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COST-EFFECTIVE DESIGN OF THREE PHASE INDUCTION MOTOR: AN OPTIMIZATION APPROACH

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The cost-effective design could be done in many ways, such as by reducing the cost of energy lost, reducing manufacturing cost, reducing annual maintenance costs, *etc.* 3-phase induction motors are extensively used as the most effective machine in the industry because they are reliable and economical. The cost-effective design of this motor is a great challenge for engineers. The Induction motor design is a non-linear and multivariable optimization problem. So, the entire problem depends on the selection of variables and constraints. Lesser number of constraints leads the poor performance, and on the other hand, improper selection of bounds of the variables gives the odd dimension of the motor. The proposed work deals with the design and optimization of the cost of production subject to various constraints with a selected number of variables. A gravitational search algorithm (GSA) is used to get the desired optimal results, and based on that, the performance indices and cost of production are calculated. The proposed algorithm is used to find the optimal cost for two motors, and finally, the output is compared with the particle swarm optimization (PSO) to validate the results. The production of GSA shows more acceptable values of design parameters and performance indices, which are projected in the result section and discussed in the conclusion section.

1. INTRODUCTION

The induction motor is one of the best electrical machines used in the industry for cheap and reliable operations. It has a wide range of applications with wide varieties available in the market for suitable ratings. Since 50 % to 60 % of the machinery cost of industry is due to induction motors, a small reduction in price will affect the production cost. The present work intends to reduce the cost of production of induction motors from a design perspective with the help of optimization techniques [1]. The cost-effective design is beneficial for the industry, especially for mass production. Still, at the same time, performance is equally vital in the long run from a quality point of view. Design variables with their proper bounds will control the dimensions of the motor and hence reduce the cost, but the selection of constraints affects the performance directly [1, 2]. The design problem is nonlinear in nature, subject to variables and constraints. It is a challenging task to frame the objective function and the constraints function also. To achieve proper design parameters with low cost and appreciable performance, thirteen design variables and ten constraints are considered.

The objective function contains variables and constraints most relevant to the cost-effective design and performance of the induction motor. The solution depends on the proper selection and the number of design variables and constraints, which leads to global optima. It is observed that most design problems generally use two types of objective functions: the cost of material and maintenance [2]. The objective functions ensure manufacturers' security when considering the cost of the material. Still, the consumer and manufacturer's interest will be secured when the objective function is taken as production and maintenance cost. Several optimization techniques have been used successfully to solve the design problems, such as genetic algorithm (GA), bacterial foraging, evolutionary method, simulated annealing, particle swarm, ant colony *etc.* [3, 4]. These techniques fail to ensure reaching near global optima, either due to improper selection of optimization process or insufficient design variables and constraints. The design has been made with two sample motors of different ratings, and a gravitational search algorithm does optimization.

The main contribution of this paper is to optimize the cost of production by GSA with many variables and constraints [5]. The gravitational search algorithm was first proposed in 2009 and became more popular due to its accuracy and smooth convergence characteristic in engineering applications. The algorithm works based on Newton's law of gravity and motion and can give the output very near its global minimum. The details of the algorithm and problem formation of the function to be optimized are provided in sections (V) and (IV). First, the proposed algorithm optimizes the objective function, and the results are compared with the output obtained from particle swarm optimization (PSO) [6]. It is clear from the comparative analysis that GSA works decently and gives better results than PSO. The objective function is framed with many variables and constraints, which are given in the problem formulation part, and the supportive terminology is highlighted in the appendix. The details of the convergence characteristic are clearly discussed in the results section to conclude at the end.

