International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2010	Issue 2	Volume 2	Number 1	Pages 55-59

ADVANCED PARTICLE SWARM OPTIMIZATION USED FOR OPTIMAL DESIGN OF SINGLE-PHASE INDUCTION MOTOR

M. Mahdavi H. Monsef

School of Electrical and Computer Engineering, University of Tehran, Tehran, Iran
me.mahdavi@ece.ut.ac.ir, hmonsef@ut.ac.ir

Abstract- The main goal of optimal design of single phase induction motors with permanent capacitor is maximization of the efficiency and minimizing the manufacturing cost. Mathematical classic methods can be used for design of these motors but they need to linearization and simplification in model and formulas. This linearization is caused that design precision decreases while random search methods such as genetic algorithm (GA) and advanced particle swarm optimization (APSO) do not need to model linearization. Regarding the fact that random search methods can be used for design and optimization processes with relative high precision, in this study, APSO algorithm is used for designing single-phase induction motor with permanent capacitor. The objective function is motor efficiency. The results evaluation reveals that the motor design by APSO algorithm is caused that the efficiency increases in comparison with classic methods and GA.

Keywords: APSO, Sigle-phase Induction Motor, Design.

I. INTRODUCTION

The single-phase induction motors with permanent capacitor like other types of induction machines play important role in extension of welfare. For an equal rated output power, these motors are bigger and more expensive than three-phase induction ones. Low machine noise, soft operation and high reliability are their most important advantages [1].

Practically, experimental methods are usually used for design of the single-phase induction motors. In other words, geometrical dimensions of machine and windings, form of winding distribution, capacitor value and amount of materials which are used for manufacturing the main core of motor are obtained from relative experimental formulas. Then regarding this data, efficiency, power factor, manufacturing cost, starting and break-down torque, motor slip and starting current are calculated. Although these calculated values are usually acceptable but they are not optimal. Therefore, other methods such as mathematical classic [2] and random search methods can be used for obtaining the better and optimal solutions.

Using the classic methods without linearization of model is not possible. This linearization is caused that design precision decreases while random search methods such as genetic algorithm (GA) [3-5] and advanced particle swarm optimization (APSO) algorithm [6] do not require the linearization and can be used simply for optimizing the non-linear equations with respectively high precision.

Until now, much research has been done on the fields of design [7] optimization of efficiency [7, 8] and torque [9] of single-phase induction motors. In Ref. [7], single-phase induction motor has been designed for obtaining maximum efficiency using mathematical classic methods. Authors in [8], proposes a semiconductor device called triac for maximizing the efficiency of single-phase induction motor with permanent capacitor. But using this device is caused harmonic in main-phase winding. In [9], maximum torque of a single-phase induction motor has been calculated using a controlled capacitor.

Regarding the high precision and speed convergence of random search methods particularly APSO algorithm in optimization processes [6], in this study, a single-phase induction motor with permanent capacitor is designed in order to obtain the maximum efficiency using advanced particle swarm optimization. PSO is a novel population based metaheuristic, which utilize the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as a useful tool for engineering optimization. Unlike the other heuristic techniques, it has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. Also, it suffices to specify the objective function and to place finite bounds on the optimized parameters. The results show that efficiency obtained by advanced PSO algorithm is more than one obtained by mathematical classic methods and GA. Moreover, it can be seen that speed convergence of proposed method is more than GA.

This paper is organized as follows: The mathematical model of single-phase induction motor with permanent capacitor is represented in section 2. Sections 3 and 4 describe completely the advanced particle swarm optimization algorithm and solution method of the problem respectively. Finally, simulation results are given in section 5 and conclusion is represented in section 6.

