Performance Improvement of Induction Motor by using Particle Swarm Optimization

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.Abstract: *The squirrel-cage Induction motors (SCIMs) are widely used in most of the industrial and commercial applications because of their rugged low cost constriction. About 80% of induction motor plays a vital role to increase the economy of the developing countries. However when oversized, most of the motor operate with low efficiency and power factor (PF). The average energy consumed by a motor during its life cycle is about 40-80 times of the initial cost. It is very essential to maintain the efficiency and PF of the motor within the desired level during variable load condition. In this paper a design optimization method is proposed where the optimal design of multi flux stator winding is shown to improve motor efficiency and PF in a wide load range is proposed using* ***P****article* ***S****warm* ***O****ptimization (PSO) algorithm and finally to achieve optimal design parameters of SCIM which produce maximum efficiency, power factor and with less losses. The implementation of this algorithm is more efficient and also it can be handling effectively. The important of this work is highlighted comparing with resent research and the results are discussed.*

Keywords: *Efficiency, Induction Motor, Multi-Flux, Optimization, PSO, Power factor.*

1. Introduction

Three phase squirrel-cage induction motors (SCIMs) are widely used for various industrial and domestic applications such as pump drives, variable speed drives etc. More than 80% of the electrical motors are three-phase SCIMs because of low production costs, more reliability and other features. Induction motors are the main energy consuming devices in industries contributing to more than 80% of electromechanical energy consumption. Most of the large sized three-phase SCIMs operate with low efficiency [2,3]and low power factor[4], which are the most important causes of poor power factor in industrial installations. Therefore in the SCIMs design optimization with improved energy efficiency and power factor are the key issues of the day [5,6].The PSO optimization algorithm considered to optimize the induction motor.

For the design optimization of SCIMs, the most frequently used objective functions are the motor efficiency and power factor [5,19,20,]. Several techniques such as Genetic Algorithm,Neural Networks [21] 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 PSO is a modern, evolutionary, population-based, search algorithm, characterized as conceptually simple, easy to implement and computationally efficient [21, 23, 24].PSO has also been found to be robust in solving problems featuring nonlinearity, nondifferentiability and high dimensionality.

The PSO, first introduced by Kennedy and Eberhart [7] is a flexible, robust, population based stochastic search/optimization algorithm with inherent parallelism. In recent years this method has gained popularity over its competitors and is increasingly gaining acceptance for solving many optimization problems [8], due to its simplicity, superior convergence characteristics and high solution quality. The PSO parameters are employed in this paper for solving the induction motor design optimization problem considered in terms of maximizing the efficiency and PF. Finally, the PSO algorithm has been optimized the design parameters and it was compared with conventional design methods [9, 10].

In this paper, a multiple stator winding induction motor is proposed with different possible winding connections [25, 26], which allow the magnetizing flux to be regulated up to ten different levels. Alternatively, for the same magnetizing flux of induction motor can operate up to ten different voltage levels, in which both the efficiency and power factor can be maximized as a function of load. The application of the proposed design in such motors can lead to significant energy savings and efficiency [5], a power factor improvement. This novel method for multi objective design and optimization can be of great value in industry due to its flexibility, particularly, for variable load applications in which significant energy savings can be obtained by PSO based design using multi-flux level [1, 15] (multiple stator winding) problem as proposed for induction motor and obtained optimal parameters are compared with conventionally designed induction motor.

2. Problem Formulation

The problem in the induction motor design is to select an appropriate combination of the design variables [11] 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[12]. Therefore the number of design variables selection is important in the motor design optimization[13]. 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$X(X_1, X_2, \ldots, X_n)$, such that $J(X)$ is a maximum subject to $g_j(X) \geq 0$, $j = 1, 2, \ldots$ mand $xL_i \leq xL_i \leq xU_{ii} = 1, 2, \ldots n$, 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[14,15], it depends on the design variables $X = (X_1, X_2, X_3 \ldots Xn)$, the corresponding optimization problem can be written as:

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

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

(a).Ampere conductors, (m) - X_1 (b). Ratio of stack length to pole pitch- X_2, (c).Stator slot depth to width ratio - X_3 ,(d).Stator core depth (mm) - X_4 (e) Average air gap flux densities (T) - X_5(f) Stator current densities (A/mm^2) - X_6 (g) 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 Loss, d). Friction Loss, e).Full Load Efficiency, f).Stator Temperature Rise, g).Maximum Rotor Temperature Rise, h).Full Load Slip, i).Starting to Full-Load

Torque Ratio, j). Maximum to Full-Load Torque ratio, k).Starting to Full-Load Current Ratio, l). Full Load Power Factor.

The design and optimization of SCIM requires a particular attention in the choice of the objective functionthat usually concerns economic or performance features[16,17]. 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:

$$W_{SCL} = 3 \cdot I_{ph}^2 \cdot R_s \ , \qquad (1)$$

where I_{ph} is the phase current (A) and R_S is the equivalent per-phase stator resistance (Ω).

