CHAPTER 5

DESIGN OF MULTIFLUX CONNECTION INDUCTION MOTOR USING EXTREME LEARNING MACHINE ALGORITHM

5.1 INTRODUCTION

In general, the learning speed of the Feed Forward Neural Networks is far slower than required and it has been a major bottle neck in their applications for the past decades (Kentli 2009). Two key reasons are that the slow gradient-based learning algorithms are extensively used to train Neural Networks and all the parameters of the networks are tuned iteratively by using such learning algorithms. Unlike these conventional implementations, a new learning algorithm called Extreme Learning Machine Algorithm (ELMA) is proposed for Single-hidden Layer Feed Forward Neural networks (SLFNs) which randomly chooses hidden nodes and analytically determines the output weights of SLFNs. (Guang-Bin Huang 2006).

This algorithm tends to provide a good generalization performance at an extremely fast learning speed. The experimental results based on a few artificial and real bench mark function approximations and classification problems including very large complex applications show that the new algorithm can produce good generalization performance in most cases and can learn thousands of times faster than the conventional popular learning algorithms for Feed Forward Neural Networks.
In ELMA, all the parameters of multi-layer neural networks based on gradient descent-based learning methods need to be learned. Many iterative learning steps are usually required to obtain a better learning performance. So, gradient descent based learning methods are slow due to the improper learning steps or may easily converge to local minimums. Finally, the ELMA based design values and it was compared with conventional design methods. However, the ELMA optimization is being tailored to exploit the structure of the optimization model (Guang-Bin Huang 2006). Robustness and ill-conditioning are not big issues, since the algorithm needs to be effective only for a narrow class of functions and constraints and high accuracy solutions (Kral 2009). To summarize, the desirable properties of an Extreme Machine Learning Algorithm are follows,

- Good generalization.
- Scalability to large problems.
- Good performance in practice in term of execution times and memory requirements.
- Simple and easy implementation of the algorithm.
- Exploitation of problem structure.
- Fast convergence to an approximate solution
- Robustness and numerical stability for class of machine learning models
- Theoretically known convergence and complexity.

Feed Forward Neural Networks have been extensively used in many fields due to their ability to approximate complex nonlinear mappings directly from the input samples and to provide models for a large class of natural and artificial phenomena that are difficult to handle using classical parametric
techniques. On the other hand, they lacks faster learning algorithms for Neural Networks. The traditional learning algorithms are usually far slower than required. It is not surprising to see that it may take several hours, several days, or even more time to train neural networks by using traditional methods (Bennett 2006). From a mathematical point of view, research on the approximation capabilities of Feed Forward Neural Networks has focused on two aspects, universal approximation on compact input sets and approximation in a finite set of training samples.

Many researchers have explored the universal approximation capabilities of standard multi-layer feed forward neural networks. Hornik proved that when the activation function is continuous, bounded and non-constant, continuous mappings can then be approximated in measure by neural networks over compact input sets. Leshno improved the results of Hornik and proved that feed forward networks with a non-polynomial activation function can approximate continuous functions.

In real applications, the Neural Networks are trained in finite training set. Huang and Babri show that SLFNs with at most N hidden nodes and with almost any nonlinear activation function can exactly learn N distinct observations. It should be noted that the input weights (linking the input layer to the first hidden layer) and hidden layer biases need to be adjusted in all these previous theoretical research as well as in all the practical learning algorithms of feed forward neural networks.

Traditionally, all the parameters of the feed forward networks need to be tuned and thus there exists the dependency between different layers of parameters (weights and biases). For past decades, gradient descent-based methods have mainly been used in various learning algorithms of feed
forward neural networks. However, it is clear that gradient descent-based learning methods are generally very slow due to improper learning steps or may easily converge to local minima. And many iterative learning steps may be required by such learning algorithms in order to obtain better learning performance.

5.2 PROPOSED EXTREME LEARNING MACHINE ALGORITHM

An extremely simple and efficient method to train SLFNs is proposed in this section, the conventional gradient-based solution of SLFNs. The popular learning algorithm used in the Feed Forward Neural Networks is the Back Propagation (BP) Learning Algorithm, where gradients can be computed efficiently by Propagation from the output to the input. There are several issues on BP Learning Algorithms,

- When the learning rate $Z$ is too small, the learning algorithm converges very slowly. However, when $Z$ is too large, the algorithm becomes unstable and diverges.

