

Using of Particle Swarm Optimization for Loss Minimization of Vector-controlled Induction Motors

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Abstract This paper presents a new online loss minimization for an induction motor drive. Among the many loss minimization algorithms (LMAs) for an induction motor, a particle swarm optimization (PSO) has the advantages of fast response and high accuracy. However, the performance of the PSO and other optimization algorithms depend on the accuracy of the modeling of the motor drive and losses. In the development of the loss model, there is always a tradeoff between accuracy and complexity. This paper presents a new online optimization to determine an optimum flux level for the efficiency optimization of the vector-controlled induction motor drive. An induction motor (IM) model in d-q coordinates is referenced to the rotor magnetizing current. This transformation results in no leakage inductance on the rotor side, thus the decomposition into d-q components in the steady-state motor model can be utilized in deriving the motor loss model. The suggested algorithm is simple for implementation.

Keywords Induction Machine, Loss Minimization, Magnetizing Current, Particle Swarm Optimization

1. Introduction

More than 50% of the electrical energy produced is consumed by motors, and induction motors are one of the most widely used in electrical drives because of their reliability, ruggedness and relatively low cost. The Induction motors have a high efficiency at rated speed and torque. However, at light loads, motor efficiency decreases drastically due to an imbalance between the copper and the core losses. Electrical motor losses consist of grid loss, converter loss, motor loss and transmission loss. In an effort to improve efficiency, there have been improvements in the materials, design and construction techniques. However, converter loss and motor loss are still greatly dependent on control strategies, especially when the motor operates at light load [1]-[2].

The control strategy to improve motor efficiency can be

divided into two categories: 1) search controller (SC) and 2) loss-model-based controller (LMC). The basic principle of the search controller is to measure the input power and then iteratively search for the flux level (or its equivalent variables) until the minimum input power is detected for a given torque and speed [3]. Important drawbacks of the search controller are the slow convergence and torque ripples. The model-based controller computes losses by using the machine model and selects a flux level that minimizes the losses [4]–[9]. LMC is fast and does not produce torque ripple. However, the accuracy depends on the correct modeling of the motor drive and the losses. Garcia *et al.* [4] developed a closed-form equation for the optimum flux level in the field-oriented frame. This approach is utilized in an even more simplified form by rearranging the stator resistor [5]. The same approach is utilized by Bernal *et al.* [6] in deriving a generalized model for the different types of motor. However, in the loss models used in [4]–[6], the leakage inductance is neglected in order to simplify the induction motor equivalent circuit. Lim *et al.* [7] developed a simplified loss model without sacrificing the leakage inductance, but the developed expression for an optimum flux level has a different format from the one in [4]. Nasir *et al.* [8] proposed a new online loss-minimization-based algorithm (LMA). In this paper by using the loss model of induction motor and by derived from the power equation, optimum magnetizing current for torque and speed of motor is obtained. In addition, Waheeda *et al.* [9] by using the loss model introduced in [8] and genetic algorithm, optimized the current magnetizing of induction motor to improve the efficiency.

In this research paper, an online loss minimization algorithm based on particle swarm optimization is proposed for loss minimization of FOC induction motor drives. The machine efficiency can be improved by reducing the electrical input power by minimizing the total losses. About 80% of the total losses are copper and iron losses [9]. Therefore, the focus of this paper is on the minimization of these losses which are collectively known as electromagnetic losses. Other losses are neglected. By a proper adjustment of the magnetic flux, an appropriate

balance between copper and iron losses is achieved to minimize the electromagnetic losses.

The ideal loss model will be an accurate and simple one. In this paper, an induction motor model with an iron loss resistor is referenced to the rotor magnetizing current, thus no leakage inductance is considered on the rotor side. Based on this model, we can derive the equation to find an optimum flux level in the same fashion as the one in [4], which is widely used for the development of the LMA, without neglecting leakage inductance. The performance of the proposed optimization algorithm is tested in simulation at different operation conditions. The result show that the performance of the drive with PSO algorithm is improved in terms of power saving and fast responding as compared to without optimization and other optimization algorithm such as LMA and GA.

2. Induction Motor and Loss Model

According to the literatures there are two approaches of modeling of IM taking in to account the iron loss, namely parallel and series iron loss model. Even though the series model has less number of differential equations, a parallel model is superior than the other one [9].

In this section we present the induction motor model and this loss model respectively.

Induction Motor Model

An equivalent circuit for IM can be varied by the different choices of flux linkage constants [8]. In this paper, we utilize an equivalent circuit referenced to the rotor magnetizing current by defining the rotor flux as $\psi_r = L_m i_{mr}$. The notion for this transformation is illustrated in Fig. 1. An iron loss resistor R'_f is added in parallel to the magnetizing inductance in a reference frame fixed to the rotor magnetizing current, and the d-axis has been aligned in the direction of the magnetizing current i_{mr} as shown in Figs. 2 and 3. Defining the differential operator $p \equiv d/dt$, the space vector motor model in a rotating reference frame is

given by (1)–(2), where $\omega_e = d\theta_e/dt$ is the electrical angular speed of the rotor and $\omega_r = d\theta_r/dt$ is the electrical rotor speed.

$$u_s = R_s i_s + pL'_s i_s + j\omega_e L'_s i_s + pL'_m i_m + j\omega_e L'_m i_m \quad (1)$$

$$i_s = i_m + i_f + i_r = i_m + (p + j\omega_e)(L'_m / R'_f) i_m + (p + j(\omega_e - \omega_r))(L'_m / R'_r) i_m \quad (2)$$