The Rotor Copper Loss are given by:

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

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

The Stator Iron Loss are given by:

$$W_{SIL} = W_t \cdot W_{tk} + W_c \cdot W_{ck} \ , \qquad (3)$$

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:

$$, \eta = \frac{1000 \ P_o}{1000 \ P_o + W_{SCL} + W_{RCL} + W_{SIL} + W_F} \times 100 \qquad (4)$$

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 [18].The temperature rise is directly proportional to the heat developed due to losses and indirectly proportional to cooling surface area, according to (5):

$$\theta_{ms} = \frac{\tau_c (SCL + SIL)}{S_s} \ , \qquad (5)$$

where the cooling coefficient is:

$$\text{Cooling coefficicent} \tau_c = \frac{0.03 - 0.05}{1 + 0.1u} u = \frac{2\pi f D}{P} \ , \qquad (6)$$

and the total effective cooling surface area is:

$$S_s = S_i (1 + 0.1u) + S_0 \ , \qquad (7)$$

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.

The calculations of rotor temperature rise are based on similar considerations as that of stator temperature rise. The cooling surface is calculated from the rotor dimension. Thus the full load rotor temperature rise is calculated as

$$\theta_{mr} = \frac{\tau_c W_{RCL}}{S_r} \tag{8}$$

Where, S_r is total rotor cooling surface area
The full load slip is given by:

$$s = \frac{W_{RCL}}{1000P_o + W_{RCL} + W_F} \tag{9}$$

The summation of friction and windage losses is assumed to be 1%

Starting torque to full load torque ratio is given by:

$$\text{Ratio}, = \frac{T_{st}}{T_{fl}} \ , \tag{10}$$

Where T_{st} is starting torque, T_{fl} is full load torque

Maximum torque to full load torque ratio is given by:

$$\text{Ratio}, = \frac{T_{\max}}{T_{fl}} , \tag{11}$$

Where T_{max} is maximum Torque
Starting to Full Load Current Ratio is given by:

$$\text{Ratio}, = \frac{I_0}{I_{ph}} , \tag{12}$$

where I_0 is total no-load current in amps, I_{ph} is phase current in amps

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Full Load Power Factor is given by:

$$PF = \frac{R_s + G_4}{\sqrt{\{(R_s + G_4)^2 + (X_5 + G_5)^2\}}} \tag{13}$$

Whereas R_S is stator resistance in ohms, X_5 is average air gap flux density (wb / m^2), G_4, G_5 is magnetizing constants

Each design variables are correlated with constraints as follows.

There are two basic expressions needed for deriving the design formulae of induction or any electric motors. They are: E.M.F and output equations. The derivations in present work of optimal design pertain to induction motors in terms of the variables chosen [14], [15].

The E.M.F equation for a motor is given by

$$E_{ph} = 4.44 K_w f \phi \, T_{ph} \tag{14}$$

The output equation for a three-phase induction motor is written as

$$S = 3E_{ph} I_{ph} * 10^{-3} \ \text{KVA} \tag{15}$$

The term specific electric loading is defined as the number of r.m.s ampere conductors per unit length of gap surface circumference. The present work considers ampere conductors per meter as a variable (x_1) and can be expressed as

$$x_1 = \frac{6T_{ph} I_{ph}}{\pi D} \tag{16}$$

The term specific magnetic loading is the average magnetic flux density over the whole surface of the air-gap and can be expressed as follows. It is also considered as a variable in the present work.

$$x_5 = \frac{\phi p}{\pi D L} \tag{17}$$

Use of expressions (A1) – (A4), the volume of the motor is

$$D^2 L = \frac{1000SP}{2.22 K_w \pi^2 f x_1 x_5} \ \text{m}^3 \tag{18}$$

The separation of main dimensions D and L can be done from the expression (5) by approximately choosing the ratio of core length to pole pitch, which in the present case is considered as a variable. Thus,

$$D = \frac{1}{\pi} \sqrt[3]{\frac{1000SP^2}{2.22 K_w f x_1 x_2 x_5}} \tag{19}$$

and

$$L = x_2 \frac{\pi D}{p} = x_2 Y \quad (20)$$

The calculation of net length of the core which considers the stacking factor for sheets as well as the allowance for the ventilating ducts is given by

$$L_i = K_i (L - 0.001 n_d w_d) \quad (21)$$

Total number of conductors per slot can be derived from the equations (14) – (17) which is always an integer and are to be rounded off)

$$Z_{1s} = \frac{6E_{ph}}{4.44 f K_w S_1 Y^2 x_2 x_5} \quad (22)$$

The area of stator slot can be calculated with the assigned slot fullness factor as

$$a_{ss} = \frac{1000S}{2.22 K_w f Y^2 S_f x_2 x_5 x_6} \quad (23)$$

the stator slot depth to width ratio facilitates the separation of slot area into depth and width. Hence the depth of slot can be expressed as

$$d_{ss} = \sqrt{\frac{1000 S x_3}{2.22 K_w f Y^2 S_1 S_f x_2 x_5 x_6}} \quad (24)$$

