Optimal Design of Induction Motor using Genetic Algorithm with Different Rotor Slot Number

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Abstract

Efficiency is affected by the geometry parameter and rotor slot number selection therefore a Genetic Algorithm based optimal design of a three-phase squirrel cage induction motor is applied to improve the efficiency of IM 2.2kW-4P from efficiency class IE2 to IE 4 motor design. An analytical calculation will investigate power, losses, and efficiency with different geometrical parameters of stator/rotor. Different constraints and different variables are imposed to achieve the best design within a specified range of variables. A genetic algorithm is used to achieve optimal design of the Squirrel Cage Induction motor-SCIM 2.2kW-4P with 36 stator slots/ 28,32, 40, and 44 rotor bars are verified under starting and constant speed. Their electromagnetic characteristics, such as electromagnetic torque, stator current, and magnetic flux density are compared in between two configurations. The paper contributes that the proper geometry parameters have a strong impact on the induction motor efficiency and the best design is applied for a 2.2kW induction motor with fixed stator and rotor diameters. The results obtained after running the optimization technique give visible improvements in efficiency as well as cost. To obtain the best design efficiency and cost of material is obtained using multi-objective Genetic Algorithm.

Keywords

Electromagnetic force-EMF, Squirrel Cage Induction motor-SCIM

Introduction

Energy Demand is increasing day by day and Power generation is also pressurized to maintain Continuity and Generate a huge amount of power to match demand. So, the increasing imbalance between generation and demand made us focus on energy Conservation. All the Transmission lines are operating at full load. The goal of this paper is to give a contribution to the design optimization of a three-phase squirrel cage induction motor using two different objective functions: namely "Efficiency" and "active Material Weight". A GA method for designing of three-phase squirrel cage induction motor have developed in Rakeshkumar Chaudharyl 2016, M. Çunka and R. Akkaya 2006, J. Haataja and J. Pyrhones 2000 K. B. Mohammad 2004. In this study, Genetic Algorithm coupling to MATLAB for calculation and FEM-CAD for geometry drawing is used as an optimization method the SCIM 2.2kW-4P with variables of stator/rotor diameter, the depth and width of the stator/rotor slots, and the air-gap length. The efficiency and losses of some simulated induction motors with different rotor slot numbers have been shown and discussed. Three of the rotor slot selected numbers are 28, 32, and 40 with skewing rotor slots.

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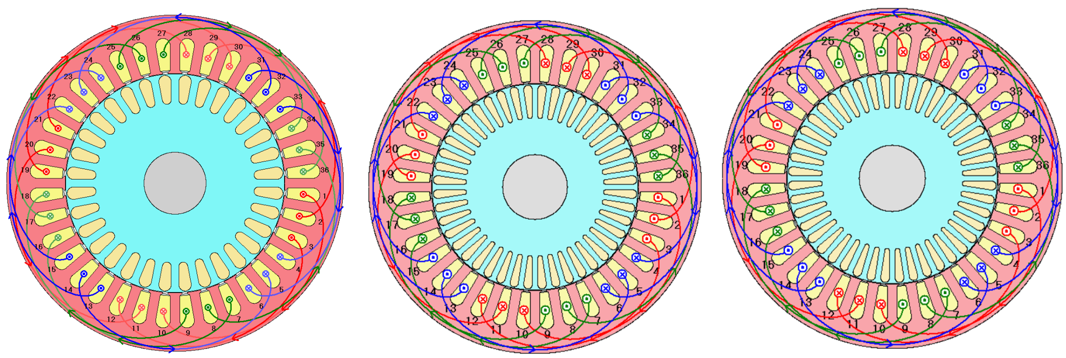
CONVENTIONAL DESIGN OF IM 2.2kW-4P

This study is based on 36 stator slots and 32/40/44 rotor bars and the three-phase SCIM specification and ratings are shown in Figure 1 and Table 1.



a. 36 stator slots/ 32rotor bars b. 36 stator slots/40 rotor bars c. 36 stator slots /44 rotor bars

Figure 1. SCIM 2.2 kW-4P 36 stator slots and 32/40/44 rotor bars

Air-gap eccentricity can be related to different manufacturing inaccuracies, such as construction tolerances, bearings, and shaft bending in J. Kappatou 2008. The eccentricity appears to some extends in all electrical machines and it has been studied from different points of view e.g. as related to its effect on the losses in J.-W. Kim 2005 or unbalanced magnetic pull.