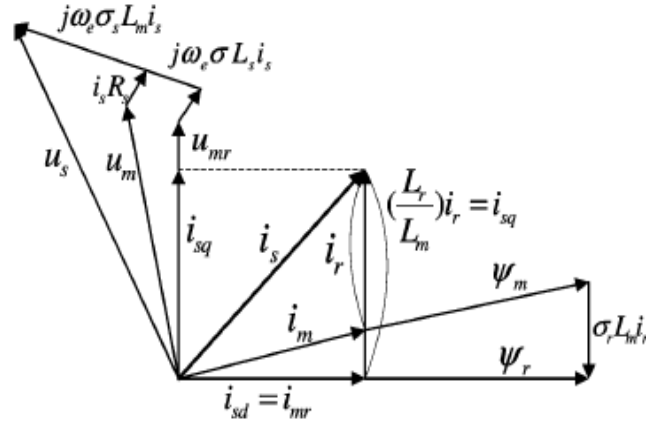


Figure 1. Phasor diagram of steady-state equivalent circuits of an induction motor [8].

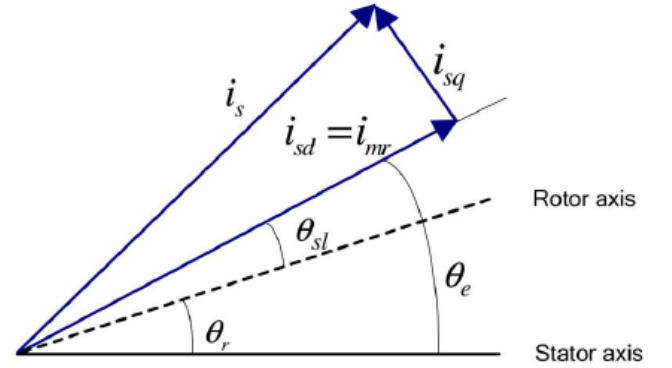


Figure 2. Phasor diagram of equivalent circuit and rotor field angle definition [8].

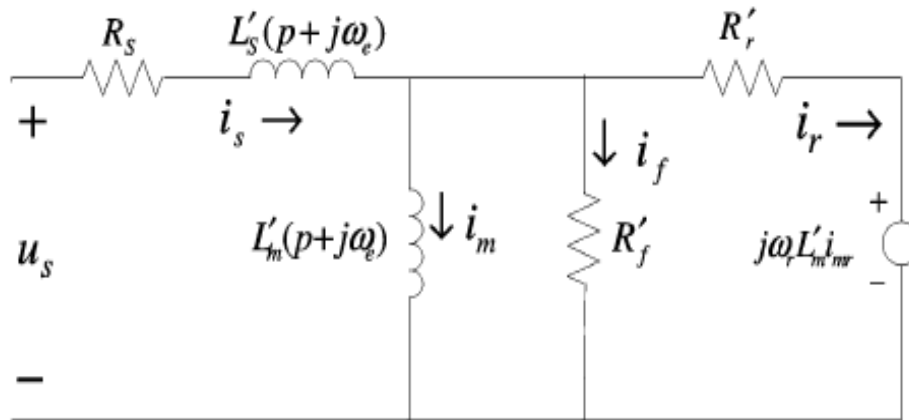


Figure 3. Space vector equivalent circuit in a rotor-flux-oriented reference frame including an iron loss resistor [8].

Using $u_s = u_{sd} + ju_{sq}$, $i_s = i_{sd} + ji_{sq}$, $i_m = i_{md} + ji_{mq}$ and $i_{mq} = 0$, $i_{md} = i_{mr} = \text{constant}$ for rotor-flux-orientation control scheme, we obtain from (1)-(2) that

$$u_{sd} = R_s i_{sd} + pL'_s i_{sd} - \omega_e L'_s i_{sq} + pL'_m i_{mr} \quad (3)$$

$$u_{sq} = R_s i_{sq} + pL'_s i_{sq} + \omega_e L'_s i_{sd} + \omega_e L'_m i_{mr} \quad (4)$$

$$i_{sd} = i_{mr} + p(L'_m / R'_f + L'_m / R'_r) i_{mr} \quad (5)$$

$$i_{sq} = \omega_e (L'_m / R'_f) i_{mr} + (\omega_e - \omega_r) (L'_m / R'_r) i_{mr} \quad (6)$$

Let $R_t = R'_f \parallel R'_r$, from (3) the magnetizing current can be expressed by:

$$\begin{aligned} i_{mr} &= 1 / (1 + p(L'_m / R'_r + L'_m / R'_f)) i_{sd} \\ &= 1 / (1 + pL'_m / R'_t) i_{sd} \end{aligned} \quad (7)$$

From (6), the slip speed can be derived as:

$$\begin{aligned} \omega_{slip} &= (R'_r / L'_m) i_{sq} / i_{mr} - \omega_e R'_r / R'_f \\ &= (R'_t / L'_m) i_{sq} / i_{mr} - \omega_r R'_t / R'_f \end{aligned} \quad (8)$$

In the steady state of this motor model, there is no leakage inductance on the rotor side and the sum of the recalculated rotor current i_r and the iron current i_f is perpendicular to the magnetizing current i_{mr} . Because of this, the circuit illustrates decomposition of the stator current i_s into the rotor flux-oriented components: $i_{sd} = i_{mr}$ which forms the flux ψ_r , and $i_{sq} = i_f + i_r$ which is related to the control of torque developed by the motor. Note that due to the existence of i_f , i_r controls the torque. From the motor model (3)–(6), the steady-state IM equivalent circuit in a field-oriented frame can be shown as in Fig. 4. Fig. 4(a) can easily be derived from (3) and (5) and Fig. 4(b) can easily be derived from (4) and (6) considering that the terms with differentiation will be zero in steady state [8].

