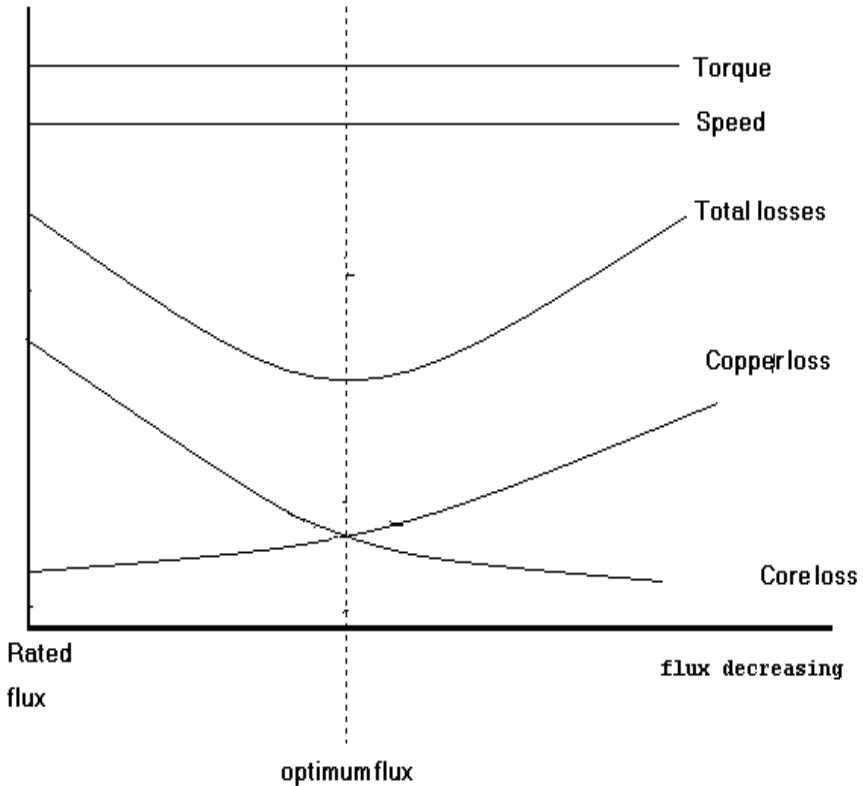


Figure 2. Losses variation of the motor with varying flux

The function of the losses minimization of the motor problem can be formulated as follows:  
 Minimize Total Losses which are a function of  $\lambda$ ,  $T_e$ , and  $\omega_r$

- The losses formula is the cost function of PSO. The particle swarm optimization (PSO) technique is used for minimizing this cost function.
- The PSO is applied to evaluate the optimal rotor flux that minimizes the motor losses at any operating point. Figure 3 presents the flowchart of the execution of PSO, which evaluates the optimal flux by using MATLAB /SIMULINK.

