Technical and Economic Design of Three Phase Induction motor Using The Multicriterion Optimization Method

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Abstract

This paper describes the optimum design of three phase induction motor for which three objective function regarding motor efficiency, starting torque and temperature rise as objective function. Multicriterion optimization technique is applied to finding the optimal solution. The proposed method implemented on a test motor and the results are compared with the, Conventional design and Simulated Annealing technique(SA) method and also compared with the original motor dimensions . The results show that the Multicriterion Optimization method (MCDM) gave better result

الخلاصة

هذا البحث يصف التصميم المثالي للمحرك الحثى ثلاثي الأطوار والذي يتضمن ثلاثة أهداف وظائفي فيما يتعلق بالمحرك الكفاءة و العزم وارتفاع درجة الحرارة. الطريقة المقترحة جربت على أحد المحركات و قورنت مع الطريقة التقليدية وطريقة (تقنية التَّلْدين المُقَلَّدةِ) وكذلك قورنت النتائج مع إبعاد المحرك الاصلى النتائج بينت أن طريقة التعدد المعياري أعطت أفضل النتائج (SA)

1. Introduction

Interest in means of optimization of electric machine design is high because of increased cost of electrical energy and pressures for its conservation, plus the increased competition in world markets. The objective of the optimization process is usually to minimize the cost of the machine or to maximize the efficiency of the machine. This paper is concerned with the optimization of three different objective functions namely efficiency, Starting torque and temperature rise.

Three phase Induction motors are the most widely used in domestic, commercial and various industrial applications. Particularly, the squirrel cage rotor type is characterized by its simplicity, robustness and low cost [1], which has always made it very attractive, and it has therefore captured the leading place in industrial sectors. As a result of its extensive use in the industry, induction motors consume a considerable percentage of the overall produced electrical energy. The minimization of electrical energy consumption through a better motor design becomes a major concern. In means of optimization of electric machine design is high because of increased cost of electrical energy and pressures for its conservation, plus the increased competition in world markets. The objective of the optimization process is usually to minimize the temperature rise or to maximize the efficiency of the machine. In the design of induction motors, as in all design problems, the engineer is faced with making a decision in the face of competing objectives[1-3]. The design problem is considered as an optimization process by which the designer seeks the best design. In certain approaches, the optimization is achieved by applying the principles of nonlinear programming. In stating a nonlinear programming problem, the basic variables are to be defined and an objective function is to be minimized (or maximized) subjected to non violated constraints[4]. The objective function is a scalar when the designer is interested in achieving one goal. These are many papers, [2-7] that represent the design problem of an induction motor (IM) as a scalar nonlinear programming problem. In the applications of nonlinear programming techniques to optimize the design of IM the objective function may be the annual cost, the material cost, the power factor, or the weight as in airplanes, or a certain performance parameter. In such cases the designer deals with the objective function in a scalar form. In fact, the designer of an induction motor, as in all design problems, is interested in achieving more than one goal. In such case the objective function is defined as a vector function consisting elements each one representing a goal. The goals may be given equal or different weights according to the design requirements[5,7,8.9]. The functions are non-commensurable and usually some of them are in conflict with others. In general there is no single solution which gives the best values for all functions. But the designer will concern on a set of solutions known as non-dominant (non-inferior, Pareto) set. Where he can select the preferred one which achieves his goal to large extent and this design is considered as the optimal solution for the problem. In this case the problem is known as a multicriterion optimization problem. The available papers to the authors, which represents the design problem of a three-phase IM as a multicriterion optimization problem, is that due to [9-16]. In this study the idea of multicriterion optimization approach is applied to the design of three phase induction motor. The multicriterion optimization problem is defined as a multiple criteria decision making (MCDM) problem. In this study the design of a three-phase induction motor is represented as a multicriterion optimization problem with three objective functions, which are full loud efficiency. temperature rise and starting torque.

2. MATHEMATICAL FORMULATION OF THE DESIGN PROBLEM :

A general nonlinear programming problem can be stated in mathematical terms and the multicriterion optimization problem can be stated: as follows[ ]:

$$\boxed{\min_{x \in F} f_1(x), f_2(x), \ldots, f_k(x) \qquad (1)}$$

where , $x \in R^n$, $f_i : R^n \mapsto R$, , and F is the feasible set of problem (1) which is described by inequalities as follows:

$$\boxed{F = \{x \in R^n : g_i(x) \le 0, i = 1, 2, \ldots, p\}. \qquad (2)}$$

Furthermore, in the considered case, we have some additional features.