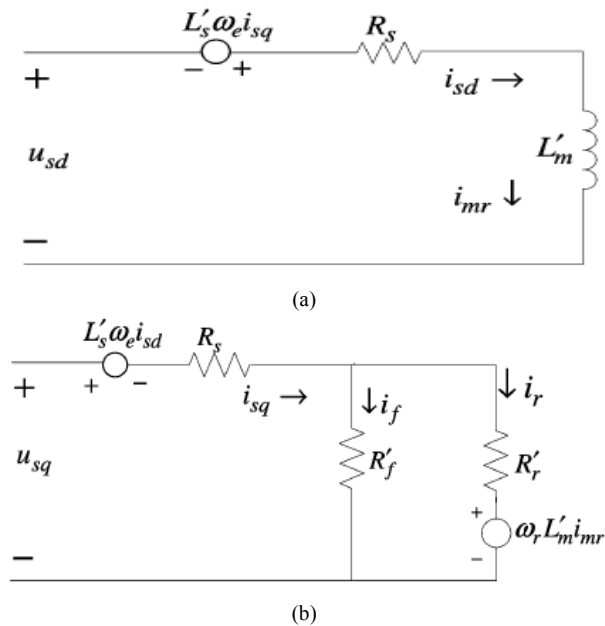


Figure 4. Steady-state IM equivalent circuit in: (a) d-axis and (b) q-axis [8].

Loss Model

In the development of the loss model, a typical method for model simplicity used in previous research is to ignore the leakage inductance. The decomposition feature of the proposed motor model makes the derivation of the loss model more straightforward without any assumption for model simplicity. Stator copper, rotor copper and iron losses dominate the overall power loss compared to stray, friction, windage, and converter losses [8]. In the current work, stray, friction, windage, and converter losses are neglected. From Fig. 4, the total loss is given by:

$$\begin{aligned} P_{total} &= P_{cu} + P_{iron} + P_{cur} \\ &= R_s (i_{sd}^2 + i_{sq}^2) + R'_f (i_{sq} - i_r)^2 + R'_r i_r^2 \end{aligned} \quad (9)$$

Where P_{cus} is stator copper losses, P_{iron} is iron losses and P_{cur} : is rotor copper losses. Since only the stator voltage and the current are real state variables, we need to express the total losses in terms of i_{sd} and i_{sq} .

From Fig. 4, the rotor current can be expressed as:

$$\begin{aligned} i_r &= i_{sq} - i_f = i_{sq} - (R'_r / R'_f) i_r - \omega_r (L'_m / R'_f) i_{sd} \\ &= (R'_f / (R'_f + R'_r)) i_{sq} - \omega_r (L'_m / (R'_f + R'_r)) i_{sd} \end{aligned} \quad (10)$$

Substituting i_r from (10) into (9) yields:

$$\begin{aligned} P_{total} &= R_d i_{sd}^2 + R_q i_{sq}^2, \\ R_d &= R_s + (L'_m)^2 / (R'_f + R'_r) \omega_r^2, \\ R_q &= R_s + R'_f R'_r / (R'_f + R'_r) \end{aligned} \quad (11)$$

The developed electrical torque can be expressed in different ways. From Fig. 4 and (10), one can express the torque as:

$$\begin{aligned} T_e &= (3/2) Z_p L'_m i_{mr} i_r = (3/2) Z_p L'_m (R'_r / (R'_f + R'_r)) i_{sq} i_{mr} - \\ &= (3/2) Z_p (L'_m i_{mr})^2 / (R'_f + R'_r) \omega_r \end{aligned} \quad (12)$$

By utilizing (8), torque can also be written as:

$$\begin{aligned} T_e &= (3/2) Z_p (L'_m i_{mr})^2 / R'_r \omega_{slip} \\ &= (3/2) Z_p L'_m i_{mr} i_{sq} - (3/2) Z_p ((L'_m i_{mr})^2 / R'_f) \omega_e \end{aligned} \quad (13)$$

If the second expression from (8) is used in (13), the torque expression (13) becomes the same as (12). The second term of the right side of (13) represents the loss in developed torque due to iron loss resistance. Since $R'_f \gg R'_r$ and $(R'_f + R'_r) \gg (L'_m i_{mr})^2$, torque (12)–(13) can be approximated as:

$$T_e \approx (3/2) Z_p L'_m i_{sq} i_{mr} = K_t i_{sq} i_{mr} \quad (14)$$

Where, $K_t = (3/2) Z_p L'_m$.

