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Optimizing Design Variables for High Efficiency Induction Motor Considering Cost Effect by Using Genetic Algorithm

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Abstract – The characteristics of an induction motor vary with the number of parameters and the performance relationship between the parameters also is implicit. In case of the induction motor design, we generally should estimate many objective physical quantities in the optimization procedure. In this article, the multi objective design optimization based on genetic algorithm is applied for the three phase induction motor. The efficiency, starting torque, and material cost are selected for the objectives. The validity of the design results is also clarified by comparison between calculated results and measured ones

Keywords: High efficiency, Cost, Optimization, Genetic algorithm, Design variable, Induction motor

1. Introduction

Electric motors consume over half of all electricity, and so consequently the need for energy conservation is accelerating the requirement for increased levels of electric motor efficiency [1]. Improving efficiency to higher level through the selection of an appropriate combination of the design factors can be effective way to reduce the consumption of electricity. In order to maximize efficiency, new technology has been developed such as copper die-casting motor and lower core loss electrical steel. However, these methods result in rising cost and require special manufacturing technology [2].

As the optimization of induction motor is multivariable and has numerous constraints, it has been studied continuously in electrical engineering. The method of "boundary search along active constrains" was proposed by Appelbaum in 1987 [3]. Nonlinear analytical iterative field field-circuit model (AIM) was introduced in 1996 by Madescu [4]. In this paper, multi-objective (MO) genetic algorithm (GA) is applied to optimize induction motor. There are numerous studies to solve multi objective problem in evolutionary algorithm fields. This paper adopts nondominated sorting genetic algorithm (NSGA)-II for optimization. It still remains one of the powerful multi objective handling algorithms. All parameters and crossover operators are used same as discussed in [5, 6]. The MO design of this paper is based on genetic algorithm, equivalent circuit method, and D^2L equation. The objective functions are the increase of the efficiency and the minimization of material cost. The constraints are on the starting torque and power factor. Output coefficient (C_0), airgap flux density (B_g), stator and rotor teeth flux density (B_{ts}, B_{tr}), stator current density (J_s), rotor current density (J_r) are also selected for the design parameters. For the verification of the design result, the simulation results have been compared with the experimental data.

2. Design Equation and Variables

2.1 D^2L sizing equation

The D^2L equation relates output power (P_n) and synchronous speed (n_s) to rotor volume through an output coefficient (C_0) in Eq. (1). Because the output coefficient (C_0) contains air gap flux density (B_g) and surface current density (K_1) in Eq. (2), where α is the magnetic saturation factor, Kw1 is the winding factor. D^2L equation has no relationships connecting air gap quantities with the flux density and current densities existing in the motor's interior [7].

$$D_{is}^2\mathrm{L} = \frac{1}{C_0}\frac{60}{n_s}\frac{P_n}{\eta cos\phi} \tag{1}$$

$$C_0 = \alpha K_{w1}\pi^2 K_1 B_g \tag{2}$$

As shown in Table 1, Some factors such as B_{ts}, B_{tr}, J_s, J_r, λ are added to compensate D^2L equation in induction motor design.

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Table 1. Variable description

Variables	Description
B_{ts}	Stator teeth flux density
B_{tr}	Rotor teeth flux density
J_s	Stator current density
J_r	Rotor current density
λ	$\frac{L}{\tau p}$ (Aspect ratio)

2.2 Model specification

Table 2 shows the brief specification of 37kW three phase induction motor for optimizing design. The diameter of stator and shaft are fixed respectively for assembling prototype.

Table 2. Specification of induction motor

Item	Value
Phase number	3
Input voltage [V]	380
Frequency [Hz]	60
Output power [kW]	37
Pole number	4
Stator Out Diameter [mm]	343
Shaft Diameter [mm]	70

3. Multi objective Genetic Algorithm for Optimum Design

3.1 Constrained multi-objective function

The objective function of the problem is minimization of g(X), material cost and maximization of f(X), efficiency. Material cost function g(X) includes only active materials of the electrical steel, the stator winding (copper) and the rotor conductor (aluminum) excluding frame, shaft, and bearings

$$g(x)=\text{electrical steel} + \text{copper} + \text{Aluminum} \tag{3}$$

Constraints to c(X) power factor > 0.85, starting torque/ rated torque >200%

3.2 Optimization approach

NSGA-II at generation t works as follows

Step 1) Use selection, crossover and mutation to create an offspring population Q_t from parent population P_t

Step 2) Choose best solutions from $P_t \cup Q_t$

The characteristic feature of NSGA-II is that it uses a fast non-dominated sorting and a crowded distance estimation procedure for comparing qualities among different solutions in Step 2 and the selection in Step 1. For detailed information on NSGA-II, the interested reader can see the algorithmic description of NSGA-II in [5, 6].