2. LITERATURE SURVEY

A literature survey has been conducted over the past few decades for the design and optimization of induction motors. The objective function is the proportionate sum of motor losses and motor volume, optimized by satisfying some constraints and contributed to a research article [7]. A researcher proposes a new optimization angle by controlling the ratio of copper and iron by weight to improve the optimal performance level of a three-phase induction motor [8]. The finite element method is used along with the other techniques to minimize the yearly capitalized cost. An algorithm for optimization of a three-phase induction motor design is proposed, consisting of least square data fitting and the golden section method in conjunction with Fletcher conjugate [9]. A new multi-objective function can be formed for a three-phase induction motor. It can be reduced to another objective function, which can be optimized by the finite element method [9]. A new hybrid optimization technique (genetic and modified deterministic Rosen Brock's algorithm) is

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also applied for induction motor optimization to get better results for a large 3-phase induction motor [10]. A material-to-operating unit cost of 1 kWh ratio is used to optimize a three-phase induction motor. Three phases squirrel cage induction motor has been optimized for maximum efficiency [11]. PSO minimizes losses and operating costs in the three-phase squirrel-cage induction motor [12]. A neural network approach is most suitable for predicting the optimum flux of indirect vector control of three phase induction motor [13]. A design method to optimize a three-phase induction motor for a manufacturing unit is successfully projected in a research article [14]. The genetic algorithm's application is suitable for optimizing multi-objective optimization problems, where torque, efficiency, and cost are considered [15]. The simulated annealing (SA) technique is often used to optimize the cost of material and annual losses by setting two objectives [16]. A genetic algorithm (GA) is used to reduce the manufacturing cost, and also finite element method (FEM) is applied to validate the design process [17]. An artificial intelligence method on genetic algorithms (GA) is successfully used to maximize an induction motor's efficiency [18]. The efficiency improvement by varying magnetizing current against torque current to minimize the material cost of the induction motor in a unique approach suggested to the design of induction motor by minimizing the weight is taken as an objective function [19]. FEM is used to upgrade the same motor indicated in a research paper [19]. A multi-objective optimization method to improve efficiency and power factor for a three-phase induction motor is an attempt by some researchers [20]. Parameters and dimensions are a part of the objective function to optimize by genetic algorithm [21], and finally, the conclusion has been made with the comparison with the finite element method [20]. Induction motor is widely applied in the industry to perform various tasks. Special care is given to designing the motor to achieve high-level performance at a comparatively low cost. The above study reveals that most of the time, efficiency and cost are optimized with all the popular algorithms. Still, the results are primarily affected by the design variables and constraints [22]. The number of variables and constraints affects the accuracy of the optimized results. In this paper, the optimization is done with more variables and constraints to get the properly optimized parameters of the motor to achieve high-level performance at a low cost.

3. VARIABLES AND CONSTRAINTS

Selection of the variables and design constraints for a machine design problem should be made with utmost care. Variables are the function of design parameters and constraints controlling the field performance of the motor [23]. This design considers a few unimportant dimensions constant, such as slot opening, tooth tip height, etc. The design variables with their bounds are given below in Table 1. The dimensions of the motor chosen as independent variables are x_4 and x_5.

Some of the variables specified below can be changed their values in discrete steps like x_{12} & x_{13}. Variables such as x_{10} & x_{11} can be allowed to vary according to the nature of the problem. The given problem is optimized with the variation of all the parameters within a range of values. The dimensions other than selected variables from x_1 to x_{13} are kept constant during the optimization process. The values of the winding factors are chosen in such a manner that a suitable winding structure can be achieved, and it is considered constant for optimization. The mathematical formulation of the objective function (cost of production) in terms of the independent variables has been formulated and given in the eq. (4), followed by eq. (1)-(3). The specification related to the machine's performance has been constructed and termed as a constraints function of this nonlinear problem.

The constraint functions from $g_1(x)$ to $g_5(x)$ are the outputs, and $g_7(x)$ to $g_9(x)$ for magnetic saturation and temperature rise; $g_6(x)$ is the special type of constraint because if its value is not satisfied, then the design would not be feasible. The constraints and their limits are projected as follows.