Then in the steady state $i_{sq} = T_e / (K_t i_{mr})$ and $i_{sd} = i_{mr}$. Thus the total loss in the steady state can be written in terms of magnetizing current i_{mr} [8].

$$P_{total} = R_d i_{mr}^2 + R_q (T_e / (K_t i_{mr}))^2 \quad (15)$$

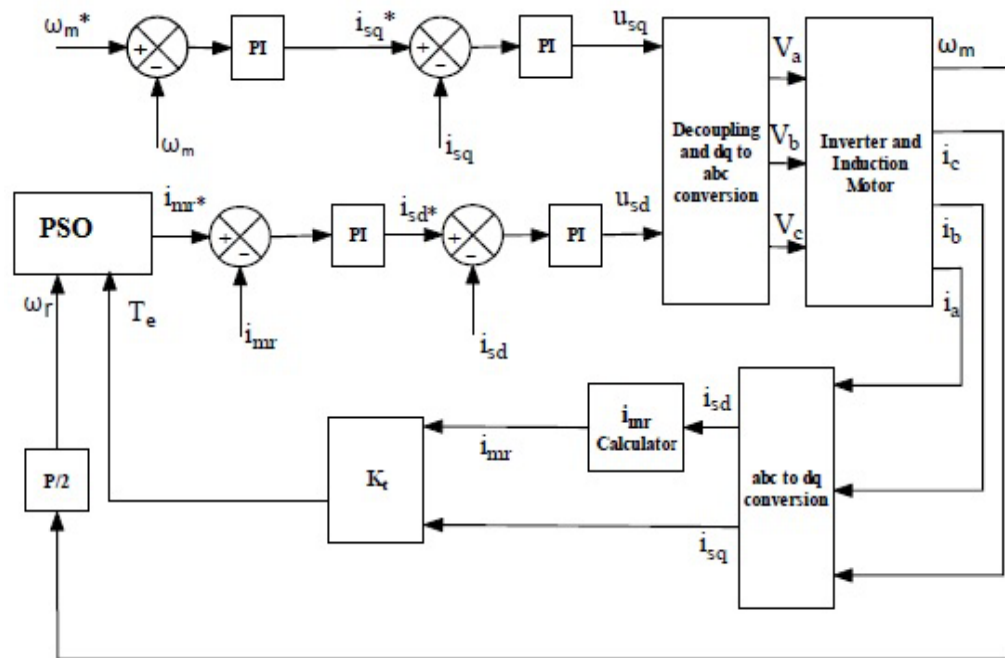


Figure 5. Block diagram of proposed loss minimization scheme for IM

3. Mechanism of Loss Minimization

The iron loss can be minimized by using a minimum possible field flux corresponding to a given torque and motor speed. The stator copper loss component due to the magnetizing current is consequently minimized. The flux can be reduced by decreasing the flux component current i_{mr} . Because under vector control condition, the electromagnetic torque produced is proportional to the product of the rotor flux and torque component of the stator current i_{sq} , in order to maintain the same torque with reduced rotor flux, this torque component of stator current must be increased. By a proper adjustment of the magnetic flux, an appropriate balance between copper and iron losses can be achieved to minimize the electromagnetic losses.

Block Diagram of the Proposed System

A simplified block diagram of the proposed optimization method is shown in Fig. 5; it is implemented in a classical rotor flux oriented control (FOC). In this scheme two phase currents are measured in order to calculate the electromagnetic torque. The torque and the speed are the parameters used by the particle swarm optimization algorithm to minimize the objective function which is the total loss of the motor (15). PSO algorithm output is a reference value of magnetizing current (which corresponds to minimum loss for the given torque and speed) to the motor.

PSO Algorithm Procedure

Some evolutionary optimization algorithms like GA, ICA, honey bee algorithm [10]-[11] are presented for optimization of complicated fitness functions.

This optimization procedure consists of searching the optimum magnetizing current (flux) value for a given torque and speed relying on PSO algorithm, [12]. PSO is an efficient algorithm for population-based optimization invented by Kennedy and Eberhart (1995) and further developed in recent years. It is inspired by the social behavior of animals, e.g. bird flocking or fish schooling. Compared with other optimization algorithms, PSO is particularly well suited to complex optimization problems, with faster convergence rate. An additional advantage is that PSO requires fewer parameters for regulation than other optimization algorithms. In PSO, a "particle", located at any point in D-dimensional search space, represents a potential solution to the optimization problem.

1) Possible Topologies of PSO:

- *Star topology*: In this topology each particle can communicate with members of swarm and each particle tends to flow global best of population. This topology is used in global best algorithm.
- *Ring topology*: In this topology each particle communicates with N neighbor particles and each particle tends to follow movement of best particle among neighbor particles. This topology is used in local best algorithm.
- *Wheel topology*: This topology is based on movement of peregrine birds that all particles completely follow one leader particle. In this topology, members of swarm communicate with one particle known as canonical particle that regulates self-position to best particle position, and if this regulation improves its fitness, declares this improvement to other particles. This topology is used in individual best algorithm.

These topologies are shown in Figs. 6.

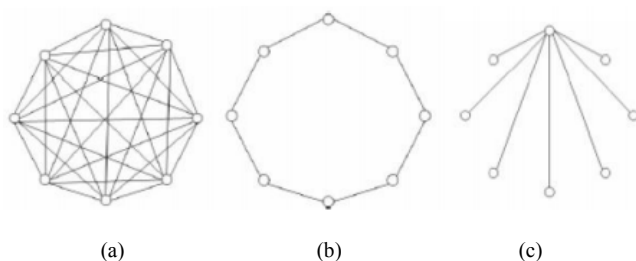


Figure 6. Topologies of PSO: a) Star topology b) Ring Topology c) Wheel Topology

Types of PSO Algorithm

Based on these topologies three type of algorithm have been developed, which are as follows:

- *Individual best*: This algorithm is based on wheel topology and is similar to one group of climbers that are not connected to each other and move based on self-experiences along their paths.
- *Local best*: this algorithm uses ring topology, so that particles are affected by best particle in neighbor region.
- *Global best*: This algorithm applies star topology. Movement of each particle is based on self-experiences and movement of other particles. Movement of particles completely depend on other particle's movement.