II. MATHEMATICAL MODEL OF SINGLE PHASE INDUCTION MOTOR

The mathematical model is described by following equations (1) to (10):

$$X_{1m} = 2\pi f \mu_0 L \sum_{i=1}^{S_s/P} [(\frac{h_1}{3w_s} + \frac{h_2}{w_s})(S_{mi})^2 \quad (1)$$

$$X_{1a} = 2\pi f \mu_0 L \sum_{i=1}^{S_s/P} [(\frac{h_1}{3w_s} + \frac{h_2}{w_s})(S_{ai})^2 \quad (2)$$

$$X_m = K_x \times 0.2546 \times K_m C_{sk} \quad (3)$$

$$K_x = [2\pi f (Z \times K_{wm})^2 \times 10^{-8}] \quad (4)$$

$$K_m = \frac{\pi D_i L}{P^2 \times 1.28 \times L_g} \quad (5)$$

$$C_{sk} = \frac{\sin(\alpha/2)}{\pi\alpha/360} \quad (6)$$

$$R_{1m} = \rho \frac{(\pi(D_i/2) + 2L)}{\pi({D_{1m}}^2/4)} T_m \quad (7)$$

$$R_{1a} = \rho \frac{(\pi(D_i/2) + 2L)}{\pi({D_{1a}}^2/4)} T_a \quad (8)$$

$$R_{2m} = 4{N_m}^2 {K_{wm}}^2 \times \rho[\frac{L_b}{A_b N_b} + (\frac{2}{\pi} \times \frac{D_m}{P^2 A_e})] \quad (9)$$

$$X_c = \frac{1}{2\pi f C} \quad (10)$$

$$Z_{1m} = R_{1m} + jX_{1m} \quad (11)$$

$$Z_{1a} = R_{1a} + jX_{1a} - jX_c \quad (12)$$

$$Z_f = \frac{jX_m(R_{2m}/S)}{jX_m + (R_{2m}/S)} \quad (13)$$

$$Z_b = \frac{jX_m(R_{2m}/2-S)}{jX_m + (R_{2m}/2-S)} \quad (14)$$

$$Z_d = \frac{1}{2}(\frac{Z_{1a}}{a^2} - Z_{1m}) \quad (15)$$

$$R_f = real(Z_f) \quad (16)$$

$$R_b = real(Z_b) \quad (17)$$

$$V_{mf} = (V_t/2) \times (1 - j/a) \quad (18)$$

$$V_{mb} = (V_t/2) \times (1 + j/a) \quad (19)$$

$$I_{mf} = \frac{V_{mf}(Z_{1a} + Z_b + Z_d) + V_{mb} Z_d}{(Z_{1m} + Z_f + Z_d)(Z_{1a} + Z_b + Z_d) - {Z_d}^2} \quad (20)$$

$$I_{mb} = \frac{V_{mb}(Z_{1m} + Z_f + Z_d) + V_{mf} Z_d}{(Z_{1m} + Z_f + Z_d)(Z_{1a} + Z_b + Z_d) - {Z_d}^2} \quad (21)$$

$$I_m = I_{mf} + I_{mb} \quad (22)$$

$$I_a = \frac{jI_{mf}}{a} - \frac{jI_{mb}}{a} \quad (23)$$

$$I_L = I_m + I_a \quad (24)$$

$$I_L = |I_L| \angle \theta \quad (25)$$

$$Pf = \cos(\theta) \quad (26)$$

$$P_{out} = 2(R_f {I_{mf}}^2 - R_b {I_{mb}}^2)(1-S) - P_{rot} \quad (27)$$

$$P_{in} = |V_L| \times |I_L| \times Pf \quad (28)$$

$$\eta = \frac{P_{out}}{P_{in}} \quad (29)$$

where, $a = T_a / T_m$ and:

L: Stator core length.
h_1: Main-phase winding height.
h_2: Auxiliary-phase winding height.
w_s: Stator slot width.
S_{mi}: Number of conductors of main-phase winding in ith slot.
S_{ai}: Number of conductors of auxiliary-phase winding in ith slot.
Z: Total number of conductors of windings.
K_{wm}: Winding factor of the auxiliary-phase winding.
D_i: Stator bore diameter.
P: Number of poles.
L_g: Air gap length.
ρ: Copper resistivity.
D_{1m}: Wire diameter of main-phase winding.
T_m: Number of turns in series of main-phase winding.
D_{1a}: Wire diameter of auxiliary-phase winding.
T_a: Number of turns in series of auxiliary-phase winding.
α: Pole pitch.
N_m: Number of conductors of main-phase winding.
L_b: Length of one conductor of rotor.
A_b: Cross section of one conductor of rotor.
N_b: Number of conductors of rotor.
A_e: End average area of one turn of stator windings.
D_m: End average diameter of one turn of stator windings.
S: Motor slip.