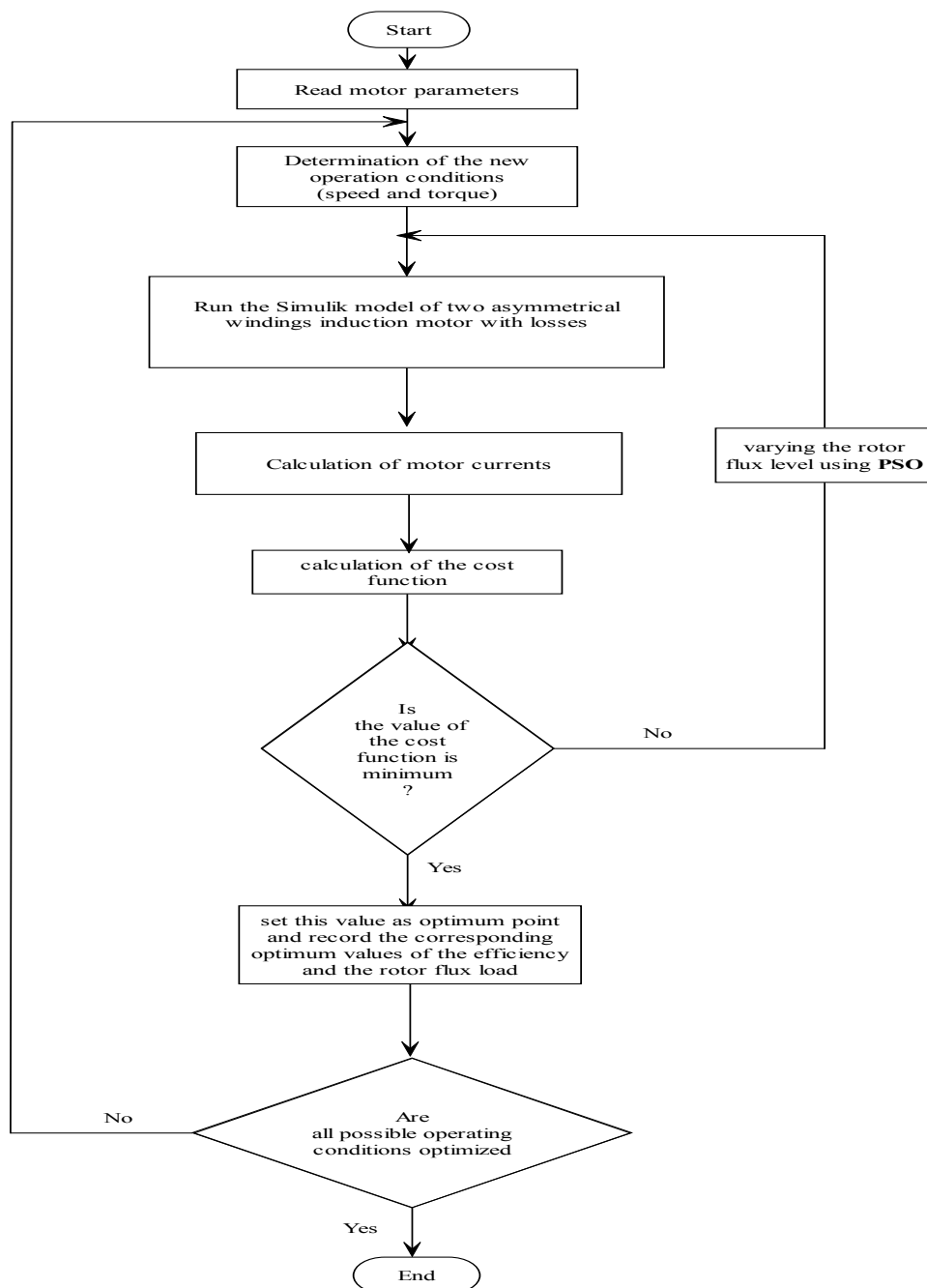


Figure 3. The flowchart of the execution of PSO



The optimal flux is the input of the indirect rotor flux oriented controller. The indirect field-oriented controller generates the required two reference currents to drive the motor corresponding to the optimal flux. These currents are fed to the hysteresis current controller of the two-level inverter. The switching pattern is generated according to the difference between the reference current and the load current through the hysteresis band. Figure 4 shows a whole control diagram of the proposed losses-minimization control system.