- Another peculiarity of the error surface that impacts the performance of the BP Learning Algorithm is the presence of the local minima. It is undesirable that the learning algorithm stops at a local minimum if it is located far above the global minima.

- Neural Network may be over-trained by using BP algorithms and obtain worse generalization performance. Thus, validation and suitable stopping methods are required in the LOSS function minimization procedure.

- Gradient-based learning is very time-consuming in most applications. The aim of the present research is to resolve the above issues related to gradient-based algorithms and propose an Efficient Learning Algorithm for Feed Forward Neural Networks.
5.3 PROBLEM FORMULATION

The Figure 5.1 shows the flow chart for Extreme Learning Machine Algorithm. Thus, a simple learning method for SLFNs called Extreme Learning Machine (ELM) can be summarized as follows,

![Flow Chart for Extreme Learning Machine Algorithm](image-url)

Figure 5.1 Flow Chart for Extreme Learning Machine Algorithm
Step 1: Randomly assign

Step 2: Calculate the hidden layer output matrix H.

Step 3: Calculate the output weight $bb_{\frac{1}{2}} HyT$,

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

A set $X$ of seven independent variables which affect the 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 in mm - $x_4$
(e) Average air gap flux densities in Wb/m$^2$ - $x_5$
(f) Stator current densities in A/mm$^2$ - $x_6$
(g) Rotor current densities in 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:

- Stator Copper Loss
- Rotor Copper Loss
- Stator Iron Loss
- Friction Loss
- Full Load Efficiency
The design and optimization of SCIM requires particular attention to the choice of the objective function that usually concerns economic or performance features. In the proposed design, the main objective is to improve the efficiency during light loads. The expression of the objective function, in terms of the design variables are summarized in the form of different constraints as follows,

The stator copper loss as given by the equation (5.1),

\[ W_{SCL} = 3 \cdot I_{ph}^2 \cdot R_s \] (5.1)

where \( I_{ph} \) is the phase current in amps (A) and \( R_s \) is the equivalent per-phase stator resistance in ohms (Ω).

The rotor copper loss as given by the equation (5.2),

\[ W_{RCL} = \frac{\rho \cdot S_2 \cdot I_b^2}{a_b} \left( L + \frac{2D_e}{P} \right) \] (5.2)

where \( \rho \) is a resistivity of the winding (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 and $a_b$ is the area of the bar.

The stator iron loss as given by the equation (5.3),

$$W_{SIL} = W_t \cdot W_{tk} + W_c \cdot W_{ck}$$  \hspace{1cm} (5.3)

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 percentage of full load efficiency is given by the equation (5.4),

$$\eta = \frac{1000 P_o}{1000P_o + W_{SCL} + W_{RCL} - W_{SIL} - W_F} \times 100$$  \hspace{1cm} (5.4)

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 $\theta_{ms}$ is a determining factor. The assumption is that cooling by convection, conduction and radiation is proportional to the temperature rise (Piotr Gnacinski 2008).

The temperature rise is directly proportional to the heat developed due to the losses and indirectly proportional to the cooling surface area as given in the equation (5.5),

$$\theta_{ms} = \frac{\tau_c (W_{SCL} + W_{SIL})}{S_S}$$  \hspace{1cm} (5.5)
where the cooling coefficient as given in the equation (5.6),

\[
\text{Cooling coefficient } \tau_c = \frac{0.03-0.05}{1+0.1u} \quad \text{where } u = \frac{2\pi |D|}{P}
\]  

(5.6)

and the total effective cooling surface area as given in the equation (5.7),

\[
S_s = S_i (1 + 0.1u) + S_o
\]

(5.7)

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

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 given in the equation (5.8),

\[
\theta_{mr} = \frac{\tau_c W_{RCL}}{S_r}
\]

(5.8)

Where,

- \( S_r \) is total rotor cooling surface area

The full load slip as given in the equation (5.9),

\[
s = \frac{W_{RCL}}{1000P_o + W_{RCL} + W_F}
\]

(5.9)

The summation of the friction and windage losses is assumed to be 1% Starting torque to full load torque ratio as given in the equation (5.10),
\[ \text{Ratio} = \frac{T_{st}}{T_{fl}} \]  

(5.10)

Where, \( T_{st} \) is starting torque, \( T_{fl} \) is full load torque.

Maximum torque to full load torque ratio as given in the equation (5.11),

\[ \text{Ratio} = \frac{T_{\text{max}}}{T_{fl}} \]  

(5.11)

Where, \( T_{\text{max}} \) is maximum Torque.

