Optimal Design of Induction Motor for a Spinning Machine Using Population Based Metaheuristics

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Abstract— **This paper deals with the design optimization of a squirrel-cage three-phase induction motor, selected as the driving power of spinning machine in textile industry, using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Efficiency, which decides the operating or running cost of the motor (industry), is considered as objective function. First, the algorithms are applied to design a general purpose motor with seven variables and nine performance related parameters with their nominal values as constraints. To make the machine feasible, practically acceptable to serve in textile industries and less operating cost, certain constraints are modified in accordance with the demands in spinning application. Comparison of the optimum designs with the industrial (existing) motor reveals that the motor designed for textile load diagram consumes less power input. Economical analysis is also given.**

Keywords-Induction motor, spinning machine, design optimization, particle swarm optimization, genetic algorithms

I. INTRODUCTION

Three-phase induction motors (IMs) are the most frequently used machines in various electrical drives. About 70% of all industrial loads on a utility are represented by induction motors [1]. Textile industries are found to be energy-intensive (4% energy cost in total input cost) compared to other industries like chemical, food, computer manufacturing, etc., and hence extensive research has been focused on such industries in the past to reduce the energy cost (operating cost) and the total input cost [2]. To achieve minimum operating cost or maximum efficiency, the induction motor can be designed optimally with the help of numerical techniques. Many techniques: statistical method [3], Monto Corlo [4], Sequential Unconstraint Minimization Technique (SUMT) [5], Hook Jeeves (HJ), [6], modified Hook Jeeves (MHJ) [7], Han Powel method [8], unconstrained Rosenbrock [9], and constrained Rosenbrock method (Hill algorithm) [10] have been applied successfully in IM design in the past and few of them on special design like motor design for electric vehicle [11], variable speed drives [12] and aerospace applications [13]. Nature Inspired Algorithms (NIA) has also been applied in the design of IM [14], [15], etc. As the best of our knowledge, motor design for textile mill application has not been reported and comparison has not been made with the existing industrial motors.

The organization of this paper is as follows. Section II discusses the problem formulation with variables and constraints. Section III gives the design modification of motor for textile mill applications. In section IV, GA and PSO algorithms are given; section V gives the experimental settings and the results discussion. Finally the paper concludes with section VI.

II. FORMULATION OF IM DESIGN PROBLEM

The design of the induction motors means to determine the geometry and all data required for manufacturing so as to satisfy a vector of performance variables together with a set of constraints. The general nonlinear programming problem is given by nonlinear objective function f, which is to be minimized /maximized with respect to the design variables $X = (x_1, x_2, \ldots\ldots, x_n)$ and the nonlinear inequality and equality constraints. This can be formulated by,

$$\textit{Minimize / Maximize} \quad f(X)$$

Subject to: $g_j(X) \le 0$, $j = 1,2,\ldots, p$ (1)

$$h_k(X) = 0, \; k = 1,2,\ldots, q \quad (2)$$

$$x_{i\min} \le x_i \le x_{i\max} \; (i = 1,\ldots\ldots, n) \quad (3)$$

Where, p and q are the number of inequality and equality constraints respectively and n is the number of variables.

A. Variables

A set X of seven independent variables which affect constraints and objective function is listed below;

(1) ampere conductors/m, x_1
(2) ratio of stack length to pole pitch, x_2
(3) stator slot depth to width ratio, x_3
(4) stator core depth (mm), x_4
(5) average air gap flux densities (wb/m^2), x_5
(6) stator winding current densities (A/mm^2), x_6
(7) Rotor winding current densities (A/mm^2), x_7

B. Constraints

The constraints imposed into the design of induction motor for general applications are:

(1) maximum stator tooth flux density, wb/m^2 ≤ 2

(2) stator temperature rise, °C ≤ 70
(3) full load efficiency, pu ≥ 0.8
(4) no load current, pu ≤ 0.5
(5) starting torque, pu ≥ 1.5
(6) maximum torque, pu ≥ 2.2
(7) slip, pu ≤ 0.05
(8) full load power factor ≥ 0.8
(9) rotor temperature rise, °C ≤ 70

C. *Objective function*

In order to reduce the running cost of the motor with typical high load cycles of industrial or commercial applications, higher efficiency is more important. Maximization of motor efficiency is considered as objective function in the optimization process.