4. DESIGN PROBLEM FORMULATION

An equivalent circuit of the Induction motor has been derived to express the design constraints. Figure 1 below contains the parameters given in the nomenclature section. It is a per-phase model of a three-phase induction motor. There are seven parameters, namely stator resistance (R_S), stator leakage reactance (X_{Sl}), magnetizing reactance (X_0), core loss resistance (R_0), leakage reactance of rotor (X_{r2}), and the resistance of rotor (R_{r2}) and load ($R_r^{/}/S$). Design variables are chosen with utmost care because many variables affect the dimensions and performance of the motor, many variables make the objective function more complicated, and the problem's solution becomes time-consuming due to non-linearity [24]. So, the design variables chosen are given in Table 1 from $x_1 \rightarrow x_{13}$. This paper aims to reduce production costs with an efficient optimization technique with many constraints to achieve the best performance.

The cost of production is taken as an objective function of eq. (4), which is the sum of the three quantities given as i) Cost of iron (A_1); ii) cost of copper (A_2); iii) punching cost (A_3), and their expression are given in eq. (1)-(3).

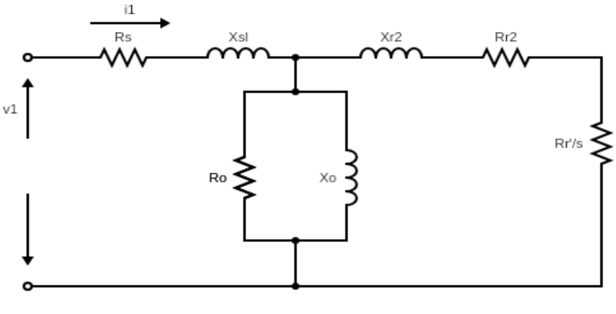

Fig. 1 – Equivalent circuit model of the three-phase induction motor.

$$A_1 = k_1 x_1 \left[\left\{ \frac{p}{2}\left(x_{11}^2 - x_{10}^2 \right) - x_{12} x_2 x_3 \right\} - \left\{ \frac{p}{4}\left(x_{10} - 2x_8 \right)^2 - x_5 x_6 x_{13} \right\} \right], \tag{1}$$

$$A_2 = k_2 M_1 \left(\frac{x_4}{k_w x_1 x_7 x_{10}} \right) \left\{ \frac{x_1 + p\left(x_3 + x_{10} \right) L_{NALT}}{x_{12}} \right\} (NCC \times NCPP) \tag{2}$$

$$A_3 = \left(A_1 + A_2 \right)/5 . \tag{3}$$

Punching cost is taken as 20 % of the total cost, and the overall objective function becomes as follows

$$F(x) = A_1 + A_2 + A_3 , \tag{4}$$

$$T_P = \frac{M_2}{w_s \left(1 + \frac{X_{sl}}{X_o} + \frac{R_s}{R_o} \right) \left(R_s + \sqrt{R_s^2 + \left\{ X_{sl} + \left(1 + \frac{X_{sl}}{X_o} + \frac{R_s}{R_o} \right) X_{r2} \right\}^2} \right)}, \tag{5}$$

$$T_s=\frac{M_2R_{st}}{1.5w_s\left[\left\{R_s+\left(1+\frac{X_{sl}}{X_o}+\frac{R_s}{R_o}\right)R_{st}\right\}^2+\left\{X_{ss}+\left(1+\frac{X_{sl}}{X_o}+\frac{R_s}{R_o}\right)\left(X_{RS}\right)\right\}^2\right]},\quad(6)$$

$$S_f=\frac{P-\sqrt{P^2-4CD}}{2C},\quad(7)$$

$$I_{sto}=\frac{M_3}{\sqrt{\left(R_s+\left(1+\frac{X_{ss}}{X_o}+\frac{R_s}{R_o}\right)R_{st}\right)^2+\left(X_{ss}+\left(1+\frac{X_{ss}}{X_o}+\frac{R_s}{R_o}\right)X_{RS}\right)^2}},\quad(8)$$

