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Losses Optimization of Induction Motor Using Particle Swarm Optimization Technique

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ABSTRACT

This paper is aimed at using Particle Swarm Optimization technique (PSO) to minimize the losses in an induction motor in order to improve the efficiency. The optimal design of an induction motor for minimum copper losses is taken to minimize the loss of the motor. This was carried out using the power loss equation as the objective function and coding in m-file, which is simulated alongside the PSO program in MATLAB in order to achieve the best values of the parameter chosen and thereby having a minimized losses. The result of the simulation shows an improvement of 4.23% in the machine's efficiency (from 93.24% to 97.47%). Hence, indicating that with the modification of the chosen parameters, the efficiency of the induction motor can be improved. However, although the PSO is a faster convergence optimization technique, other techniques can be used in order to make a comparison of the efficiency value.

1. Introduction

An alternating current (AC) motor is an electric motor driven by an alternating current supply. The AC motor commonly consists of two basic parts; stator, which has coils supplied with alternating current to produce a rotating magnetic field, and rotor which is attached to the output shaft producing a second rotating magnetic field. The rotor magnetic field may be produced by permanent magnets, reluctance saliency, direct current (DC) electrical winding or alternating current (AC) electrical winding.

There are basically two main types of AC motors; synchronous and asynchronous (induction) motors. The induction motor (asynchronous motor) always depend on a small difference in speed between the stator rotating magnetic field and the rotor shaft speed called slip to induce current (rotor current) in the rotor AC winding. There are basically two types of induction motor depending upon the input supply. There are single phase induction motors and three phase induction motors. Single-phase induction motors are not a self-starting motor and 3-phase induction motor are a self-starting motor. The 3-phase induction motors are commonly used as industrial drives due to their self-starting ability, they are also dependable and cost-effective. Single-phase induction motors are used broadly for smaller loads, such as household appliances like fans, water pumps. Over 50% of the electrical energy produced is consumed by motors, with induction

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motors been generally applied in electrical drives due to its robustness, sureness and economic value (Rashtchi & Bizhani, 2015).

Optimization has been defined as a way of making system functional involving determination of the optimum values of given objective function of a domain, by systematically selecting the input values from a range of constraints and computing the value of the function in order to achieve the best value or result (Merriam-Webster's dictionary, 2019). Owing to the high energy utilization and the large number of installed generating units, a small enhancement in efficiency can have significant impact on the entire energy consumptions. Induction motor losses are usually split into five components: stator copper losses, rotor copper losses, iron losses, mechanical losses and stray losses.

1.1. Overview of PSO Algorithm

Particle Swarm Optimization technique (PSO) was developed by James Kennedy and Russell Eberhart in 1995 to serve as an efficient technique for population-based optimization and has been reviewed further in recent years (Kennedy & Eberhart, 1995). PSO is based on the analogy of swarm of bird and school of fish (Lim & Nam, 2004). PSO mimics the behaviour of individuals in swarm to minimize the survival of the species.

In PSO, each individual makes his decision using his own experience together with other individual experience (Clerc & Kennedy, 2002). The algorithm, which is based on metaphor of social interaction, search's a space by adjusting the trajectories of moving points in a multidimensional space. The individual particles are drawn stochastically towards the position of present velocity of each individual, their own previous best performance, and the best previous performance of their neighbour (Abido, 2002).

There are three basic algorithms involved in the search process of PSO: Individual best, local best and global best (Rashtchi & Bizhani, 2015). The PSO has an attractive feature of having an easy way of implementing and no gradient information is required. Which can be used to solve a wide dimension of different optimization problems (Allaoua *et al*., 2008). Like other optimization techniques, the simulated annealing, ant colony, the PSO involves iterative process based in random decisions (Kikpatrick *et al*., 1983; Dorigo & Stützle, 2004). Unlike the Generic Algorithm and other empirical algorithms, PSO has the flexibility to manage the stability between the global and local exploration of the search space. This distinctive characteristic of PSO overcomes the early convergence problem and improves the search capability (Kusko & Galler, 1983).

The particle swarm optimizer has been found to perform better in optimization as compared to the composite optimization, the firefly algorithm (Lukasik & Żak, 2009; Gupta et al, 2015). In comparison with other optimization algorithms, PSO is particularly well appropriate to complex optimization problems, with faster convergence rate. In addition, it requires lesser parameters for regulation than other optimization algorithms (Rashtchi & Bizhani, 2015).

1.2. Review of Related Literature

An important input to loss reduction in motor drives was presented, which shows that motor losses can be reduced largely by individually controlling the voltage and frequency for AC motors, and the field current and armature voltage for DC motors (Kusko & Galler, 1983). Fuzzy logic controller was also used in minimizing the losses of a separately excited DC motor. This was carried out by finding the optimal field current that produces the optimal flux with respect to the load torque to the motor shaft (Issa, 2013).

