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Design optimization of permanent magnet synchronous motor using Taguchi method and experimental validation

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Abstract: The critical dimensions of magnet and its positional parameters in a permanent magnet synchronous motor (PMSM) are optimized using Taguchi method. L16 Orthogonal Array (OA) was used in Taguchi method to optimize the magnet width $w$ and thickness $t$, and magnet position parameters i.e., $D_1$, $O_1$, and Rib. Using the D-optimal design criterion, 52 data points for five factors were selected for optimization of power factor and efficiency using response surface methodology to perform the sensitivity analysis. Regression model for efficiency and power factor are modeled using analysis of variance results. A 1.07 kW capacity PMSM was designed based on the optimized parameters and making use of efficient computational resource, i.e., RMxprt tool of the ANSYS Maxwell software and drive system in ANSYS Simplorer for real time results and performance study. The performance of PMSM in terms of line current, load torque, and efficiency has been verified with the experimental results and the efficiency data available in literature. The results were found to be in a good agreement. Confirmation test results showed that the Taguchi method is very successful in the optimization of permanent magnet synchronous motor dimensions.

Keywords: efficiency; permanent magnet synchronous motor; power factor; Taguchi method.

1 Introduction

Industries require different kind of variable torque and speed drives in various applications such as in overhead cranes, conveyor belts, arm of robots, etc. for which Direct Current (DC) and Alternating Current (AC) motor drives are used. Induction motors and synchronous motors are the two main types of AC motor presently used. The permanent magnet synchronous motor (PMSM) is an AC synchronous motor whose field excitation is provided by permanent magnets and has a sinusoidal back electromotive force (EMF) waveform. The permanent magnet synchronous machine has several advantages such as a maintenance-free operation, high controllability, robustness against the environment, high power factor and high efficiency. Due to many positive qualities and environmental friendly PMSM are widely used in different applications.

A considerable amount of work on the electrical motor design optimization has been carried out using Taguchi method in recent years. However, Taguchi method of optimization in the field of motor design optimization of PMSM is very limited and unknown. Genichi Taguchi has developed the Taguchi method in 1940s. This method is different than the traditional design of experiment in different ways such as planning of experiments, quality defining, and noise to signal analysis etc. Due to various advantages over the traditional design of experiment, Taguchi method is popularly used by researchers in the various fields of engineering, medicines, environmental science, etc. Future challenge to the world is the energy challenges and the issues of global environmental changes. This has drawn the Investigator to various energy efficient programs. 40–50% electric consumption in the industries is due to various motor-driven systems. Hence, a huge amount of energy can be saved by designing an energy efficient motor or by improving the efficiency of a motor by optimal design approach. Due to relatively higher efficiency and power factor, PMSM are preferred over the induction motor. Many research works on PMSMs in literature focused on the development of rotor design, improving the steady-state analytical model and the utilization of transient time-step finite element method (FEM) for synchronization analysis. Till 2008 various efficiency standards were focused on the induction motor. Due to increasing difficulties faced by the global manufacturers the Intentional Electro-technical Commission (IEC) compiled a new global standard (IEC 60034-30) in 2008 to unify the electrical machine standards.

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in different literatures [1–3]. This standard was applicable for three-phase induction motors having power capability ranging from 0.75 to 375 kW, voltage up to 1000 V, having two to six poles operating at continuously or on a periodic basis of having duty above 80%. The design for the reduction of cogging torque of a brushless DC Permanent Magnet Spindle motor using Taguchi method has been reported first time in 1998 by Chen et al. [4]. Use of Taguchi method for the design of Permanent Magnet Synchronous Machine (PMSM) and line start PMSM are found in references [5–14]. The Taguchi’s method was used by Lee et al. [15] in which L36 main OA over a whole pole was taken with 18 static points being used for outer design to minimize the peak air gap flux density spikes in an outer rotor PMSM caused due to stator slot openings. Xu et al. [16] used Taguchi method for optimization of magnetizing parameters. The optimization of rotor design was carried out by Kim et al. [17] considering the starting torque and efficiency. It was reported that the analytical method takes longer time for calculation of optimal solution. Duan and Ionel [18] presented the design optimization methods for a permanent-magnet synchronous motor.