$$\cos\phi=\frac{\left\lfloor Z_A+Z_1\left(1+Y_MZ_A\right)\right\rfloor}{\left(1+Y_MZ_A\right)},\quad(9)$$

$$T=\frac{L_T}{c_1\left\{e_1px_1x_{10}+e_2px_1x_{11}+e_3\,{}^{p}\!/_{2}\,(x_{11}^2-x_{10}^2)\right\}},\quad(10)$$

$$B_d=\frac{(p/4)x_7x_{11}}{S_f\left(x_{11}-x_{10}-2x_3\right)},\quad(11)$$

$$B_T=\frac{M_4px_7x_{11}}{S_fx_{12}W_T},\quad(12)$$

$$J_{sc}=\frac{SI_P}{NCC\times NCPP\times x_4}.\quad(13)$$

Table 1

Constraints& variables with limitations

$g_1(x)=a_1-2.5\geq 0$	$g_9(x)=a_7-4\leq 0$	$0.3\leq x_7\leq 0.9$
$g_2(x)=a_2-1.5\geq 0$	$g_{10}(x)=a_8-0.8\geq 0$	$0.5\leq x_8\leq 2$
$g_3(x)=S_f-2.5\leq 0$	$250\leq x_1\leq 350$	$10\leq x_9\leq 50$
$g_4(x)=a_3-6.5\leq 0$	$10\leq x_2\leq 25$	$25\leq x_{10}\leq 100$
$g_5(x)=a_4-0.86\geq 0$	$25\leq x_3\leq 50$	$300\leq x_{11}\leq 1000$
$g_6(x)=T_r-80\leq 0$	$2\leq x_4\leq 20$	$20\leq x_{12}\leq 100$
$g_7(x)=a_5-1.6\leq 0$	$2\leq x_5\leq 15$	$20\leq x_{13}\leq 100$
$g_8(x)=a_6-1.8\leq 0$	$25\leq x_6\leq 50$	-----------

A gravitational search algorithm is used to find the minimum value of the solutions, and the design variables obtained concerning optimal solutions are taken to find the design parameters through the induction motor design sub-routine. The objective function is again optimized by particle swarm optimization to compare the design parameters and show the proposed algorithm's effectiveness.

3.1. THE ALGORITHM (GSA)

It is one kind of new heuristic algorithm proposed in 2009 by Rashedi et al. Gravitational search algorithm deals with Newton's law of gravity and motion. GSA consists of a set of masses called agents [5]. The masses undergo different mathematical operations to find the minimum value of a function through simulation, which is dependent on Newton's law. 'n' number of masses is placed in different positions within search space, and the position of i^{th} masses is expressed by

$$Z_i=\left(z_i^1,....,z_i^d,....,z_i^n\right),\quad i=1,2,......,n,$$

where z_i^d indicates the placement of the i^{th} mass having d^{th} dimension within the search space defined by n dimension.

The gravitational force of the mass $'j'$ acts on the mass $'i'$ for a definite time $'t'$ is described by

$$P_{ij}^d(t)=g_{tc}(t)\frac{m_{pi}(t)xm_{kj}(t)}{E_{ij}(t)+e}\left(x_j^d(t)-x_i^d(t)\right),\quad(14)$$

m_i and m_j are the masses of i^{th} and j^{th} objects, respectively, $g_c(t)$ and $E_{ij}(t)$ are the gravitational constant and Euclidian distance within objects $'i'$ and $'j'$, respectively.

The sum of the force acting on the mass $'i'$ according to

$$P_i^{kd}(t)=\sum_{\substack{j=i\\ j\neq i}}^{m}P_{ij}^d\left(rand_j\right)\quad(15)$$

where $rand_j$ is the randomly generated number between intervals (0,1).