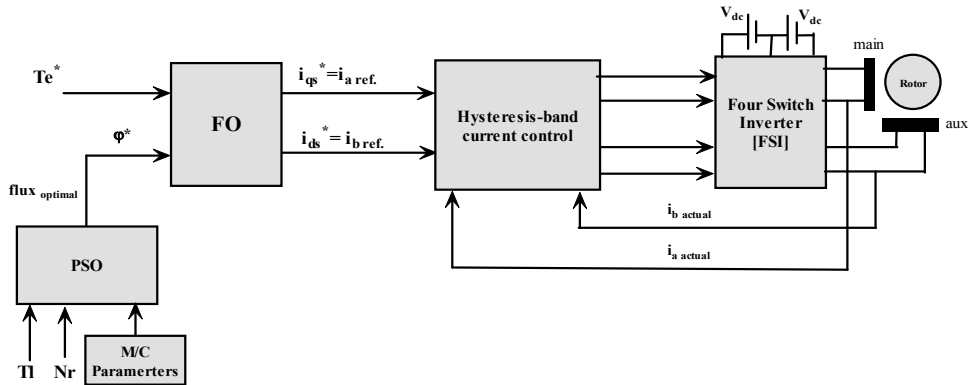


Figure 4. Proposed losses minimization control system

**2.4 Simulation study with FOC**

The motor used in this study has the following parameters, which were measured by using experimental tests . The FOC module is developed with closed loop speed control. The input of the FOC module is the reference speed and the rated rotor flux. The field-oriented controller generates the required reference currents to drive the motor as shown in fig.5. These currents are based on the flux level, which determines the value of direct current, and the reference torque, which determines the value of quadrature current. The reference torque is calculated according to the speed error. In this section, six-cases of motor operation with FOC are presented.

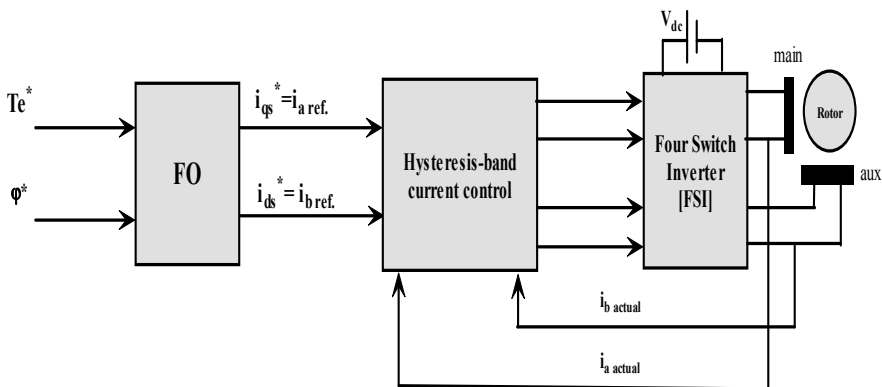
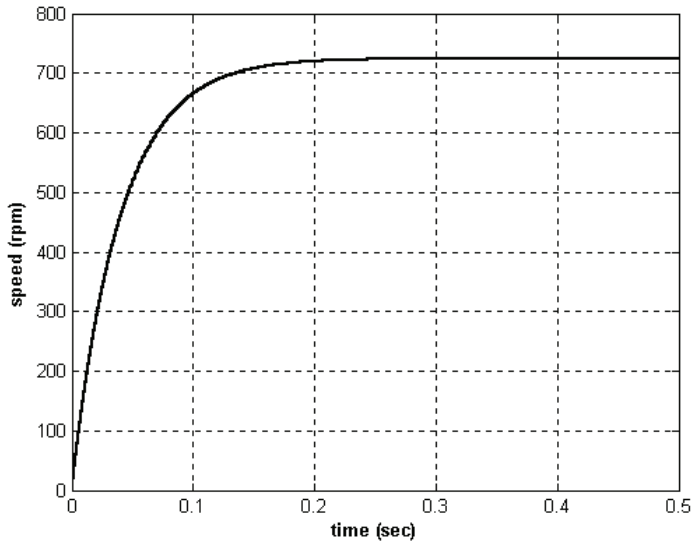


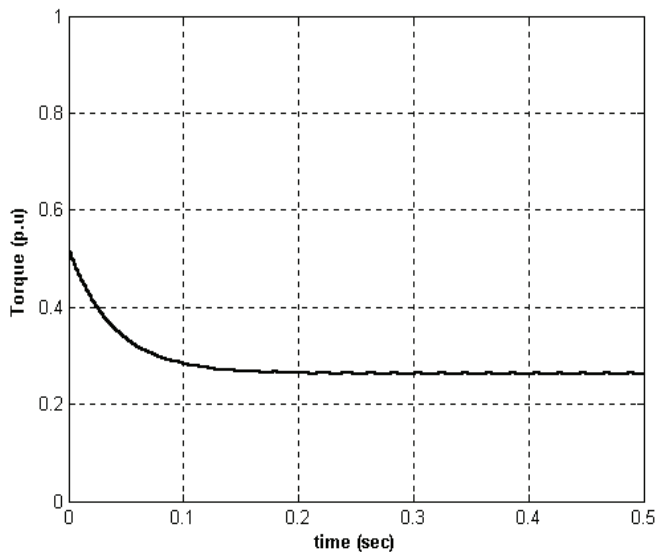
Figure 5. Block diagram of indirect rotor flux oriented control of the motor

Figure 6 shows the performance of the motor at case (1), where the motor is loaded by 0.25p.u. The control technique based on the PI controller has been developed. The proportional ( $K_p$ ) and integral ( $K_i$ ) constants of PI controller are chosen by trial and error. The speed-time curve for the motor is shown in fig. 6a. It is noticed that the speed oscillations are eliminated when the FOC is applied to the drive system.