Stator core outside diameter can be expressed as

$$OD = D + 0.002 D_{ss} + 0.002 x_4 \quad (25)$$

Using the equations (15), (16), (17), the rotor bar current and area can be expressed with the assumption that the rotor ampere turns at full load are 85% of stator ampere turns at full load as

$$I_b = \frac{850S}{2.22 K_w f Y^2 S_2 x_2 x_5} \quad (26)$$

and

$$a_b = \frac{382.88S}{K_w f Y^2 S_2 x_2 x_5 x_7} \quad (27)$$

Cage induction motors normally use the rotors with skewed slots (normally by one slot pitch) and give better performance. The length of the bar is slightly more than the core length, usually by 0.03m. The rotor slot area with the assigned value of rotor slot fullness factor can be calculated as

$$a_{sr} = \frac{a_b}{S_{fr}} \quad (28)$$

for cast iron $S_{fr} = 1$

The depth and width of the rotor slots can be expressed in terms of stator slot depth

$$d_{sr} = \frac{a_{sr} S_2 x_3}{S_1 d_{ss}} \quad (29)$$

$$W_{sr} = \frac{S_1 d_{ss}}{S_2 x_3} \quad (30)$$

The mean end ring diameter can be expressed as

$$D_e = D - 0.002 I_g - 0.002 d_{sr} \quad (31)$$

The rotor end ring current in terms of rotor bar current is given by

$$I_e = \frac{S_2 I_b}{\pi p} \quad (32)$$

End ring cross section (in mm^2) can be calculated as

$$a_e = \frac{I_e}{x_7} = \frac{S_2 a_b}{\pi p} \quad (33)$$

With the assumption of same core flux density on stator and rotor side the depth of stator and rotor core behind the slot will remain same; the rotor inner diameter can be expressed as

$$ID = D - 0.002 l_g - 0.002 d_{sr} - 0.002 x_4 \quad (34)$$

3. Design and Optimization

3.1 Design and Optimization of Multiple Flux Stators Winding Using PSO

In this design, the PSO is used to find a set of design variables which ensure that the function F(X) has a minimum value and all the constraints are satisfied. The penalty-parameter-less approach is used to optimize the design. Hence the optimal design problem reduces to obtaining the design variables which correspond to the minimum value of an unconstrained function J(X). The procedure for optimal design of induction motor is as follows:

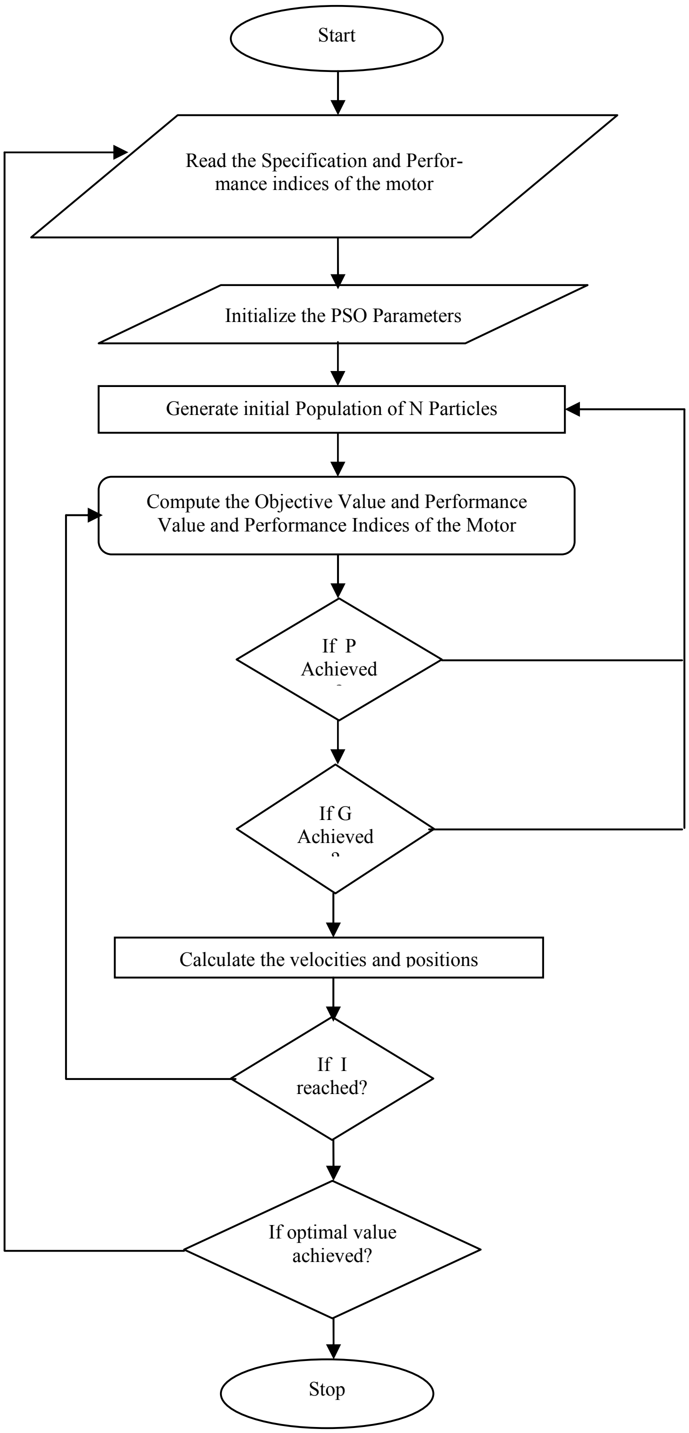

Fig.1 Flowchart for PSO Based Optimization Process

1) *Read specifications* and performance indices of the motor;

2) *Initialize* PSO parameters such as Wmax, Wmin, C1, C2 and Itermax;

3) *Generate initial population* of N particles (design variables) with random positions and velocities;

4) *Compute* objective value and performance indices of the motor;

5) *Calculate fitness :* Evaluate the fitness value of current particle;

6) *Update personal best:* Compare the fitness value of each particle with its $_{Pbests.}$ If the current value is better than $_{Pbest,}$ then set $_{Pbest}$value to the current value;

7) *Update global best*: Compare the fitness value of each particle with $_{Gbest.}$ If the current value is better than $_{Gbest,}$ set $_{Gbest}$to the current particle's value;

8) *Update velocities*: Calculate velocities.