GSA is derived from Newton's laws of motion, where the acceleration of i^{th} particle in time $'t'$ is expressed as

$$f_i^d(t)=\frac{P_i^d(t)}{m_i(t)}\quad(16)$$

The updated velocity of the particle is determined by the current velocity plus the acceleration of the particle. Similarly, the position is continuously changing by the current position and the velocity by eq. (17) and (18), respectively

$$y_i^d(t+1)=rand_i xy_i^d(t)+f_i^d(t)$$

$$x_i^d(t+1)=x_i^d+y_i^d(t+1)$$

The value of the gravitational constant is initialized and decreases with time according to the search rule to maintain the accuracy of the result. So, the gravitational constant is defined as $g_c(t)=g_{c0}e^{-t/T}$, where the gravitational constant is the function of initial value and time [25].

The masses are evaluated using the following fitness equations and based on which weighing factor is given to individual masses. This means a better particle has a higher force and goes slowly. Masses are continuously updated by

$$m_i(t)=\frac{Fitness_i(t)-wrst(t)}{B_i(t)-wrst(t)},$$

where *Fitness* (t) is the fitness of the i^{th} particle at the t, $B_i(t)$, and $wrst(t)$ best and worst particle, respectively.

Best and worst values are calculated both for maximization and minimization problems

$$B(t)=\min_{i\in\{1,....m\}}Fitness_i(t)$$

$$wrst(t)=\max_{i\in\{1,....m\}}Fitness_i(t),$$

$$B(t)=\max_{i\in\{1,....m\}}Fitness_i(t)$$

$$wrst(t)=\min_{i\in\{1,....m\}}Fitness_i(t).$$

3.2. STEPS OF THE ALGORITHM (GSA)

The steps of the Gravitational search algorithm are as follows for the cost-effective design of an induction motor [26]:

Step 1: identify the search space according to the problem specified.

Step 2: generate the population as defined between ranges of values.

Step 3: evaluation of the fitness functions of the particle.

Step 4: update the gravitational constant, best and worst of the population, mass, *etc*.
Step 5: calculate the sum of all the forces acting in different directions.
Step 6: update acceleration and velocity.
Step 7: update positions.
Step 8: Continue steps 3 to step 7 until the stop criterion is satisfied.
Step 9: stop.
Step 10: end.

3.3. PARTICLE SWARM OPTIMIZATION (PSO):

Particle swarm optimization is one of the most efficient tools for optimization in engineering applications. It exists within the domain of artificial intelligence. It is a distributed-behavior type algorithm that performs tasks like multidimensional searches. The algorithm moves particles in the search space based on position and velocity [22]. Swarm Intelligence is considered a branch of Artificial Intelligence connected with the concept of different biological phenomena that computers can implement to optimize a scheduled task. In swarm intelligence, we focus on the behavior of the organisms in nature. All particles will fly all over the search domain. The direction of the swarm is identified by the neighboring particles and their history of experience [27, 28].

Let X and V be the particle's coordinates and velocity, respectively. The position of the i^{th} particle at k^{th} iteration is described by $X_{i,k}^{k} = \left[X_{i,1,}X_{i,2,}.......X_{i,N}\right]$. The velocity, along with its position, is derived by

$$V_{i,k}^{k} = \left[V_{i,1,}V_{i,2,}.......V_{i,N}\right]$$

$$\begin{aligned} V_{i,n}^{k+1} &= W \times V_{i,n}^{k} + C_1 \times rand_1 \times \left(PB_{i,n} - X_{i,n}^{k}\right) + \\ &+ C_2 \times rand_2 \times \left(GB_n - X_{i.n}^{k}\right) \\ i &= 1,2.........M;\ n = 1,2........N \end{aligned} \tag{20}$$