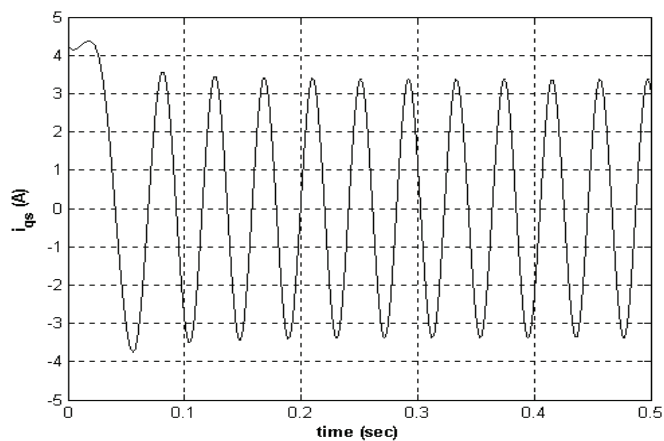
Figure 6b illustrates the developed torque-time curve of the motor. In this figure, the pulsating torque is eliminated.



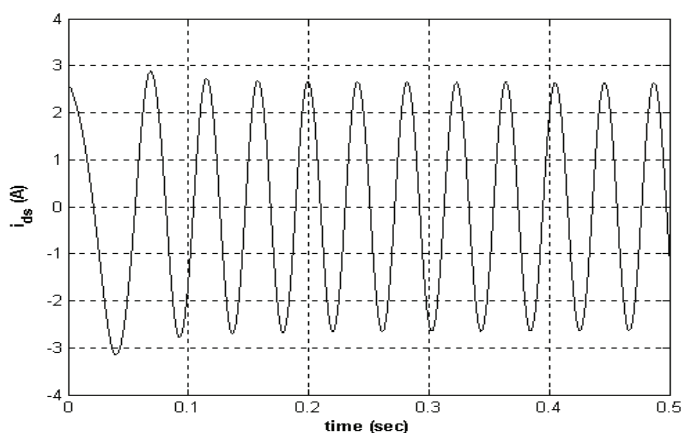
(a)



(b)



(c)



(d)

Figure 6. Simulation results of the motor at case (1), (a) Speed-time curve, (b) Torque-time curve, (c) The stator current in q-axis, (d) the stator current in d-axis

The efficiency is calculated from equation (33). Therefore, the efficiency is found to be equal to 33.85 %. The six-cases are summarized in Table 1.

Torque load ( $T_L$ ) p.u	Speed (N)	Flux rated p.u	Efficiency (%)
0.25	$0.5 N_{rated}$	1	33.85
0.375	$0.5 N_{rated}$	1	36.51
0.5	$0.5 N_{rated}$	1	48.21
0.6125	$0.5 N_{rated}$	1	55.15
0.75	$0.5 N_{rated}$	1	60.175
1	$0.5 N_{rated}$	1	63.54

Table 1. The summary of the cases

It is clear that, the indirect field-oriented controller with a rated rotor flux generally exhibits poor efficiency of the motor at light load. If significant energy savings need to be obtained, it is necessary to optimize the efficiency of the motor. The optimum efficiency of the motor is obtained by the evaluation of the optimal rotor flux level.

## 2.5 Losses minimization control scheme

As swarm intelligence is based on real life observations of social animals (usually insects), it is more flexibility and robust than any traditional optimization methods. PSO method is a member of the wide category of swarm intelligence methods (SI). In this section, PSO is applied to evaluate the optimal flux that minimizes the motor losses. The problem can be formulated as follows:

Minimize Total Losses which are a function of  $\lambda$ ,  $T_e$ , and  $\omega_r$

- The motor used as a two-asymmetrical windings induction motor. The parameters used are shown in Table 2 [10].