9) *Update positions*: Calculate positions.

10) *Return* to step (4) until the current iteration reaches the maximum iteration number;

11) *Output* the optimal design variables of the motor in the last iteration.

3.2. Different Types of Stator Winding Connections

Three phase squirrel-cage induction motor has six numbers of input terminals. So, it can be possible to connect either star or delta connection mode but each phase energized two sets of turns in the stator winding. These two sets of turns can be connected either in series or parallel with the input supply to cause variation of either star to delta or delta to star connection mode. What can he achieved easily various level of flux at required loads. These are the following different possibilities of stator winding connections are presented below as shown in figures 2 to 11.

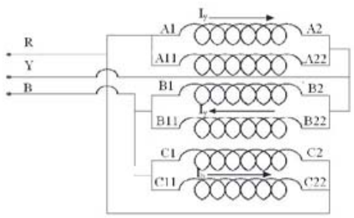

Fig. 2: Delta Parallel (DP) Connection.

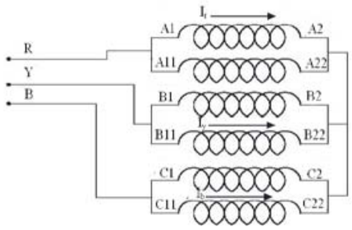

Fig. 3: Star-Parallel (YP) Connection.

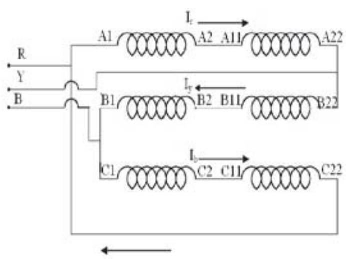

Fig. 4: Delta-series type I (DS1) Connection.

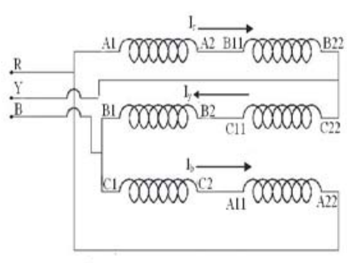

Fig. 5: Delta-series type II (DS2) Connection.

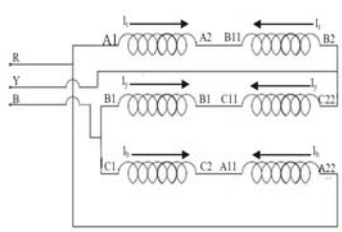

Fig. 6: Delta-series type III (DS3) Connection.

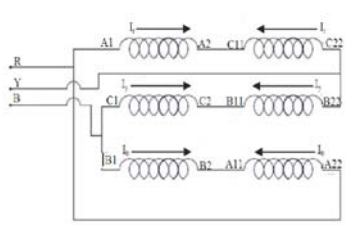

Fig. 7: Delta-series type IV (DS4) Connection.

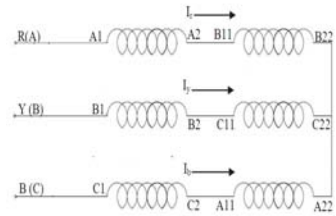

Fig. 8: Star Delta (YD) Connection.

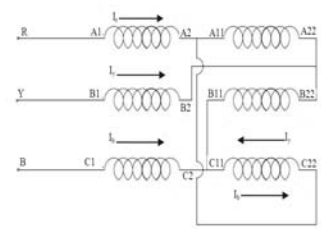

Fig. 9: Star-series type I (YS1) Connection.

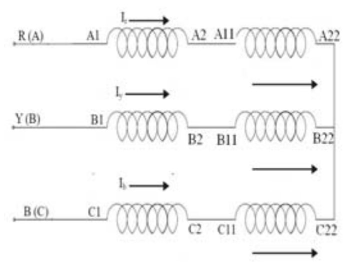

Fig. 10: Star-series type II (YS2) Connection.

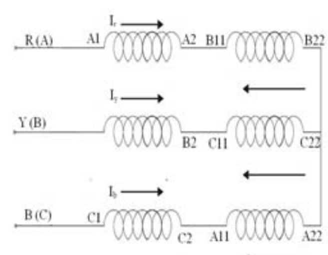

Fig. 11: Star-series type III (YS3) Connection

4. Simulation Results and Discussion

4.1 Conventional Design

In Fig.12.(a) & (b). shows a conventional design of percentage of efficiency Vs percentage of load for various types of stator winding and Fig.13.(a) & (b). depicts a power factor Vs output power load for various types of stator winding. The motor efficiency and factor are considered stator winding connection modes. The intersection points are identified. The YS2 is connection was not considered in those zones because it does not contribute to the improvement of the resultant motor efficiency curve.

4.2. Optimal Design

In Fig. 14. .(a) & (b). shows exhibits optimal design results for percentage of efficiency Vs percentage of load for various types of stator winding (Case-1) and Fig.15 .(a) & (b). shows power factor Vs output power load for various types of stator winding (Case-1).

