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Realization on Particle Swarm Optimized Design of Induction Motor Via SPEED/PC-IMD

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***Abstract*— This paper presents an optimal design and its realization of poly-phase induction motor using Quadratic Interpolation based Particle Swarm Optimization (QI-PSO). The optimization algorithm considers the efficiency, starting torque and temperature rise as objective function (which are considered separately) and nine performance related items as constraints. The QI-PSO algorithm was implemented on a test motor and the results are compared with the Simulated Annealing (SA) technique, Standard Particle Swarm Optimization (SPSO), and normal design. Some benchmark problems are used for validating QI-PSO. From the test results QI-PSO gave better results and more suitable to motor's design optimization. Optimized variables are realized by PC-IMD (Induction Motor Drives) of SPEED (Scottish Power Electronics and Electric Drives) software. C++ code is used for implementing entire algorithms.**

***Index Terms*—design optimization, induction motor, particle swarm optimization, SPEED/PC-IMD software, quadratic interpolation.**

I. INTRODUCTION

Three phase induction motors 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]. Recently oil prices, on which electricity and other public utility rates are highly dependent, are rapidly increasing. It, therefore, becomes imperative that major attention be paid to the efficiency and operating cost of induction motors [2]. To achieve minimum energy cost or maximum efficiency, the induction motor should either redesign or fed through an inverter.

In general, there are two broad approaches to improve the induction motor efficiency, namely optimal design (OD) and optimal control (OC). Many researchers have been reported several techniques on both the broad approaches. Some OC algorithms use slip speed [3], [4], rotor flux [5]-[8], power input [7], [9], and voltage [10] as variables to optimize the motor performance. Some of the evolutionary algorithms for OD are available in the literatures [11] - [15]. In Ref. [14], authors used SA for getting optimum design of three test motors with three different objective functions. In Ref. [16], authors discussed their experience in the design of inverter-fed induction motors.

Since engineering problems require global optima, academic as well as industrial experts are giving more attention to evolutionary searching techniques such as genetic algorithm, PSO, SA, differential evolution, etc. This paper is concerned with the OD using QI-PSO and considers three objectives namely, maximum efficiency, maximum starting torque, and minimum temperature rise and is organized as follows. Section II briefly explains PSO and QI-PSO algorithms; section III discusses the problem formulation with variables and constraints. Section IV gives the detailed discussion on the results of QI-PSO algorithm and their comparison with other algorithms. Validation of QI-PSO is given in section V.

II. PARTICLE SWARM OPTIMIZATION

Electrical Engineering community has shown a significant interest in evolutionary algorithms for obtaining the global optimum solution to its problems. Some common EAs are Genetic Algorithms (GA), Evolutionary Programming (EP), Particle Swarm Optimization (PSO), Differential Evolution (DE) etc.

A. Standard Particle Swarm Optimization

PSO technique is a population based stochastic search technique first introduced by Kennedy and Eberhart [17]. PSO can be represented by the concept of velocity and position [18]. The two basic equations which govern the working of PSO are that of velocity vector (v_{id}) and position vector (x_{id}) are given by

$$v_{id} = \omega v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \qquad (1)$$

$$x_{id} = x_{id} + v_{id} \qquad (2)$$

The first part of equation (1) represents the inertia of the previous velocity, the second part is useful to personal thinking of the particle, and the third part represents the cooperation among particles and is therefore named as the social component [19]. Acceleration constants c_1, c_2 [18] and inertia weight ω [20] are the predefined by the user and r_1, r_2 are the uniformly generated random numbers in the range of [0, 1].