A review of Efficiency Optimization of Induction Motor Drive was carried out, it was concerned on performance based variables for minimization. In their review, the utilization of Artificial Intelligence (AI) techniques such as artificial neural network, fuzzy logic, expert systems; Genetic algorithm and differential evolution were carried out (Gupta *et al*., 2015). The minimization of losses of a vector controlled induction motor using particle swarm optimization was also presented. It considered also, both the copper (stator and rotor), and the iron losses for minimization. Using the steady state component and torque component of the stator current as variables (Rashtchi & Bizhani, 2015).

The optimization of losses of an induction motor was carried out where both copper and iron losses only were considered for minimization using the Genetic algorithm (Tyo *et al.*, 2016). Based on the above literature review, this paper will be presenting a technique of loss minimization of the copper losses using the particle swarm optimization (PSO) method. It will first derive the loss equation followed by coding in MATLAB and subsequently simulating. The PSO has been observed to have a higher convergence rate and more efficient as compared to the usual direct search optimization technique.

2. Methodology

Optimization of induction motor design is one of the important aspects in electrical engineering design. The induction motor design optimization problem is formulated in mathematical terms as a nonlinear programming problem. The paper consists of copper loss power equation (objective function), which is minimized to achieve the optimal efficiency. The algorithm of the PSO code employed is as follows (Mishra & Narain, 2013):

The i^{th} particle in the swarm in the d-dimensional space is represented as:

$$X_i = (x(i,1), x(i,2), x(i,3), \dots\dots\dots\dots\dots . x(i,d)) \tag{1}$$

The best previous positions of the i^{th} particle are represented as:

$$P_{best} = (P_{best}(i,1), P_{best}(i,2), P_{best}(i,3), \dots\dots\dots\dots\dots . P_{best}(i,d)) \tag{2}$$

The index of the best particle among the group is G_{best} *(i, d).*

Velocity of the i^{th} particle is represented as:

$$V_i = (v(i,1), v(i,2), v(i,3), \dots\dots\dots\dots\dots . v(i,d)) \tag{3}$$

The updated velocity and the distance from P_{best} *(i, m)* to G_{best} *(i, m)* is given as;

$$V(i,m^{t+1}) = W^{*}V(i,m^{t}) + C_1^{*}rand(\quad)^{*}\left(P_{best}(i,m) - X(i,m^{t})\right) + C_2^{*}rand(\quad)^{*}(G_{best}\,(i,m) - X(i,m^{t})) \tag{4}$$

$$X(i,m_{(t+1)}) = X(i,m_{(t)}) + V(i,m_{(t+1)}) \tag{5}$$

For *i* =1, 2, 3.......n.

m = 1, 2, 3......d.

where *n*, is the Number of particles in the group, *d* is the dimension index, *t* is the Pointer of iteration, *V(i, m(t))* is the Velocity of particle at iteration *i*, W is the Inertia weight factor, C_1 and C_2 are the Acceleration Constant, rand ( ) is the Random number between 0 and 1, *X(i, m(t))* is the Current position of the particle *i* at iteration, P_{best} is the Best previous position of the i^{th} particle, G_{best} is the Best particle among all the particle in the swarming population. The flow chart of the process is presented in Figure 1.

2.1 Derivation of Copper Loss Power Equation

The objective function, the Copper loss (P_c), comprises of the rotor bar loss(P_b), end ring loss (P_e), and the stator copper loss (P_s).

Stator Copper Loss, P_s

$$P_s = mI_s^2 R_S \tag{6}$$

But $R_s = \rho_c l_{s/A_s}$ (7)

Also,

$$A_s = {}^{I_s}/_{\delta_s} \tag{8}$$

I_s is the stator current (A), R_s is the resistance of stator (Ω), ρ_c is the resistivity of copper(Ω/m), A_s is theCross sectional area of the stator (m^2), δ_s is the stator current density(A/mm^2), m is the number of phase, l_s is the stator length (m).

$$P_s = mI_s\delta_s\rho_c l_s. \tag{9}$$

Rotor Bar Loss (P_b*)*

$$\mathrm{P_b = I_b^2 R_b N_r} \tag{10}$$

But

$$R_b = \rho_c l_{b/}\mathrm{A}_{\boldsymbol{b}} \tag{11}$$

Also,

$$A_b = I_b/\delta_b \tag{12}$$

I_b is theRotor bar current (A), R_b is the resistance of rotor bar (Ω), A_b is the Cross sectional area of the rotor (m^2), δ_b is the rotor bar current density(A/mm^2), N_r, is the armature slots l_b is the rotor length (m).

$$\mathrm{P_b} = \mathrm{I_b}\delta_\mathrm{b}\rho_c \mathrm{l_b}\mathrm{N_r} \tag{13}$$