In Fig. 16.(a) & (b). shows exhibits optimal design results for percentage of efficiency Vs percentage of load for various types of stator winding (Case-2) and Fig.17.(a) & (b). shows power factor Vs output power load for various types of stator winding (Case-2).

In Table–I a comparison for conventional design and optimal design in made. The two different cases are considered in the three phase induction motor design:Case 1. The power loss effect is not included in the objective function, Case 2. The power loss effect is included in the objective function.

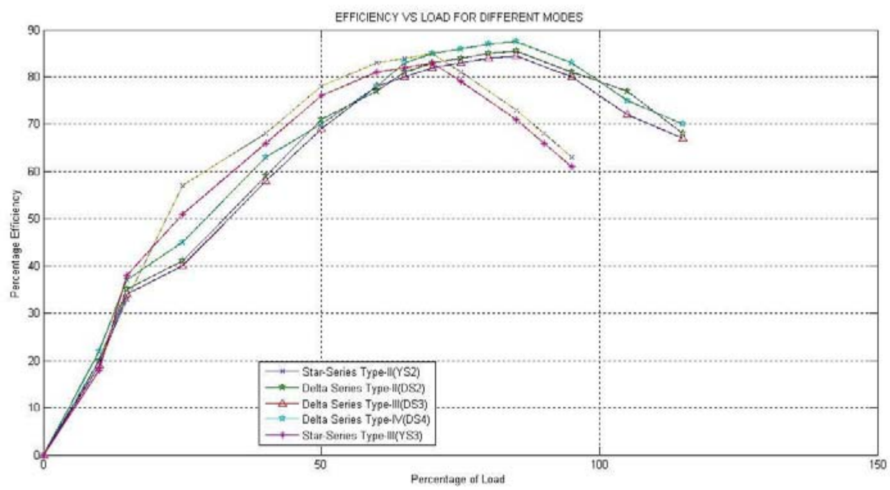

Fig. 12.(a) Percentage of Efficiency Vs percentage of load for YS2, DS2, DS3, DS4 and YS3 connections.

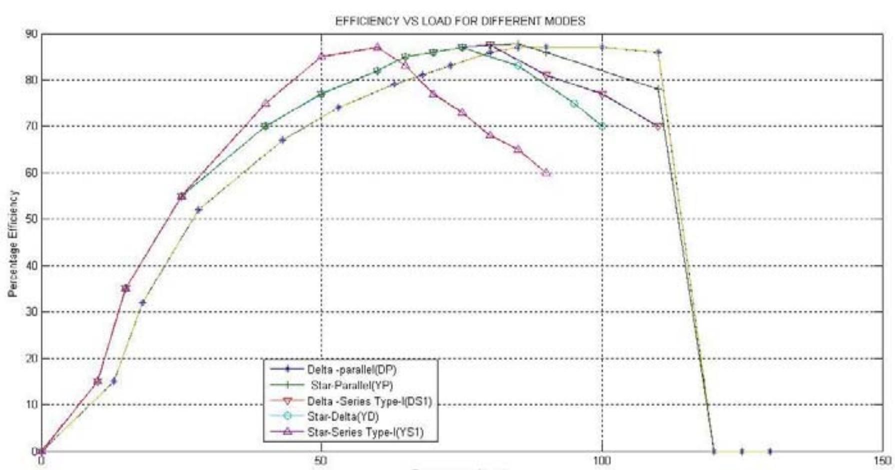

Fig. 12.(b) Percentage of Efficiency Vs percentage of load for DP, YP, DS1, YD and YS1connections.

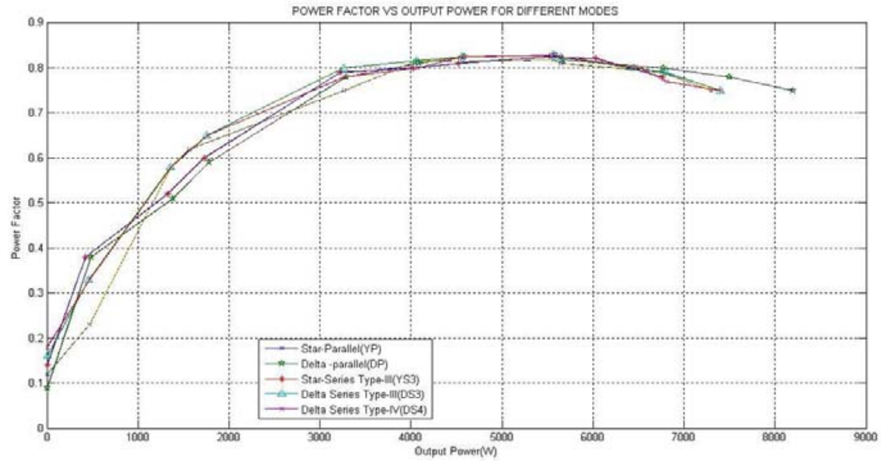

Fig. 13.(a) Power factor Vs Output power load for: YP, DP, YS3, DS3 and DS4 connections.