B. Improved Particle Swarm Optimization

The Quadratic Interpolation (QI) with Particle Swarm Optimization (QI-PSO) algorithm proposed by Millie Pant, Et.al [21] which works initially like SPSO and do crossover to find new particle and it is accepted in the swarm only if it is better than the worst particle present in the swarm. The process is repeated iteratively until a better solution is obtained. It uses a = X_{min}, (the leader having minimum function value) and two other randomly selected particles {b, c} (a, b and c are different particles) from the swarm (tribe) to

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determine the coordinates of the new particle $\tilde{x}^i = (\tilde{x}^1, \tilde{x}^2, \ldots\ldots, \tilde{x}^n)$, where

$$\tilde{x}^i = 0.5 * \frac{(b^{i^2} - c^{i^2}) * f(a) + (c^{i^2} - a^{i^2}) * f(b) + (a^{i^2} - b^{i^2}) * f(c)}{(b^i - c^i) * f(a) + (c^i - a^i) * f(b) + (a^i - b^i) * f(c)} \tag{3}$$

The flow of QIPSO algorithm is shown in Fig.1

```
Step1: Initialization.
  For each particle i in the population:
Step1.1: Initialize the particles (X[i]) with Uniform
         distributed random numbers.
Step1.2: Initialize particle's velocity V[i].
Step1.3: Evaluate the objective function of X[i],
         and assigned the value to fitness[i].
Step2: Position and Velocity updation
  For each particle i:
Step 2.1: Update V[i] and X[i] according
          to equations (1) and (2).
Step2.2: Evaluate fitness[i].
Step2.3: If fitness[i] < Pbest_fitness[i] then
           $P_{best}$[i] =X[i], Pbest_fitness[i] =fitness[i].
Step2.4: Update $P_{gbest}$ by the particle with current
          least fitness among the population.
Step 3: Find the new particle using Equation (3)
        If new particle is better than worst particle in
        the swarm, replace worst particle by the new
        particle
Step 4  Go to step 2 until stopping criterion is reached.
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Fig. 1. Flow of QI-PSO for motor's design optimization

III. PROBLEM FORMULATION