Selection of magnetic material is very important in the design of PMSM. Sigrid Jacobs et al. [19] have studied on the magnetic material optimization for hybrid vehicle PMSM drives. They have studied the effectiveness of different grades of steel materials based on the efficiency of the machine using finite element (FE) simulations. Peter Sekerák et al. [20] have designed PMSM with ferrites because of its popularity due to their low cost and cost increasing of NdFeB. The effect of two magnet materials SmCo and ferrite magnets on optimal design of a high speed synchronous machine for different rotor speeds was investigated by Martin et al. [21].

Other important parameters in PMSM design are magnet size, rotor pole data, cogging torque, etc. Uğur Demir and Mustafa Caner Aküner [22] used Taguchi method and conventional method to optimize the critical rotor pole data of line-start permanent magnet synchronous motor with an objective function of maximization of efficiency and power factor based on the data obtained from Maxwell 3D and RMxpert. Jikai Si et al. [23] used Taguchi method and surface response methods for optimization of peak value of cogging torque, ratio of average torque and weight of permanent magnet, torque ripple and total harmonic distortion in back EMF. Fujishima et al. [24] minimized the area of magnet material of an outer rotor PMSM subject to the constraints \( T_{\text{max}} = 7490 \text{ Nm} \) and open circuit induced voltage \( E_{\text{o}} = 1500 \text{ V} \). The constraints were included in the total objective function as weighted penalty factors. The combination of GA and FEM results in more CPU time and for this reason RSM is combined along with GA and FEM for optimization purpose and CPU time is reduced significantly. Cvetkovski and Petkovska [25] have studied the topology optimization for optimal design of a permanent magnet synchronous motor based on the efficiency maximization using Genetic Algorithm. 2D finite element method is used for magnetic field computation and analysis of PMSM. Response surface optimization of PMSM is studied in Jolly and Jabber [26], Fang et al. [27], Jolly et al. [28], Park et al. [29] where design of experiment is used and a second order polynomial function is used to create the response surface. Different number of design experiments is used by the researchers to find an optimal solution. Manko et al. [30] have used the simplest design of experiments (DoE) by applying Taguchi method and optimized the design of PMSM. Two different optimization goals are used by the authors. These goals are the reduction of the motor volume and maximization of the efficiency.

The most of the research work carried out on the PMSM motor design optimization focused on the single objective functions considering either the efficiency or power factor whereas in many applications simultaneous optimum performance of several parameters are required. In the present investigation the magnet dimensions and rotor positions are optimized considering the efficiency and power factor. Taguchi method was used in the study. The optimized data are used to design PMSM using finite element method and the model is then run for simulation. The simulation results are validated by experimental results and available in literature.

## 2 PMSM design procedure

PMSM with an interior magnet rotor is designed with ANSYS Maxwell software. Based on the preliminary results [31] different combinations of the width and thickness of magnets, magnet position in the rotor i.e., \( D1, O1 \), and Rib are tried. In the present work, 1.07 kW capacity motor having four poles with a rated speed of 4000 rpm has been selected, and magnet size and position, rotor with embedded magnets, damper windings for the rotor and a stator is designed. ANSYS Maxwell software is used to design the PMSM. Finite element method (FEM) approach is used in the ANSYS Maxwell software. The model for the machine was developed in RMxpert which requires data related to the stator, the stator windings, the stator slots, the rotor and the poles. The rotor can be designed with or without dampers. In this work, dampers were used which facilitate the PMSM to start like an induction motor (IM). Materials used for different
components of PMSM are presented in Table 1. The various parameters such as $D_1$, $O_1$, $Rib$, magnet width, and magnet thickness were optimized for maximum efficiency and power factor. One of the design of PMSM using RMxpert as shown in Figure 1 which was checked and validated by the software. A solution setup was created to specify the load type, rated output power, rated voltage, rated speed, and the operating temperature for the analysis purpose. Finally, the PMSM was simulated on the basis of its design and solution setup added. The results are presented in subsequent sections.