Parameters	Value
Population size	10
Max. iter	50
c1	0.5
c2	0.5
Max. weight	1.4
Min. weight	0.1
r1	[ 0,1]
r2	[ 0,1]
Lbnd	0.2
upbnd	2

Table 2. PSO Algorithm Parameters

A simplified block diagram of the proposed speed control scheme is shown in fig.7.

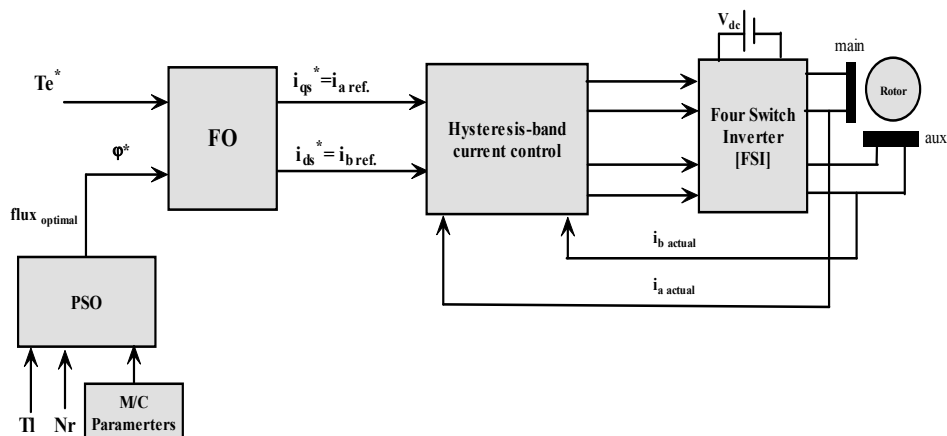
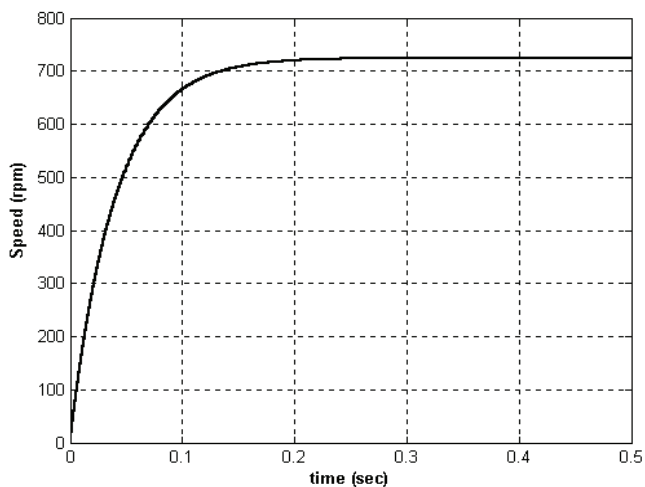


Figure 7. Proposed losses minimization control system

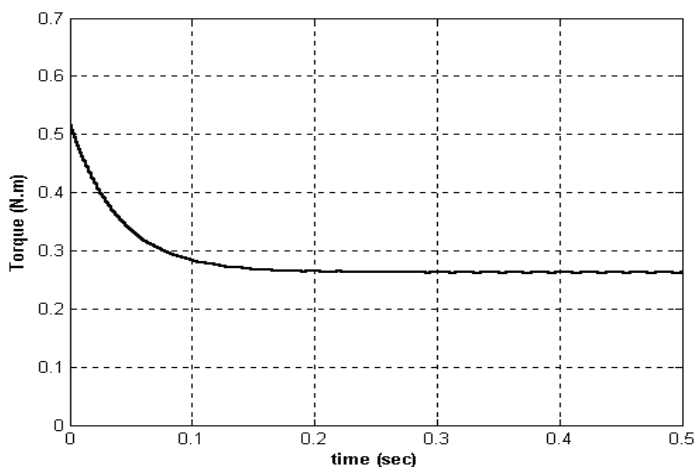
A Four-Switch Inverter (FSI) feeds the two-asymmetrical windings induction motor. The optimal flux is fed to the indirect rotor flux oriented control. The indirect field-oriented control generates the required reference current to drive the motor corresponding to this flux

