International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 5, Number 4 (2012), pp. 393-409

http://www.irphouse.com

Design of Induction Motor using Multiple Flux Technique

S.S. Sivaraju[1]* and N. Devarajan[2]

[1*]*Department of Electrical and Electronics Engineering,*
RVS College of Engineering and Technology, Coimbatore, Tamilnadu, India
E-mail: sssivaraju@gmail.com
[2]*Department of Electrical and Electronics Engineering,*
Government College of Technology, Coimbatore, Tamilnadu, India.
E-mail: profdevarajan@yahoo.com

Abstract

More than 80% of three-phase Squirrel Cage Induction Motors (SCIMs) are widely used in industrial and domestic applications because of the relatively low cost and high reliability. When oversized, most of these motors operate with low efficiency and power factor. Adjustable flux motors with multiple winding connections can be an energy efficient solution in variable and fixed load applications, improving the efficiency and power factor by means of properly adapting motor flux to the actual load. In this paper, a design optimization method is proposed. The optimal design of multiconnection, multiflux stator winding to improve motor efficiency and power factor in a wide load range is proposed using Genetic Algorithm (GA). This algorithm is a population-based search algorithm characterized as conceptually simple, easy to implement and computationally efficient. A parameter-less loss approach is incorporated in the proposed algorithm to handle the constraints effectively. A comparison of the final optimum designs with the existing design for a 7.5-kW motor is presented, demonstrating that the optimal designs produce larger efficiency in all load range. The importance of this work is highlighted by the recent concerns about the need to achieve energy savings in industry.

Keywords*:* Design, Genetic Algorithm, Induction Motor, Multiflux, Multiconnection Winding.

Introduction

Three-phase Squirrel-Cage Induction Motors (SCIMs) are widely used in various industrial and domestic fixed and variable speed applications. More than 80% of the electrical motors are SCIMs because of their relatively low cost, high reliability and high efficiency. SCIMs are the main energy consuming devices in most industries contributing to more than 80% of electromechanical energy consumption. Most oversized SCIMs operate with low efficiency and power factor, which is the most important cause of poor power factor in industrial installations. Therefore, in the SCIM design optimization, the energy efficiency and power factor are key issues.

The equivalent circuit of induction motor is shown in Figure. 1. The model is popular and well understood among engineers and, despite its shortcomings, offer reasonably good prediction with modest computational effort. This model is basically a per-phase representation of a three-phase SCIM in the frequency domain, comprising of 6 model lumped parameters, namely, stator resistance R_1, stator leakage reactance X_{01}, magnetizing reactance X_m, core loss resistance R_m, rotor leakage reactance X_{02} , and rotor resistance R_2/s, which is a function the slip s. In this study, the approaches and methods used to calculate the motor performances are based on the work presented in [3].

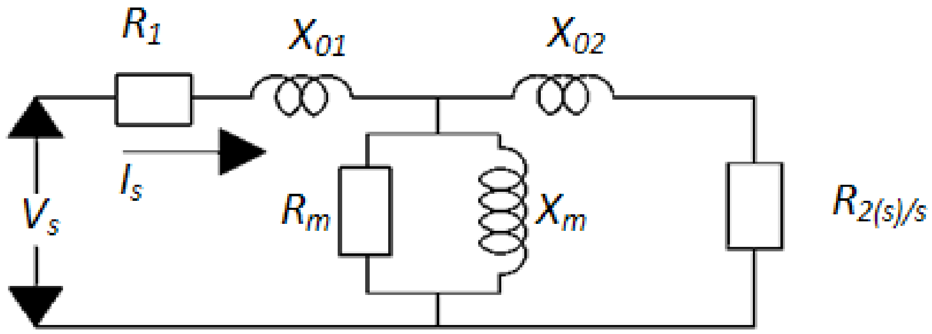


Figure 1: Equivalent circuit of induction motor

In the past, the design of SCIM has been attempted for achieving better performance characteristics in terms of efficiency, power factor and operating temperature [1, 4, 5, 7, 8, 14]. These were carried out on trial and error method which is solely based on professional experience and analytical studies. Digital computers have made possible to use better optimization techniques in the design of electrical machines [1,2,6,9,10,12].

For the design optimization of SCIMs, the most frequently used objective functions are the motor efficiency and power factor [7,9, 13]. Several techniques such as Genetic Algorithm (GA), Neural Networks [8] and Fuzzy Logic have been used to solve the SCIM design problems. However, these techniques do not always guarantee the global optimal solution. They normally provide suboptimal solution. The GA is a modern, evolutionary, population-based, search algorithm, characterized as conceptually simple, easy to implement and computationally efficient [8,11,12]. GA has also been found to be robust in solving problems featuring nonlinearity, nondifferentiability and high dimensionality.

In this study, the multiflux SCIM described in [4,5], with different possible winding connections, which allows the magnetizing flux to be adjusted up to six different levels, is being considered. Alternatively, for the same magnetizing flux, such motor can operate with up to six different voltage levels, in which both the efficiency and power factor can be maximized as a function of load [4,5]. The application of the proposed design in such motors can lead to significant energy savings and efficiency, power factor improvement. This novel motor can be of great value in industry due to its flexibility, particularly, for variable load fixed-speed applications in which significant energy savings can be obtained. The optimization of such motors using the proposed GA algorithm is presented, leading to improvement of efficiency and power factor. GA-based design technique of multiflux stator winding problem is proposed in the paper.

