Artificial Bee Colony Based Design Optimization of a Six-Phase Induction Motor

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Abstract **—Artificial Bee Colony Algorithm (ABC) has been used to optimize the design of a six-phase induction motor (SPIM). Multi-objective function has been considered for optimization. Comparison of the optimum design using Artificial Bee Colony Algorithm with that of traditional design and Genetic Algorithm (GA) based optimum design has been presented, which shows that improved design can be achieved by Artificial Bee Colony technique of optimization. Comparison of the results obtained has been done to find the fittest method of optimization for the said purpose. Performances of the induction motor have been evaluated for each design effectively.**

Keywords *— artificial bee colony algorithm; efficiency; optimum design; objective function; six-phase induction motor.*

I. Introduction

During the year 1990, study of multiphase electric machines got pace. It came practically in the beginning of recent century. The usages of multi-phase induction motors are prime in propulsion system of ship, traction purpose and other applications where high power is involved [2-4]. Multi-phase induction motor has increased efficiency and reduces the pulsating torque. It has less copper loss in comparison to the three-phase induction machine of equivalent rating [5-6]. Noise level of the Multiphase induction motors is less than that of three-phase induction motors [7]. With some phases kept open circuited, these motors can start and run normally [8-11]. Providing concentrated winding, torque improvement is achieved in case of multi-phase induction machines [11].

GA based optimization of induction motor has been presented in [1, 13-14]. Abbas and Aftan [15] have given Numerical Function Optimization by Quantum ABC algorithm. Paper [2] showed that multiphase system is energy efficient and rugged. E. Levi et al. [4] presented that multiphase induction motors find application in high power industrial applications. In [9], it is given that with one phase open-circuit, no zero sequence current is produced i.e., no need of neutral line and a smooth non-pulsating torque can be produced for multiphase machine. Paper [7] reported that multiphase application in propulsion system is fault tolerant. Optimization using Artificial Bee Colony method has been performed here for optimum design of induction motor with six-phase stator winding.

Next section deals with the description of the artificial bee Colony method of optimization. Section-III has the description of traditional design of Induction Motor. ABC based design program, related objective functions and involved constraints are presented in section IV. Discussions and conclusions are given in the following sections.

II. Artificial Bee Colony Optimization Algorithm

ABC algorithm is a crowed dependent, top level general strategy algorithm depending on the searching activities of honey bee commune [12]. ABC model has three important things: employed, onlooker and scout bees. There are three concepts in ABC: food sources, employed and unemployed bees.

Bee colony has one employed bees' part and other onlooker bees' part. Every employed bee has one food source. Getting information from the employed bees, the onlookers select a source of food. After the process, scout bees come into the scenario for random development of new food sources. For optimization in ABC algorithm, the number of solutions in the population is the number of food sources. One solution is the position of one source of food. Quality of nectar is the fitness parameter of the associated solution.

A bee randomly selects the position of food sources and measures their fitness parameters. Then the employed bees distribute this information of nectar value or fitness of the food sources with the onlooker bees. Then, every employed bee comes back to the previously visited food source and selects another food source using its cognitive information in the vicinity of the current one.

Onlooker bee uses employed bees' information to select a food source. The probability for selection of the food sources gets augmented with the increase of measured value of its nectar quality or fitness value [12]. With highest nectar quality or food source fitness value, the onlookers select that food source. With the memorization of this position of food source, employed bees go to another one in neighbourhood based on visual information. Random generation of food sources have been achieved by the scout bees who develop abandoned food sources by the onlooker bees and makes it as a new food source to be explored. This process of searching can be presented as follows:

Schematic pseudo code of ABC procedure:

- Initialization of problem parameters.
- Initialisation of memory for food sources.
- Do (Conditional Loop) :
  The bees employed go to the source of food.
  Onlooker bees go to a selected source of food.

Scout bees go to develop new food sources.
The best source of food is sent to memory allotted.

- While: End criterion is reached.

III. Six-Phase Induction Motor Design

The traditional design procedure reflects the experiences of manufacturers. In this design method, the designer starts the design process by selecting the values of parameters of design, which is followed by iteration in order to obtain the required design.