1) An analytical representation of

$$f_i(x),\ i = 1, 2, \ldots, k, \quad \text{and}\ g_i(x),\ i = 1, 2, \ldots, p,$$

is not available and, hence, no derivative information can be used in the solution process.

2)The constraints $g_i(x), i = 1, 2, \ldots, p$ are not restrictive in that it is relatively easy to produce afeasible point and remain in the feasible region. We denote by the $f(x) \in R^k$ vector made up of all the objective functions, that is,

$$f(x) = (f_1(x), f_2(x), \ldots, f_k(x)).$$

An ideal solution of (1) would be a point $x^* \in F$ such that

$$f_i(x^*) \le f_i(x), \quad \forall x \in F, \quad \forall i \in \{1,\dots,k\}.$$

Unfortunately, such a point x^* seldom exists, therefore (1) turns into finding some or all the Pareto optimal solutions, that is, points satisfying the following definition.

A point $x^* \in F$ is a Pareto-optimal solution of (1) if there does not exist any feasible point such that

and
$$f_i(x) \le f_i(x^*), \qquad \forall i \in \{1,\dots,k\}$$
$$f_j(x) < f_j(x^*)$$
$$j \in \{1,2,\dots,k\}.$$

for at least one index . There exists a wide variety of methods that can be used to compute Pareto optimal points. A widely used technique consists of reducing the multiobjective problem (1) to a single-objective one by means of so-called

"secularization" procedure. A first choice consists of transforming (1) into a sequence of constrained problems in which a particular objective function $f_i(x)$ is minimized and the remaining ones are "constrained" to keep their values below a prefixed upper bound. A second choice consists of minimizing a function which is a "combination" of all the objective functions of (1). In this paper, we adopt the second strategy since the first one would require an efficient derivative-free algorithm for a global optimization problem with a feasible set complicated by the presence of hard constraints (namely, those involving the bounds on the objective functions).We employ three different secularization techniques. The first one consists of assigning each objective function

a cost coefficient and then minimizing the function obtained by summing up all the objective functions scaled by their cost coefficients, that is

$$\boxed{\min_{x\in F} \sum_{i=1}^{k} c^i f_i(x). \qquad (3)}$$

The second method consists of choosing an "ideal optimal value" for each objective function and then minimizing the Euclidean distance between the actual vector of objective functions and the vector made up of the ideal values, that is

$$\boxed{\min_{x\in F} \sum_{i=1}^{k} \left(f_i(x) - z_i^{\mathrm{id}}\right)^2 \qquad (4)}$$

Where z_i^{id} stands for the the ideal value. The third strategy is similar to the second one in that we consider again the differences , $f_i(x) - z_i^{\mathrm{id}}, i = 1,2,\dots,k,$, but this time we consider the following problem:

$$\min_{x \in F} \max_{i=1,2,\ldots,k} \left| f_i(x) - z_i^{\text{id}} \right|. \qquad (5)$$

It is possible to prove that each global minimum point of problems (3), (4), and (5) is a Pareto-optimal solution for (1) (see [3]). Obviously, the global solutions of problems (3)–(5) are affected by the coefficients c_i and the ideal values z_i^{id}.

Naturally, the choice of these values can be done by exploiting any possible a priori knowledge on the underlying optimal design problem. In this paper, we decided to determine these quantities without requiring any a priori information. For this reason, we first solve global optimization problems, namely

$$z_i^* = \min_{x \in F} f_i(x). \qquad (6)$$

Then, we set

$$c_i = \frac{1}{z_i^*} \text{ and } z_i^{\text{id}} = z_i^*.$$

3.Applying (MCDM)Optimization to the design of Induction machine

The design optimization of electric motors requires a particular attention in the choice of the objective function that usually concerns economic or performance features. For this reason, we have chosen three conflicting objective functions that can affect the design optimization of three phase induction motors. Particularly:. The following steps were followed in the implementation.

3.1 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.