Table 1. Technical parameters of SCIM 2.2 kW

Rated Output Power	2.2 kW
Number of Phases	3
Rated Voltage 400 V	380 VAC
Rated Current	4.7 A
Air gap	0.33mm
Stator Slot	36
Rotor bars	32 40 and 44
Efficiency	82.3%

DESIGN OPTIMIZATION OF INDUCTION MOTOR

Design Variables are quantities that are used in designing the induction motor, which is made free to take any value within its specified limits during the optimization process which objective functions satisfy to give the best results. For the proposed SICM in this paper, all variables will be so adjusted that the motor gives the highest efficiency satisfying all constraints. Table 2 introduces induction motor design to incorporate constraints on specifications, so no constraint is violated. Some important performance parameters are taken as constraints to have a feasible design to have an optimal value of efficiency.

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Table 2. Constraints on specifications of SCIM 2.2 kW

Abrev.	**Parameters**	**Units**	**Search regions**
D	Inner stator diameter	mm	$114 \le D \le 118$
λ	Geometric report	-------	$0.75 \le \lambda \le 1$
h_{t1}	Stator Slot height	mm	$10 \le h_{t1} \le 14$
h_{j1}	Back iron thickness	mm	$14 \le h_{j1} \le 18$
δ	Air-gap length	mm	$0.3 \le \delta \le 0.6$
B_{t1}	Stator tooth flux density	T	$1.3 \le B_{t1} \le 1.7$
B_{t2}	Rotor tooth flux density	T	$1.4 \le B_{t2} \le 1.8$
MW	Machine weight	kG	$10 \le M \le 15$

To improve efficiency, the geometry and configuration approach will be investigated. These methods are summarized as follows:

- Geometry Optimization of closed rotor slots for cage induction motors: It is a formal optimization procedure to determine the design shape of the parallel and rectangle slots to obtain maximum efficiency. This method involves the use of an analytical calculation coupled to a finite-element method to calculate the machine performance
- Minimum-time minimum-loss speed control of induction motors: A minimum-loss algorithm for induction motors is applied to achieve high efficiency by limiting additional loss and stray loss under controlling saturation level. In the steady-state, a minimum-loss control algorithm is applied to improve the efficiency by evaluating total losses and checking magnetizing currents.

Design Approach for Improving Efficiency

The combination of a computer-aided design with artificial intelligent optimization techniques forms an important tool, especially in the engineering design process of high performances and costly systems. In the field of electrical machines, due to the complicated nature of the functions describing their performances, the optimization problem of such machines is a multivariable constrained nonlinear problem. For optimizing the induction machine efficiency, a computed design process coupled to a genetic algorithm has been developed, according to Figure 2.

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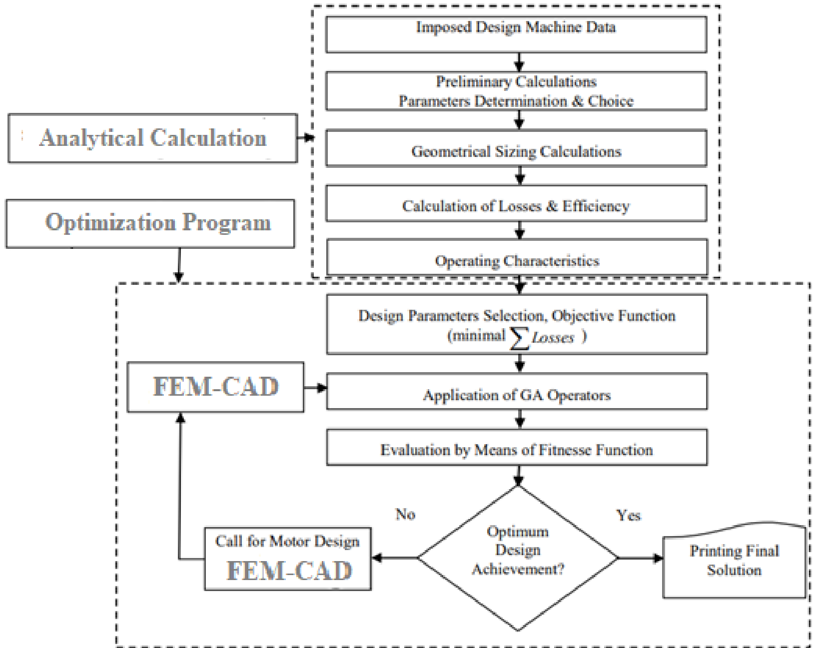

Figure 2. SCIM 2.2 kW-4P

The implementation of this method leads to the development of a design program for induction machines, which includes magnetic, electric, and mechanical calculations. Among the obtained results are the machine equivalent circuit parameters as depicted in figure 2.