The efficiency of induction motor can be written as

$$\eta = \frac{1000P_o}{1000P_o + P_{cus} + P_{cur} + P_{iron} + P_{mech}} \quad (4)$$

where, Po is the output power (watts) of the machine, P_{cus}, P_{cur}, P_{iron} and P_{mech} are stator copper, rotor copper, iron and mechanical losses, respectively. Detailed expressions for the objective function and constraints can be seen in [16].

III. TEXTILE SPINNING MACHINE

Spinning machine manufactures the cotton into yarn that winded in spindles and used to feed cone winding machine. After that it can be used to make end products (clothing) with the help of weaving machine. Three-phase squirrel-cage induction motor is employed as main drive and its shaft load is decided by the quantity of yarn in the spindles which varies from zero (when the process starts) to full (when process completes). Therefore the motor shaft load varies from very light to rated, shown in Figure 1. Discrete nature of load diagram is considered for ease analysis. In Figure 1, 'T' is the time consumption for the completion of one process.

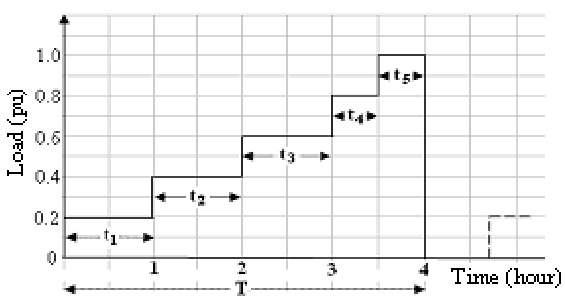

Figure 1. Average load diagram of a typical spinning ring frame drive motor

As shown in Figure 1, the motor employed in spinning machine is undergone partial loads in most of its operating hours. In addition with this feature, there are no sudden changes in the load torque and the required starting torque is less. It is noted that the motor efficiency and power factor are poor in case of partial load. To improve them, new designs suitable for textile mill applications are proposed by modifying the constraints which were used in section II (B). No-load current, main source for the core losses in the motor, should be maintained as low as possible during light or partial loads. The modified constraints are:

- no load current, pu ≤ 0.35
- starting torque, pu ≥ 1.2
- maximum torque, pu ≥ 1.75

A. *Operating Cost Calculation*

Total energy cost (TEC) of a motor is an important issue in the industry. On an average standard motors consume electricity equivalent to 60-100 times its purchasing price during its working life. Industrial tariff comprises (i) energy charge, (ii) fixed demand charge.

Energy cost calculation

The energy cost of the induction motor per year is calculated as in (5). Power factor penalty is not considered in this paper because almost all the industries have centralized power factor correction equipments.

$$S = C_e * T * P_{in} \quad (5)$$

where S - Energy cost per year, C_e - Energy cost (US $/kWh), T - Total operating hour/year,
P_{in} - Input power of the motor (KW).

Demand cost calculation

Demand charge cost (D) consumed by the motor per year can be calculated as

$$D = C_d * 12 * P_{in} \quad (6)$$

where, C_d - Demand cost per month (US $)
The total energy cost per year of the motor is

$$TEC = P_{in}\{(C_e * T) + (C_d * 12)\} \quad (7)$$

IV. OPTIMIZATION ALGORITHMS

A. *Real Coded Genetic Algorithm*

Genetic algorithms are perhaps the most commonly used search techniques for obtaining the global optimal solution of optimization problems. These are based on the principles of natural genetics and natural selection as introduced by Holland [17] and further described by Goldberg [18]. Initially binary encoded version of GA was introduced, however, with the passage of time it was observed that real coded Genetic Algorithms are more efficient for solving problems having continuous variables. GA maintains a set of candidate solutions ζ. In each generation, a new ζ is evolved from the old ζ, and as the generation proceeds, the set of solutions in ζ converges to global minimum. New solution points are generated with the help of selection, crossover and mutation operators. A simple arithmetic crossover operator is used in the present work. It linearly combines two parent chromosome vectors to produce two new offsprings as follows:

Offspring1=a**Parent1*+(1-a)**Parent2;* (8)
Offspring2=(1–a)**Parent1*+a**Parent2;* (9)

where 'a' is a random weighting factor which can take a value between – 0.5 and 0.5.