Genetic Algorithm Problem Formulationm

The problem in the induction motor design is to select an appropriate combination of the design variables which can minimize the losses and improve the power factor of SCIMs during light loading periods, without reducing the full-load performance. The design process is much complicated while using too many variables[15]. Therefore the number of design variables selection is important in the motor design optimization. The design has some constraints, to guarantee same motor performance indices. The design optimization problem can be formulated as a general nonlinear programming problem of the standard form Find x (x_1, x_2, … x_n), such that $J(x)$ is a maximum subject to $g_j(x) \geq 0$, $j = 1, 2, \ldots m$ and $xL_i \leq xL_i \leq xU_{ii} = 1, 2, \ldots n$, where is the set of independent design variables with their lower and upper limits as xL_i and xU_i, for all n variables. J(x) is the objective function to be optimized and $g_i(x)$ is the constraint imposed on the design.

If J is the objective function to maximize the efficiency, it depends on the design variables $x = (x_1, x_2, x_3 \ldots x_n)$, the corresponding optimization problem can be written as:

$$\begin{cases} MAX \quad J(x) \\ Subject \quad to\ G(x) \geq 0 \end{cases}$$

A set x of seven independent variables which affect constraints and objective function is listed below:

- 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 (T),x_5
- Stator current densities (A/mm^2), x_6
- Rotor current densities (A/mm^2), x_7

The remaining parameters can be expressed in terms of these variables or may be treated as fixed for a particular design.

The following factors are considered as SCIM design constraints: (a) Stator Copper Loss; (b) Rotor Copper Loss; (c) Stator Iron Losses; (d) Friction losses; (e) Stator Temperature Rise; (f) Full Load Efficiency.

The design and optimization of SCIM requires a particular attention in the choice of the objective function that usually concerns economic or performance features. In this proposed design, our main objective to improve the efficiency during light loads. The expression of objective function, in terms of the design variables are summarized in the form of different constraints as follows.

The Stator Copper Loss are given by:

$$W_{SCL} = 3.I_{ph}^{2} \times R_{s} \quad 1$$

where I_{ph} is the phase current in amps and R_S is the equivalent per-phase stator resistance in ohms.

The resistance of the stator winding can be calculated with the known value of specific resistivity of the winding materials by

$$R_s = \frac{\rho_r E_{ph} x_6}{2.22 K_w f\, I_{ph} \tau\, x_5} + (1 + \frac{1.15}{x_2} + \frac{0.12}{x_2\, \tau}) \quad 2$$

$$where\ \ E_{ph} = 4.44 K_w f \phi\, T_{ph} \quad 3$$

The Rotor Copper Loss are given by:

$$W_{RCL} = \frac{\rho_r S_2 I_b^2}{a_b} (L_r + \frac{2 D_e}{P}) \quad 4$$

where ρ_r is a constant (0.021), $S_2$is the number of rotor slots, I_b is the rotor bar current in Amps, D_e is the mean end-ring diameter in mm, L_r is the length of the rotor core in m, and P is the number of poles.

The mean end ring diameter can be expressed as

$$D_e = D - 0.002 I_g - 0.002 d_{sr} \quad 5$$

The rotor slot depth can be expressed as

$$d_{sr} = \frac{a_{sr} S_2 x_3}{S_1 d_{ss}} \quad 6$$

The stator slot depth to width ratio

$$d_{ss} = \sqrt{\frac{1000 S\, x_3}{2.22 K_w f\, \tau^2 S_1 S_2 x_2 x_5 x_6}} \qquad 7$$

The rotor current can be expressed as

$$I_b = \frac{850\ S}{2.22 K_w f\ \tau^2 S_2 x_2 x_5} \qquad 8$$

The length of the core can be expressed as

$$L = x_2 \frac{\pi D}{p} = x_2 \tau \qquad 9$$

The area of the bar can be expressed as

$$a_b = \frac{382.88\ S}{K_w f\ S_2\ \tau^2 x_2 x_5 x_7} \qquad 10$$

The kVA rating of the machine can be expressed as

$$S = 3 E_{ph} I_{ph} \times 10^{-3}\, kVA \qquad 11$$

The Stator Iron Loss are given by:

$$W_{SIL} = W_t - W_{tk} + W_c - W_{ck} \qquad 12$$

where W_t is the weight of the stator teeth, W_c is the weight of the stator core, W_{tk} is the losses in stator tooth portion (W/kg), and W_{ck} is the losses in stator core (W/kg).

The Full Load Efficiency is given in percentage by:

$$\eta = \frac{1000 P_O}{1000 P_O + W_{SCL} + W_{RCL} + W_{SIL} + W_F} \qquad 13$$

where P_o is the output power (kW) and W_F are the friction losses (W). The stray load losses are neglected in the analysis.

For continuously rated machines, the final stator temperature rise θ_{ms} is a determining factor and with the assumption that cooling by convection, conduction and radiation is proportional to the temperature rise [3].The temperature rise is directly proportional to the heat developed due to losses and indirectly proportional to cooling surface area, according to (14):

$$\theta_{ms} = \frac{\tau_c (W_{SCL} + W_{SIL})}{S_S} \qquad 14$$

where τ_c is cooling coefficient:

$$\text{Cooling coefficient} \quad \tau_c = \frac{0.03\text{–}0.05}{1+0.1u} u \quad \text{where } u = \frac{2\Pi fD}{P} \qquad 15$$

and the total effective cooling surface area is:

$$S_s = S_I(1 + 0.1u) + S_o \qquad 16$$

where S_i and S_o are the inside and outside cylindrical surface area of the motor respectively.