Starting to full load current ratio as given in the equation (5.12),

\[ \text{Ratio} = \frac{I_0}{I_{ph}} \]  

(5.12)

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

Full Load Power Factor as given by the equation (5.13),

\[ PF = \frac{R_s + G_4}{\sqrt{\{(R_s + G_4)^2 + (x_5 + G_5)^2\}}} \]  

(5.13)

where \( R_s \) is stator resistance in ohms, \( x_5 \) is average air gap flux density (wb / m\(^2\)), \( G_4 \) and \( G_5 \) is magnetizing constants.

5.4 IMPLEMENTATION OF EXTREME LEARNING MACHINE ALGORITHM FOR 2.2 kW AND 7.5 kW INDUCTION MOTOR

In the ELMA, the output weights are analytically computed by using the MP generalized instead of the iterative learning scheme. Structure of the Extreme Learning Machine Algorithm is shown in the Figure 5.2.
The Figure 5.3 shows the process of Extreme Learning Machine Algorithm. It consists of a single-hidden layer Feed Forward Networks. The significant features of ELM can be summarized as follows,

![Diagram](image.png)

**Figure 5.2 The structure of Extreme Learning Machine Algorithm**

- **Start**
- **Assignment**
  - (Arbitrary input weight $W_i$
  - Arbitrary hidden layer bias $b_i$)
- **Calculation $H$**
  - (The hidden layer output matrix $H$)
- **Calculation $W$**
  - (The output weight $W=HT$)
- **End**

**Figure 5.3 Process of Extreme Learning Machine Algorithm**
The learning speed of ELM is extremely fast. It can train SLFNs much faster than the classical learning methods.

The ELMA tends to reach not only the smallest training error but also the smallest norm of weights. Thus, the ELMA tends to have good performance for Neural Networks.

The ELMA learning algorithm can be used to train SLFNs with non-differentiable activation functions.

The ELM tends to reach the solutions straightforward without such trivial issues.

The three phase SCIM has six numbers of input terminals. Hence, it is possible to connect the different connection modes with each phase energized into two sets of winding in the stator. These two sets of winding can be connected either in series or in parallel with the input supply, to cause a variation of the connection mode. Different possibilities of stator winding connections are presented in the Figures 3.3 to 3.12 of the chapter 3.

5.5 DESIGN OF 2.2 kW AND 7.5 kW INDUCTION MOTOR USING EXTREME LEARNING MACHINE ALGORITHM

5.5.1 Comparison of the Conventional and Optimal Design data for 2.2 kW Three Phase SCIM

The results of the comparison of different stator winding connections and the different percentage of load for conventional and optimal designs for 2.2 kW induction motor shown in the Tables 5.1, 5.2, 5.3 and 5.4. The Table 5.5 shows the comparison of optimum values for maximum power factor and efficiency of different connections for of 2.2 kW three phase
SCIM. The Table 5.6 shows the comparison of the conventional and optimal design values for 2.2 kW induction motor.

Table 5.1  Comparison of the conventional and optimal design data for 2.2 kW three phase SCIM with \( \Delta P \), \( YP \) and \( \Delta S1 \) connections

<table>
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<tr>
<th>Stator Mode Connections</th>
<th>% of Load</th>
<th>Maximum Efficiency</th>
<th>Maximum Power Factor</th>
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Table 5.2  Comparison of the conventional and optimal design data for 2.2 kW three phase SCIM with $Y\Delta$, $YS1$ and $YS2$ connections

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<th>Stator Mode Connections</th>
<th>% of Load</th>
<th>Maximum Efficiency</th>
<th>Maximum Power Factor</th>
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Table 5.3  Comparison of the conventional and optimal design data for 2.2 kW three phase SCIM with ΔS2, ΔS3 and ΔS4 connections

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<th>Stator Mode Connections</th>
<th>% of Load</th>
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Table 5.4  Comparison of the conventional and optimal design data for 2.2 kW three phase SCIM with YS3 connection

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<th>Maximum power factor</th>
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Table 5.5  Comparison of the optimum data for 2.2 kW three phase SCIM with different connections

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Table 5.6 Comparison of the conventional and optimal design data for 2.2 kW induction motor

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<td>Length of stator in m</td>
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<td>Diameter of stator in m</td>
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<td>Ratio of L/ τ</td>
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<td>Outer diameter of stator in m</td>
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<td>Stator depth to width ratio</td>
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<td>Stator core depth in mm</td>
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<td>Stator Copper Loss in watts</td>
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<td>Rotor Copper Loss in watts</td>
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<td>Average Power Factor</td>
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5.5.2 Performance Characteristics of the Optimum Design for 2.2 kW SCIM using Extreme Learning Machine Algorithm

The Performance characteristics of optimum design three phase SCIM are displayed. Figures 5.4 (a) and (b) show the optimal design results for efficiency characteristics and Figures 5.5 (a) and (b) shows the power factor characteristics for 2.2 kW SCIM different types of stator winding connections.