A. The Sizing Euation

The sizing equation is as follows:

$$S=11K_{w1}\times ac\times (D/1000)^2\times (L/1000)\times n$$

where S = motor rating in Watt,
B_{av}= specific loading-magnetic (Tesla),
ac = specific loading-electrical (A/m),
D = inner diameter of the stator (mm),
L = active length of the motor (mm),
K_{w1}= winding factor,
and n = rated speed (r. p. s).
The designer selects the values for B_{av} and ac during starting of the design process. The saturation point is the limit of B_{av} for the used materials, also for losses viz. hysteresis, eddy current and stray and also for cooling, the load pattern, duty cycle.

B. The Aspect Ratio

D^2L of the machine is calculated by using equation (1) after selecting ac and B. The aspect ratio λ can be defined as

$$\lambda = \frac{L}{\frac{\pi D}{P}} = \frac{L}{Y} \qquad (1)$$

where, Y =distance between pair of poles in m,
P= number of poles.
After selecting λ, the calculation of L and D are done. A good λ increases induced *EMF* with less coil length. The coil area and the induced EMF are proportional to each other for the same flux density.

C. Selection of Current Density

The current density J_s helps to find the cross sectional area of the copper wire used for a certain rated current I, as shown below:

$$A_W = \frac{I}{J_S} \qquad (2)$$

D. Selection of Flux Density

The flux densities of cores and teeth are selected in the vicinity of knee point of the *B-H* curve for full utilization of the material.

E. Electrical Machine Design Process

At the outset, the values of machine efficiency (*eff*) *and* power factor (*pf*) are assumed in order to calculate the rating S in *VA as* follows-

$$S = (P_{out}/eff) \times pf \qquad (3)$$

Here, P_{out}= output power rating.
Calculating S, the values of ac, B_{av} and λ are chosen to determine L and D using the sizing equation. Determination of the number of turns and diameter of the coil of the stator winding are done with the specified rated voltage and current density for a given winding layout. After selecting the flux density in the core tooth, the width and the core thickness are calculated. Considering the slot area required by the winding and also the teeth area and the area of the core, the outer diameter of the machine is calculated. Traditional rules are used for rotor designs. Preparing complete design, its performance parameters are determined and compared with that of selected ones. For any kind of disagreement, the assumed values or the design parameters are modified. The design process is repeated again and goes on repeating until the agreement is fulfilled.

The flow chart of electrical machine design by traditional process is shown in Fig. 1.

IV. ABC Based Design Program

In this paper, MATLAB program has been written for the said application and run successfully. This program minimizes the rotor copper loss and the stator copper loss in terms of the stated design variables to be optimized. The efficiency and the power factor have been optimized and those optimized values are incorporated in the main program for optimum design. Thus, the parameters of SPIM have been evaluated and the values are checked without violating the constraints. The developed design program is completely indigenous. As the design optimization of multi-phase (six-phase) induction motor requires objective function concerning performance features, the copper losses in the stator and rotor are taken as objective functions to be minimized.

Fig.1 depicts traditional electrical machine design process, where current density, flux density, magnetic and electric loading, aspect ratio etc. are selected manually. The efficiency and the power factor are assumed and the design is prepared. With the result obtained, it is checked that whether the assumptions are agreed. If not, again the process is repeated. With agreement, it is checked that whether design requirement is agreed or not. If not, again the process is repeated. With agreement, the results are obtained.

The multi-objective approach is applied to this problem. The following multi-objective formulations have been considered:

1. Minimization of the stator copper loss:

$$SCLsim = 6I_{ph}^{\,2}R_s \qquad (4)$$

where I_{ph} = phase current in amperes and
R_s= stator winding resistance in ohms.

2. Minimization the rotor copper loss:

$$RCLsim = r_r\, S_2\, I_b^{\,2}/ab\,(L_r+2D_e/P) \qquad (5)$$

where r_r =0.021, S_2= number of slots in the rotor , I_b= current in rotor bar (Amps), D_e = mean diameter of end ring (mm), L_r= core length (m) and P = number of poles .
Fig. 2 shows the design variables taken as motor variables for the optimization:
Length of stator Core (equal for rotor) (x_1), inner stator diameter (x_2), stator slot depth (x_3), stator teeth width (x_4), stator core depth (x_5), efficiency (x_6) power factor (x_7).
The flowchart for optimum design by Artificial Bee Colony Algorithm is shown Fig. 3.