Machine design optimization is not only running of a mathematical optimization iterative procedure. There are some other important steps, which are required to be followed before the implementation of the optimization technique. Selection of objective functions, variables and constraints are the main steps. A problem in the selection of variables is that the design problem of IM would have been very much complicated using too many variables [22]. A general nonlinear programming problem can be stated in mathematical terms as follows.

Find X= $(x_1, x_2 \ldots . x_n)$ such that
F(x) is a minimum or maximum
$g_i(x) \geq 0$, i=1, 2,….m

F_i is known as objective function which is to be minimized or maximized; g_i's are constants and x_i's are the variables. The following variables and constraints [23] are considered to get optimal values of objective functions.

A. Variables

The following variables $(x_1 \ldots \ldots x_7)$ are considered,

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

B. Constraints

To make a motor practically feasible and acceptable, the constraints have a big role in it. The constraint which gets most effected with the variation in the objective function should be considered with special care. The constraints $(C_1 \ldots \ldots C_9)$ imposed into induction motor design in this paper is as follows which are expressed in terms of variables

maximum stator tooth flux density,wb/m^2 ≤ 2, C_1
stator temperature rise, °C ≤ 70, C_2
full load efficiency, pu ≥ 0.8, C_3
no load current, pu ≤ 0.5, C_4
starting torque, pu ≥ 1.5, C_5
maximum torque, pu ≥ 2.2, C_6
slip, pu ≤ 0.05, C_7
full load power factor ≥ 0.8, C_8
rotor temperature rise, °C ≤ 70, C_9

C. Objective Functions

The objective function is mostly chosen keeping in mind the customers demand and the profit of manufacturer. Three different objective functions are considered in this paper while designing the machine using optimization algorithms. The objective functions are,

F(x) = A; Maximization of Efficiency
F(x) = B; Maximization of Starting torque
F(x) = C; Minimization of temperature rise in the stator circuit of the motor

IV. RESULTS AND DISCUSSION

The PSO algorithm is implemented to optimize the design of induction motor whose specifications are available in appendix. The results of QI-PSO algorithm in the motor design and their comparison with SPSO, SA and normal design are given in the Table I, II, and III.

