Induction Motor Design with Limited Harmonic Currents Using Particle Swarm Optimization

C. Thanga Raj, S. P. Srivastava, and Pramod Agarwal

Abstract**—**This paper presents an optimal design 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 ten performance related items including harmonic current 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. C++ code is used for implementing entire algorithms.

Keywords**—**Design**,** harmonics, induction motor, particle swarm optimization

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 be redesigned 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 experiences in the design of inverter-fed induction motors. From their analysis, they concluded that the magnitude of the higher order harmonic currents should be as low as possible to have the minimum torque pulsation in the motor. Therefore the harmonic current is considered as one of the constraints in this paper.

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 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

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

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

$$x_{id} = x_{id} + v_{id} \tag{2}$$

The first part of equation (1) represents the inertia of the previous velocity, the second part is useful to personal thinking of the particle, 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 determine the coordinates of the new particle $\tilde{x}^i = (\tilde{x}^1, \tilde{x}^2, ...\tilde{x}^n)$, where

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$$\tilde{x}^i = \frac{1}{2}\frac{(b^{i^2}-c^{i^2})*f(a)+(c^{i^2}-a^{i^2})*f(b)+(a^{i^2}-b^{i^2})*f(c)}{(b^i-c^i)*f(a)+(c^i-a^i)*f(b)+(a^i-b^i)*f(c)} \quad (3)$$

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 partcle 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

A very important problem in the IM design is to select the independent variables and the problem would have been very much complicated using too many variables [22]. Therefore variables selection is important in the motor design optimization. A general nonlinear programming problem can be stated in mathematical terms as follows.

Find X= $(x_1, x_2.....x_n)$ 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 $(x_1......x_7)$ 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/mm2), x_6
Rotor winding current densities (A/mm2), x_7

B. Constraints

The constraints $(C_1.......C_{10})$ imposed into induction motor design in this paper is as follows which are expressed in terms of variables

maximum stator tooth flux density,wb/m2 ≤ 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
harmonic rotor current, pu ≤ 0.1, C_{10}

C. Objective Functions

Three different objective functions are considered 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

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 V shows the improvement of QI-PSO in comparison with other algorithms.

If the harmonic current (see in appendix) is considered as one of the constraints, the trends of the design variables, constraints and objective functions are shown in Table IV. Depth of the stator slot is greater at starting torque as objective function and the diameter of the stator bore in minimum. At temperature rise as objection function, limited harmonic current offers higher width of the stator slot, the tooth flux density and minimum temperature rise in the motor. The variations in the objective functions due to limited harmonic current are shown in Table VI.

TABLE I
OPTIMUM DESIGN RESULTS FOR EFFICIENCY MAXIMIZATION (WITHOUT C_{10})

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 (WITHOUT C_{10})

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 (Without C_{10})

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
Optimum Design Results When Limited Harmonic Current at Rated Frequency

Items	F(x) = A		F(x) = B		F(x) = C	
	SPSO	QIPSO	SPSO	QIPSO	SPSO	QIPSO
Width of the stator slot (m)	0.0044	0.0045	0.00563	0.00480	0.0054	0.00508
Depth of the stator slot (m)	0.0242	0.018	0.01973	0.0247	0.0169	0.0174
Width of the rotor slot (m)	0.0036	0.00368	0.00461	0.00393	0.0044	0.00416
Depth of the rotor slot (m)	0.0086	0.00812	0.00502	0.00318	0.00679	0.00745
Air gap flux density ((wb/m^2)	1.722	1.471	1.5065	2.00	1.680	2.00
Air-gap length (m)	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Full load slip	0.49	0.05	0.045	0.061	0.05	0.045
Stator bore diameter (m)	0.10	0.1014	0.123	0.088	0.0953	0.0918
Stator outer diameter (m)	0.203	0.199	0.205	0.179	0.1804	0.174
Stack length (m)	0.094	0.12	0.097	0.113	0.147	0.1138
Temperature rise, °C	40.83	40.62	45.08	40.617	**37.72**	**36.54**
Efficiency	**0.812**	**0.813**	0.799	0.808	0.809	0.81
Starting torque, pu.	1.89	2.11	**2.73**	**3.85**	2.11	2.67
Power factor	0.79	0.802	0.809	0.811	0.825	0.847

TABLE V
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

TABLE VI
VARIATIONS IN THE OPTIMAL VALUES OF THE OBJECTIVE FUNCTIONS WHEN LIMITED HARMONIC CURRENT

Objective Function	Test Motor -3hp	
	SPSO	QIPSO
F(x) = A	-0.021	-0.0226
F(x) = B	-0.838	-1.116
F(x) = C	-4.75	-1.75

TABLE VII
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 VIII
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