B. Particle Swarm Optimization

Particle swarm optimization technique is a population based stochastic search technique first suggested by Kennedy and Eberhart in 1995 [19]. The mechanism of PSO is inspired from the complex social behavior shown by the natural species. For a D-dimensional search space the position of the ith particle is represented as $Xi = (x_{i1},x_{i2},..x_{iD})$. Each particle maintains a memory of its previous best position $Pi = (p_{i1}, p_{i2}\dots p_{iD})$ and a velocity $Vi = (v_{i1}, v_{i2},\dots v_{iD})$ along each dimension . At each iteration, the P vector of the particle with best fitness in the local neighborhood, designated g, and the P vector of the current particle are combined to adjust the velocity along each dimension and a new position of the particle is determined using that velocity. The two basic equations which govern the working of PSO are that of velocity vector and position vector are given by:

$$v_{id} = wv_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \quad (10)$$

$$x_{id} = x_{id} + v_{id} \quad (11)$$

The first part of equation (10) represents the inertia of the previous velocity, the second part tells us about the personal thinking of the particle and the third part represents the cooperation among particles and is therefore named as the social component. Acceleration constants c_1, c_2 and inertia weight ω are predefined by the user and r_1, r_2 are the uniformly generated random numbers in the range of [0, 1].

V. Experimental Settings and Results Discussion

A. Experimental Settings

The main parameters of PSO algorithm are inertia weight w and acceleration constants c_1 and c_2. After performing a number of experiments and going through various PSO versions available in literature, the present work considered the following experimental settings: the inertial weight w is taken to be linearly decreasing from 0.9 to 0.5. Acceleration constants c_1 and c_2 are taken as 2.0 each and r_1, r_2 are taken as the uniformly distributed random numbers between 0 and 1. In Genetic algorithms Roulette wheel selection is used and probability of crossover and mutations are taken as 0.7 and 0.9 respectively. For handling constraints, the approach based on repair methods suggested in [20] is used. Both the algorithms were implemented using Turbo C++ on a PC compatible with Pentium IV, a 3.2 GHz processor and 2 GB of RAM.

B. Results Discussion

The motor with nominal ratings, shown in Table I, is considered for optimization. Motor design and its results discussion are categorized into two: 1) for general purpose motor, 2) motor for textile spinning applications. The results of fresh design of an induction motor obtained from different optimization algorithms are shown in Table II.

TABLE I. Specification of squirrel-cage induction motor

Capacity	7.5 kW
Voltage per phase	400 volts
Frequency	50 Hz
Number of poles	4
Number of stator slots	36
Number of rotor slots	44

1) Motor Design for General Applications

GA algorithm is produced better efficiency in comparison with PSO. One reason for achieving the same is less rotor resistance (shown in Table II) and hence less rotor copper losses in the motor designed by GA. Starting torque, due to less rotor resistance, in the design using GA is lower than PSO but it is good enough to start the machine. On the other hand, increase in the manufacturing cost of the machine by 25.19%. This is because of increase in the weights of active materials. Since a motor consumes electricity equivalent to its manufacturing cost in just three weeks of continuous use, small increase in manufacturing cost does not produce any significant effects on process industries. Stator copper losses (main source for stator temperature rise) are high in the design using GA and hence temperature rise in the motor is high in comparison with PSO.

Cost per weight ($/kg) of iron and copper are considered 4.7 and 8.2, respectively as in [11].

2) Motor Design for Textile Spinning Applications

PSO is produced higher full load efficiency of the motor in comparison with GA. But these values are higher in case of general purpose motor designed by these algorithms. The limitation in no-load current

and the corresponding magnetizing current is the reason for the same. Higher power factor is achieved in the special designs due to less magnetizing current in comparison with general purpose motor. Manufacturing costs of new designs are increased due to the increase of active materials used.