This stator temperature optimization is an important design aspect and becoming a more important component of the electric motor design process due to the push for reduced weights and costs and increased efficiency. To obtain an accurate analytical thermal model, all the important heat transfer paths must be included in the network and suitable algorithms should be used to calculate thermal resistances for such paths. This usually requires the experience of a heat transfer specialist, to use his skills and experience to construct an accurate thermal network. However, motor optimal design mathematical model have developed genetic algorithm, which automatically constructs an electric motor thermal network from the users inputs for motor geometry and their selection of materials and cooling coefficient.

In the most general sense, GA-based optimization is a stochastic search method that involves random generation of potential design solutions and then systematically evaluating and refining the solutions until optimal solution is met.

There are following three fundamental operators involved in the search process as genetic algorithm, namely, *selection*, *crossover*, and *mutation*.

The *selection* is a process in which individual strings are selected according to their fitness. The selection probability can be defined by the selection probability P_j and the objective function $F(xi)$.

The *crossover* is the most powerful genetic operator. One of the commonly used methods for crossover is single-point crossover. As shown in the following examples, a crossover point is selected between the first and the last bits of the chromosome. Then binary code to the right of the crossover point of *chromosome 1* goes to *offspring 2* and *chromosome 2* passes its code to *offspring 1*. This operation takes place with a defined probability P_c that statistically represents the number of individuals involved in the crossover process.

The *mutation* is a common genetic manipulation operator and it involves the random alteration of genes during the process of copying a chromosome from one generation to the next. Raising the ratio of mutations, increases the algorithm's freedom to search outside the current region of parameter space. Mutation changes from a "1" to a "0" or vice versa. It may be illustrated as 110000010_110001010.

The genetic algorithm implementation steps are shown in Fig. 2 and are as follow:

- Define parameter and objective function (Initializing);
- Generate first population at random;
- Evaluate population by objective function;
- Test convergence. If satisfied then stop else continue;
- Start reproduction process (Selection, Crossover and Mutation);
- New generation. To continue the optimization, return to GA point that produces optimal results in many practical problems is composed of the following three operators.

The SCIM design to maximize power factor and efficiency is done using GA approach. Then the parameter-less loss approach is incorporated in the proposed algorithm to handle the constraints effectively.

The flow chart of the design and optimization procedure is depicted in Fig. 3. Each every block consists of some specific objectives to achieve optimal solutions. Execution of the program starts with motor required performance specifications and initial motor design variables, the number of generations, population size (upper and lower limits), crossover rate and mutation rate. The each and every design parameter of three phase squirrel-cage induction motor both stator and rotor layout must calculated. Then the optimization process should be carried out based fundamental operators (selection crossover mutations) of genetic algorithm and the specification of objective functions. This optimization process has been evaluated for each and every individual population (specific limits) of the design variables.

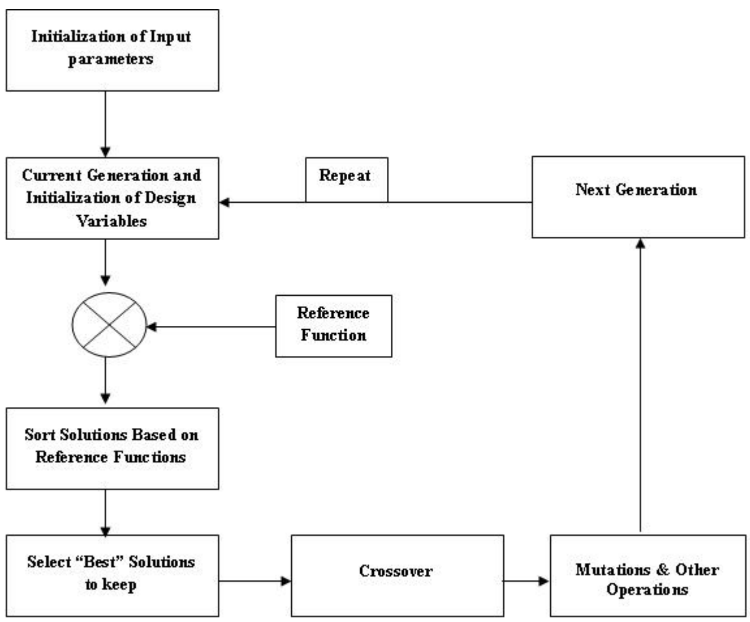


Figure 2: The main steps in a GA.