When QI-PSO algorithm considered efficiency of the motor as an objective function, the resulting design gave considerably better results than normal design and also quite better than SA and SPSO. Temperature rise and slip are lower in QI-PSO but main dimensions are higher than other methods so that volume will be higher. Required air-gap flux density in QI-PSO is nearly 300% more than SA.

For Starting torque maximization also, QI-PSO offers better results than others significantly. In this case, main dimensions are higher but temperature rise considerably reduced. Full load slip in QI-PSO is smaller than normal design and SA.

For temperature rise minimization, again QI-PSO performed well which improvement percentage is 18.37%, 4.57% and 10.03% compared to normal design, SA and SPSO respectively. Here main dimensions are lower and efficiency is slightly better than others. For over all performance QI-PSO gave good results than others so that it can be used for design optimization of induction motor. Table IV shows the improvement of QI-PSO in comparison with other algorithms.

From the design results presented in Tables I-III, particularly the following variables are dominated in QI-PSO to get optimum value of all objective functions;

1. Width of the stator slot
2. Depth of the rotor slot
3. Length of the stator stack

The effects of above variables on the objective functions or related parameters are realized by using ranging option in SPEED/PC-IMD software which is designed by University of Glasgow for modern motors. It is available Induction motors (poly-phase/single-phase), brushless permanent magnet motors (square wave/sinusoidal wave), switched reluctance motors, synchronous reluctance motors, and commutator machines. The results are shown in Figs. 2-10.

Taking the width of stator slot (W_{ss}), its value in all the objective functions is higher at QI-PSO than SA, SPSO and normal design. Efficiency and torque are achieved higher in QI-PSO due to higher value of W_{ss}, shown in Fig. 2 and 3. Similarly total losses (indirectly temperature) offered by the motor are lower in case of higher W_{ss} and is shown in Fig. 4.

TABLE I
OPTIMUM DESIGN RESULTS FOR EFFICIENCY MAXIMIZATION

Items	Normal [14]	SA [14]	SPSO	QIPSO
Width of the stator slot (m)	0.00132	0.0011	0.00487	0.00433
Depth of the stator slot (m)	0.021	0.0159	0.01962	0.01515