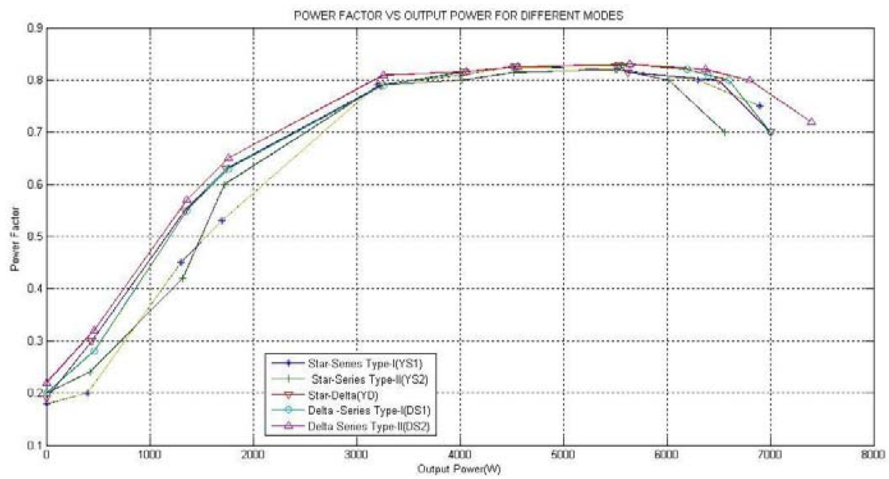

Fig. 13.(b) Power factor Vs Output power load for: YS1,YS2,YD,DS1and DS2 connections.

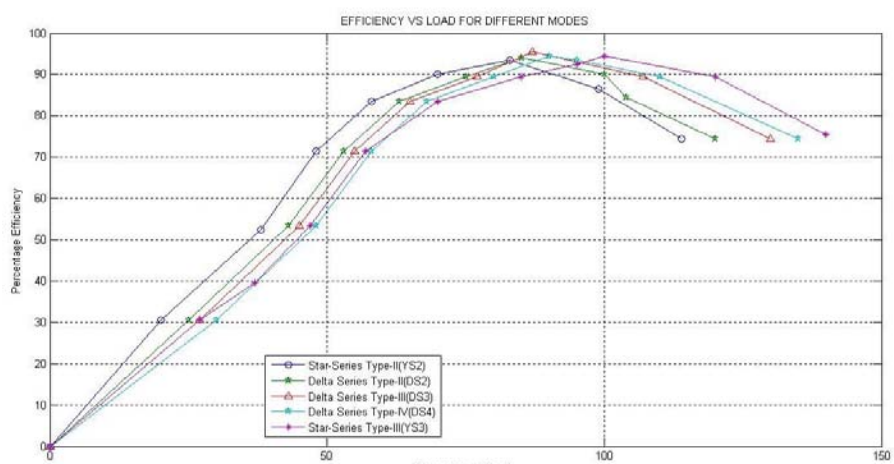

Fig. 14.(a) Percentage of Efficiency Vs Percentage of load for YS2, DS2, DS3, DS4 and YS3 connections.

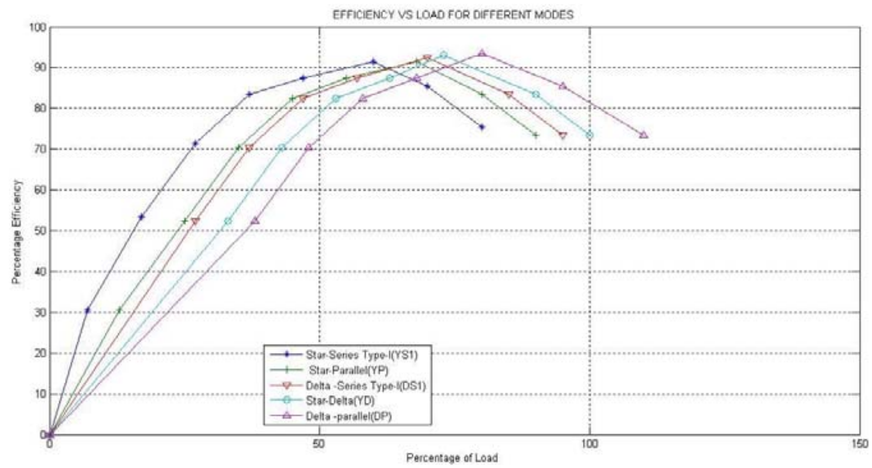

Fig. 14.(b) Percentage of Efficiency Vs Percentage of load for YS1, YP, DS1, YS1, YD and DP connections.

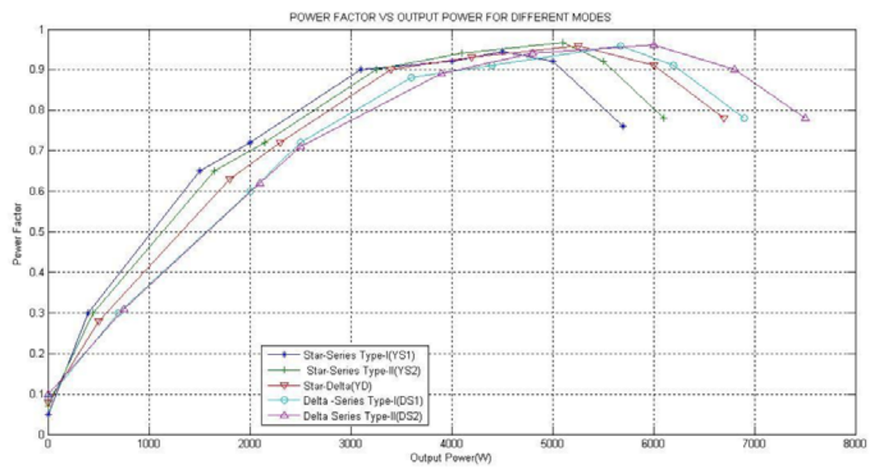

Fig.15.(a) Power factor Vs Output Power load for YS1,YS2, YD,DS1 and DS2connections.