Since in the present work global best method is used, this method is briefly described in the next section.

2) Global Best Method

Implementation steps of this algorithm are as follows [12]:

1-Random generating of primary population,

2-Particles fitness calculation respect to their current position.

3-Comparsion current fitness of particles with their best experience:

$$\text{if: } F(P_i) > pbest_i \\ \text{then } pbest_i = F(P_i), \quad \overline{xpbest}_i = \overline{x}_i(t)$$

4-Comparsion of the current fitness of particles with the best experience of all particles:

$$\text{if: } F(P_i) > gbest \\ \text{then } gbest = F(P_i), \quad \overline{xgbest} = \overline{x}_i(t)$$

5-Change in velocity of each particle according to (16):

$$\overline{v}_i(t) = \overline{v}_i(t-1) + r_1 c_1 (\overline{xpbest}_i - \overline{x}_i(t)) + r_2 c_2 (\overline{xgbest} - \overline{x}_i(t)) \quad (16)$$

6-The particle position change to new position according to (17):

$$\overline{x}_i(t) = \overline{x}_i(t-1) + \overline{v}_i(t) \quad (17)$$

7- Algorithm is iterated from step 2 until the convergence is obtained.

4. Simulation Results

The simulation of efficiency optimization of induction motor using particle swarm optimization algorithm is performed by using Matlab/simulink software, the results of different cases are given below. The induction machine parameters are shown in TABLE 1. The aim to use the optimization algorithm is to let the motor work at variable flux to minimize the loss and hence optimize efficiency, also to prove the effectiveness and the robustness of the proposed algorithm the motor drive was tested at different range of speeds.

Table 1. Induction Motor and PSO Data Used For Simulation

Parameter	Value
Power	9 kW
Voltage	460 V
Stator resistance	0.399Ω
Referred rotor resistance	0.3107Ω
Referred iron loss resistance	570.7Ω
Number of pole pair	2
Referred stator inductance	6.3mH
Referred mutual inductance	53mH
Inertia constant	0.05 kgm ²
Rated speed	1750 rev/min
Friction coefficient	0.0006
Frequency	60Hz
Inertia Weight	1
Personal Learning Coefficient (c1)	1
Global Learning Coefficient (c2)	1

Using the PSO algorithm in MATLAB, loss equation (15) is minimized to obtain the value of reference magnetizing current. Simulation is done for different speeds and torques and loss is found to be reduced very much and efficiency is improved at light loads with PSO algorithm.

Simulation is carried out for a speed of 180rad/s and a torque of 5Nm. Using PSO algorithm the magnetizing current obtained is 5.98A and this reference value is applied to the motor for loss minimization (See Fig. 10).

When the magnetizing current is reduced to 5.98A, there will be corresponding reduction in flux level and thus core loss is reduced. But to meet the torque, according to equation (14) there should be corresponding increase in q-axis stator current. Then the copper loss is increased. The maximum efficiency will be obtained for the motor when core loss equals copper loss.

PSO finds the magnetizing current for a particular torque and speed where efficiency is maximum. Fig.7 to Fig.11

show the speed, torque, three phase stator currents, magnetizing current and q-axis stator current respectively. The results show that by using PSO algorithm for optimization of magnetizing current, performance of

induction machine do not change. However, efficiency of motor improves in this optimization. At steady state since $i_{sd} = i_{mr}$, the magnetizing current is minimized to 5.98A corresponding to the given torque and speed.