Width of the rotor slot (m)	0.0068	0.005	0.00399	0.00355
Depth of the rotor slot (m)	0.0093	0.0091	0.00634	0.00660
Air gap flux density (wb/m^2)	0.6	0.521	2.000	2.00
Air-gap length (m)	0.0003	0.0003	0.0005	0.0005
Full load slip	0.0699	0.056	0.0488	0.0416
Stator bore diameter (m)	0.105	0.102	0.0902	0.0890
Stator outer diameter (m)	0.181	0.177	0.208	0.1913
Stack length (m)	0.125	0.097	0.1269	0.109
Temperature rise, °C	46.8178	41.391	44.463	39.83
Efficiency	**0.80309**	**0.82848**	**0.833**	**0.8356**
Starting torque, pu.	1.2027	1.3444	3.226	3.730
Power factor	0.8041	0.8333	0.840	0.800

TABLE II
OPTIMUM DESIGN RESULTS FOR STARTING TORQUE MAXIMIZATION

Items	Normal [14]	SA [14]	SPSO	QIPSO
Width of the stator slot (m)	0.00132	0.0012	0.00464	0.00555
Depth of the stator slot (m)	0.021	0.0187	0.02272	0.02118
Width of the rotor slot (m)	0.0068	0.0056	0.00379	0.00454
Depth of the rotor slot (m)	0.0093	0.0071	0.00537	0.00291
Air gap flux density (wb/m^2)	0.6	0.4713	1.1805	2.00
Air-gap length (m)	0.0003	0.0004	0.0005	0.0005
Full load slip	0.0699	0.0645	0.046	0.0505
Stator bore diameter (m)	0.105	0.1028	0.111	0.0999
Stator outer diameter (m)	0.181	0.1733	0.252	0.2179
Stack length (m)	0.125	0.1162	0.164	0.114
Temperature rise, °C	46.8178	64.475	53.11	41.810
Efficiency	0.8030	0.79179	0.813	0.825
Starting torque, pu	**1.2027**	**1.3776**	**3.568**	**4.966**
Power factor	0.8041	0.7938	0.863	0.813

TABLE III
OPTIMUM DESIGN RESULTS FOR TEMPERATURE RISE MINIMIZATION

Items	Normal [14]	SA [14]	SPSO	QIPSO
Width of the stator slot (m)	0.00132	0.0013	0.00444	0.00457
Depth of the stator slot (m)	0.021	0.0236	0.01919	0.02258
Width of the rotor slot (m)	0.0068	0.005	0.00363	0.00374
Depth of the rotor slot (m)	0.0093	0.0093	0.00652	0.00499
Air gap flux density (wb/m^2)	0.6	0.439	2.000	1.632
Air-gap length (m)	0.0003	0.0004	0.0005	0.0005
Full load slip	0.0699	0.0684	0.05	0.0536
Stator bore diameter (m)	0.105	0.101	0.085	0.189
Stator outer diameter (m)	0.181	0.171	0.1919	0.099
Stack length (m)	0.125	0.1216	0.124	0.114
Temperature rise, °C	**46.8178**	**40.0391**	**42.47**	**38.209**
Efficiency	0.80309	0.803748	0.827	0.814
Starting torque, pu.	1.2027	1.117	3.098	3.133
Power factor	0.8041	0.7814	0.830	0.858

TABLE IV
IMPROVEMENT PERCENTAGE USING QI-PSO IN COMPARISON WITH NORMAL DESIGN, SPSO AND SA