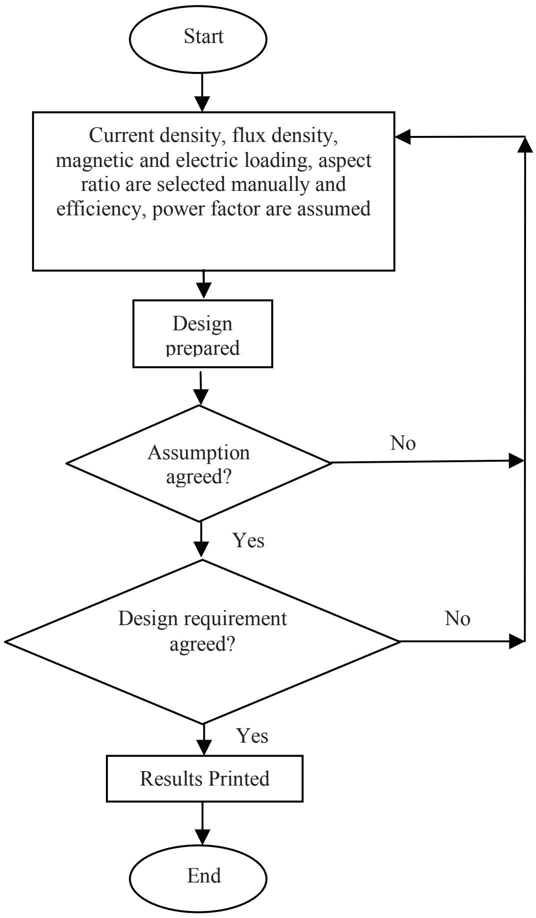

Fig. 1. Flow chart of traditional electrical machine design

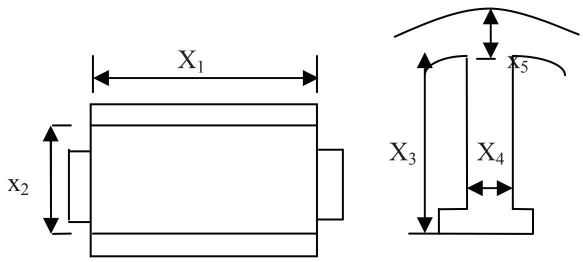

Fig. 2. Optimization variables of stator dimensions [1].

Stator resistance, $R_s = \rho T_s L_{mts}/a_s$ (6)

where, ρ=0.021 Ω/m at 75°c.

a_s= area of cross-section of the conductor.

L_{mts}= mean turn length

From the above equation, the expression for the stator resistance has been obtained in terms of the design variables to be optimized.

Stator current per phase,

I_{ph}=Power/(η×PF×no. of ph×V_{ph}) (7)

where, η=efficiency, PF = Power Factor, V_{ph} = Voltage per phase.

From equation (7), the expression for per phase current has been obtained in terms of motor variables to be optimized. Both are used to form the desired equation for stator copper loss and that has been taken here as objective function for minimization. Simultaneously, motor variables taken in this paper are optimized.

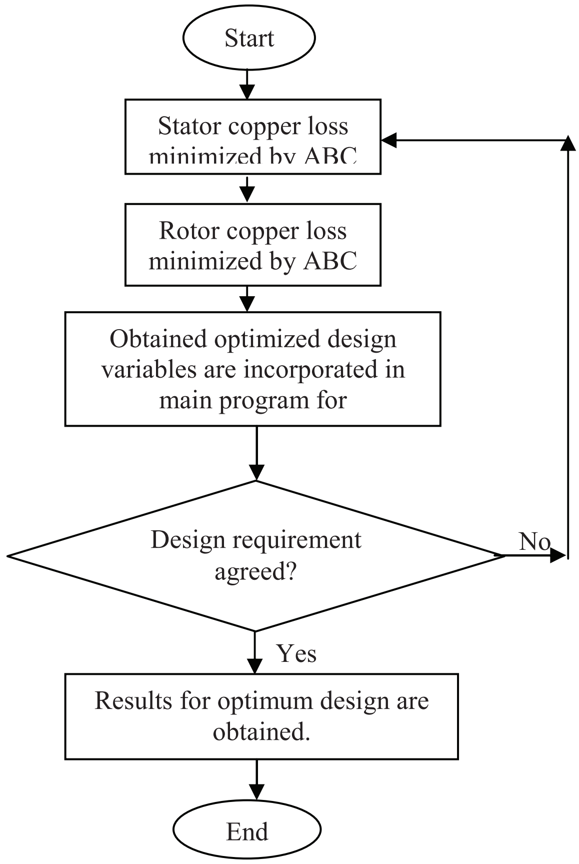

Fig.3. Flow chart of proposed ABC based optimum electrical machine design.