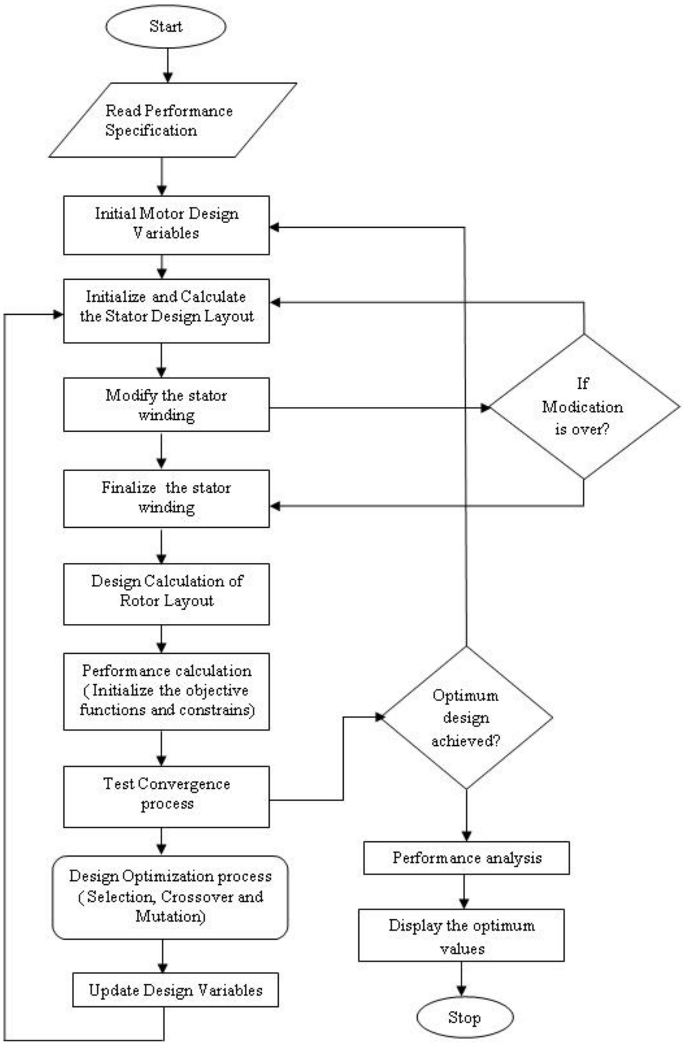


Figure 3: Flow chart for design and GA-based optimization process

Table 1: Assigned Value of Parameters used in Motor Design

Parameter	Assigned values
Winding factor	0.96
Stator slot opening, mm	3.0
Rotor slot opening, mm	2.0
Stator slot wedge height, mm	3.0
Rotor slot wedge height, mm	2.0
Stator slot fullness factor	0.35
Rotor slot fullness factor	1.0
Radial air gap length, mm	0.5
Cooling coefficient	0.03

Table 2: Lower and Upper Bounds of Variables and Constraints

Variables (implicit) or Constraints (explicit)	Lower	Upper
Ampere Conductors/m	15000	25000
Ratio of Stack Length to Pole Pitch	0.9	2.0
Stator Slot Depth to Width Ratio	3.0	5.5
Stator Core Depth (mm)	2.0	5.0
Average Air Gap Flux Densities (Wb/m^2)	0.4	0.8
Stator Winding Current Densities (A/mm^2)	4.0	15.0
Rotor Winding Current Densities (A/mm^2)	4.0	15.0
Maximum Stator Tooth Flux Density,Wb/m^2	0.5	2.0
Stator Temperature Rise, °C	20.0	70.0
Full Load Efficiency, %	80.0	100.0
No Load Current, pu	0.02	0.5
Starting Torque, pu	1.5	10.0
Maximum Torque, pu	2.2	10.0
Slip, pu	0.01	0.05
Full Load Power Factor	0.8	1.0
Rotor Temperature Rise, °C	10.0	70.0

In Table.1 is assigned value of parameters used in motor design and Table. 2 lower and upper bounds of variables and constraints are used for optimal design through to improve the power factor and efficiency. These upper and lower limits are used fixed as GA then GA will optimize and it should be 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 be achieve optimal design values this optimal design values to shows better efficiency and power factor of SCIM until this process the algorithm cannot be terminate.

Results From GA-based Optimization

The multiflux SCIM being considered in the presented study, has two sets of turns in each phase which can be connected either in series or parallel with the input voltage supply. Thus, it is possible to achieve different levels of magnetizing flux, which can be properly selected as a function of the actual load. The different possibilities of stator winding connections are presented in the Figs. 4-13 [4,5].

In Fig. 14, the efficiency as a function of load and Fig.15,the power factor as a output for the different stator connections for the conventional design (base case), is shown. These curves were obtained experimentally and used to obtain the reference/initial values of the motor parameters. In Fig. 16, the efficiency as a function of load and Fig.17,the power factor as a output for the GA-based optimized design is presented. In Table.3 a camparison results of differrent stater winding connections for for normal and optimal designs is presented. In Table 4, a comparison of the mean results for normal and optimal designs is presented. It can be concluded that the otpimized SCIM design results in significantly improved efficiency curves for all the connection modes. The parameter-less loss approach incorporated in the proposed algorithm to handle the constraints prove to be effective.

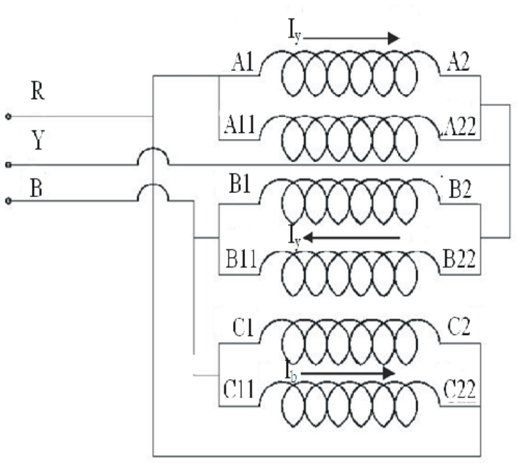


Figure 4: Delta Parallel (DP) Connection.