3.3 Experimental setting and results

In this paper, the implementation of NSGA-II follows. The population size is set to be 100. The algorithms stop after 20000 function evolutions. Initial populations are generated by uniformly randomly sampling from the feasible search space. The parent centric crossover (PCX) [6], and the polynomial mutation are used. The variance of PCX is set to be 0.15, and the distribution index of polynomial mutation is set to be 20 and the mutation rate is 1/n, where n is 7, the number of decision variables.

Table 3 shows the scope and the initial model's value of 7 variables. Stator and rotor slot combination is fixed to 48/40 in optimizing process.

Table 3. Scope of variables

Variables	Unit	Initial model	Variable Scope	
			Low	High
C_0	$[10^3 \times J/m^3]$	154	135	170
B_{ts}	[T]	1.53	1.30	1.80
B_{tr}	[T]	1.63	1.30	1.80
Bg	[T]	0.84	0.75	0.90
Js	$[A/mm^2]$	4.42	3.5	6.0
J_r	$[A/mm^2]$	2.36	1.5	3.0
λ	-	1.15	1.0	1.40

The set of non-dominated solutions with 20000 function evolutions is shown in Fig. 1. This figure shows the optimized results minimizing the active material cost at each efficiency point. The material cost is increased in proportion to efficiency, while the output coefficient (C_0) is decreased. Design point is selected at 93.6% to satisfy high efficiency level (IE 2 class >93.0%) and consider the material cost.

Fig. 2 shows the relation between other design variables and efficiency from optimized results. Aspect ratio (λ), airgap flux density (B_g), Stator and rotor current density (J_s, J_r) severely contribute to efficiency more than stator and rotor teeth flux density (B_{ts}, B_{tr})

Design variables and active material cost are compared

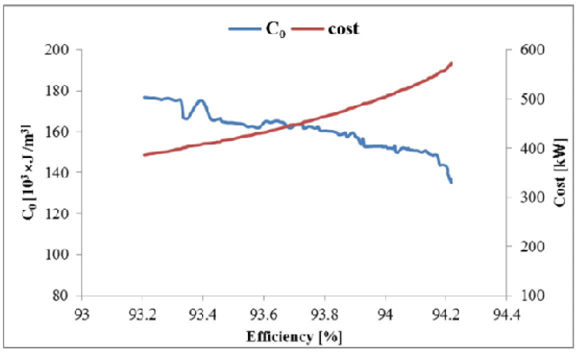
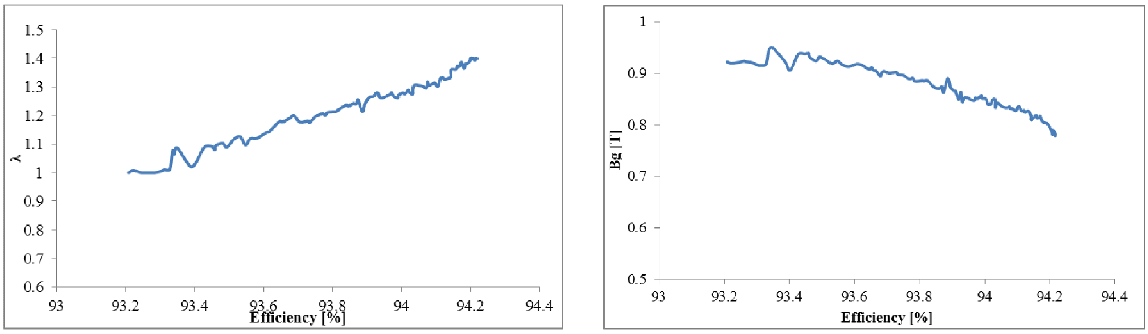
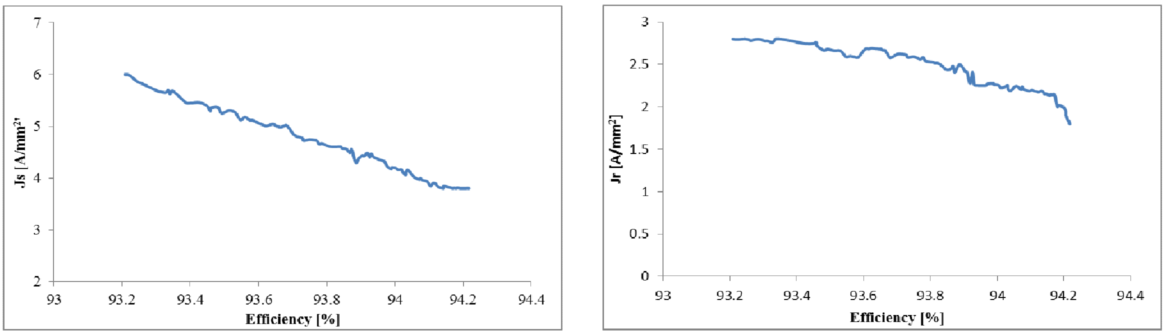