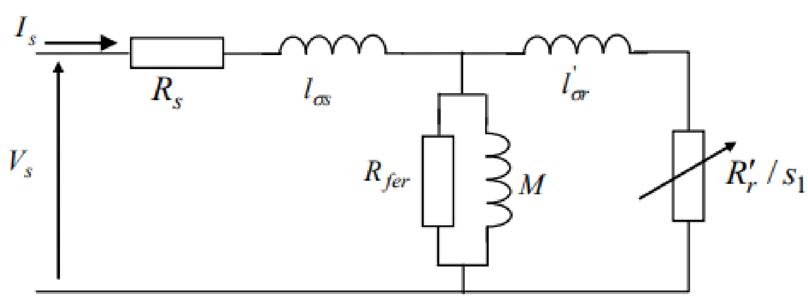

Figure 3. SCIM 2.2 kW-4P

Analytical Calculation

The analytical calculation program is implemented by a developed MATLAB program coupling to FEMM4.2 with the computed aid of CAD. The calculation parameters such as copper, iron losses are introduced as inputs for the main developed program. The windage and friction losses calculate according to a set of experimental curves of the no-load test. The inner stator diameter (D) and the core length L are the magnetic and electric variables:
For copper losses calculation, the stator coil loss P_{cu1} is given by:

$$P_{cu1} = m_1 \cdot R_s \cdot I_s^2 \tag{1}$$

The copper losses in the rotor cage P_{cu2} is:

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$$P_{cu2} = m_2 \cdot R_2 \cdot I_2^2$$

(2)

$$R_2 = R_{bar} + \frac{2 \cdot R_{ring}}{4 \cdot \sin^2 \frac{\pi \cdot p}{Z_2}}$$

(3)

The sum of the losses p $_{H+W}$ in one iron kg is given by:

$$p_{H+W} = K_H \cdot f \cdot B^2 \cdot 10^{-2} + K_W \cdot \left(S_t \cdot f_1 \cdot \hat{B}\right)^2 \cdot 10^2$$

(5)

The constants K_H , K_W for the different materials are given by normalized range.

Finally, the efficiency is:

$$\eta = \frac{P_m}{P_m + \sum Losses}$$

(5)

The above-described machine sizing procedure is applied to a radial flux induction machine using the developed design program

Genetic Algorithms (GA) Optimization Method

Genetic algorithm-based optimization is a stochastic search method that involves the random generation of potential design solutions, then systematically evaluates, and refines the solutions until a stopping criterion is met. There are three fundamental operators involved in the search process of a genetic algorithm: selection, crossover, and mutation. The genetic algorithm implementation steps are in D. Weile 1997, K. S. Tang 1997 and A. and Benoudjit 2000. it selects individuals according to their fitness. The selection probability can be defined by:

$$P_j = \frac{F(x_i)}{\sum F(x_i)}$$

(6)

Where
P_j : Selection probability;
$F(x_i)$: Objective function

The crossover includes a two-steps operation that is performed according to a defined probability P_J . Firstly, two members of the previously selected population are randomly selected. Then, an integer position along one string is selected at random, and all binary digits following this position are swapped with the second string. Consequently, two new strings are created for the next generation. The mutation is an operation that is carried out on a bit-by-bit basis. A bit of string of the yielded generation is randomly selected according to a defined probability and its value is complemented from 0 to 1. After this operation, the reproduction process is completed, and offspring is generated. Evaluation of all individuals of the new obtained population as described in the previous section. In each iteration, the parameter search space is adjusted according to the local optimum solution. The process is ended whenever a prefixed number of generations or the best of the objective function-imposed value has reached a satisfactory level. The

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analytical design program is combined with a GA sub-program optimizing the machine efficiency to form a GA optimized design procedure. The main objective function for searching the optimal design and the motor weight is taken as an optimization constraint. The optimized parameters are the inner stator diameter, geometric ratio, stator slot height, back iron thickness, air gap length, and material weight. The best and average GA fitness function evolutions correspondent on minimum losses with generations for each metal sheet type are shown in table 3:

Parameter	**Unit**	**36Slot/28Bar (Conventional design)**	**36Slot/ 32Bar**	**36Slot/ 40Bar**	**36Slot/ 44Bar**
Airgap Torque (on load)	Nm	14.86	14.93	14.91	14.80
Shaft Torque	Nm	14.46	14.41	14.39	14.31
Output Mechanical Power	Watts	2200.40	2200.00	2200.30	2200.50
Input Active Electrical Power (from Power Balance)	Watts	2676.9	2441.10	2436.10	2428.54
Total Losses (Analytic on load)	Watts	471.92	241.10	235.80	228.04
Input Reactive Power (on load)	VA	1843.80	1135.30	1169.00	1437.60
Apparent Power	VA	3250.40	2786.20	2795.60	2912.70
Power Factor (on load) (Phasor)		0.82	0.91	0.91	0.87
Power Factor (on load) (from Power Balance)		0.82	0.91	0.91	0.87
System Efficiency	%	82.34	90.12	90.32	90.61