3 Design optimisation

3.1 Taguchi design methodology

In Taguchi optimization method different factors are selected with different levels to study the effect of the factors on the performance. The DoE in Taguchi method uses specially created orthogonal arrays (OA) which allow reducing the number of experiments and time in conducting the experiments. In Taguchi method a loss function is used to calculate the deviation between the experimental and the desired values. The signal to noise ratio ($S/N$) is obtained from the loss function. Three types of quality characteristics of $S/N$ ratio are used in the analysis. These are: lower-the-better, the higher the-better, and the nominal-the-best [32]. In the analysis, $S/N$ ratio for each response is calculated as per response characteristics. In the present investigation the motor efficiency and power factor are taken for maximization. Equations (1) and (2) describes the quality characteristics.

Higher-the better

$$\frac{S}{N} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right]$$

(1)

Lower the better

$$\frac{S}{N} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]$$

(2)

Table 1: Materials of different components of PMSM.

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stator</td>
<td>Iron</td>
</tr>
<tr>
<td>2</td>
<td>Rotor</td>
<td>Cobalt</td>
</tr>
<tr>
<td>3</td>
<td>Permanent magnet</td>
<td>Neodymium iron boron (NdFeB)</td>
</tr>
<tr>
<td>4</td>
<td>Damper</td>
<td>Aluminium</td>
</tr>
</tbody>
</table>

Figure 1: View of PMSM design.

Table 2: Rotor design parameters and their levels.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet width, w (mm)</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>Magnet thickness, t (mm)</td>
<td>4 6 7.3 7.38</td>
</tr>
<tr>
<td>$D_1$ (mm)</td>
<td>63 64 – –</td>
</tr>
<tr>
<td>$O_1$ (mm)</td>
<td>21 23 – –</td>
</tr>
<tr>
<td>$Rib$ (mm)</td>
<td>0.5 4 – –</td>
</tr>
</tbody>
</table>
requires $4^2 \times 2^3 = 128$ number of experiments which can be reduced to one-eighth of 128. Hence, L16 array was selected and the details of the factors are presented in Table 3.

L16 orthogonal array (OA) was used in Taguchi method and the results of $S/N$ ratio for power factor and efficiency are shown in Figures 2 and 3 respectively. Figures 2 and 3 reveal that $S/N$ ratios for the factors giving the best power factor and efficiency are specified as $w = 20$ mm, $t = 7.38$ mm, $D_1 = 64$ mm, $O_1 = 23$ mm (all are factor 4, 4, 2, and 2) and $R_{ib} = 0.5$ mm (factor 1).

### 4 Performance simulation

PMSM with an interior magnet rotor is designed with ANSYS Maxwell software with the optimized dimensions.

![Figure 2: Effect of magnet size and position on the $S/N$ ratio for power factor.](image1)

The permanent magnets (PMs) are located in the interior of the rotor. The 3-D view of the PMSM designed with the help of software is shown in Figure 4. The motor consists of stator made of iron, rotor cage made of cobalt, aluminium rotor damper bars and the permanent magnet used is NdFeB ($\text{NdFe}_{35}$). The damper bars are used for initial starting of the motor similar to that of an induction motor.

The result of the different performance parameters of designed PMSM is achieved in ANSYS Simplorer. The PMSM designed in ANSYS Maxwell was co-simulated with the drive system designed in ANSYS Simplorer. The complete drive system consists of IGBT inverter, PMSM coupled with DC Generator for electrical loading of the PMSM and a control circuit for switching of the IGBTs in the inverter circuit. In the control circuit, pulse width modulation (PWM) technique was used by comparing three sinusoidal signals having frequency of 50 Hz, each displaced from one another by $120^\circ$, with a triangular carrier signal having frequency of 10 kHz. The complete drive system is shown in Figure 5.