Rotor bar current, $I_b = (2m_s K_{ws} T_s/S_r) \times I_s \cos\varphi$ (8)

where, m_s=no. of phase, K_{ws}=0.955, T_s=Stator turn per phase and S_r=Rotor slots per phase.

In this paper, considering the above equation and expressing in terms of design variables to be optimized, the expression for rotor copper loss has been obtained and that has been taken for minimization. Simultaneously, the motor variables to be optimized concerning this equation get optimized.

The values of these variables have been incorporated in the main design program for optimization and optimum design results are obtained. Further iteration has been done with non agreed design results and thus results for optimum design have been obtained.

V. Results and Discussions

Table-1 shows the specifications of the six phase induction motor to be optimized.

TABLE-1: Rating of induction motor (six-phase) [1].

Phase Number	6	Power rating (w)	260
Rated phase voltage (v)	110	Stator slot number	24
Supply frequency (in Hz)	50	Connection	Y
Poles Number	2	rotor slot number	18

In Table-2, there is a comparison of results between design done traditionally, Genetic Algorithm based design and ABC based optimum design.

TABLE-2: Comparison of different methods.

Quantity	Traditional Method [1]	GA [1]	ABC
Power Factor(PF)	0.99	0.99	0.99
Efficiency(η)	0.6823	0.73408	0.809946
Total Losses	121.0658	94.186	61.0090
No Load Power Factor	0.1731	0.2057	0.0443
Stator resistance (Ω)	19.93	5.69	16.3815
Equivalent resistance (Ω)	34.7880	20.3318	54.2473
Equivalent reactance (Ω)	26.0631	20.2971	17.4236
reactance magnetising (Ω)	212.8436	251.6265	250
Length of stator stack (m)	0.0816	0.11114	0.0675
Inner stator diameter (m)	0.0520	0.065569	0.0696
Inner rotor diameter (m)	0.0201	0.022	0.019
Stator teeth width (m)	0.0019	0.0036137	0.006
Stator slot depth (m)	0.0108	0.012784	0.011
Width of stator slot (m)	0.0077	0.0083161	0.0111
Stator core depth (m)	0.0082	0.017784	0.0128125

It is observed that ABC based optimum design gives greater efficiency i.e. 80.9946% than those in traditional approach and Genetic Algorithm based one. Hence, from the performance point of view, ABC provides better optimization. Total loss is 61.0090 W in case of ABC, which is lower than that of other two i.e., it provides more energy efficiency. The obtained values of the different parameters show that using ABC, the size of the six-phase induction motor becomes much smaller as compared to the other methods. Hence, the cost of material is reduced.

The efficiency, total loss, stator stack length and stator inner diameter computed using different methods have been presented graphically in the figures 4 to 7. From these figures, it is observed that the ABC based optimized design gives more efficient and smaller size of the motor having same ratings as compared to the other methods. The control parameters for optimizing rotor copper loss and stator copper loss using ABC are given in the Tables 3 and 4 respectively.

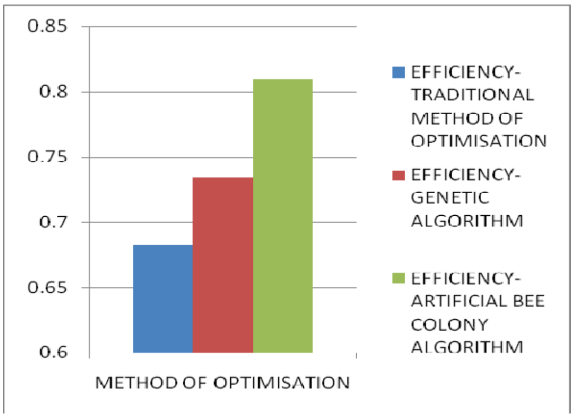

Fig. 4 Efficiency curves for *various methods.*

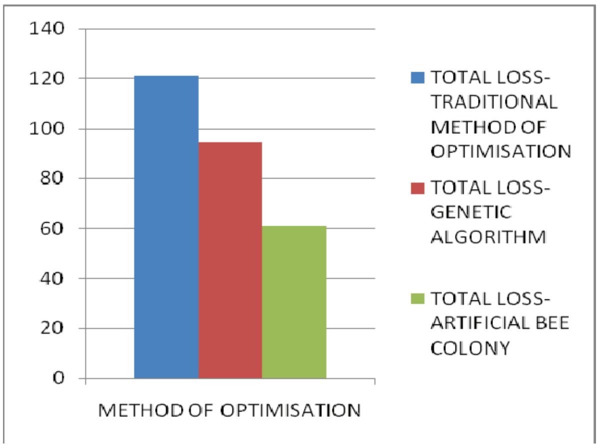

Fig.5 Total Loss curves for various methods.