Fig. 1. Optimization results (Efficiency .vs. Cost, C_0)



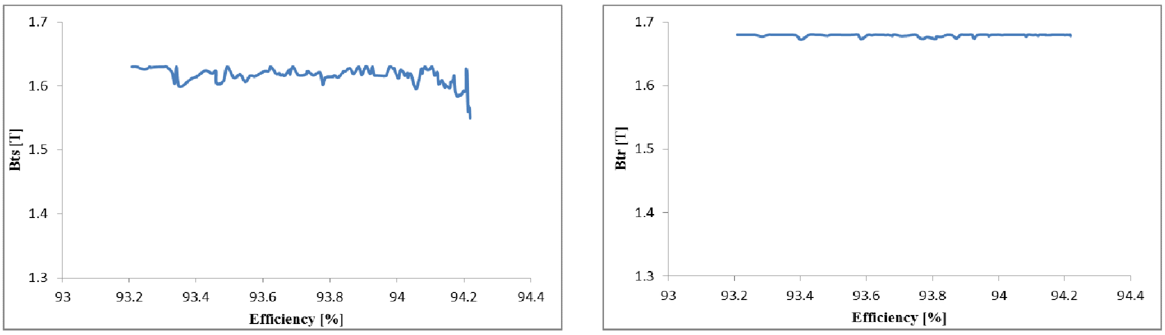
(a) Aspect ratio (λ)

(b) Airgap flux density (B_g)



(c) Stator current density (Js)

(d) Rotor current density (Jr)



(e) Stator teeth flux density (B_{ts})

(f) Rotor teeth flux density (B_{ts})

Fig. 2. Relation between efficiency and design variables

Table 4. Comparison of design variables and cost

Model	Base Model	Optimum Model
Outer / Inner Dia. [mm]	343/221	343/215
Wire Dia.	1.15×4	1.1×4
Turns per slot	24	24
The number of parallel circuit	4	
C_0 [10^3×J /m^3]	154	163
λ	1.15	1.177
Stack length [mm]	200	200
B_g [T]	0.84	0.863
B_{ts} [T]	1.53	1.61
B_{tr} [T]	1.63	1.68
J_s [mm^2]	4.42	4.82
J_r [mm^2]	2.36	2.62
Copper Weight [kg]	20.0	17.9
Material Cost [k₩]	490	468
Unit Material Price [k₩ /kg]	Copper : 11, electrical steel : 1.4, Aluminum : 3.0	

between initial model and optimum model in Table 4. It is shown that optimum model is designed to reduce the cost at the same efficiency level. Optimum model has same size with initial model but copper weight is reduced by 10%

4. Characteristics and Test Results

4.1 Equivalent circuit analysis

Characteristics of the model are analyzed by equivalent circuit method. Circuit parameters of Fig. 3 are calculated and the characteristics of induction motor are analyzed. Table 5 shows the results of equivalent parameters. The parameters are calculated by simulation program following equivalent circuit theory [8]. The leakage reactance of stator and rotor (X_s and X_r) is calculated considering leakage flux lines which cross the stator and, respectively, the rotor slots, end-turn flux, zig-zag flux, and airgap flux. The rotor resistance (R_r) is equivalent value using bar and end-ring resistance [8].

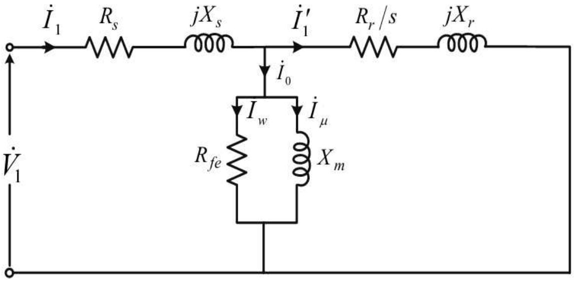


Fig. 3. Equivalent circuit of poly phase induction motor

Table 5. Analysis results of equivalent circuit method

Items	unit	Base model	Optimum model
Efficiency	%	93.6	93.6
Power factor	%	86.1	87.1
Rated phase current	A	69.9	68.9
Stator resistance (R_s) at 25℃	Ω	0.0483	0.0517
Rotor resistance (R_r) at 25℃	Ω	0.0266	0.0288
Stator leakage reactance(X_s)	Ω	0.232	0.225
Rotor leakage reactance(X_r)	Ω	0.278	0.274
Magnetizing reactance (X_m)	Ω	7.68	8.109

4.2 Test method and results.

Efficiency test is performed following IEC 60034-2-1 method. It is a loss segregation test method using a dynamo facility [9, 10].