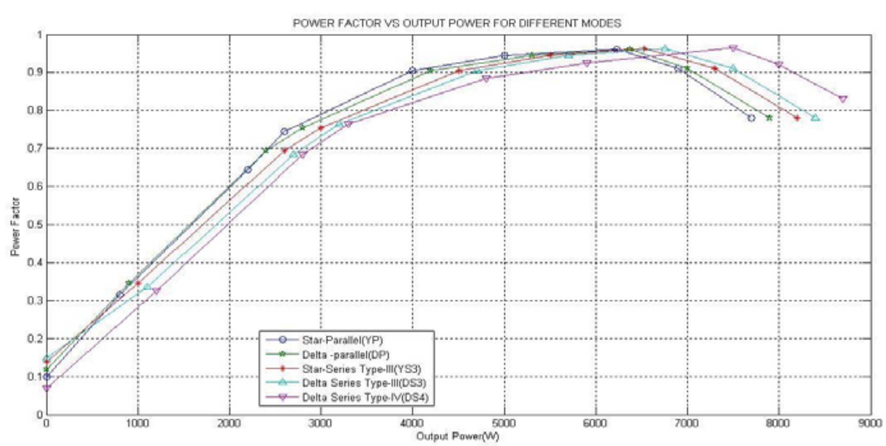

Fig.15.(b) Power factor Vs Output Power load for YP,DP, YS3,DS3 and DS4 connections.

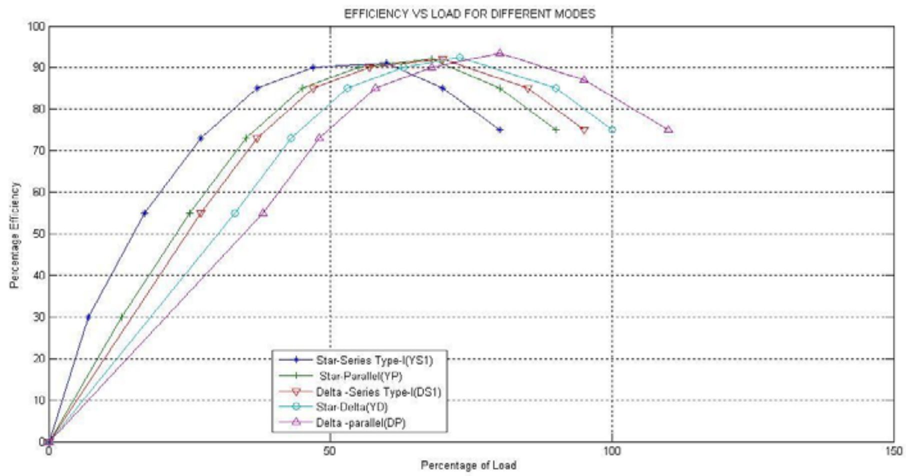

Fig. 16.(a) Percentage of Efficiency Vs Percentage of load for YS1, YP, DS1, YD and DP Connections

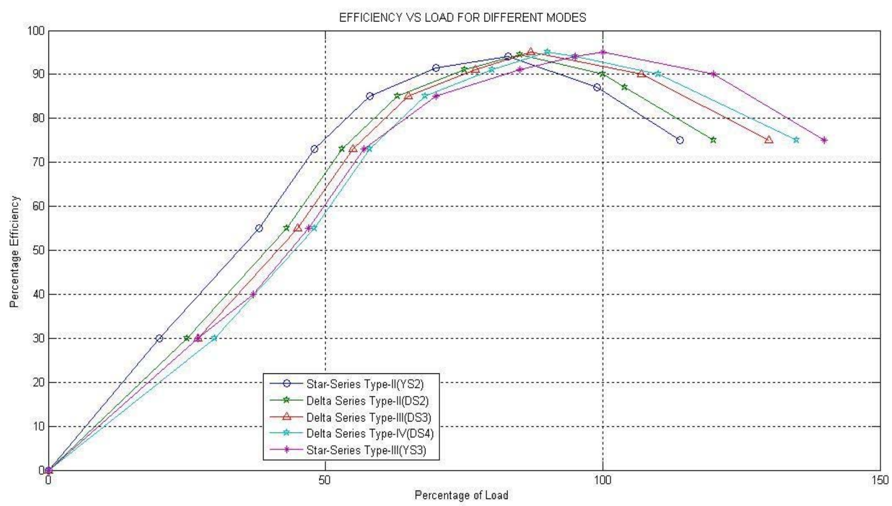

Fig. 16.(b) Percentage of Efficiency Vs Percentage of load for: YS2, DS2, DS3, DS4 and YS3 connections.