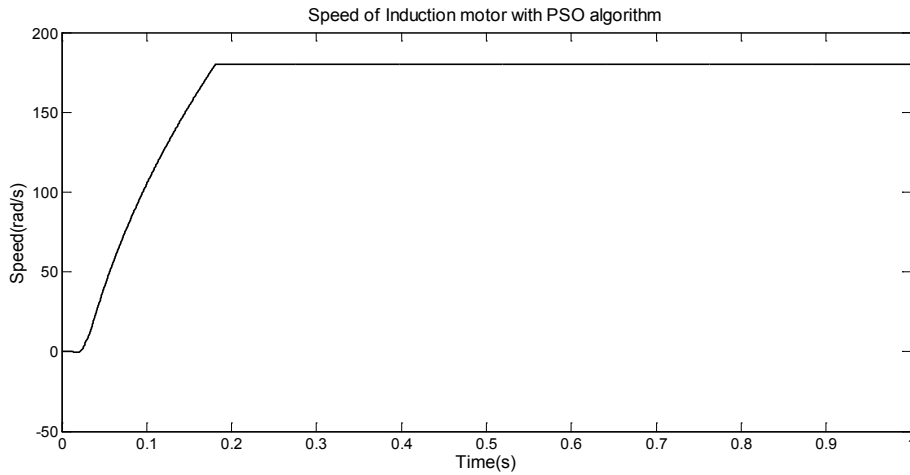


Figure 7. Speed of induction motor with PSO algorithm

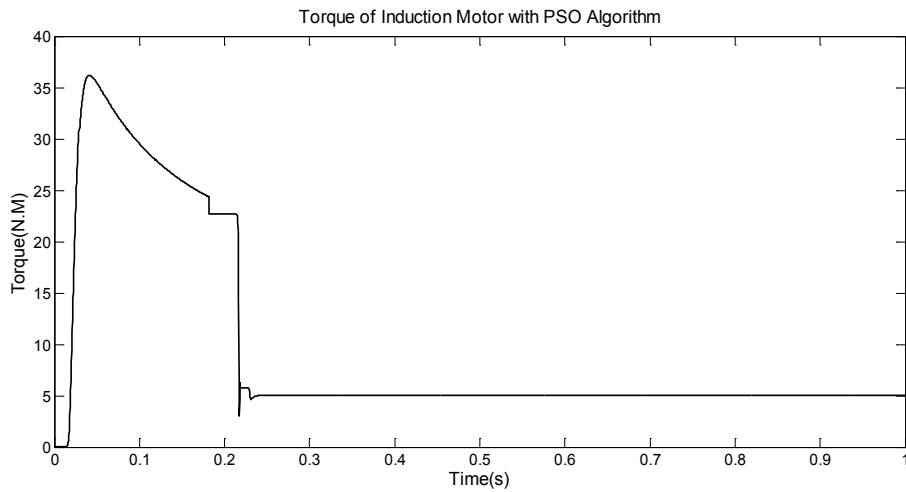


Figure 8. Torque of induction motor with PSO algorithm

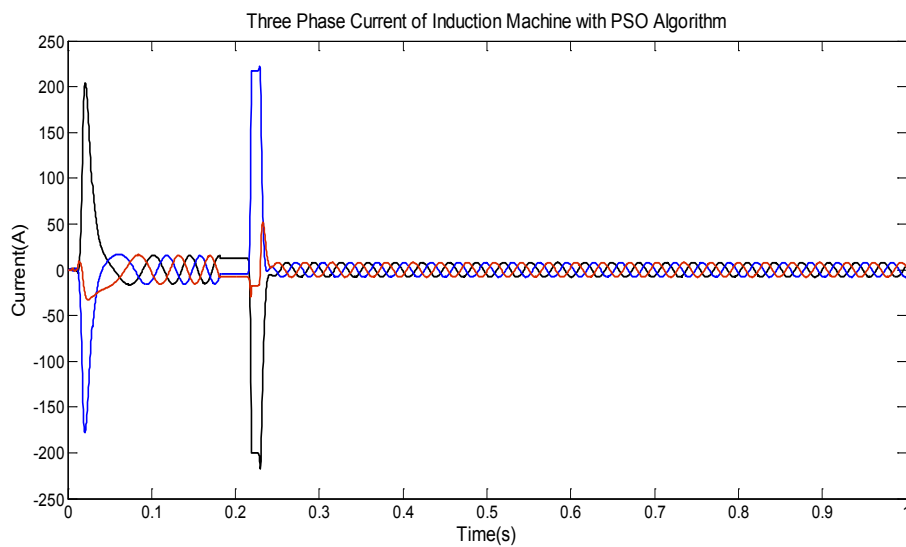


Figure 9. Three phase currents of induction motor with PSO algorithm

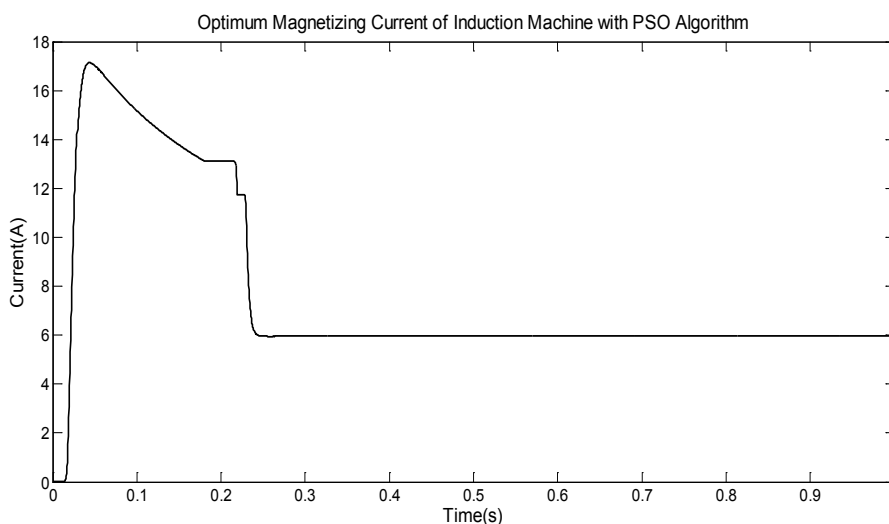


Figure 10. Optimum magnetizing current of induction machine with PSO algorithm

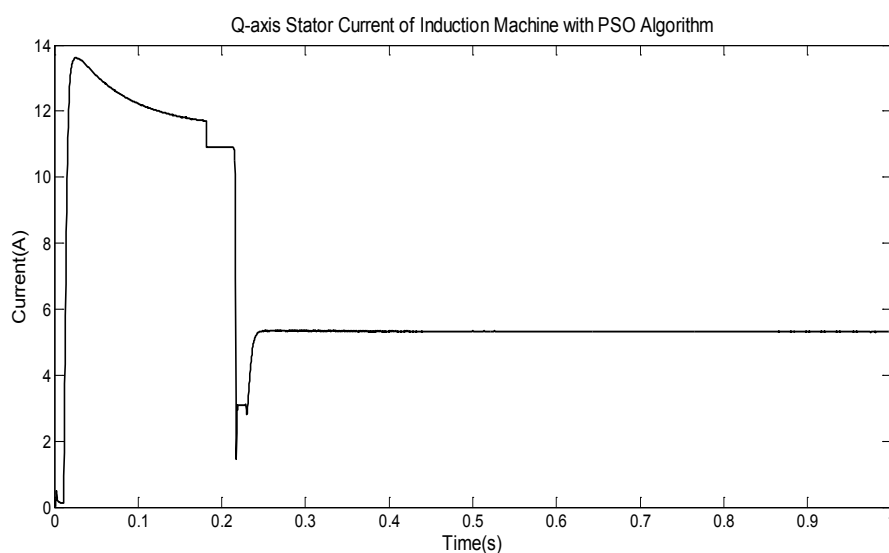


Figure 11. Q-axis current of induction machine with PSO algorithm

Simulations are done for speeds 157rad/s and 100rad/s with different load torques with and without optimization. Efficiency vs output power and power loss vs output power are plotted for the above two cases. In both cases the maximum efficiency is almost same. Figs. 12 and 13, represent the efficiency and power loss with and without PSO at 100rad/s and Figs.14 and 15, represent the efficiency and power loss with and without PSO at 157rad/s.

Figs. 12 and 14 show that there is great efficiency improvement at light loads when using PSO procedure. Thus large amount of energy saving can be done using this method.