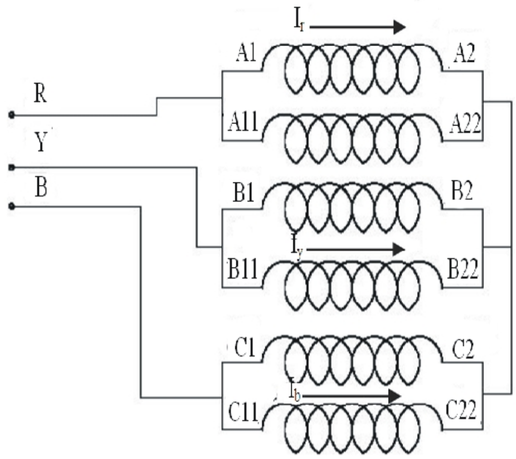


Figure 5: Star-Parallel (YP) Connection.

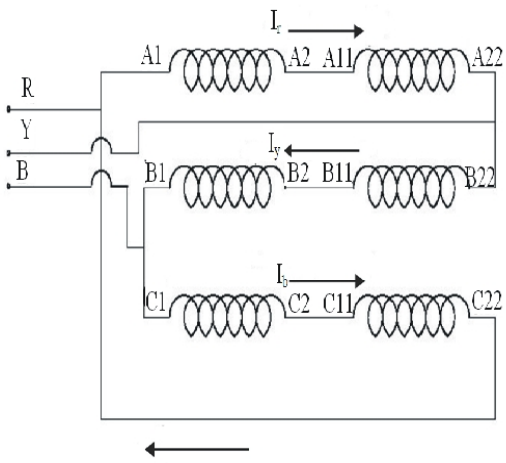


Figure 6: Delta-series type I (DS1) Connection.

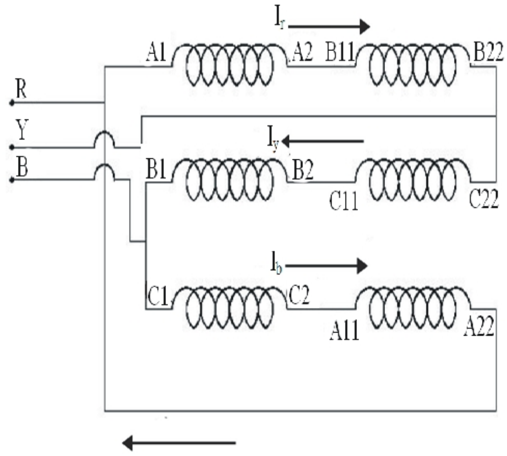


Figure 7: Delta-series type II (DS2) Connection.

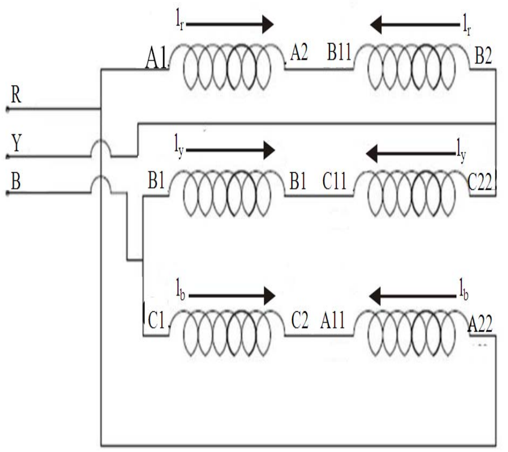


Figure 8: Delta-series type III (DS3) Connection.

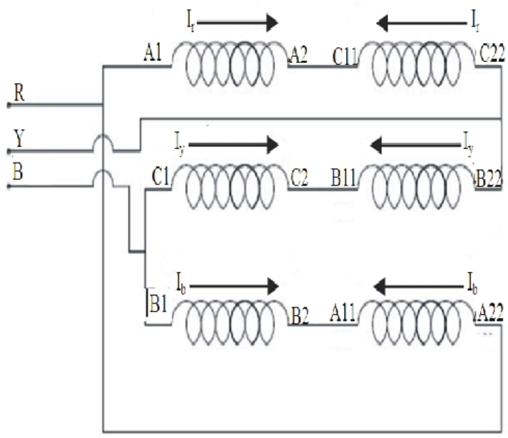


Figure 9: Delta-series type IV (DS4) Connection.

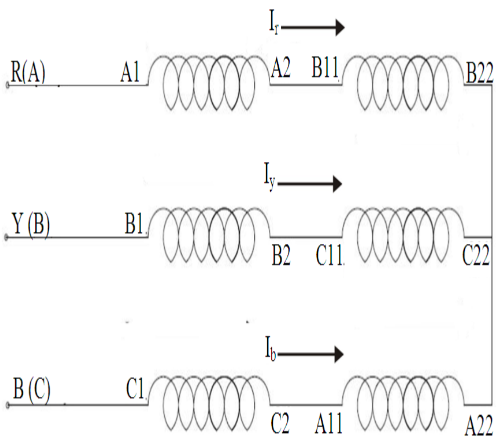


Figure 10: Star Delta (YD) Connection.

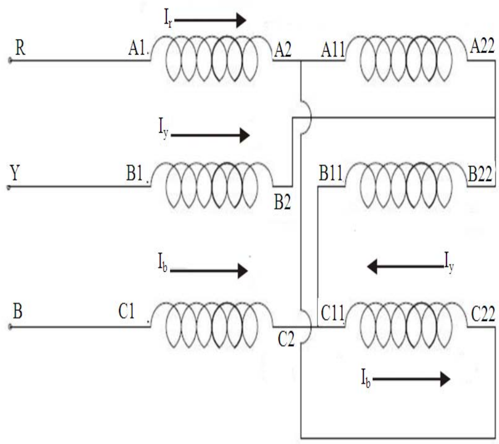


Figure 11: Star-series type I (YS1) Connection.