To see the performance of specially designed motors throughout its operations, the motor parameters are extracted from the Table II and are simulated with MATLAB/SIMULINK software. The results are compared with the existing industrial motor (R_s =0.7384, $R_r^{'}$ =0.7402, $L_s = L_r$ =3.045mH, $L_m =$ 0.1241) and is shown in Figure 2. There are large differences, especially at light load regions, in power consumption between industrial motor and optimally designed motors for textile applications using GA and PSO, shown in Table III. Most of the load regions, PSO based design is consumed less input power in comparison with general design. At region t_5 (full load), proposed designs are consumed more power in comparison with industrial load due to magnetizing current limitation. Starting torque and pull-out torques in all designs are good enough to drive the load.

TABLE II. MOTOR DESIGN FOR GENERAL AND TEXTILE APPLICATIONS

Quantity	Optimization Algorithm			
	General design		Textile design	
	GA	PSO	GA	PSO
Stator bore diameter (m)	0.158827	0.167751	0.177729	0.162077
Stator outer diameter (m)	0.298222	0.271253	0.286934	0.259626
Stack length (m)	0.115569	0.125914	0.140671	0.253731
Stator resistance (Ω)	1.44619	1.23867	1.22076	2.13949
Rotor resistance (referred to stator ,Ω)	1.22087	2.34196	2.7799	1.08647
Stator reactance (Ω)	3.77705	2.03959	5.43888	2.04917
Rotor reactance (Ω)	1.37725	1.13206	1.61251	1.50089
Magnetizing reactance (Ω)	85.0223	84.0837	126.355	107.126
Efficiency	0.88685	0.870836	0.856901	0.853054
Power factor	0.890502	0.903755	0.916836	0.940647
Starting torque to rated torque ratio	1.50449	4.07263	1.79834	1.91545
Pull out torque to rated torque ratio	2.93627	4.26588	2.48461	3.19928
Cost of the materials ($)	269.845	215.54	268.585	421.359
Total weight of the materials (Kg)	51.8833	41.1759	50.2385	83.4226
Stator slot width (m)	0.005759	0.006152	0.006813	0.004336
Stator slot depth (m)	0.023105	0.022443	0.02877	0.014475
Rotor slot width (m)	0.004712	0.005033	0.005574	0.003547
Rotor slot depth (m)	0.007559	0.003413	0.003737	0.010403
Stator core depth (m)	0.046592	0.027103	0.025833	0.032744
Ampere conductor per meter	21896.9	19364.8	20947.4	17055
Air-gap flux density (wb/m^2)	0.698288	0.649382	0.478896	0.4
Stator winding current density (A/mm^2	6.51509	7.80258	4.73519	9.28913
Rotor winding current density (A/mm^2)	5.92425	11.5538	10.845	4.3747
Stator tooth flux density (wb/m^2)	1.95685	1.85789	1.34498	0.983704
Stator temperature rise (^{o}C)	55.0857	41.7124	44.2133	43.9256
No-load to full load current ratio	0.482335	0.487572	0.325065	0.349716