<u>End Ring Loss (P_e)</u>

$$\mathrm{P_e} = 2\mathrm{I_e^2R_e} \tag{14}$$

But

$$\mathrm{R_e} = {}^{\rho_c l_e}/_{A_e} \tag{15}$$

$$l_e = \pi \mathrm{D_e} \tag{16}$$

$$A_e = I_e/\delta_e \tag{17}$$

Then,

$$R_e = \delta_e\rho_c\pi D_e/I_e \tag{18}$$

I_e is the end ring current (A), R_e is the resistance of end ring (Ω), A_e is the Cross sectional area of the end ring (m^2), δ_e is the end ring current density(A/mm^2), l_e is the end ring length (m), D_e is the diameter of end ring (m).

$$P_e = 2I_e\delta_e\rho_c\pi D_e \tag{19}$$

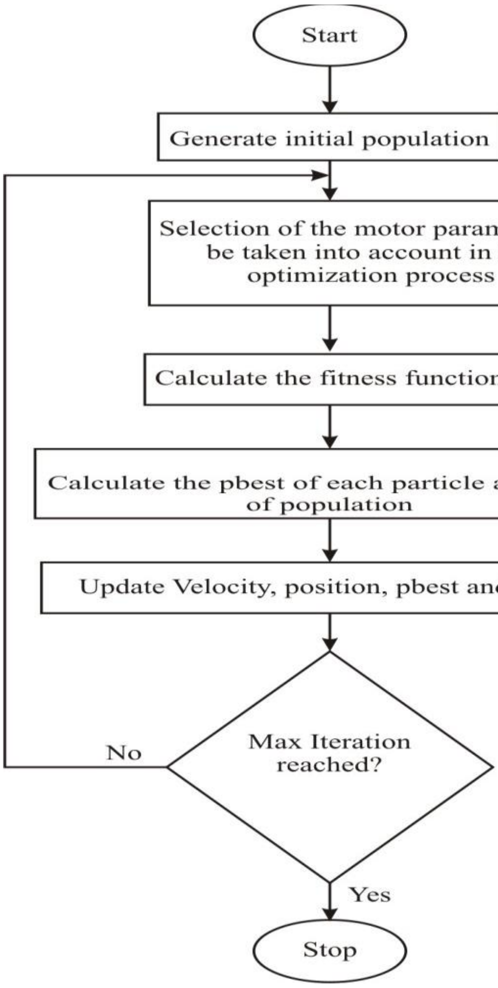

Figure 1. PSO flow chart

Total Copper Loss

$$P_c = P_s + P_b + P_e = mI_s\rho_c\delta_s l_s + N_r I_b \rho_c \delta_b l_b + 2I_e\delta_e\rho_c\pi D_e \tag{20}$$

2.2 M-File Coding

The coding of the Objective function (copper loss power equation), the equality and inequality constraints in conjunction with the PSO test file were carried out using MATLAB R2016a m-file environment (Alam, 2016).

2.3 Parameter of Motor

The parameter of the induction motor used in the optimization is based on a designed work (Agbachi *et al.,* 2012).

Rated Output = 9.86kVA, Voltage V = 415V, Supply Frequency, f = 50Hz, Number of Phases, m = 3, Number of poles, P = 4, Full load Efficiency, η = 0.87, Full load power factor = 0.87, Specific magnetic loading, B_{av} = 0.45wb/m^2, Specific electric loading, ac = 23,000A/m, Gross core length,l_s = 140mm, Length of air gap,l_g = 0.3497mm, Stator Winding factor, K_{ws} = 0.955, Number of stator slot S_s= 36, Stator current density δ_s = 3.93A/mm^2, Rotor diameter, D_r = 164.3mm, Number of rotor slots, N_r = 44, Number of rotor bars per slot, Z_{sr} = 1, Rotor winding factor, K_{wr} = 1, Current density of rotor, δ_b = 4.99A/mm^2,End ring area, A_e = 128.25mm,Length of each bar,l_b = 180mm, Depth of end ring, d_e = 12.5mm, Thickness of end ring, t_e = 10.26mm, Resistance of stator, R_S = 2.11Ω, Resistance of end rings, R_e = 0.00006431Ω, Current density of end rings, δ_e = 6A/mm^2.

With these parameters, the total copper loss was calculated using equation (19) and was found to be 666.91W.

PSO Parameter Used

The most commonly used parameters of PSO algorithm are considered as follows: (Yoshida *et al*., 2000)

Population size: 10 to 100

Inertial weight (w): 0.9 to 0.4

Acceleration factors (C_1 and C_2): 2 to 2.05

For this study therefore, the following parameters were chosen in order to satisfy the maximum range of values

Population size = 100

$C_1 = 2$

$C_2 = 2$

$w_{min} = 0.4$

$w_{max} = 0.9$

Variables Optimized

Table 1 shows variables selected to be optimized since they are physically measurable quantities in order to save cost and material.