3.1 A. Variables The following quantities are chosen as the principle design variables for the optimization

item	Stator bore diameter	Average air gap flux density	Stator current density	Air gap length	Stator slot depth	Stator slot width	Stator core depth	Rotor slot depth	Rotor slot width
symbol	X1	X2	X3	X4	X5	X6	X7	X8	X9

3.1 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 (C1…….C9) imposed into induction motor design in this paper is as follows which are expressed in terms of variables

item	temperature rise	full load efficiency	starting torque	no load current	maximum torque	slip, pu	full load power factor	Stack length	maximum stator flux density
symbol	C1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9

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3.1 C. Objective Functions

Three different objective functions are considered while designing the machine using optimization algorithms. The objective functions are,

F(x) = C1; Minimization of temperature rise
F(x) = C2; Maximization of Efficiency
F(x) = C3; Maximization of Starting torque

a good design should represent the right compromise among different objectives but the problem consists in searching this "compromise." The only tool able to solve this problem is represented by the (MCDM) approach .the following multicriterion formulations:

$$\min_{x \in F} f_1(x), -f_2(x), -f_3(x) \tag{7}$$

$$\min_{x \in F} f_1(x), -f_2(x), f_4(x) \tag{8}$$

$$\min_{x \in F} f_1(x), -f_2(x), -f_3(x), f_4(x). \tag{9}$$

This approach allows us to investigate how each single-objective and multicriterion problem affects the results in terms of performance and independent variables and, above all, allows us to have a wide range of alternative designs among which the designer can choose a better solution

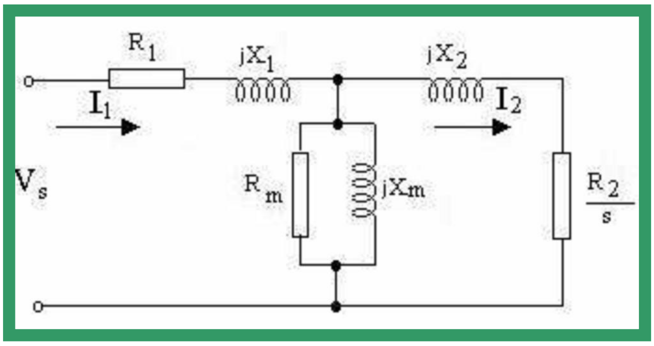
4.Optimization algorithm and design procedure

The optimal design algorithm is applied to the design of three phase induction motor for witch three objective functions regarding motor efficiency, temperature rise and starting torque are used. And the dimensions, parameters and characteristics of the optimally designed motor are compared with those of prototype one. The optimization problem is solved using weighting min-max algorithm. The proposed method approach for the optimal design of induction motors requires us to find global solutions. This algorithm, which belongs to the class of Controlled Random Search algorithms, is based on the following points

1) Initialization: The objective function is sampled on a set S of m points randomly chosen within the feasible set F.
2) Stopping criterion: If the maximum and minimum value of the objective function over S are sufficiently close to each other, the algorithm stops.
3) Search phase: $n+1$ points are randomly chosen on set . Then, by exploiting as much as possible the information on the objective function conveyed by these $n+1$ points, a new point $\tilde{x}$ is produced.
4) Updating phase: If the objective function value on the new point is better then the maximum function value, then set S is updated by adding the new point and discarding the worst one. The algorithm continues iterating

The problem solution is achieved by suggesting a design, which takes in consideration the three goals. The approach of MCDM is applied to optimize the design of a three- phase IM, which is already in production by Sate Electrical Industries Company (SEICO). The original motor dimensions are given in (Appendix-1-B-motor-2).These values represent the starting (initial) values of basic variables in the optimization procedure.

The design procedure is achieved by representing the motor by its equivalent circuit fig (1) based on the revolving magnetic field theory.. The. equivalent circuit approach will give results, which are close to the test results if the necessary modifications are taken into account. These modifications are due to skew, saturation and skin effects. The iron, friction and winding losses are taken into consideration(V.P. Sakthivel, R. Bhubaneswar and S. Subramanian ,2010).



Fig(1)The per-phase equivalent circuit model of induction motor

5. Results And Discussion

The modified Multicriterion algorithm is a solution method to the vector optimization problem. The algorithm searches both the noninferior solution set and the best compromise solution. The. optimal design results are given in tables. Which shows the solution corresponding to the minimum of each objective function. The best compromise solution with the prototypes is given in tables.The optimally designed motor shows higher efficiency, Starting Torque and minimum in Temperature rise. The optimization results suggest the following comments1 .