The maximum points are identified for different connections. The conventional design motor performance characteristics are shown in the Figures 3.14 and Figure 3.15 of the chapter 3.

![Graph showing efficiency characteristics of ΔP, YP, ΔS1, YΔ and YS1 connections](image)

**Figure 5.4(a) Efficiency characteristics of ΔP, YP, ΔS1, YΔ and YS1 connections**
Figure 5.4(b) Efficiency characteristics of YS2, ΔS2, ΔS3, ΔS4 and YS3 connections

Figure 5.5 (a) Power factor characteristics of ΔP, YP, ΔS1, YΔ and YS1 connections
Figure 5.5(b) Power factor characteristics of YS2, ΔS2, ΔS3, ΔS4 and YS3 connections

5.5.3 Comparison of the Conventional and Optimal Design data for 7.5 kW Three Phase SCIM

The comparison of the results of different stator winding connections and different percentage of load for conventional and optimal designs for 7.5 kW three phase squirrel cage induction motor are presented in the Tables 5.7, 5.8, 5.9 and 5.10.

The Table 5.11 shows the comparison of optimum data for maximum power factor and efficiency of different connections. The Table 5.12 shows the comparison of conventional and optimal design data for 7.5 kW three phase squirrel cage induction motor.
Table 5.7  Comparison of the conventional and optimal design data for 7.5 kW three phase SCIM with ΔP, YP and ΔS1 connections

<table>
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Table 5.8  Comparison of the conventional and optimal design data for 7.5 kW three phase SCIM with \( \Delta \), YS1 and YS2 connections

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Table 5.9  Comparison of the conventional and optimal design data for 7.5 kW three phase SCIM with \( \Delta S2, \Delta S3 \) and \( \Delta S4 \) connections

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Table 5.10  Comparison of the conventional and optimal design data for 7.5 kW three phase SCIM with YS3 connection

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<td>64</td>
<td>70.8</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>68</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>76</td>
<td>81.5</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>80</td>
<td>84.8</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>82</td>
<td>86.8</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>89.6</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 5.11  Comparison of the optimum data for 7.5 kW three phase SCIM with different connections

<table>
<thead>
<tr>
<th>Stator Mode Connections</th>
<th>% of Load</th>
<th>Maximum Efficiency</th>
<th>Maximum Power Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Conventional Design</td>
<td>Optimal Design</td>
</tr>
<tr>
<td>ΔP</td>
<td>60</td>
<td>86</td>
<td>91.5</td>
</tr>
<tr>
<td>YP</td>
<td>68</td>
<td>87</td>
<td>92.2</td>
</tr>
<tr>
<td>ΔS1</td>
<td>70</td>
<td>87.5</td>
<td>92</td>
</tr>
<tr>
<td>YΔ</td>
<td>75</td>
<td>88.2</td>
<td>92.5</td>
</tr>
<tr>
<td>YS1</td>
<td>80</td>
<td>86.8</td>
<td>92.5</td>
</tr>
<tr>
<td>YS2</td>
<td>83</td>
<td>88</td>
<td>92.7</td>
</tr>
<tr>
<td>ΔS2</td>
<td>85</td>
<td>89</td>
<td>92.2</td>
</tr>
<tr>
<td>ΔS3</td>
<td>87</td>
<td>90</td>
<td>92.9</td>
</tr>
<tr>
<td>ΔS4</td>
<td>90</td>
<td>90.5</td>
<td>93.89</td>
</tr>
<tr>
<td>YS3</td>
<td>100</td>
<td>89.6</td>
<td>93</td>
</tr>
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</table>
Table 5.12 Comparison of the conventional and optimal design data for 7.5 kW induction motor