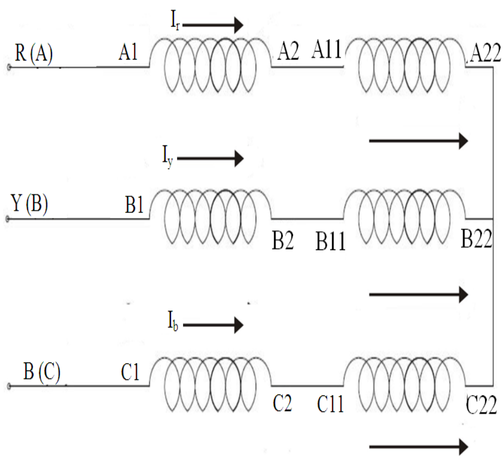


Figure 12: Star-series type II (YS2) Connection.

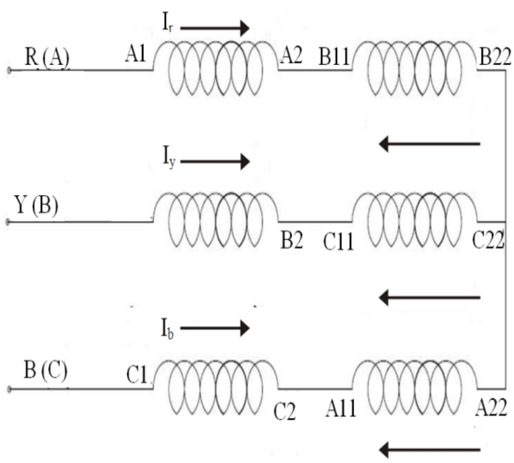


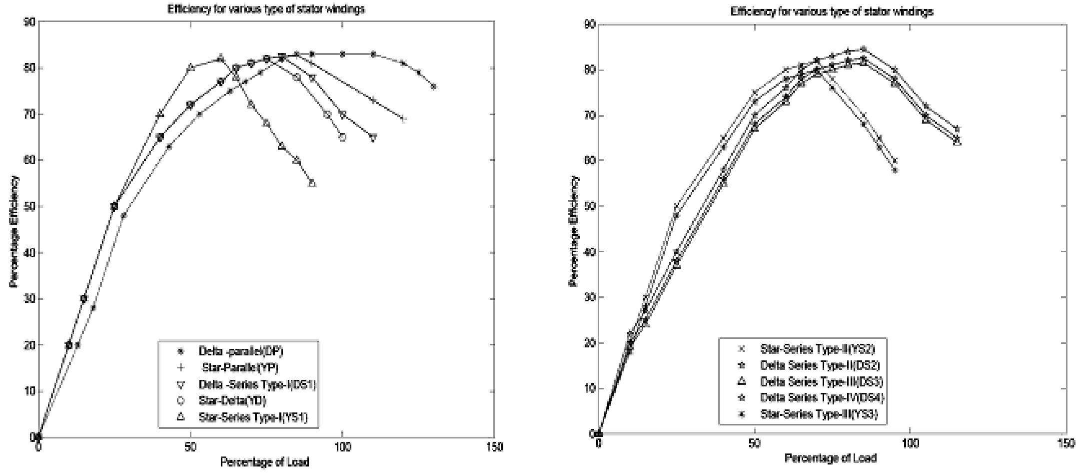
Figure 13: Star-series type III (YS3) Connection.

Table 3: Comparison of different connection for Normal Design and Optimal Design

Winding connections	Load in %	Normal design		Optimal design	
		Efficiency	Power factor	Efficiency	Power factor
YS1	0-10	84	0.8	87.30	0.89
YS2	10-12	84.5	0.8	87.42	0.88
YS3	12-15	85	0.8	88.02	0.91
YD	15-23	87	0.78	90.21	0.94
DS1	23-27	89	0.76	91.23	0.92
DS2	27-32	89	0.77	91.42	0.90
DS3	32-35	89	0.75	91.51	0.92
DS4	35-38	89	0.76	91.89	0.91
YP	38-50	90	0.8	92.43	0.90
DP	50-100	90	0.8	95.25	0.96

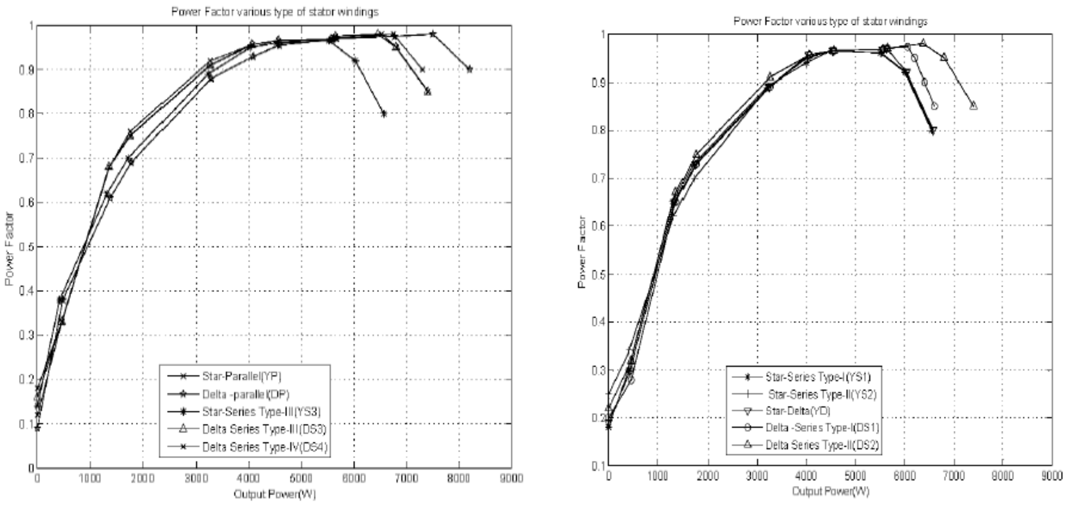
Table 4: Comparison for Normal Design and Optimal Design