## 2.6 Simulation results with FO based on PSO

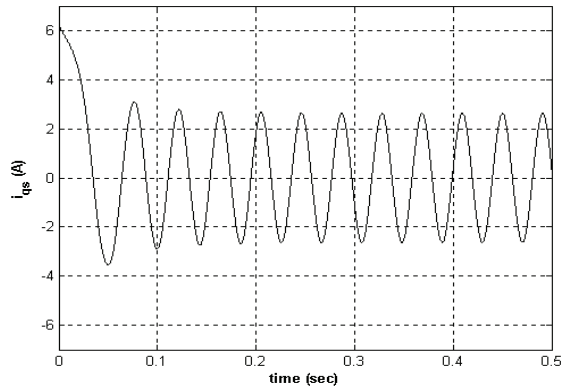
The optimal rotor flux provides the maximum efficiency at any operating point, next the previous six-cases are repeated by using FOC based on PSO. PSO will evaluate the optimal rotor flux level. This flux is fed to the FOC module. Figure 8 shows the performance of the motor at case (1), when PSO is applied side-by-side FOC.



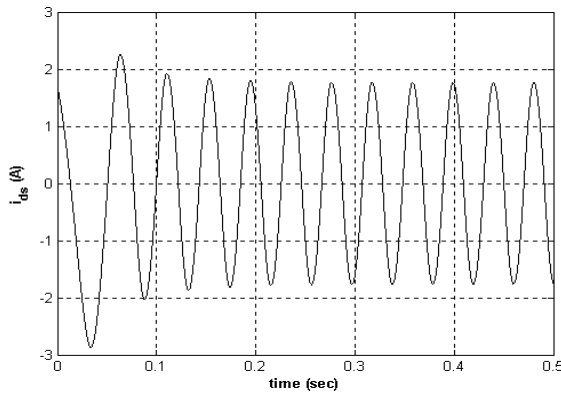
(a)



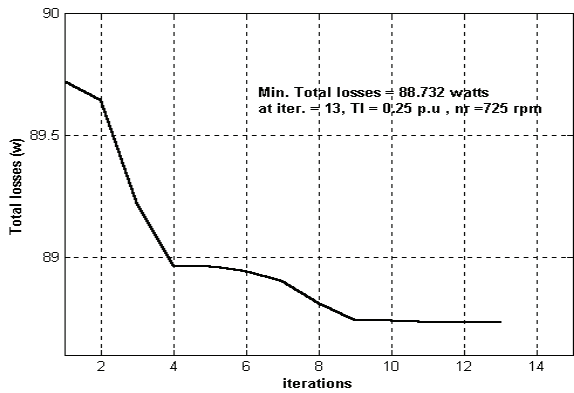
(b)



(c)



(d)



(e)

Figure 8. Simulation results of the motor at case (1). (a) Speed-time curve , (b) Torque-time curve, (c) The stator current in q-axis, (d) The stator current in d-axis, (e) Total Losses against iterations

It is noticed that, the PSO implementation increased the efficiency of the motor to 46.11% at half the rated speed. The six-cases are summarized in Table 3.

Torque load (TL) p.u	Speed (N)	Optimal flux(p.u)	Efficiency (%)
0.25	0.5 Nrated	0.636	46.11
0.375	0.5 Nrated	0.6906	49.15
0.5	0.5 Nrated	0.722	57.11
0.6125	0.5 Nrated	0.761	62.34
0.75	0.5 Nrated	0.8312	65.31
1	0.5 Nrated	0.8722	68.15

Table 3. The summary of the six-cases at optimal flux

In practical system, the flux level based on PSO at different operating points (torque and speed) is calculated and stored in a look up table. The use of look up table will enable the system to work in real time without any delay that might be needed to calculate the optimal point. The proposed controller would receive the operating point (torque and speed) and get the optimum flux from the look up table. It will generate the required reference current. It is noticed that, the efficiency with the FOC based on PSO method is higher than the efficiency with the FOC method only.