<table>
<thead>
<tr>
<th>Description</th>
<th>Conventional Design</th>
<th>Optimal Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of stator in m</td>
<td>0.360</td>
<td>0.325</td>
</tr>
<tr>
<td>Diameter of stator in m</td>
<td>0.220</td>
<td>0.190</td>
</tr>
<tr>
<td>Ratio of L/ (\tau)</td>
<td>1.34</td>
<td>1.49</td>
</tr>
<tr>
<td>Outer diameter of stator in m</td>
<td>0.44</td>
<td>0.54</td>
</tr>
<tr>
<td>Ampere conductor per meter</td>
<td>18500</td>
<td>23000</td>
</tr>
<tr>
<td>Stack length to pole pitch ratio</td>
<td>1.32</td>
<td>1.32</td>
</tr>
<tr>
<td>Stator depth to width ratio</td>
<td>4.05</td>
<td>4.1</td>
</tr>
<tr>
<td>Stator core depth in mm</td>
<td>4.23</td>
<td>4.4</td>
</tr>
<tr>
<td>Average air gap flux density in wb/m²</td>
<td>0.46</td>
<td>0.48</td>
</tr>
<tr>
<td>Stator winding current density in A/mm²</td>
<td>4.57</td>
<td>4.6</td>
</tr>
<tr>
<td>Rotor winding current density in A/mm²</td>
<td>7.76</td>
<td>7.68</td>
</tr>
<tr>
<td>Stator Iron Loss in watts</td>
<td>273.45</td>
<td>189.7</td>
</tr>
<tr>
<td>Stator Copper Loss in watts</td>
<td>287.9</td>
<td>190.7</td>
</tr>
<tr>
<td>Rotor Copper Loss in watts</td>
<td>126.7</td>
<td>119.0</td>
</tr>
<tr>
<td>Average Efficiency</td>
<td>84</td>
<td>90</td>
</tr>
<tr>
<td>Average Power Factor</td>
<td>0.85</td>
<td>0.92</td>
</tr>
</tbody>
</table>

5.5.4 Performance Characteristics of the Optimum Design for 7.5 kW SCIM using Extreme Learning Machine Algorithm

The performance characteristics of the optimum design three phase SCIM are displayed. Figures 5.6 (a) and (b) shows the optimal design results for efficiency characteristics. Figures 5.7 (a) and (b) shows the power factor characteristics for 7.5 kW SCIM with different types of stator winding connections. The maximum points are identified for different connections. The conventional design motor performance characteristics are shown in the Figures 3.16 and 3.17 of the chapter 3.
Figure 5.6(a) Efficiency characteristics of YS1, YP, ΔS1, YΔ and ΔP connections

Figure 5.6(b) Efficiency characteristics of YS2, ΔS2, ΔS3, ΔS4 and YS3 connections
Figure 5.7(a) Power factor characteristics of YS1, YS2, YΔ, ΔS1 and DS2 connections

Figure 5.7(b) Power factor characteristics of YP, ΔP, YS3, ΔS3 and ΔS4 connections
5.6 SUMMARY

A three-phase stator winding with two sets of windings is proposed. The described idea can be used in motors with wide load variations and with long low load in service periods. ELMA based design approach has been successfully applied for 2.2 kW and 7.5 kW, three phase, 4-pole, 50 Hz, multiflux, SCIM to improve the efficiency and power factor resulting from each possible connection modes.

A software package that analyzes and optimizes the performance of multi-flux SCIM has been developed. The results of simulation demonstrate that the proposed method can lead to significant improvement in the efficiency and power factor of multi-flux SCIM, contributing to an increase in energy savings.

Using ELMA, efficiency and power factor are improved for different winding configurations. It is observed that efficiency that is 81.3% in the conventional design for 2.2 kW induction motor improved to 90% in ELMA. Similarly, the power factor that is 0.83 for the conventional design improved to 0.91 in ELMA.

For 7.5 kW induction motor, efficiency that is 84% in the conventional design improved to 91% in ELMA. Similarly, the power factor is improved to 0.92. It is 0.85 for the conventional design. Optimal design parameters are presented for 2.2 kW and 7.5 kW induction motor.

For 2.2 kW, at full load star series type-3 (YS3) connection provides an efficiency of 93.9% and power factor of 0.94. At 60% of full load Delta – Parallel (DP) connection provides an efficiency of 92.5% and a power factor of 0.93.
For 7.5 kW, at 68% of full load Star-Parallel (YP) connection provides an efficiency of 92.2% and a power factor of 0.92. At full load Star Series type-3 (YS3) connection provides an efficiency of 93% and a power factor of 0.93. Considerable performance improvements are observed in ELMA, when compared to the conventional design.