Description	Normal Design	Optimal Design
Diameter of Stator in m	0.387	0.364
Length of Stator in m	0.563	0.543
Ratio L/τ	1.342	1.495
Outer diameter of stator in m	0.448	0.418
Stack length to pole pitch ratio	1.325	1.428
Stator depth to width ratio	4.055	4.100
Stator core depth in mm	4.238	4.475
Average air gap flux density (Wb / mm^2)	0.468	0.482
Stator current density A/mm^2	4.570	4.600
Rotor current density A/mm^2	7.760	7.680
Stator Iron Losses (W_{SIL}) in watts	287.930	191.750
Stator Copper Loss (W_{SCL}) in watts	287.93	191.75
Rotor Copper Loss (W_{RCL}) in watts	123.720	72.840
Maximum Temperature rise in centigrade	77.27	72.84
Total Loss in watts	217.924	181.044
Full Load Efficiency (η)	*85.97*	*92.32*
Full Load Power Factor (P.F)	0.8	0.91



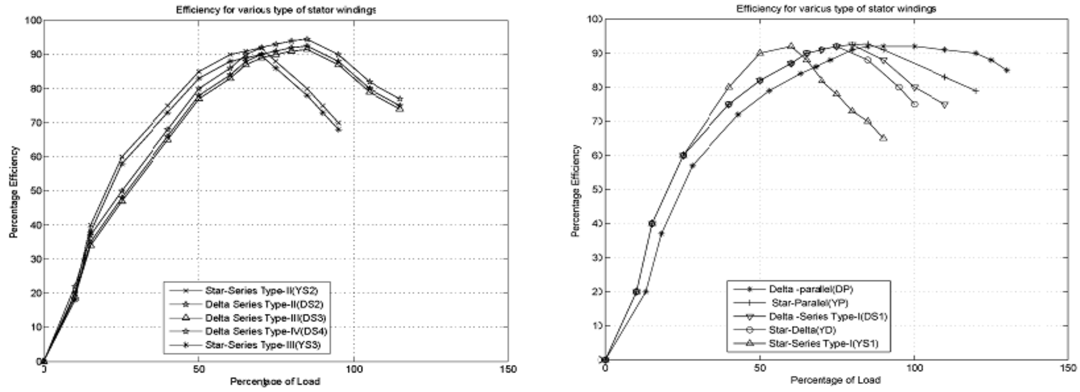
(a) (b).

Figure 14: Efficiency as a function of percentage load for: (a) DP, YP, DS1, YD and YS1 connections. (b) YS2, DS2, DS3, DS4 and YS3 connections.



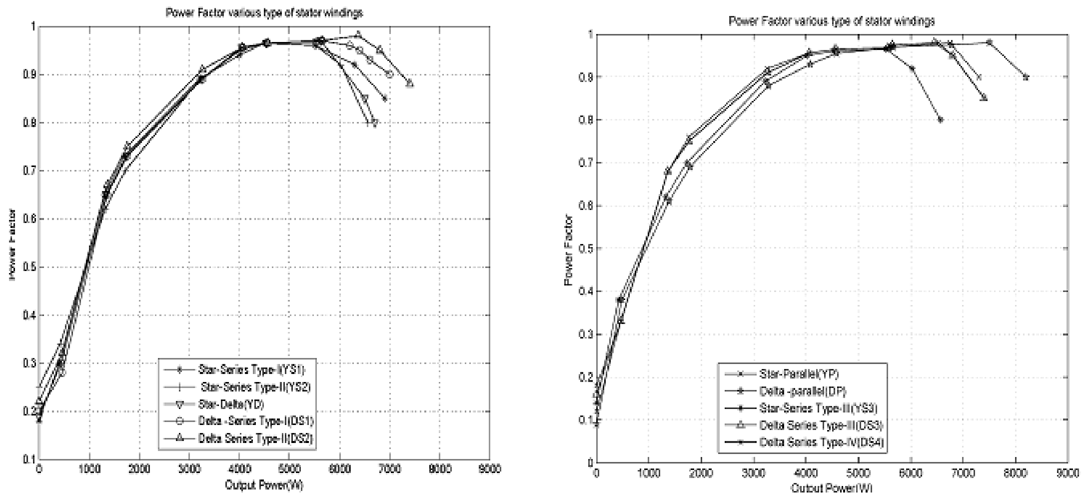
(a). (b).

Figure 15: Power Factor as a function of output power for:(a) YP,DP,YS3,DS3 and DS4 connections.(b) YS1,YS2,YD,DS1 and DS2 connections.



(a). (b).

Figure 16: Efficiency as a function of percentage load for: (a) YS2, DS2, DS3, DS4 and YS3 connections. (b) DP, YP, DS1, YD and YS1 connections.



(a). (b).

Figure 17: Power Factor as a function of output power for:(a) YS1,YS2,YD,DS1 and DS2 connections.(b) YP,DP,YS3,DS3 and DS4 connections.