1.The minimization of the single objective function, gives rise to a significant improvement of the chosen term, but affects heavily the other ones. Particularly,
the optimization of motor efficiency allows to reach a very interesting result that permits to label the motor as “high efficiency motor” according to the new European classification scheme [5].

2.(MCDM) Optimization method is implemented to optimize the design of induction motor whose specifications are available in appendix. The results of proposed method design and their comparison with(SA) and normal design are given in the Tables 1,2, 3, 4 and 5..

3.When (MCDM) considered efficiency of the motor as an objective function table(2) the resulting design gave considerably better results than normal design and also quite better than (SA)method. Temperature rise and slip are lower in (MCDM) but main dimensions are higher than other methods.

4.For Starting torque maximization ,table(3) also, (MCDM) Optimization method offers better results than others significantly. In this case, main dimensions are higher but temperature rise considerably reduced. Full load slip in (MCDM) Optimization method is smaller than normal design and SA.

5. For temperature rise minimization table(4), again (MCDM) Optimization method performed well which improvement percentage is 18.37%, 4.57% compared to normal design and(SA)method. Here main dimensions are lower and efficiency is slightly better than others. For over all performance (MCDM) Optimization method gave good results than others so that it can be used for design optimization of induction motor.

6.From the design results presented in tables (2) and(4), particularly the following variables are dominated in (MCDM) Optimization method to get optimum value of all objective functions;

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

Table(1):Optimum Design Results For Minimization of temperature rise

Variables	Conventional design	Objective function Efficiency	Objective function Temperature Rise	Objective function Starting Torque
Width of the stator slot (m)	0.00132	0.00433	0.00457	0.00555
Depth of the stator slot (m)	0.021	0.01515	0.02258	0.02118
Width of the rotor slot (m)	0.0068	0.00355	0.00374	0.00454
Depth of the rotor slot (m)	0.0093	0.00660	0.00499	0.00291
Air gap flux density (wb/m2)	0.6	2.00	1.632	2.00
Air-gap length (m)	0.0003	0.0005	0.0005	0.0005
Full load slip	0.0699	0.0416	0.0536	0.0505
Stator bore diameter (m)	0.105	0.0890	0.189	0.0999
Stator outer diameter (m)	0.181	0.1913	0.099	0.2179
Stack length (m)	0.125	0.109	0.114	0.114
Temperature rise, °C	46.8178	39.83	38.209	41.810
Efficiency %	0.80309	0.8356	0.814	0.825
Starting torque, pu.	1.2027	3.730	3.133	4.966
Power factor	0.8041	0.800	0.858	0.813

Table (2):Optimum Design Results For Efficiency Maximization

Items	Conventional design	(SA) method	Proposed method
Width of the stator slot (m)	0.00132	0.0011	0.004223
Depth of the stator slot (m)	0.021	0.0159	0.014815
Width of the rotor slot (m)	0.0068	0.005	0.003615
Depth of the rotor slot (m)	0.0093	0.0091	0.006599
Air gap flux density (wb/m2)	0.6	0.521	1.4320
Air-gap length (m)	0.0003	0.0003	0.00046
Full load slip	0.0699	0.056	0.0416
Stator bore diameter (m)	0.105	0.102	0.0890
Stator outer diameter (m)	0.181	0.177	0.1913
Stack length (m)	0.125	0. 097	0.1109
Temperature rise, °C	46.8178	٤١.٣٩١	39.713
Efficiency %	0.80309	0.82848	0.84856
Starting torque, pu.	1.2027	1.3444	3.73120
Power factor	0.8041	0.8333	0.82100

Table (3):Optimum Design Results For Starting Torque Maximization

Items	Conventional design	SA method	Proposed method
Width of the stator slot (m)	0.00132	0.0012	0.004955
Depth of the stator slot (m)	0.021	0.0187	0.0211
Width of the rotor slot (m)	0.0068	0.0056	0.00444
Depth of the rotor slot (m)	0.0093	0.0071	0.00293
Air gap flux density (wb/m2)	0.6	0.4713	1.4320
Air-gap length (m)	0.0003	0.0004	0.0005
Full load slip	0.0699	0.0645	0.05
Stator bore diameter (m)	0.105	0.1028	0.0989
Stator outer diameter (m)	0.181	01733	0.21709
Stack length (m)	0.125	0.1162	0.1144
Temperature rise, °C	46.8178	64.475	41.610
Efficiency %	0.80309	0.79179	0.8365
Starting torque, pu.	1.2027	1.3776	4.9776
Power factor	0.8041	0.7938	0.813