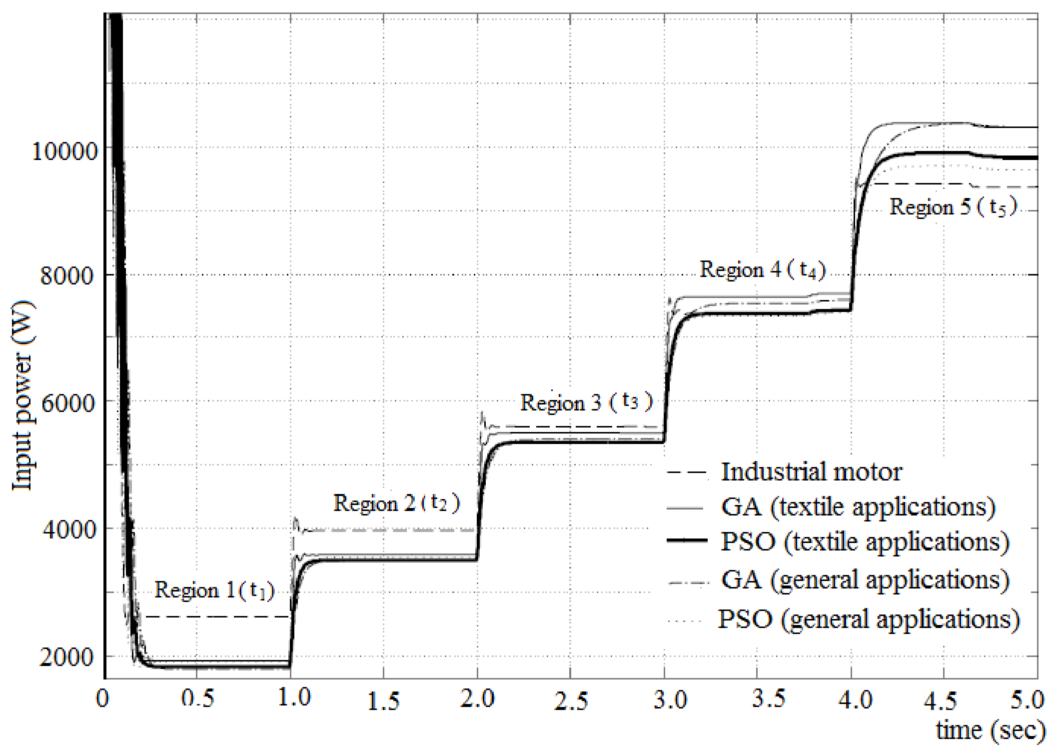

Figure 2. Simulation results of proposed designs for textile mill load diagram

TABLE III. COMPARISON OF POWER CONSUMPTION IN MOTORS WITH DIFFERENT DESIGNS

Algorithms	Input power of motor under textile mill load diagram (W)				
	Region 1	Region 2	Region 3	Region 4	Region 5
Industrial motor	2609	3952	5996	7428	9442
GA (textile)	1776	3483	5596	7556	10300
PSO (textile)	1817	3486	5346	7380	9825
GA (general)	1908	3576	5494	7637	10378
PSO (general)	1901	3528	5362	7342	9700

TABLE IV. ECONOMIC ANALYSIS OF PROPOSED DESIGNS

Algorithms	Less power consumption (kW) of proposed motors in comparison with industrial motor					Total kW saving	S ($/year)	D ($/year)	Total saving ($/year)
	t_1	t_2	t_3	t_4	t_5				
GA (textile)	0.883	0.469	0.400	-0.128	-0.858	0.766	104.69	61.22	165.89
PSO (textile)	0.792	0.466	0.650	0.048	-0.308	1.648	225.24	131.70	356.94

3) *Economic Analysis*

Economic analysis of proposed design with respect to given load diagram at the following electricity tariff and assuming 355 days of operation/year with 5 processes per day is summarized in Table IV. PSO based design is offered more savings ($357) in terms of operating cost in comparison with industrial motor.

Maximum demand (KVA) charges: US $ .66/month
Energy (kWh) charges: US $ 0.077/kWh
(1 US $= IRS 45 approximately)

VI. CONCLUSION

This paper has presented the design optimization of a squirrel-cage three-phase induction motor using basic GA and PSO algorithms. A 7.5 kW motor has been designed as an illustrative example. Textile spinning load was considered to the input of design optimization for minimum operating cost of the motor. Results were compared with the typical industrial motor. On the basis of the results obtained, one may draw the following conclusions:

- The constraint, no load current was more influenced in the optimized design for minimum power consumption or more savings especially on light loads
- $357 can be saved in a 7.5kW motor per year if it is designed with the consideration of service conditions i.e. load diagram. This saving will be more in case of large capacity motors
- Small increase in manufacturing cost of the motor can be allowed when efficiency or operating cost optimization is performed. This will not produce any significant effects on the economics of process industries
- PSO algorithm is suitable to the design of induction motors for industrial applications particularly textile mills.

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