Acknowledgment

The authors wish to thank M/s RVS College of Engineering and Technology, Coimbatore for providing infrastructure facility to perfom the presented work.

List of symbols

P_0 Power in kW

W_{SCL} Stator Copper Loss in watts

W_{RCL}	Rotor Copper Loss in watts
W_{SIL}	Stator Iron Losses in watts
W_F	Friction losses in watts
I_{ph}	Phase Current in Amps
R_s	Stator Resistance in ohms
E_{ph}	Voltage per phase in volts
f	Frequency in Hz
K_W	Winding factor
L	Length of the core in m (stator)
D	Diameter of stator in m
P	No. of poles
I_b	Rotor bar current in Amps
S_1	No. of stator slots
S_2	No. of rotor slots
ρ_r	Resistivity of material of bars and rings (constant -0.021 ohms/ m and mm^2)
T_{ph}	Turns per phase
Φ	Flux per pole in Wb
τ	Pole pitch in mm
S	kVA rating of the machine
η	Efficiency of the machine
L_r	Length of rotor core in m
a_b	Rotor bar area m^2
a_{sr}	Area of the rotor slots
τ_c	Cooling coefficient
d_{sr}	Depth of the rotor slot in mm
l_g	Radial Air Gap Length in m
D_e	Mean end ring diameter in mm
a_{sr}	Rotor slot area m^2
d_{ss}	Depth of the stator slot in mm
W_t	Weight of the stator teeth
W_c	Weight of the stator core
W_{tk}	losses in stator tooth portion (W/kg),
W_{ck}	losses in stator core portion (W/kg).

x_1 Ampere conductors/m

x_2 Stack length / pole pitch ratio

x_3 Stator slot depth to width ratio

x_4 Stator core depth in mm

x_5 Average air gap flux density (wb/m^2)

x_6 Stator current density (A/mm^2)

x_7 Rotor current density (A/mm^2)

References

[1] C. Kral, A. Haumer and C. Grabner: “Consistent Induction Motor Parameters for the Calculation of Partial Load Efficiencies”, Proc. of the World Congress Eng., I: 1-3, 2009.

[2] D. Ismail, K. Anayet and N. Indra, M. Dina M.M. Ahmad, and A. Rosnazri, “Design Guidelines For Recycling AC Induction Motors,” American Journal of Applied Sciences, Science Publications, Vol.3 (10), pp. 2054-2058, 2006.

[3] E. El-kholy, “High performance induction motor drive based on adaptive variable structure control,” J. Electr. Eng., Vol. 56, pp.64-70, 2005.

[4] F. J. T. E. Ferreira and Aníbal T. de Almeida, “Novel Multiflux Level, Three-phase, Squirrel-cage Induction Motor for Efficiency and Power Factor Maximization,” IEEE Trans. Energy Conversion, Vol. 23, 2008.

[5] Fernando J. T. E. Ferreiral and Mihail V. Cistelecan, “ Simulating Multi-Connection, Three-Phase, SquirrelCage,Induction Motors by Means of Changing the Per-Phase Equivalent Circuit Parameters” Proc. of the International Conference on Electrical Machines,2008.

[6] G. Liuzzi, S. Lucidi, V. Piccialli and M. Villani, “Design of induction motors using a mixed-variable approach,” Computational Management Science, Springer-Verlag, 2005.

[7] H. S. John, J. D. Kueck, M. Olszewski, D. Casada, P. J. Otaduy and L. M. Tolbert: “Comparison of Induction Motor Field Efficiency Evaluation Methods”, IEEE Tran. Industry Appl., Vol.34.1998.

[8] K. Ranjith Kumar, D.Sakthibala and S.Palaniswami, “Efficiency Optimization of Induction Motor Drive using Soft Computing Techniques,” Inter. Journal of Computer Applications, Vol. 3, No.1, pp. 6-12, June 2010.

[9] Kentli, “A survey on design optimization studies of induction motors during the last decade,” J. Electrical Electronics Eng., Vol. 2, pp.969-975.2009.

[10] O. Muravlev and O. Muravleva, “Energetic Parameters of Induction Motors as the Basis of Energy Saving in a Variable Speed Drive,” Electrical Power Quality and Utilization, Eugenia Vekhter Tomsk Polytechnic Univ., Russia 2005.

[11] Piotr Gnacinski, "Windings temperature and loss of life of an induction machine under voltage unbalance combined with over- or under voltages," IEEE Trans. Energy Conversion, Vol.23, pp.63-371, 2008.

[12] R.Subramanian, S.N. Sivanandam and C. Vimalarani, "An optimization of design for s4-duty induction motor using constraints normalization based violation technique," J. Comp. Sci., 6: 107-111, 2010.

[13] R.Thangaraj, T.R. Chelliah, P. Bouvry, M. Pant and A. Abraham, "Optimal design of induction motor for a spinning machine using population based metaheuristics," Proc. of the Inter. Conf. on Computer Information Systems Industrial Management Applications, 2010.

[14] S.Manoharan, N. Devarajan and S. Deivasahayam, "Review on efficiency improvement in squirrel cage induction motor by using DCR technology," J. Electr. Eng., Vol. 60, pp.227-236, 2009.

[15] S.Sornmuang, and S. Sujitjorn, "GA-Based PIDA control design optimization with an application to ac motor speed control," Int. J. Math. Comp. Sim., Vol. 3, pp.67-80, 2010.