Leakage reactance of main and auxiliary-phase winding, magnetizing reactance, resistance of main and auxiliary-phase winding and resistance of rotor that has been moved to stator main-phase winding are calculated from (1), (2), (3), (7), (8) and (9), respectively. (10) to (14) describe reactance of capacitor, impedance of main and auxiliary-phase winding, and the forward and backward rotating components of the equivalent circuit's impedance respectively. Also, the forward and backward rotating components of the voltage and current in the main and auxiliary-phase winding, the current in main and auxiliary-phase winding, line current, power factor, output and input powers, and finally efficiency are defined as (18) to (29).

III. ADVANCED PSO ALGORITHM

Particle swarm optimization algorithm, which is tailored for optimizing difficult numerical functions and based on metaphor of human social interaction, is capable of mimicking the ability of human societies to process knowledge [11]. It has roots in two main component methodologies: artificial life (such as bird flocking, fish schooling and swarming); and, evolutionary computation. Its key concept is that potential solutions are flown through hyperspace and are accelerated towards better or more optimum solutions. Its paradigm can be implemented in simple form of computer codes and is computationally inexpensive in terms of both memory requirements and speed. It lies somewhere in between evolutionary programming and the genetic algorithms. As in evolutionary computation paradigms, the concept of fitness is employed and candidate solutions to the problem are termed particles or sometimes individuals, each of which adjusts its flying based on the flying experiences of both itself and its companion. It keeps track of its coordinates in hyperspace which are associated with its previous best fitness solution, and also of its counterpart corresponding to the overall best value acquired thus far by any other particle in the population. Vectors are taken as presentation of particles since most optimization problems are convenient for such variable presentations.

In fact, the fundamental principles of swarm intelligence are adaptability, diverse response, proximity, quality, and stability. It is adaptive corresponding to the change of the best group value. The allocation of responses between the individual and group values ensures a diversity of response. The higher dimensional space calculations of the PSO concept are performed over a series of time steps. The population is responding to the quality factors of the previous best individual values and the previous best group values. The principle of stability is adhered to since the population changes its state if and only if the best group value changes. As it is reported in [12], this optimization technique can be used to solve many of the same kinds of problems as GA [13, 14, 15] and does not suffer from some of GAs difficulties. It has also been found to be robust in solving problem featuring non-linearing, non-differentiability and high-dimensionality. PSO is the search method to improve the speed of convergence and find the global optimum value of fitness function.

PSO starts with a population of random solutions ''particles'' in a D-dimension space. The *i*th particle is represented by $X_i = (x_{i1}, x_{i2}, \ldots, x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle *i* (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, \ldots, p_{iD})$. The global version of the PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population. PSO consists of, at each step, changing the velocity of each particle toward its pbest and gbest according to (30). The velocity of particle *i* is represented as $V_i = (v_{i1}, v_{i2} \ldots v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest. The position of the *i*th particle is then updated according to (31) [11], [12].

$$v_{id}(t+1) = w \times v_{id}(t) + c_1 r_1 (P_{id} - x_{id}(t)) + c_2 r_2 (P_{gd} - x_{id}(t)) \quad (30)$$

$$x_{id}(t+1) = x_{id}(t) + c v_{id}(t+1) \quad (31)$$

Where, P_{id} and P_{gd} are *pbest* and *gbest*. Several modifications have been proposed in the literature to improve the PSO algorithm speed and convergence toward the global minimum. One modification is to introduce a local-oriented paradigm (*lbest*) with different neighborhoods. It is concluded that *gbest* version performs best in terms of median number of iterations to converge. However, *pbest* version with neighborhoods of two is most resistant to local minima. The results of past experiments about PSO show that ω was not considered at an early stage of PSO algorithm. However, ω affects the iteration number to find an optimal solution. If the value of ω is low, the convergence will be fast, but the solution will fall into the local minimum. On the other hand, if the value will increase, the iteration number will also increase and therefore the convergence will be slow. Usually, for running the PSO algorithm, value of inertia weight is adjusted in training process. It was shown that PSO algorithm is further improved via using a time decreasing inertia weight, which leads to a reduction in the number of iterations [16].