Motor efficiency,η is defined as a ratio of output mechanical power to the input electrical power.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} \tag{4}$$

where P_{loss} is the total losses in the motor including stator (P_{stator}) and rotor copper loss (P_{rotor}), iron loss(P_{core}), friction and windage loss (P_{fw})and stray load loss (P_{stray}). The core loss, friction and windage loss are determined from the no-load operation of the motor at variable voltage ranging from 125% of the rated voltage to 20%. The stator, rotor and stray losses are determined from load tests, whereby the motor is coupled to a dynamometer [11].

The stator loss is measured as I^2R loss in the stator winding. The rotor copper loss is determined as a product of the slip (s) and the airgap power in Eq. (5).

$$P_{rotor} = (P_{in} - P_{stator} - P_{fw}) \times s \tag{5}$$

In the IEEE standard 112B and the IEC 60034-2-1s, the stray load loss (SLL) is determined by subtracting the conventional losses from the apparent total loss (Papp). The apparent total loss is the difference between the input power and output power at the load point of interest

$$P_L = P_{in} - P_{out} - (P_{core} + P_{fw} + P_{stator} + P_{rotor}) \tag{6}$$

where PL is the residual loss. The residual loss data at six load points shall be smoothed by using the linear regression method based on expressing the losses as a function of the square of the load torque in Eq. (7) where A(slop) and B(offset) are constant coefficients. The offset B is removed to obtain the correct stray load loss. The lope is used to calculate the stray load loss using Eq. (8) [9-11].

$$\mathrm{Y} = AT^2 + B \tag{7}$$

$$P_{stray} = AT^2 \tag{8}$$

Fig. 4 shows the residual losses at six load points (P_L), regression line (Y) and P_{stray} of optimum model.

Table 6 and 7 shows the load test and no-load test results of optimum model respectively to determine losses.

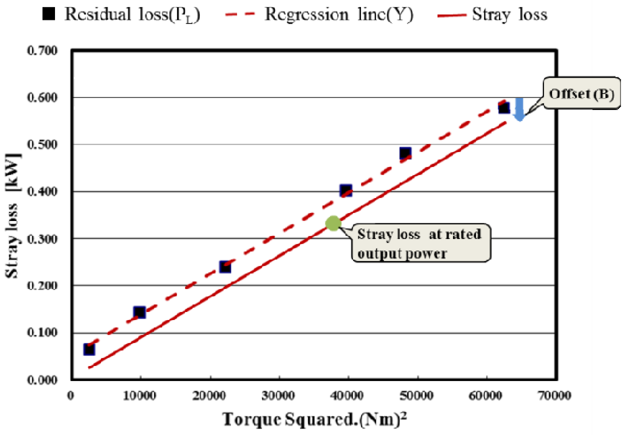


Fig. 4. Plot to determine stray load loss (optimum model)

Table 6. Load test results of optimum model

Output power/ rated [%]	125	110	100	75	50	25
Torque[Nm]	249.9	219.4	199.1	148.8	98.8	49.2
Input[kW]	49.9	43.7	39.6	29.6	19.9	10.3
Current[A]	85.6	75.9	69.3	54.2	40.4	29.3
Speed[rpm]	1767	1772	1775	1780	1788	1793
Temperature of winding[°C]	101.6	101.8	101.6	99.6	98.3	96.7
Voltage[V]	380.9	379.8	380.4	379.6	380.5	380.3

Table 7. No-load test results of optimum model

Input voltage/rated [%]	125	100	80	60	50	35	20
Voltage[V]	475	380	304	228	190	133	76
current[A]	45.0	24.8	18.0	12.8	10.5	7.4	5.0
Input[kW]	2.21	0.88	0.64	0.49	0.45	0.38	0.31

4.3. Comparison of analysis and test results

The core and rotor assembly for the prototype are shown in Fig. 5. Core and rotor conductor were made by press mold and aluminum die casting respectively. In Table 8, test results of losses and efficiency of optimum model are compared with the simulation results (equivalent circuit method). The iron loss is analyzed considering fundamental frequency loss and surface loss. The surface loss is calculated by the method of Francis Johns [12]. The friction and windage loss is calculated by the equation of Toshitaro Takeuch [13]. The simulation result of stray load loss is calculated 0.9% of input power. Efficiency test result is lower than that of simulation but satisfies high efficiency level (IE 2 class > 93.0%).