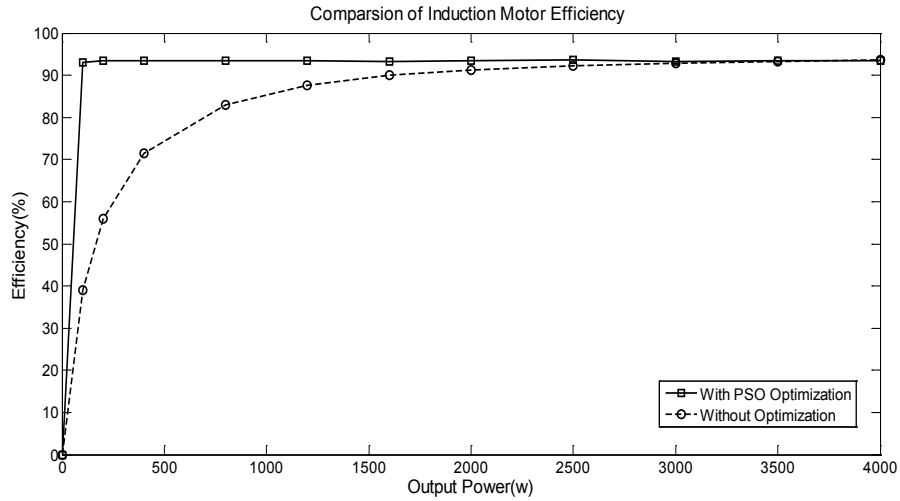


Figure 12. Motor efficiency for a speed of 100rad/s

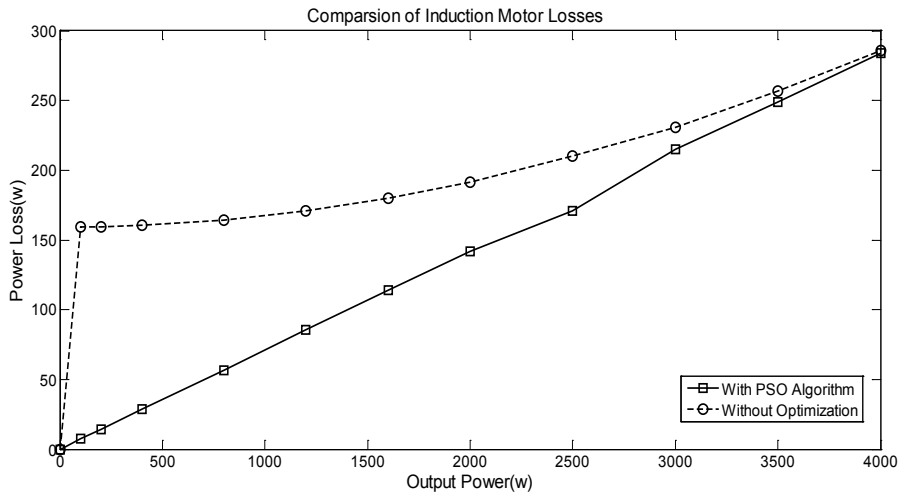


Figure 13. Motor power loss for a speed of 100rad/s

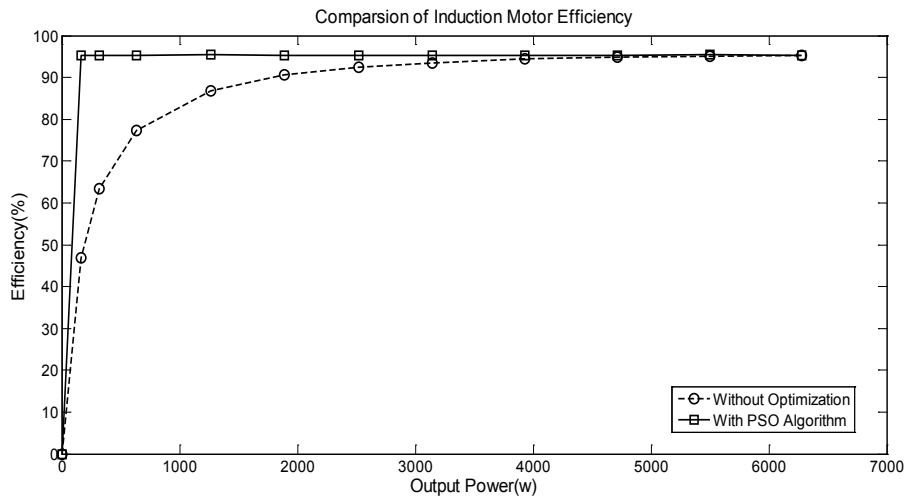


Figure 14. Motor efficiency for a speed of 157rad/s

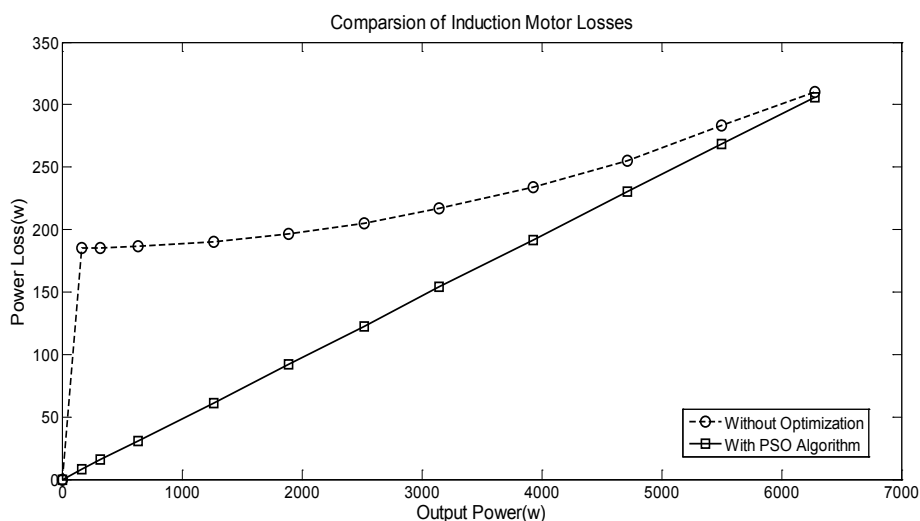


Figure 15. Motor power loss for a speed of 157rad/s

Table 2. Comparison of Induction Machine Parameters in PSO Procedure and Without Optimization

T_e	Power Loss (With PSO)	Power Loss (Without PSO)	I_{mr} (With PSO)	I_{mr} (Without PSO)	I_{sq} (With PSO)	I_{sq} (Without PSO)	Efficiency (With PSO)	Efficiency (Without PSO)
1	7.96	198.9	2.66	18.87	2.26	0.92	95.3	48.64
2	16.13	199.2	3.77	18.86	3.396	0.727	95.2	64.94
4	32.68	200.1	5.33	18.87	4.75	1.359	95.19	78.47
8	63.80	203.8	7.53	18.87	6.73	2.66	95.19	87.67
12	95.30	210.2	9.22	18.87	8.21	4.01	95.2	91.17
16	126.2	219.5	10.65	18.87	9.37	5.40	95.23	92.94
20	158.9	230.2	11.91	18.87	10.57	6.16	95.19	94.61
25	198.7	248	13.31	18.87	11.82	8.32	95.19	94.79
30	237.7	270	14.58	18.87	12.98	10	95.2	95.25
35	278.5	295	15.75	18.87	13.96	11.65	95.18	95.53
40	317.8	325.4	17.81	18.87	15.86	13.36	95.19	95.68

Furthermore other simulations are done for comparison of values of the magnetizing current i_{mr} , q-axis stator current i_{sq} and efficiency for different load torques at a constant speed of 180 rad/s for with PSO algorithm and without optimization (See Table. 2). From this, it can be seen in simulation with PSO algorithm when the load torque is increased, value of i_{mr} (optimum value) at minimum loss condition also increased. Since i_{sq} increasing, the required torque is developed to meet the torque demand. Nevertheless in simulation without optimization values of magnetizing current are constant.