$$\begin{aligned} Y_{i,n}^{k+1} &= Y_{i,n}^{k} + V_{i,n}^{k+1} \text{ if } \left(Y_{\min}\right)_{i,n} \le Y_{i}^{k+1} \le \left(Y_{\max}\right)_{i,n} \\ &= \left(Y_{\min}\right)_{i,n} \text{ if } Y_{i,n}^{k+1} < \left(Y_{\min}\right)_{i,n} \\ &= \left(Y_{\max}\right)_{i,n} \text{ if } Y_{i,n}^{k+1} > \left(Y_{\max}\right)_{i,n} \end{aligned} \tag{21}$$

where M and N are the numbers of particles in swarm number of dimensions, respectively; K is the number of iterations; $X_{i,n}^{k+1'}$ is the k^{th} Number of iterations at i^{th} position; $R_{i,n}^{k}$ is the k^{th} number of iterations for the velocity at the i^{th} position; W is the weighting factor; C_j is the accelerating coefficient; (*rand*) is the randomly generated number between 0 and 1; (PB) (*PB*) is the personal best of i^{th} particle, and GB is the best result globally.

The speed of the convergence depends on accelerating factors C_1 and C_2. The factors for a particular problem should be appropriately adjusted because if the factors are high the problem converges quickly. The weighting factor maintains the equilibrium point between local and global optima. The optimization process will slow with the present particle position if the value of the accelerating factors is small. The weighting factor is determined by

$$S = S_{\max} - \left(S_{\max} - S_{\min}\right) \times {}^{G_c}\!/\!{}_{G_{\max}} \tag{22}$$

$S_{\max}$ and $S_{\min}$ are the initial and final weighting factors; G_c is the current number of generations, and $G_{\max}$ is the maximum number of generations.

There are two kinds of variety for Swarm Intelligence:

- Ant colony optimization (ACO), where the algorithm is derived based on the activity of the ants.
- Particle swarm optimization (PSO), where the behavior of a group of birds is considered

This group of birds is known as a ‘swarm‘. PSO is used to search the value of a set of design variables with the objective function's optimum value, maintaining the restrictions imposed on it [6]. Steps involve particle swarm optimization.

Step 1: initialize all the parameters.
Step 2: generate a random population with their position and corresponding velocities.
Step 3: compute the value of the objective function and performance.
Step 4: calculate fitness value.
Step 5: update personal best by comparing the fitness of each particle with the individual best; if it is found better, then take the current value as the best.
Step 6: update the global fitness of each particle to be compared with their global best if the present value is found to be better than the global best, then the current value is the global best.
Step 7: calculate the velocities using eq. (3).
Step 8: compute new positions by using eq. (4).
Step 9: go back to step 3 and continue until it reaches the maximum number of iterations.
Step: 10 outputs.

5. **RESULTS AND DISCUSSION**

The results are given in Table 2 and Table 3 for the optimal values of the design variables and performance indexes, respectively.

Table 2

Optimal design variables of Motor 1

	Motor 1			Motor 2		
Variables	Conventional design method	GSA	PSO	Conventional design method	GSA	PSO
Length of stator core (x_1) [mm]	260	255	259	325	320	322
Stator slot width (x_2) [mm]	12.8	12	12.3	17	16.2	16.8
Stator slot depth (x_3) [mm]	34.5	32.5	35.6	38.5	38	38.3
Cross sectional area of stator conductor (x_4) [mm]	3.98	3.68	3.78	15.2	15	15.6
Rotor slot width (x_5) [mm]	3.9	3.82	3.91	11.9	10.8	11.6
Rotor slot depth (x_6) [mm]	33.24	32.86	32.89	30.9	30.2	30.6
Flux density of air gap (x_7) [Wb/m^2]	0.50	0.45	0.47	0.68	0.65	0.69
Length of air gap (x_8) [mm]	0.78	0.72	0.75	1.20	0.98	1.10
End ring width (x_9) [mm]	20	25	27	32	30	33
Stator internal diameter(x_{10}) [mm]	50	45	45	90	84	86
Stator external diameter (x_{11})[mm]	310	305	308	610	615	614
No. of stator slots (x_{12})	32	30	30	64	62	64
No. of rotor slots (x_{13})	34	32	34	66	64	66