Objective Function	Test Motor -3hp		
	Normal	SA	SPSO
F(x) = A	4.04	0.86	0.312
F(x) = B	312.9	260.48	40.02
F(x) = C	18.37	4.57	10.03

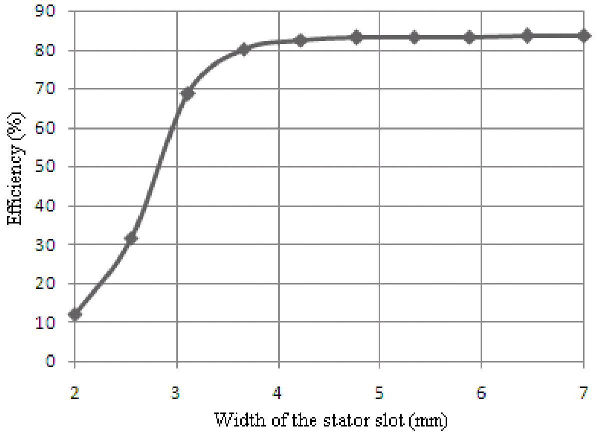

Fig. 2. Efficiency versus width of the stator slot in the optimized motor

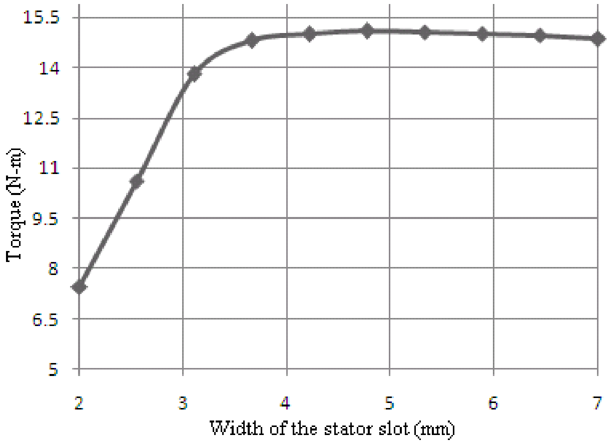

Fig. 3. Torque versus width of the stator slot in the optimized motor

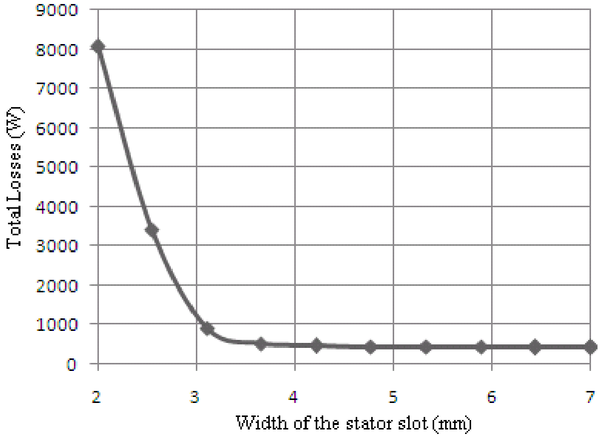

Fig. 4. Total losses versus width of the stator slot in the optimized motor

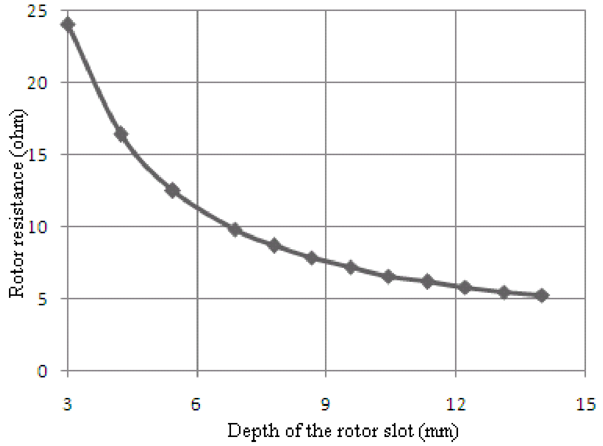

Fig. 5. Rotor resistance versus depth of the rotor slot in the optimized motor

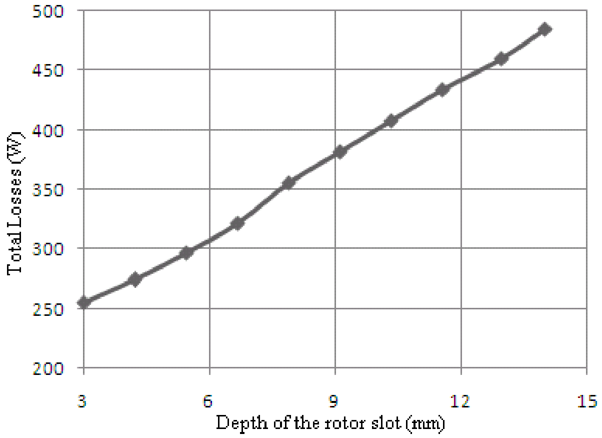

Fig. 6. Total losses versus depth of the rotor slot in the optimized motor

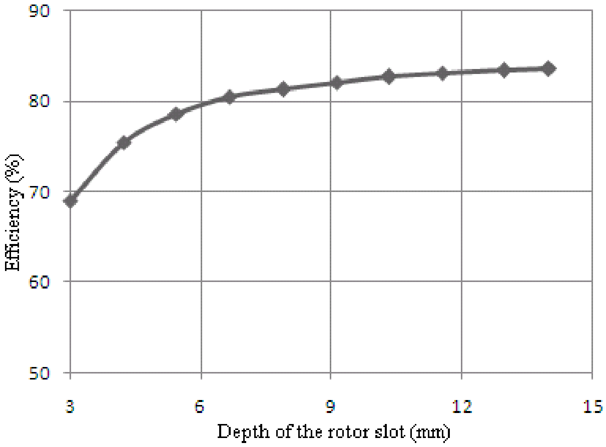

Fig. 7. Efficiency versus depth of the rotor slot in the optimized motor

Taking the depth of the rotor slot (D_{sr}), motor offers higher torque and minimum losses at low D_{sr}, shown in Fig. 5 & 6. The value of D_{sr} in QI-PSO is smaller than all other algorithms so that it gave good performance in terms of maximum torque and minimum temperature rise, shown in Table II and III respectively. Since lower D_{sr} offers lower efficiency, shown in Fig. 7, QI-PSO takes higher D_{sr} in F(X)=A compared to other objective functions for maximizing efficiency, keeping F(X)=B and F(X)=C are optimum.

Taking the length of the stator stack (L_{st}) in efficiency maximization, its value is higher in QI-PSO than SA so that higher efficiency offered by QI-PSO, shown in Fig. 8. On the other hand, its value is lower in F(X) =B and F(X) =C for managing higher torque and lower temperature rise because higher L_{st} offers lower torque and losses, shown in Fig. 9 and 10. Hence QI-PSO has chosen intermediate value (neither higher nor lower) to get all objective functions optimally.

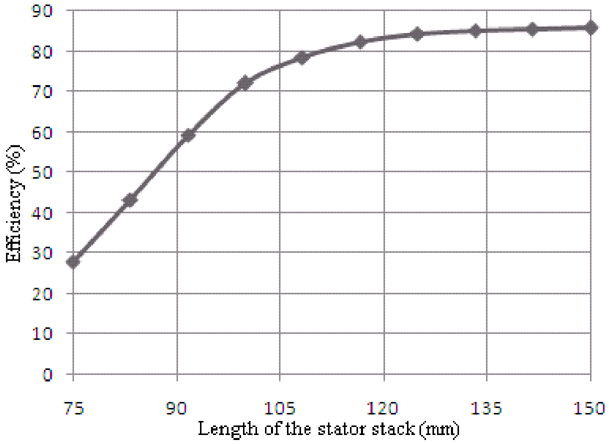

Fig. 8. Efficiency versus stator stack length in the optimized motor

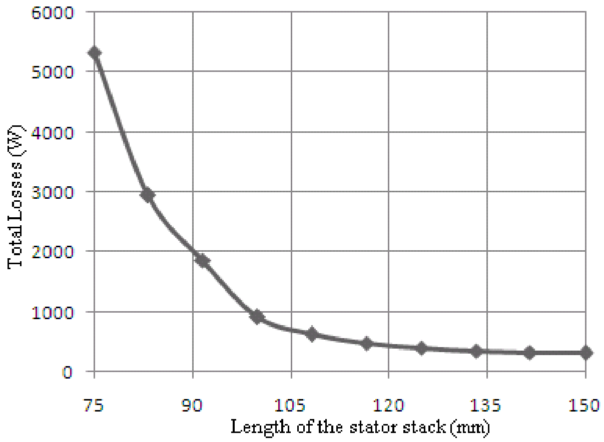

Fig. 9. Total losses versus stator stack length in the optimized motor

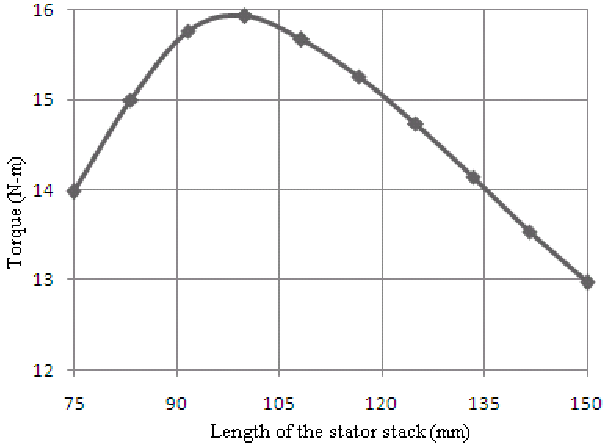

Fig. 10. Torque versus stator stack length in the optimized motor

V. VALIDATION OF QI-PSO WITH STANDARD BENCHMARK PROBLEMS