Table 1. Variables Optimized

Description	Independent variable	Initial values	Variables
Stator length	(l_s)	0.1379	X1
Rotor bar length	(l_b)	0.1800	X2
End ring diameter	(D_e)	0.0128	X3

2.4 Constraints and Bounds Limits

The constraints; inequality and equality were imposed on the design. The imposed constraints are presented in Table 2 (Abdelhadi *et al.*, 2004). The boundary limits imposed in the design is presented in Table 3.

Table 2. Constraints

Inequality constraint	Equality constraint
$l_s \leq K_{ws}\pi\, ^{D}/_{P}$	$D_e = 0.9D$
$l_s + 0.02 \leq l_b$	

Table 3. Bound Limits

Bounds	**X1**	**X2**	**X3**
Lower Bound (LB)	0.1000	0.1500	0.0100
Upper Bound (UB)	1.0000	0.2000	1.0000

3. Results and Discussion

With the total copper loss equation as the objective function, the result (Figure 2) shows that the PSO converges fast in 44.817seconds. This value was based on the performance of the PC used. For an effective results, 10 runs were allocated for the simulation out of which the 1st run provides the best result values. The optimized result of the variables from the PSO is as shown in the Table 4.

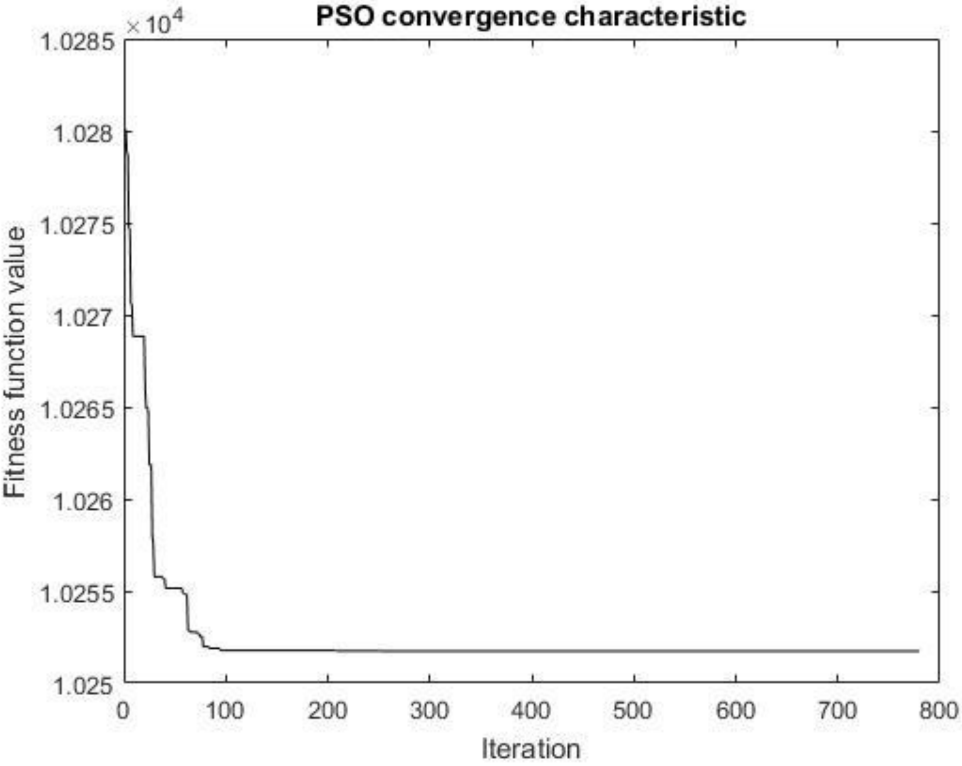

Figure 2. PSO convergence characteristics

Table 4. Optimized Result

Variables	X1	X2	X3
Values	0.1300	0.1500	0.1463

This minimized value from the copper power loss was therefore calculated using applying equation (20) with the optimized results and was found to be 249.4740W corresponding to that gotten from the MATLAB simulation; 249.4426W. This minimized copper power loss has therefore improved the efficiency of the motor from 93.24% to 97.47%.

The fast convergence of the fitness function makes PSO an effect tool in optimization technique.

4. Conclusion

This paper has shown the fastness of convergence of the PSO in providing the best performance of the fitness function. The copper losses reduced from 666.91W to 249.4426W. This shows that with the variation of some few parameters of the induction motor, the losses can be significantly reduced. Hence, leading to an increase in efficiency. With this, it can be found out that the efficiency of an induction motor is related to the losses, therefore, it is however, recommended that more losses; iron loss, stray loss and hysteresis losses can also be added to the overall power loss equation for the purpose of finding an optimal value of their respective variables in order to achieve a better efficiency.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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