Table 3

The optimal value of performance indexes for Motors 1 & 2

	Motor 1			Motor 2		
Performance indexes (constraints)	Conventional design method	GSA	PSO	Conventional design method	GSA	PSO
Ratio of pull-out torque to full load torque (a_1)	3.02	2.56	2.82	2.89	2.74	2.65
Ratio of starting torque to full load torque(a_2)	2.2	1.78	1.86	2.5	2.34	2.47
Full load % slip (S_f)	0.027	0.0248	0.0235	0.0211	0.0242	0.0238
Ratio of starting current to full load current (a_3)	6.22	5.62	5.70	6.48	5.7	5.73
Power factor at full load (a_4)	0.862	0.885	0.875	0.88	0.871	0.870
Temperature rise (T_r)	79	75	78	80	78	78
Flux density in yoke in (a_5) [Wb/m^2]	1.3	1.17	1.23	1.26	1.21	1.25
Flux density in the teeth of Stator in (a_6) [Wb/m^2]	1.21	1.18	1.23	1.5	1.27	1.32
Current of stator conductor in (a_7) [A/mm^2]	4	3.2	3.5	4	3.6	3.7
Efficiency (a_8)	85	88	86	87	90	89

Table 4

Comparison among different results of both Motors

	Motor 1		Motor 2	
Item	GSA	PSO	GSA	PSO
Maximum cost of manufacturing (Rs)	6160.60	6380.45	48230.15	47320.40
Minimum cost of manufacturing (Rs)	5805.25	6110.54	44354.52	45123.70
Mean cost (Rs)	5965.56	6243.65	46125.56	46330.25
Standard deviation of cost (Rs)	85.39	66.32	1105.45	780.64

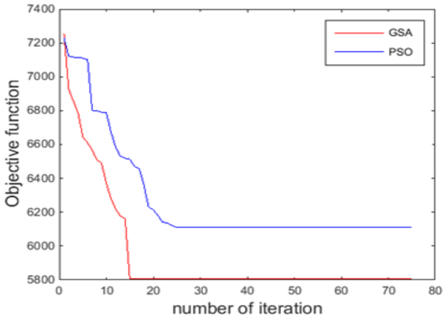

Fig. 2 – Convergence graph of Motor 1.

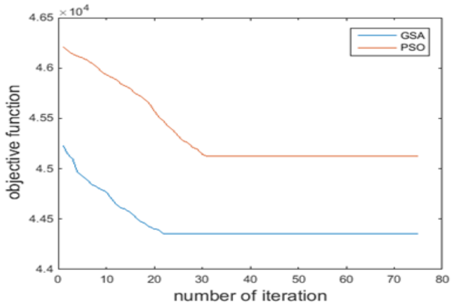

Fig. 3 – Convergence graph of Motor 2.

Two motors (5 kW and 50 kW) are designed by the conventional method, GSA and PSO, and compared to project the performance of GSA. The specification of the motors is given in the appendix, and the values of the design constraints are shown in Table 1.

Parameters are taken for the PSO algorithm as follows: Population is 20; acceleration factor is 1.5. The minimum cost is Rs 5805.25 and Rs 6110.54 in the case of GSA and PSO, respectively, for Motor 1. Again, the optimal cost is Rs 44354.52 and Rs 45123.70 for GSA and PSO, respectively, in the case of Motor 2.

Other comparative parameters like mean cost and standard deviation of Table 4 give better results in the GSA conventional design values of all parameters are shown in a separate column to conclude how the optimized parameters vary with the conventional design process. The convergence graph of GSA and PSO for Motor 1 is projected in Fig. 2, and for Motor 2, it is given in Fig. 3

It is clear from Fig. 1 that GSA converges quickly and smoothly as compared to the PSO. Only the last seventy-five data near the convergence area is taken to plot the graph out of around a thousand no. of iterations plotted near the convergence area. The second motor (Motor 2) shows the convergence of 50 kW motor, where the performance is like motor 1, but value of convergence is different. There are 20 independent trials run of the simulation has been made to obtain steady results. The best value has been considered and projected in the respective tables.