Table. 4 is the weight of variables and constraints are used for optimal design to improve the power factor and efficiency. These upper and lower limits are used fixed as GA then GA will optimize, and it should find optimal values at maximum efficiency and power factor. Then to perform the test convergence process if the optimal designed values are not achieved the motor initial design variables must be updated and fix the new population range within specified limits of individual variables then continue the optimization process and it should achieve optimal design values this optimal design values to shows better efficiency and power factor of SCIM until this process the algorithm cannot be terminated.

Table 4. Weight comparison of SCIM 2.2 kW

Components	**Materials**	**36Slot/ 32Bar**	**36Slot/ 40Bar**	**36Slot/ 44Bar**
Stator Lam (Back Iron)	M470-50A	4.31	4.36	4.46
Stator Lam (Tooth)	M470-50A	1.84	1.87	1.90
Armature Winding [Active]	Copper (Pure)	0.89	0.90	0.92
Armature EWdg [Front]	Copper (Pure)	0.49	0.50	0.51
Armature EWdg [Rear]	Copper (Pure)	0.49	0.50	0.51
Rotor Lam (Back Iron)	M470-50A	1.27	1.29	1.49
Rot Inter Lam (Back Iron)	M470-50A	0.00	0.00	0.00
Rotor Lam (Tooth)	M470-50A	1.83	1.83	1.78
Rotor Cage Top Bar	Aluminium	0.37	0.38	0.36
Rotor Cage (Front End)	Aluminium	0.10	0.11	0.10
Rotor Cage (Rear End)	Aluminium	0.10	0.11	0.10
Rotor Cage		0.58	0.60	0.57
Total		**12.42**	**12.58**	**12.88**

Results in table 4 show that efficiency of three design gives higher efficiency of IE 4 class, The design of 36 slot/44 bar has highest efficiency and cost compared to design 1 & 2. In designs 1&2 Active Material cost is taken as objective

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function cost decreases but efficiency also decreases. To choose the best value of efficiency or cost to compromise in another value of objective function. To solve this problem; a method of "dual optimization" can be implemented with two objective functions together. An NSGA-II programs in MATLAB in Deb K 2002 and 2006 is used for dual optimization with efficiency and active material cost as the objective function

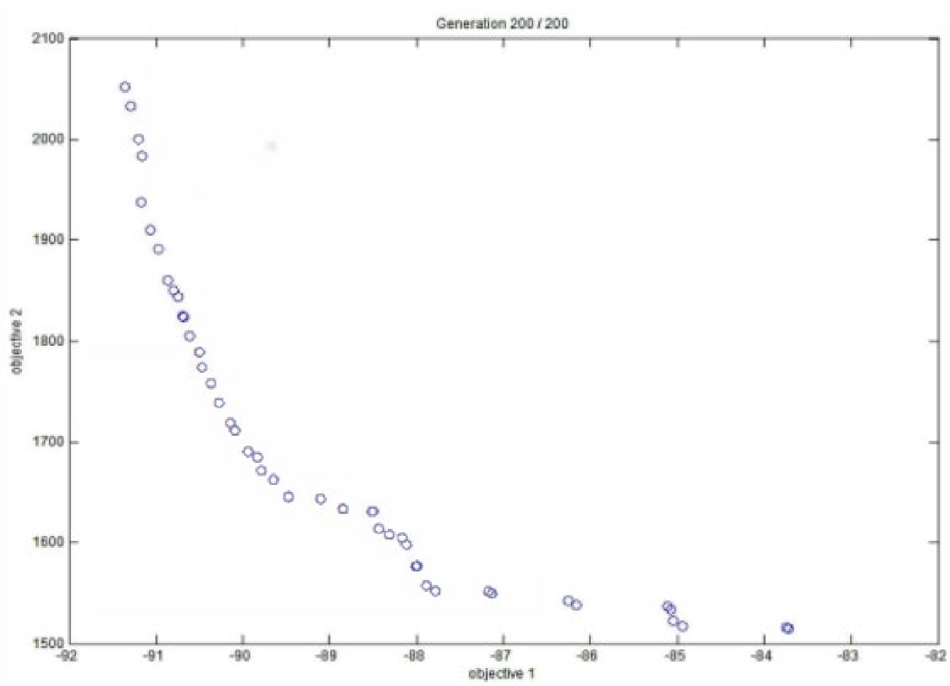

Figure 4 MATLAB results for Efficiency and Cost as Objective Function

Figure 4 shows the relation between two objective functions this is obtained using NSGA-II Program in MATLAB. The numbers of generations selected are 200 and 50 populations for each generation. The above graph shows that with the higher efficiency; the cost of the motor is higher, and it decreases with a decreased efficiency. The proposed design with 90.6% (higher IE4) can be designed as per requirement from results obtained using the NSGA-II program.