## 2.7 Experimental Results

To verify the validity of the proposed control scheme, a laboratory prototype is built and tested. The basic elements of the proposed experimental scheme are shown in fig. 9 and fig. 10. The experimental results of the motor are achieved by coupling the motor to an eddy current dynamometer. The experimental results are achieved using two control methods:

- Field-Oriented Control [FOC], and
- Field-Oriented Control [FOC] based on PSO.

The reference and the actual motor currents are fed to the hysteresis current controller. The switching pattern of the two-level four-switch inverter [FSI] is generated according to the difference between the reference currents and the load currents. Figure 11 shows the experimental results of the motor with FOC at case (1), where the motor is loaded by  $T_l = 0.25$  p.u.

The measured input power of the motor is about 169 watts, and then the efficiency is calculated about 44.92 %, whereas the efficiency with FOC is 32.30 %. It is noticed that, the PSO implementation increased the efficiency of the motor by 12.62 %. The cases are summarized in Table 4 as follows.

Cases	FOC			FOC with PSO		
	Flux p.u	Power Input	$\eta$ (%)	Flux p.u	Power Input	$\eta$ (%)
(1)	1	235	32.3	0.636	169	44.92
(2)	1	323	35.2	0.690	243	47.06

Table 5 the summary of the two-cases

The improvement of the efficiency in case (1) is around 12.62 % when PSO is applied. The improvement of the efficiency in case (2) is around 11.84 %, where the motor is loaded by  $T_l = 0.375$  p.u. These results demonstrate that, the FOC based on PSO method saves more energy than conventional FOC method. Thus, the efficiency with PSO is improved than it's at FOC.

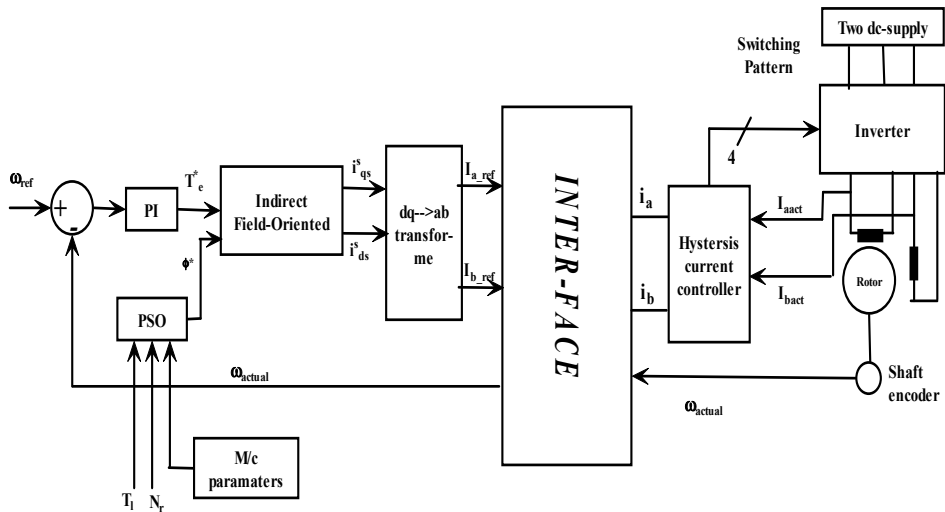


Figure 9. Block diagram of the proposed drive system

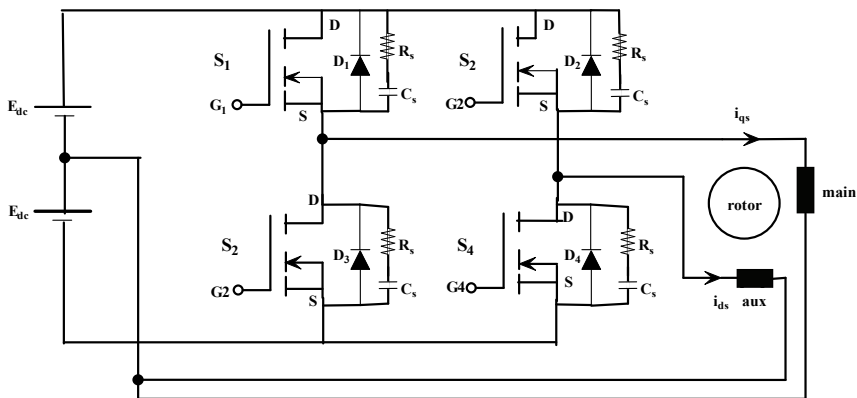


Figure 10. The power circuit of Four Switch inverter [FSI]