In (30), term of $c_1 r_1 (P_{id} - x_{id}(t))$ represents the individual movement and term of $c_2 r_2 (P_{gd} - x_{id}(t))$ represents the social behavior in finding the global best solution. High searching speed is essential in determining the proper parameters when much iteration is involved. Therefore, several methods have been proposed to improve the PSO algorithm speed and convergence toward the global minimum until now. One method to use is the advanced PSO algorithm. This technique can improve PSO performance by putting the adaptively changing terms. These changing terms are caused that the parameters of the original PSO algorithm can change according to the convergence rate which is presented by the fitness. Thus, the original PSO is changed like this:

$$r_1 = 1 - \frac{P_{id}}{P_i} + rand$$
$$r_2 = 1 - \frac{P_{gd}}{P_i} + rand \quad (32)$$

Where, rand is the random value between 0 and 1. r_1 can influence the movement of the second term (individual term) as a weight factor. In early searching stage, the difference of between *pbest* and *gbest* are the fitness values at the best position of between *pbest* and P_i is relatively bigger than that in the last stage. Accordingly, the value of $(1 - \frac{P_{id}}{P_i})$, is also bigger than that in the last stage. As an individual particle approaches near the individual best position, the movement of individual particle becomes gradually slow. So we can expect faster convergence than the original. r_2 has an effect on the movement of the third term (group). Likewise, it is interpreted as follows:

$$P_{gd} \le P_{id} \le P_i \quad (33)$$

Because *gbest* is supposed as optimal and lowest value in entire particles' fitness values, (30) can be derived. (31) can be easily derived from (30). If the particles converge to the optimal value, *pbest* and P_i will have the same value, *gbest*. Therefore, the replaced $(1 - \frac{P_{id}}{P_i})$ and $(1 - \frac{P_{gd}}{P_i})$ will become zero, so that the second and third terms will move slowly. It can derive the fast searching. Figure 1 shows the flowchart of the advanced PSO algorithm.

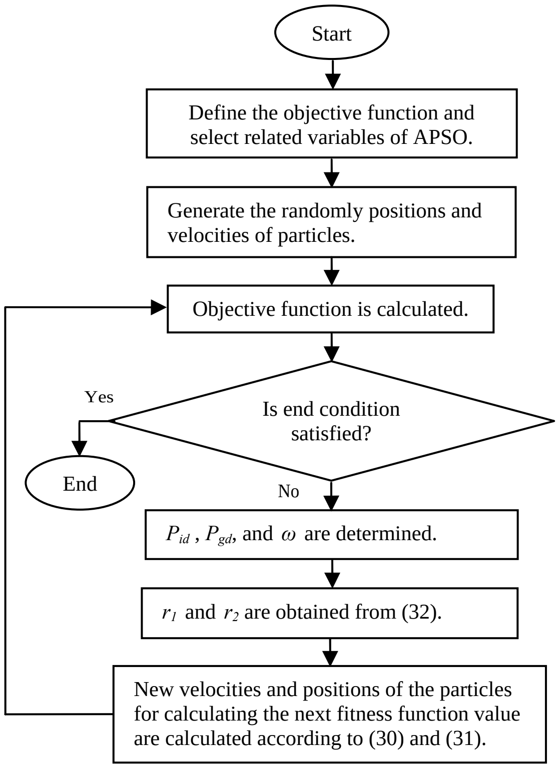

Figure 1. APSO algorithm operating process

IV. OBJECTIVE FUNCTION OF THE PROBLEM

The goal is design of single-phase induction motor with permanent capacitor to obtain the maximum motor efficiency. Therefore, objective function of the optimization problem is defined as follows:

$$F = \eta = \frac{P_{out}}{P_{in}} \tag{34}$$

Several restrictions have to be modeled in a mathematical representation to ensure that the mathematical solutions are in line with the design requirements. These constraints are as follows:

$$\begin{aligned} &\cos(\theta) > 0.9 \\ &T_{sn} > 1 \\ &T_{bn} > 1.1 \\ &\eta = \max \ \ value \\ &I_{sn} < 4 \end{aligned} \tag{35}$$

Where, $\cos(\theta)$, T_{sn}, T_{bn} and I_{sn} are power factor, starting torque to rated torque ratio, break-down torque to rated torque ratio and starting current to rated current ratio respectively.