6. **CONCLUSION**

The paper deals with the design and optimization based on a gravitational search algorithm whose results are compared with other sets of design parameters obtained from particle swarm optimization and conventional design process. In this paper, an attempt has been made to frame the objective function with many variables and constraints in such a way that it can give better values of the design parameters. In the literature survey section, most of the induction motor design has been done with various optimization algorithms. The problem uses a minimum number of variables and constraints to give a simple shape of the objective function [29]. This objective function usually gives inaccurate design parameters, leading to poor motor performance due to an inadequate number of variables and constraints [30]. The method that has been applied to optimize is the gravitational search algorithm, which is newly proposed as one of the most acceptable optimization methods. The results show that GSA performs better than PSO in the conventional design reference frames. The computation time of convergence for GSA is quite less than PSO, proving that GSA converges faster than the PSO.

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APPENDIX

Nomenclature:

M_1, M_2, M_3, M_4: Constants; X_{sl}: Stator reactance per phase; X_{ss}: Slot leakage reactance per phase; X_{r2}: Rotor reactance per phase (referred); X_0: Magnetizing reactance; R_0: Core loss resistance; R_S: Stator resistance per phase; R_{st}: Rotor resistance at starting (referred); X_{RS}: Reactance of rotor at starting (referred); S_f : Full load slip; I_{sto}: Current during starting;

$$Z_A = \left({}^{R_{r2}}\!/\!{}_{S_f} + \mathrm{j}X_{r2} \right);\ Z_1 = \left(R_S + \mathrm{j}X_S \right);\ Y_M = \left({}^{1}\!/\!{}_{R_o} - {}^{\mathrm{j}}\!/\!{}_{X_M} \right)$$

L_T: Total losses (Stator copper loss, rotor copper loss, iron loss); e_1, e_2, e_3: Empirical constants (Depends on the peripheral speed of rotor); B_d: Magnetic flux density in the yoke; B_T: Stator teeth flux density; J_{sc}: Current density (stator conductor); W_T: Stator teeth width; SI_p: Stator current per phase; NCC: Number of parallel paths; NCPP: Number of conductors in parallel; I_{NALT}: Length of mean turn; k_1, k_2: Constants; R_{r2}: Rotor resistance per phase (referred); $R'_{r2} = R_{r2}\left(1 - S_f\right)$; k_w: Winding factor.

Supporting Formulation

$$P = \frac{3V^2 R_{r2}}{P_{out}} - 2R_S \left(R_{r2}\right)\left(1 + \frac{X_{sl}}{X_o} + \frac{R_s}{R_o}\right),\ D = \left[\left(1 + \frac{X_{sl}}{X_o} + \frac{R_s}{R_o}\right) R_{r2}\right]^2$$

,

$$C = R_S{}^2 + \left[X_{sl} + \left(1 + \frac{X_{sl}}{X_o} + \frac{R_s}{R_o}\right)\left(X_{r2}\right)\right]^2 + \frac{3V^2\left(R_{r2}\right)}{P_{out}}$$

Design Constants:

Weight of iron per unit volume -7600 kg/m^3; Weight of Copper per unit volume -8900 kg/m^3; Resistivity (Cu) for Stator bar 2.5x10^{-8} Ωm; cost per kg of Copper-Rs.225/kg; Resistivity (Cu) for rotor bar 2.1x10^{-8} Ωm; Cost per kg of Iron-Rs.40/kg.

Motor 1: SCIM; Voltage: 415 V; Phases: 3; Frequency: 50 Hz; Poles: 4
Output: 5 kW.

Motor 2: SCIM; Voltage: 415 V; Phases: 3; Frequency: 50 Hz; Poles: 4; Output: 50 kW.

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