(a) Core (b) Rotor assembly

Fig. 5. Core and rotor assembly for prototype

Table 8. Analysis and test results at rated output power

Items	Base model	Optimum model	
	Analysis	Analysis	Test
Stator copper loss [W]	856	906	940
Rotor copper loss [W]	457	488	530
Iron loss [W]	562	497	468
Friction & Windage loss [W]	263	242	290
Stray load loss [W]	370	370	342
Rated phase current [A]	69.9	68.9	69.3
Power factor [%]	86.1	87.1	86.8
Efficiency [%]	93.6	93.6	93.5

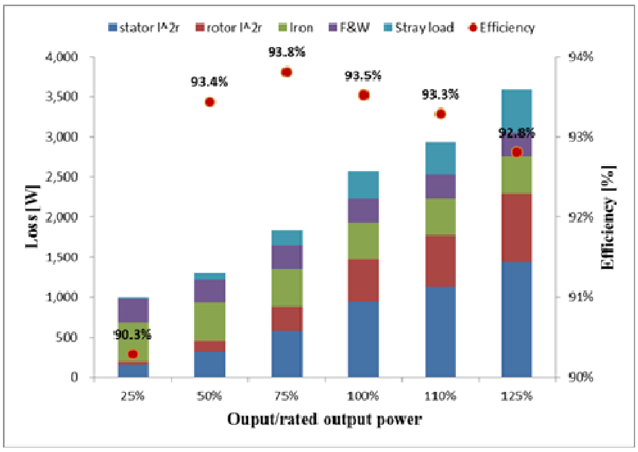


Fig. 6. Loss and efficiency .vs. output power

Fig. 6 shows the loss distribution and efficiency according to output power from test results of optimum model. The efficiency is the highest at 75% load point satisfies high efficiency level (IE 2 class) in region between 50% and 110% load point.

5. Conclusion

In this paper, the optimum design method is introduced to minimize the material cost of the high efficiency induction motor by using multi objective genetic algorithm and equivalent circuit method. Using this method, efficiency and power factor are achieved to the goal and the material cost is minimized by about 5% compared with the initial model. As efficiency level of electric motors has increased recently, material cost is rising in proportion to efficiency. The design process proposed in this paper will be useful for minimizing material cost in the electric motor design with many design variables.

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References

[1] M. Deivasahayam, "Energy Conservation through Efficiency Improvement in Squirrel Cage Induction Motors by Using Copper Die Cast", International Conference of energy efficiency in motor driven systems (eemods'05), Vol. 1, pp.92-101, September, 2005, Heidelberg, Germany.

[2] J. Haataja, J. Pyrhonen, "Improving three-phase induction motor efficiency in Europe", Power Engineering Journal, Vol. 12, pp. 81-86, 1998.

[3] J. Appelbaum, E. F. Fuchs, and J. C. White, "Optimization of three-phase induction motor design", IEEE Trans. Energy Conversion, Vol. EC-2, pp. 407-422, Sept. 1987.

[4] G. Madescu, I. Bolea, and T. J. E. Miller, "An analytical iterative model (AIM) for induction motor design", in conf. Rec. IEEE-IAS Annu. Meeting, San Diego, CA, Vol. I, pp. 556-583, 1996.

[5] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II" IEEE Trans. Evol. Computer, vol. 6, pp. 182-197, April, 2002.

[6] K. Deb, A. Anand, and D. Joshi, "A Computationally

Efficient Evolutionary Algorithm for Real-Parameter Optimization," Evol. Computer, Vol. 10, No. 4, pp. 371-395, winter, 2002.
[7] V. B. Honsinger, "Sizing equations for electrical machinery," IEEE Trans. on Magnetics, Vol. EC-2, No. 1, pp. 116-121, March, 1987.
[8] I. Boldea and S.A. Nasar, The induction machine handbook. Boca Raton: CRC Press, 2002.
[9] IEEE Std. 112, "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators," 2004.
[10] IEC 60034-2-1, "Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles" 2007.
[11] E. B. Agamloh, "An Evaluation of Induction Machine Stray Load Loss From Collated Test Results", IEEE Trans on Industry App., Vol. 46, No. 6, Nov./Dec., 2010.
[12] C. G. Veinott, Theory and Design of Small Induction Motors, New York,: McGraw-Hill Book, 1959.
[13] T. Takeuchi, Electric Machine design, Ohmsha, 1979.

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