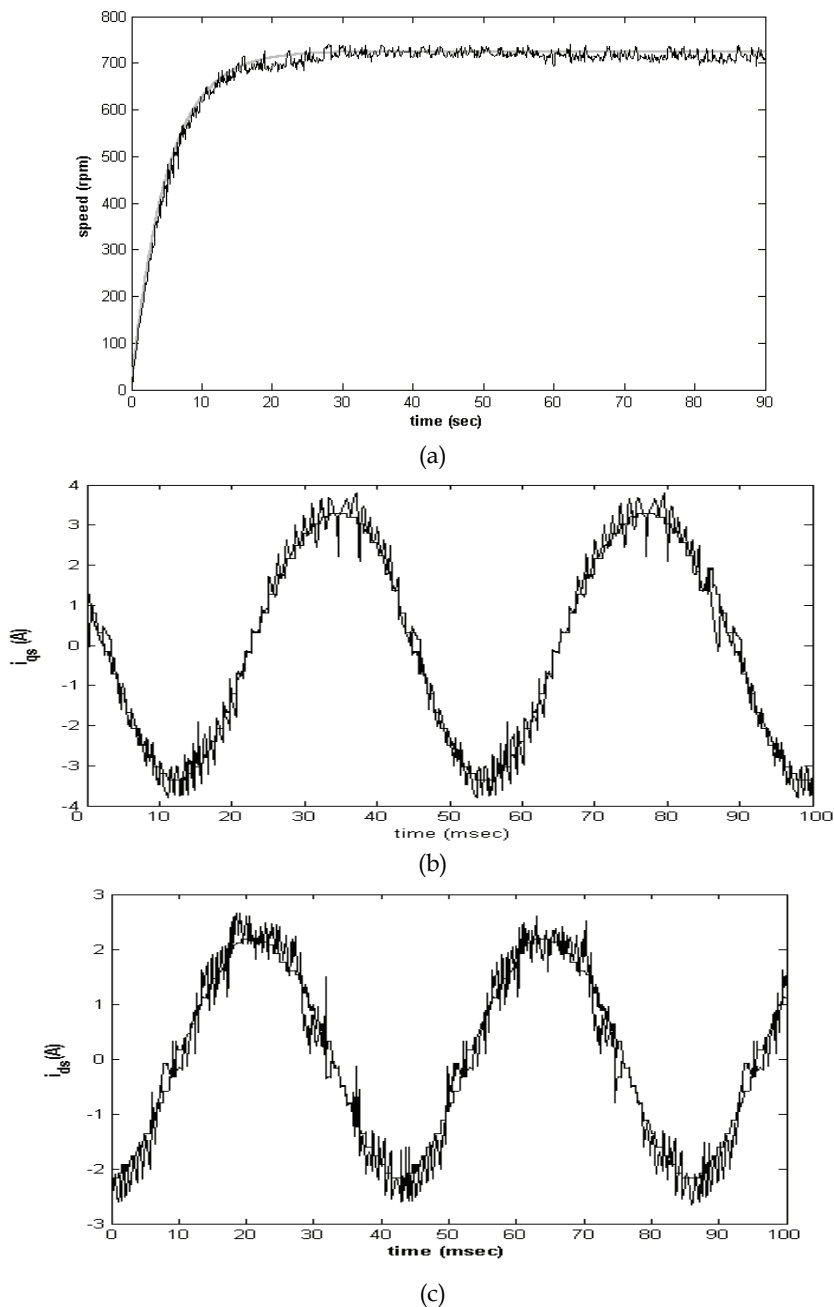


Figure 11. Experimental results of FOC method. (a) The reference and actual speed, (b) The reference and actual current in q-axis, (c) The reference and actual current in d-axis

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