To validate the performance of QI-PSO, standard benchmark problems (shown in Table V) are used and their performances are compared with SPSO. From the numerical results shown in Table VI and convergence graphs shown in Fig. 11 and 12, QI-PSO gave better results in all the test problems.

TABLE V
STANDARD BENCHMARK PROBLEMS FOR VALIDATING QI-PSO

Benchmark Problems	Ranges	Mini. Value
$f_1(x) = \sum_{i=1}^{n}(x_i^2 - 10\cos(2\pi x_i) + 10)$	[-5.12,5.12]	0
$f_2(x) = \sum_{i=1}^{n} x_i^2$	[-5.12,5.12]	0
$f_3(x) = \frac{1}{4000}\sum_{i=0}^{n-1} x_i^2 + \sum_{i=0}^{n-1}\cos(\frac{x_i}{\sqrt{i+1}}) + 1$	[-500,500]	0
$f_4(x) = \sum_{i=0}^{n-1} 100(x_{i+1} - x_i^2)^2 + (x_i - 1)^2$	[-30,30]	0

TABLE VI
RESULTS OF QI-PSO AND ITS COMPARISON WITH SPSO IN BENCHMARK PROBLEMS (MEAN FITNESS/STANDARD DEVIATION)

Function	Dim	SPSO	QIPSO	No. of times QI activated in QIPSO
f_1	2	5.57913e-015 1.63684e-014	0.00000 0.00000	469
	10	4.75341 3.07381	4.01845 1.37636	85
f_2	2	3.02769e-022 5.93778e-022	5.7574e-049 1.72705e-048	898
	10	7.27335e-005 2.88549e-004	1.09812e-007 2.58381e-007	784
f_3	2	1.11077e-012 3.3323e-011	2.46617e-016 1.99805e-016	241
	10	0.0197954 0.153591	0.0024669 0.00977076	210
f_4	2	0.00115649 0.00219637	2.72628e-011 4.97405e-011	767
	10	90.1189 26.9975	8.24632 0.755432	797

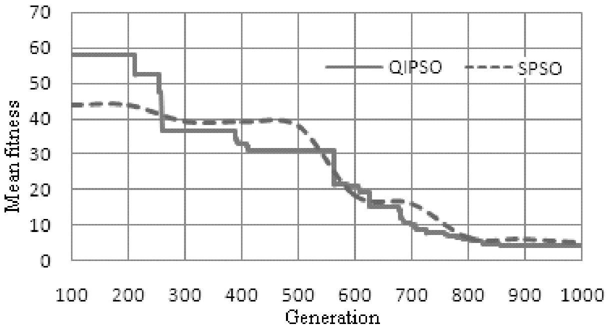

Fig. 11. Convergence graph for function f_1

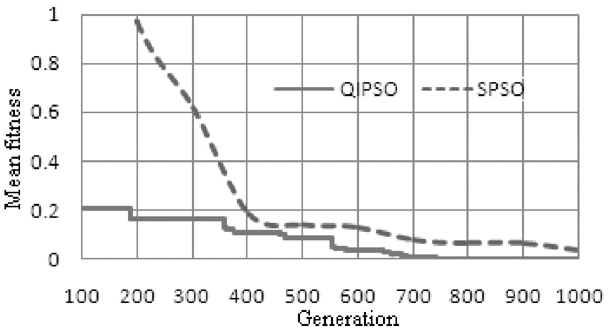

Fig. 12. Convergence graph for function f_2

VI. CONCLUSION

This paper investigated the optimal design of induction motor using QI-PSO with three objective functions, efficiency, starting torque and temperature rise. It is concluded that QI-PSO offered good results compared with SA, SPSO and normal design and it is more suitable to design optimization of induction motor. Optimized design parameters were realized by using SPEED software. QI-PSO algorithm was validated on standard benchmark problems. C++ code was used for implementing entire algorithm. SPEED/PC-IMD software is a fruitful addition in the machine design field to help motor manufacturers.

APPENDIX

Specification of Test Motor [14]

Capacity	3 hp
Voltage per phase	400 volts
Frequency	50 Hz
Number of poles	4
Number of stator slots	36
Number of rotor slots	44

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