Table (4):Optimum Design Results For Temperature Rise Minimization

Items	Conventional design	SA method	Proposed method
Width of the stator slot (m)	0.00132	0.0013	0.00357
Depth of the stator slot (m)	0.021	0.0236	0.02226
Width of the rotor slot (m)	0.0068	0.005	0.003644
Depth of the rotor slot (m)	0.0093	0.0093	0.00499
Air gap flux density (wb/m2)	0.6	0.439	1.2632
Air-gap length (m)	0.0003	0.0004	0.000501
Full load slip	0.0699	0.0684	0.0526
Stator bore diameter (m)	0.105	0.101	0.169
Stator outer diameter (m)	0.181	0.171	0.0989
Stack length (m)	0.125	0.1216	0.113
Temperature rise, °C	**46.8178**	**40.0391**	**38.19209**
Efficiency %	0.80309	0.803748	0.8134
Starting torque, pu.	1.2027	1.117	3.14033
Power factor	0.8041	0.7814	0.8658

Table (5): Comparison .(MCDM) Optimization method with normal design and SA method

Objective Function	Test Motor		
	normal	SA Method	Proposed method
F(x) = A	4.04	.86	0.52
F(x) = B	312.9	260.48	102.45
F(x) = C	18.37	4.57	9.43

In order to reach the equilibrium optimization point of the induction motor the **E**fficiency , Total losses and Torque is expressed as a function of the values motor dimensions (Equations below)

$$f(X) = 0.0003X^5 - 0.0155X^4 + 0.3483X^3 - 3.8381X^2 + 21.497X + 31.828$$

Equation (1)Efficiency versus depth of the rotor slot in the optimized motor

$$f(X) = 2E-09X^6 - 1E-06X^5 + 0.0004X^4 - 0.069X^3 + 5.9075X^2 - 258.33X + 4500.8$$

Equation (2) Efficiency versus stator stack length in the optimized motor

$$f(X) = 0.2438X^6 - 6.4433X^5 + 68.077X^4 - 363.72X^3 + 1013X^2 - 1322.8X + 615.86$$

Equation (3) Efficiency versus width of the stator slot in the optimized motor

$$f(X) = -34.894X^6 + 902.14X^5 - 9270.9X^4 + 47795X^3 - 126998X^2 + 155350X - 55367$$

Equation (4) Total losses versus width of the stator slot in the optimized motor

$$f(x) = -0.0024X^6 + 0.1211X^5 - 2.4804X^4 + 26.257X^3 - 150.66X^2 + 465.51X - 356.35$$

Equation (5)Total losses versus depth of the rotor slot in the optimized motor

$$f(X) = 6E-08X^6 - 5E-05X^5 + 0.0153X^4 - 2.6622X^3 + 268.48X^2 - 14828X + 349746$$

Equation (6)Total losses versus stator stack length in the optimized motor

$$f(X) = 0.0017X^5 - 0.07X^4 + 1.1417X^3 - 8.9X^2 + 33.007X - 31.48$$

Equation (7)Torque versus width of the stator slot in the optimized motor

$$f(X) = -8E-10X^6 + 5E-07X^5 - 0.0001X^4 + 0.0218X^3 - 1.7694X^2 + 76,222X - 1348.9$$

Equation (8) Torque versus stator stack length in the optimized motor

6. Conclusions

This paper investigated the optimal design of induction motor using MCDM with three objective functions, efficiency, starting torque and temperature rise. The weighting min-max method is used to solve this problem It is concluded offered good results compared with normal design and SA method it is more suitable to design optimization of induction motor.

7.References

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Appendix-1-A

Specification of Test Motor [Kannan, *et al.,* **2007]**
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
Y-connected, squirrel cage rotor

Appendix-1-B (original motor dimensions)

Stack length (m	0.125
Width of the stator slot (m)	0.00132
Depth of the stator slot (m)	0.021
Width of the rotor slot (m	0.0068
Depth of the rotor slot (m)	0.0093
Air gap flux density (wb/m2)	0.6
Air-gap length (m)	0.0003
Full load slip	0.0699
Stator bore diameter (m)	0.105
Stator outer diameter (m)	0.181
Power factor	0.8041
Temperature rise, °C	46.8178
Efficiency %	0.80309
Starting torque, pu.	1.2027