First, an initial population is constructed randomly and then with respect to initial position and velocity of its particles, equations (1) to (29) are calculated. But since motor slip (*S*) is unknown, all these equations are obtained versus *S*. Accordingly, output power and subsequent the efficiency is written as follows:

$$P_{out} = g(S) \ \Rightarrow \ \ \eta = f(S) \tag{36}$$

V. RESULTS AND DISCUSSION

Case study is single-phase induction motor with permanent capacitor which its characteristics are mentioned in [2] and [7]. A GA based method and the proposed algorithm (APSO) are applied to the case study and the results are given in Tables 1 and 2. Also, obtained values for problem constrains are listed in Table 3.

Table 1. Design parameters calculated by GA

Parameter	Value
Stator bore diameter (D_i)	0.13 m
Length of one conductor of rotor (L_b)	0.0945 m
Wire diameter of main-phase winding (D_{1m})	0.0019 m
Wire diameter of auxiliary-phase winding (D_{1a})	0.0019 m
Diameter of conductor of rotor	0.0062 m
Rotor slot height	0.0126 m
Capacitor value (*C*)	0.0001F
Number of slots of rotor	44
Air gap length (L_g)	0.0003 m
Efficiency (η)	0.9080

Table 2. Design parameters calculated by APSO

Parameter	Value
Stator bore diameter (D_i)	0.1268 m
Length of one conductor of rotor (L_b)	0.861 m
Wire diameter of main-phase winding (D_{1m})	0.00227 m
Wire diameter of auxiliary-phase winding (D_{1a})	0.00227 m
Diameter of conductor of rotor	0.0074 m
Rotor slot height	0.01214 m
Capacitor value (*C*)	0.00012 F
Number of slots of rotor	44
Air gap length (L_g)	0.00225 m
Efficiency (η)	0.918

Table 3. Calculated constrains by APSO

Parameter	Value	Parameter	Value
$Cos(\theta)$	0.9878	T_{bn}	1.23
T_{sn}	1.15	I_{sn}	2.27

By comparing between Tables 1 and 2, and results of reference [7], it can be seen that the calculated efficiency by APSO algorithm is more than both classic method and GA. Also, from convergence speed point of view, APSO is better than GA. Because proposed algorithm (APSO) converges to optimal solution after 350 iterations while the number of iterations of GA for convergence is 1200. Thus, the APSO algorithm by selecting the new velocity and position of particles based on previous best position of each particle and the group can improve the motor efficiency in comparison with classic methods and GA.

VI. CONCLUSIONS

In this paper, single-phase induction motor with permanent capacitor is designed using particle swarm optimization algorithm. Results evaluation reveals that using advanced particle swarm optimization algorithm for design of single-phase induction motor with permanent capacitor is caused that the machine efficiency increases in comparison with mathematical classic methods and genetic algorithm. Also, it can be said that convergence speed of advanced PSO algorithm is more than GA method. The reason is that this algorithm uses previous best position of each particle and the group to select the new velocity and position of particles.

REFERENCES

[1] V. Mittle and A. Mittal, "Design of Electrical Machines", N.C. Jain-Delhi, 2004.

[2] H. Huang, E.F. Fuchs and J.C. White, "Optimization of Single-phase Induction Motor Design, Part I: Formulation of the Optimization Technique," IEEE Transactions on Energy Conversion, Vol. 3, Issue 2, pp. 349-356, 1988.

[3] S. Jalilzadeh, A. Kazemi, H. Shayeghi and M. Mahdavi, "Technical and Economic Evaluation of Voltage Level in Transmission Network Expansion Planning Using GA", Energy Conversion and Management, Vol. 49, Issue 5, pp. 1119-1125, 2008.