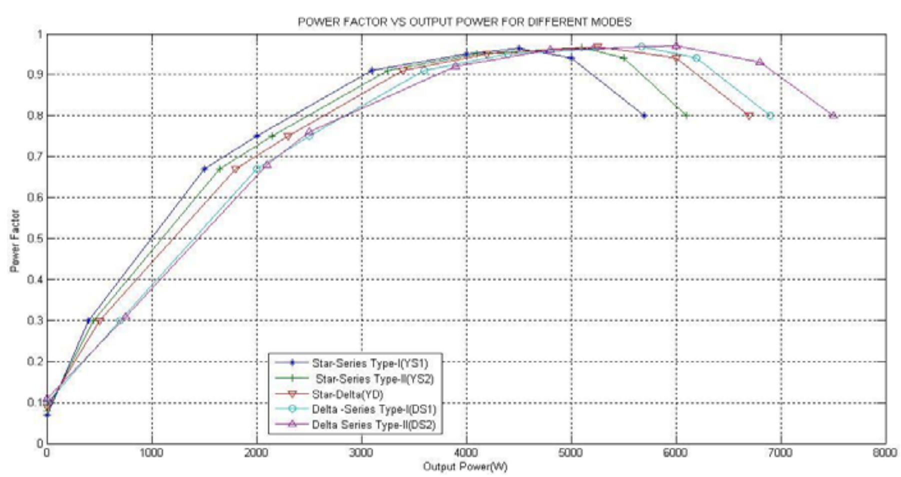

Fig. 17.(a). Power factor Vs Output Power for YS1,YS2, YD, DS1 and DS2 connections.

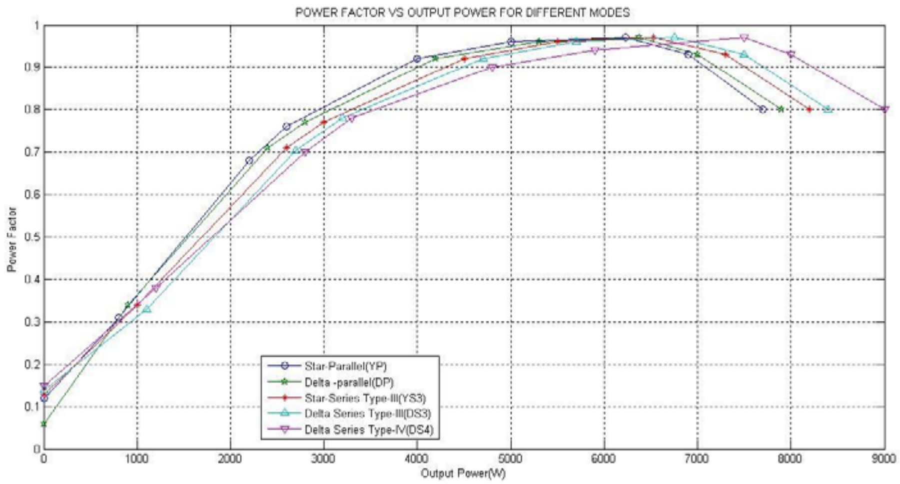

Fig. 17.(b). Power factor Vs Output Power for YP, DP, YS3,DS3 and DS4 connections.

TABLE I

Comparison for conventional Design and Optimal Design.

Sl. No	Description	Normal design	Optimal design	
			Case-1	Case-2
1	**Full-Load Efficiency (%)**	**84.176**	**95.425**	**93.427**
2.	**Full-Load Power Factor**	**0.8432**	**0.961**	**0.943**
3.	Maximum Stator Temperature Rise in C°	76.437	58.923	58.867
4.	Maximum Rotor Temperature Rise in C°	76.437	58.832	58.657
5.	Maximum to Full-Load Torque ratio	2.735	2.931	2.842
6.	Starting to Full-Load Torque Ratio	1.52	1.732	1.640
7.	Starting to Full-Load Current Ratio	4.425	5.100	4.98
8.	Length of Stator in m	0.563	0.529	0.531
9.	Diameter of Stator in m	0.387	0.359	0.360
10.	Outer Diameter of Stator in m	0.448	0.539	0.540
11.	Ratio L/τ	1.342	1.529	1.497
12	Stack Length to Pole Pitch Ratio	1.325	3.197	3.028
13	Stator Depth to Width ratio	4.055	4.237	4.198
14	Stator Core Depth in mm	4.239	4.683	4.599
15	Average Air gap Flux Density in wb / mm^2	0.468	3.193	3.098
16.	Stator Winding Current Density in A/ mm^2	4.57	7.734	7.834
17.	Rotor Winding Current Density in A/ mm^2	7.76	7.734	7.834
18.	Stator Iron Loss in watts	273.450	-	1.859
19.	Rotor Copper Loss in watts	126.720	-	36.231
20.	Stator Copper Loss in watts	287.930	-	122.876
21.	Ampere Conductors per meter	18500	18200	18300

5. Conclusion

A multiple stator winding incorporating a three-phase stator winding with two sets of turns is proposed, and also the connection modes are analyzed. The multiple stator winding can be used as a spare motor up to ten different nominal power levels and, in fact, it can operate as a high-efficiency motor for lower power levels. If necessary, at rated frequency for the nominal power, it can be used as a multi-voltage motor and can be fed with different line-to-line voltage levels without efficiency and power factor. The described concept can be used in motors with wide load variations and with long low load operating periods, in which the magnetizing flux regulation can lead to significant energy savings and power factor, efficiency improvements, as it has been optimally designed by PSO approach. An optimization technique based on PSO has been applied to the design of 7.5 kW three-phase induction motor. A package program that analyzes and optimizes induction motors in multi flux levels of stator windings and performance of the design has been developed. Comparison of the final optimum designs is made with the existing design. Finally, it is found that optimal designs produce larger efficiency, power factor and less loss of three phase squirrel cage induction motor.

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