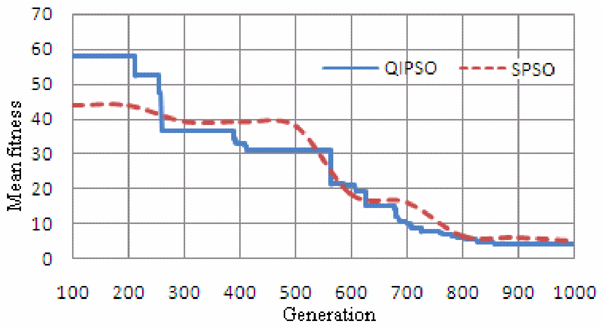


Fig. 2 Convergence graph for function f_1

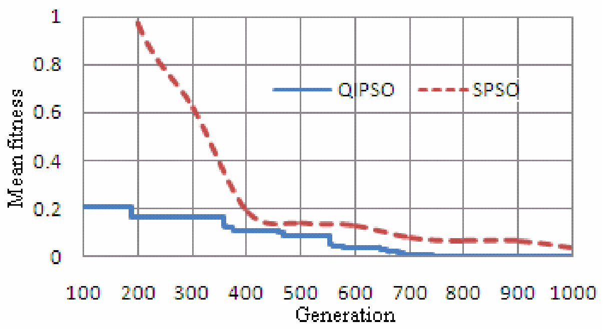


Fig. 3 Convergence graph for function f_2

V. VALIDATION OF QI-PSO WITH STANDARD BENCHMARK PROBLEMS

To validate the performance of QI-PSO, standard benchmark problems (shown in Table VII) are used and their performances are compared with SPSO. From the numerical results shown in Table VIII and convergence graphs shown in Fig. 2 and 3, QI-PSO gave better results in all the test problems.

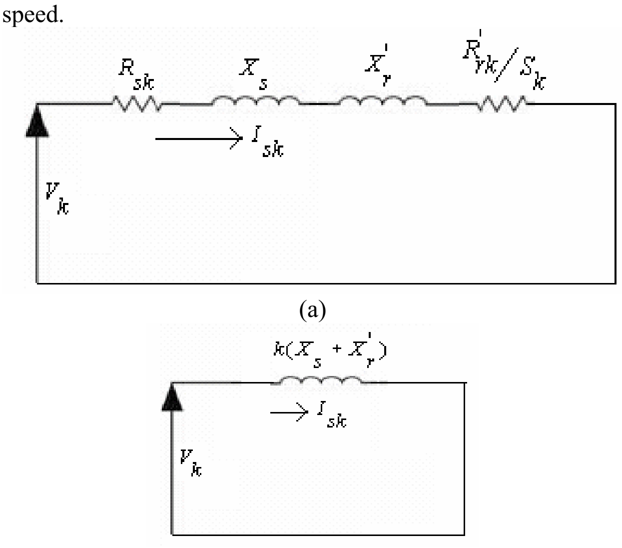
VI. CONCLUSION

This paper investigated the optimal design of induction motor using QI-PSO with three objective functions namely, efficiency, starting torque and temperature rise. Harmonic current in the motor is considered as one of the constraint to reduce torque pulsation in the motor. Efficiency and starting torque are affected when the harmonic rotor current is forced as constraint in the motor design. QI-PSO offered good results compared with SA, SPSO and normal design and it is more suitable to design optimization of induction motor. QI-PSO algorithm was validated on standard benchmark problems. C++ code was used for implementing entire algorithm.

APPENDIX

(A) Calculation of Harmonic current

Harmonic equivalent circuit [24] shown in Fig. 4, is independent of the motor sped. Thus, harmonic currents are substantially constant and independent of the motor load and speed.



(a)

(b)

Fig. 4 Harmonic equivalent circuit of the induction motor (a) full circuit, (b) simplified circuit

$$I_{sk}=\frac{V_k}{\sqrt{(R_{sk}+\frac{R'_{rk}}{S_k})+k^2(X_s+X_r^{'2})}} \qquad \text{(A1)}$$

where

V_k = harmonic rms phase voltage at a per unit frequency k.

I_{sk} = kth harmonic current at a per unit frequency k.

R_{sk}, R'_{rk} = Stator and rotor resistance at kth harmonic frequency

X_s, X'_r = Stator and rotor reactances at kth harmonic frequency

S_k = Slip at kth harmonic frequency

Since S_k is close to unity, the resistances have negligible values compared to the reactances. Now the Eq. (A1) is simplified as

$$I_{sk}=\frac{V_k}{k(X_s+X'_r)} \qquad \text{(A2)}$$

In this paper, considered up to 13th harmonics and the equation (A2) can be rewritten as

$$I_{sk}=\frac{V_{ph}}{k(X_s+X'_r)}\left(\frac{1}{5^4}+\frac{1}{7^4}+\frac{1}{11^4}+\frac{1}{13^4}\right)^{1/2} \qquad \text{(A3)}$$

where V_{ph} = Phase voltage of the motor.

(B) 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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