Conclusions

This paper has analyzed and compared the electromagnetic performance of three induction motors for industrial applications. The 44-rotor bar has the lowest iron loss. To verify the proposed design, a detailed design of a 3-phase 36-slot and 4-pole IM is assembled and verified torque, power, and efficiency performances. The back EMF waveforms have been analyzed based on the FEA modeling. The thermal simulation was implemented to validate overheat capacity. The main aim of the present investigation is to optimize the induction motor efficiency using a genetic algorithm tool. It optimizes geometric parameters such as inner stator diameter, geometric ratio, stator slot height, back iron thickness, air-gap length and stator tooth flux density, rotor tooth flux density to minimize the machine weight and maximize its efficiency. The GA optimized approach has been successfully applied on a typical 2.2 kW, 4 poles induction machine. It can be drawn from the optimized results, that the choice of the magnetic metal sheets has in important impact on machine efficiency. The achieved results with three material sheet types of this investigation have clearly demonstrated that the machine efficiency can be improved by this optimization procedure. Such achievement can be considered of great interest since it results in a paramount of energy saving and consequently an important reduction on the energy running cost.

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References

Rakeshkumar Chaudharyl 2016, M. Çunka and R. Akkaya 2006, J. Haataja and J. Pyrhones 2000 K. B. Mohammad 2004,

Rakeshkumar Chaudharyl, Ankit Shahpate12 and Sameer Patee, *"Optimal Design of Induction Motor using Genetic Algorithm and Comparision with Conventionally Designed Induction Motor"*, IEEE International Conference on Power Electronics. Intelligent Control and Energy Systems (ICPEICES-2016)

M. Çunka and R. Akkaya, *"Design Optimization of Induction Motor by Genetic Algorithm and Comparison with Existing Motor,"* Math. Comp. Applications, vol. 11, no. 3, pp. 193-203, 2006.

J. Haataja and J. Pyrhones, "*Improving Three Phase Induction Motor – Efficiency in Europe," IEEE Trans. Industrial Electronics*, vol. E-36, no., pp. 1555- 1562, Nouv /Dec 2000.

K. B. Mohammad, B. B. Sharifian and J. Mohammadi, *"Induction Motor Efficiency Estimation using Genetic Algorithm,"* IEEE Trans. Engineering, vol. 3, pp. 271-275, December 2004.

J.-W. Kim, B.-T. Kim, and B. I. Kwon, *"Optimal stator slot design of inverter-fed induction motor in consideration of harmonic losses,"* IEEE Transactions on Magnetics, vol. 41, no. 5, pp. 2012–2015, 2005.

J. Kappatou, K. Gyftakis, and A. Safacas, *"FEM study of the rotor slot design influences on the induction machine characteristics,"* in Studies in Applied Electromagnetics and Mechanics, vol. 30 of Advanced Computer Techniques in Applied Electromagnetics, IOS Press, 2008.

D. Weile and E. Michielssen, *"Genetic Algorithm Optimization Applied to Electromagnetics,"* IEEE Trans. Industrial Electronics, vol. 45, no. 3, pp. 343-353, March 1997.

K. S. Tang, K. F. Man and S. Kwong, *"Genetic Algorithms: Concepts and Applications in Engineering Design,"* IEEE Trans. Industrial Electronics, vol. 43, no. 5, pp. 519-534, October 1996.

A. Benoudjit, A. Guettafi and N. Nait Said*,"Axial Flux Induction Moteur for On-Wheel Drive Propulsion System,"* EMPS - Electic Machines and Power Systems, vol. 28, pp. 1107-1125, 2000.

Deb K; Pratap A; Agrawal S; Et ta. A Fast and Elitist *"Multi objective Genetic A1gorithm Nsga-ll "*[J]. Evolutionary Computation. 2002; 6(2): 182-197.

Deb K; Sundar J; U B R N; Et ta. *"Reference Point Based Multiobjective Optimization Using Evolutionary A1gorithms"* [J]. International Journal of Computational Intelligence Research. 2006; 2(3): 273-286.

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