[4] S. Jalilzadeh, H. Shayeghi, M. Mahdavi and H. Haddadian, "Studying Influence of Two Effective Parameters on Network Losses in Transmission Expansion Planning Using DCGA", Energy Conversion and Management, Vol. 49, Issue 11, pp. 3017-3024, 2008.

[5] A. Kazemi, S. Jalilzadeh, M. Mahdavi and H. Haddadian, "Genetic Algorithm-Based Investigation of Load Growth Factor Effect on the Network Loss in TNEP", Proceedings of 3rd IEEE Conference on Industrial Electronics and Applications, Vol. 1, pp. 764-769, 2008.

[6] A. Jalilvand, A. Kimiyaghalam, A. Ashouri and M. Mahdavi, "Advanced Particle Swarm Optimization-Based PID Parameter Optimization", Proceedings of IEEE International Multitopic Conference, pp. 429-435, 23-24 Dec. 2008.

[7] H. Huang, E.F. Fuchs and J.C. White, "Optimization of Single-Phase Induction Motor Design, Part II: The Maximum Efficiency and Minimum Cost of an Optimal Design", IEEE Transactions on Energy Conversion, Vol. 3, Issue 2, pp. 357-366, 1988.

[8] C. Mademlis, I. Koskeridis and T. Theodoulidis, "Optimization of Single-Phase Induction Motors, Part I: Maximum Energy Efficiency Control", IEEE Transactions on Energy Conversion, Vol. 20, Issue 1, pp. 187-195, 2005.

[9] T.H. Liu, "A Maximum Torque Control with a Controlled Capacitor for a Single-Phase Induction Motor" IEEE Transactions on Industrial Electronics, Vol. 42, Issue 1, pp. 17-24, 1995.

[10] V.D. Toro, "Basic Electric Machines", Prentice-Hall, 1990.

[11] R.L. Haupt and S.E. Haupt, "Practical Genetic Algorithms", John Wiley & Sons Publication, Second Edition, 2004.

[12] X.F. Xie, W.J. Zhang and Z.L. Yang, "Dissipative Particle Swarm Optimization", Proceedings of the 2002 Congress on Evolutionary Computation, Vol. 2, pp. 1456-1461, May 2002.

[13] S. Jalilzadeh, A. Kazemi, H. Shayeghi and M. Mahdavi, "Technical and Economic Evaluation of Voltage Level in Transmission Network Expansion Planning Using GA", Energy Conversion and Management, Vol. 49, Issue 5, pp. 1119-1125, 2008.

[14] H. Shayeghi, S. Jalilzadeh, M. Mahdavi and H. Haddadian, "Studying Influence of Two Effective Parameters on Network Losses in Transmission Expansion Planning Using DCGA", Energy Conversion and Management, Vol. 49, Issue 11, pp. 3017-3024, 2008.

[15] M. Mahdavi, H. Shayeghi and A. Kazemi, "DCGA Based Evaluating Role of Bundle Lines in TNEP Considering Expansion of Substations from Voltage Level Point of View", Energy Conversion and Management, Volume 50, Issue 8, pp. 2067-2073, 2009.

[16] X. Hu and R. Eberhart, "Solving Constrained Nonlinear Optimization Problem with Particle Swarm Optimization", Proceedings of the Sixth World Multiconference on Systemics, Cybernetics and Informatics, pp. 203-206, 2002.

BIOGRAPHIES

Meisam Mahdavi received the M.Sc. degree from Zanjan University (Zanjan, Iran) in Power Electrical Engineering, in 2008. Currently, he is a Ph.D. student of Power Electrical Engineering at University of Tehran (Tehran, Iran). His research interests are in the area of Power System Planning and Operation, FACTS Devices, and Parameter Identification of Electrical Machines and Transformers.

Hassan Monsef received the B.Sc. and the Ph.D. degrees from Sharif University of Technology (Tehran, Iran) and the M.Sc. degree from University of Tehran (Tehran, Iran), all in Power Electrical Engineering, in 1986, 1996, and 1989, respectively. Currently, he is an Associate Professor of Power Electrical Engineering at University of Tehran. His research interests are in the area of Restructuring of Power Systems, Power System Operation, Electric Power Quality, Control System of Power Plants and Optical Transducers.