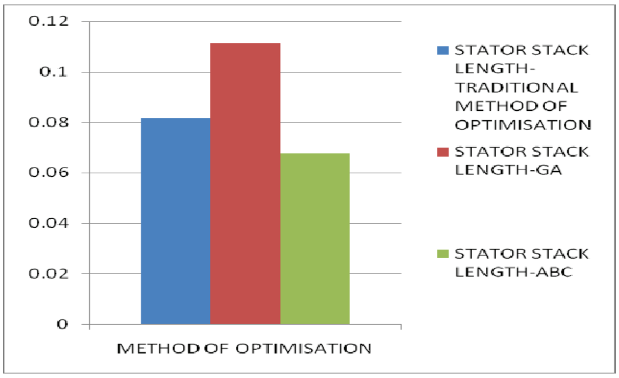

Fig.6 Stator Stack Length curves for various methods.

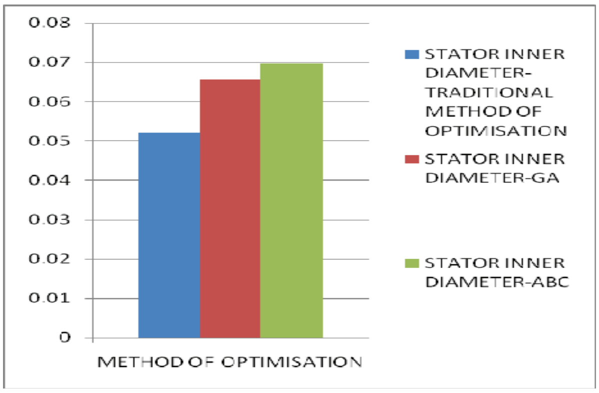

Fig.7 Stator inner diameter curves for *various methods.*

TABLE-3: ABC Control Parameter for Rotor copper loss.

Colony size	Food Number	Limit	Max. Cycle	Run Time
6	2	6	10	9

TABLE-4: ABC Control Parameter for Stator copper loss.

Colony size	Food Number	Limit	Max. Cycle	Run Time
3	3	2	10	9

The efficiency and power factor are also optimized during minimization of the stator and rotor copper losses by Artificial Bee Colony Algorithm. Some modifications from usual are made in the control parameters of ABC for the ease of calculations.

Table - 5 shows the flux density values of the motor for three methods applied here for design. As the ratio between the inner diameter of stator and stator tooth width is less with ABC method, the maximum flux density is decreased in case of optimum design by ABC.

TABLE-5: Flux distribution of motor for different methods of optimization.

Quality	Traditional Method [1]	GA[1]	ABC
Stator core flux density	1.3935T	0.81312T	0.8T
Maximum stator teeth flux density	1.5035T	1.0004T	0.4472T
Rotor core Flux density	1.6T	0.93211T	0.8T
Maximum rotor teeth flux density	0.7597T	0.56167T	0.5447T

As the stator teeth maximum flux density and the stator core flux density are less in ABC based optimum design, the stator iron loss becomes less since the specific iron loss becomes less.

V. Conclusion

The design optimization of six-phase induction motor has been presented using Artificial Bee Colony Algorithm. The optimum designs using Artificial Bee Colony Optimization Algorithm, conventional design and Genetic Algorithm have been compared.

The following conclusions are made:

- Greater efficiency is achieved in case of ABC based optimum design.
- Power factor improves in case of ABC based optimum design.
- Total losses are minimized in case of ABC based optimum design.
- Magnetizing reactance becomes less in case of ABC based optimum design so the short circuit current is decreased.
- Length of Stator stack is decreased and inner stator diameter is increased. Therefore, the size is reduced for ABC based design.
- Flux Densities are lowered so that the iron loss is reduced in ABC based design.

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