When load torque is nearer or at rated value, the reference magnetizing current is at rated value, too. Thus the flux of the machine will be at rated value at rated condition. So the machine can easily run at rated load torque without any torque capability problem. Motor efficiency is almost constant at all loads and it is 95%.

5. Conclusions

A new online loss-minimization algorithm based on PSO

algorithm is proposed and simulated for vector controlled induction motor drive. The advantages of using PSO have been highlighted. Maximum efficiency is obtained for all speeds ranges and torques, because with PSO global optimum is more probable. Extensive simulation results of proposed optimization method and FOC method without optimization are investigated and compared and the superiority of the former is confirmed. It appears that non negligible energy can be saved with the use of PSO.

Nomenclature

R_s, R_r	Resistances of the stator and rotor phase winding.
L_s, L_r	Self-inductances of the stator and the rotor.
L_m	Magnetizing inductance.
R'_r	Referred rotor resistance.
R'_f	Referred iron-loss resistance
L'_s, L'_m	Referred stator and magnetizing inductances.
Z_p	Stator voltages complex space vector.

u_s, i_s vectors.	Stator voltage and current complex space
ω_e	Angular speed of the rotor flux.
ω_r	Electrical rotor speed.
ω_m	Mechanical rotor speed.
θ	Rotor flux angle.
$F(P_i)$	Fitness of i-th particle
$\bar{x}_i(t)$	Position of the i-th particle
$pbest_i$	Best fitness of i-th particle
$xpbest_i$	Position of the i-th particle related to $pbest_i$
$gbest$	Best fitness of all particles in the population
$xgbest$	Position of the particle with the best fitness
r_1, r_2	Random numbers in (0,1) distance
c_1, c_2	Acceleration coefficients

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