![Figure 3: Effect of magnet size and position on the $S/N$ ratio for efficiency.](image2)

### 4.1 Efficiency

The full load efficiency of PMSM was obtained after simulation of the designed model in RMxprt. The efficiency curve of the motor with respect to torque angle was found at four different speeds through simulation. The model was simulated at 2700, 3000, 3300, and 4000 rpm, and the results are shown in Figures 6, 7, 8, and 9. The efficiency achieved for the designed motor at 2700, 3000, 3300, and 4000 rpm were 81.47, 84.17, 87.31, and 91.27\%, respectively. The torque angle was seen to be reduced as the speed of operation increases. Initially at 2700 rpm, the torque angle for operation comes out to be $43.75^\circ$. It then
reduces to 40.13°, 37.51°, and 31.35° at 3000, 3300, and 4000 rpm, respectively.

4.2 Power factor

The simulation results show that the power factor for different combination of \( w, t, D_1, O_1 \) and \( R_{ib} \) are found to be in the range of 0.510–0.985. The improvement in power factor may be due to many reasons. In the present investigation the neodymium-iron-boron (NdFeB) magnets is used. NdFeB magnet improves the efficiency and power factor in permanent magnet synchronous machines [33]. The properties of NdFeB magnets instead allow also the use of demagnetizing current which helps in the improvement of the power factor [34]. The power factor is the ratio of active and apparent power which can be improved by proper selection of size and volume of the permanent magnet and the condition of the supply current [35, 36]. Optimum design of PMSM helps in minimizing the losses which causes increases in efficiency and power factor [37]. The effect of various design parameters on the power factor is presented in Figure 10. Figure 10 reveals that improvement in power factor can
be made by proper selection of studied design parameters. Total harmonic distortion (THD) can also distort the line voltage [38]. Less distortion is possible with a sinusoidal current from the line in phase with line voltage which improves the power factor. The non-sinusoidal voltage and current introduce a distortion factor, which reduces the total power factor. In the present investigation, total harmonic distortion was less than 4.8%.

5 Sensitivity analysis

Sensitivity analysis is a numerical approach used to estimate the impact of the design parameters to the objective functions. Mathematically, sensitivity of an objective function with respect to a design variable is the partial derivative of that function with respect to its variables. Sensitivity information is interpreted using the mathematical definition of derivatives, namely positive sensitivity values imply an increment in the objective function by a small change in design process parameter, whereas negative values state the opposite [39]. Analysis of variance technique was used to check the adequacy of the developed empirical relationship. The sensitivity Eqs. (3) and (4) represent the sensitivity on efficiency and power factor for magnet width, magnet thickness, rotor pole parameters $D_1$, $O_1$ and $Rib$, respectively.
Sensitivity is analyzed using the partial derivatives as Eqs. (3) and (4). To evaluate sensitivities, each input parameter should be varied while keeping all other input parameters constant to see how the output parameters react to these variations. The variation rate of a design parameter is defined as

\[
\frac{\partial (\text{eff})}{\partial w} = \begin{bmatrix}
-0.308564 & 1.18 \times 10^{-6} & -0.00129 & 0.00569 & -0.002098 & 0.00275 \\
-0.585544 & -0.001291 & 0.0014386 & 0.014511 & -0.01281 & 0.004677 \\
0.702962 & 0.0056922 & 0.01451 & -2.48 \times 10^{-4} & -0.0353447 & 0.0085736 \\
2.02255 & -0.00209824 & -0.012813 & -0.0353447 & 0.0085736 & 0 \\
-0.29587 & 0.00275734 & 0.00467739 & 0.00364203 & 0 & -1.58 \times 10^{-5} \\
\end{bmatrix}
\]

\[\frac{\partial (\text{pf})}{\partial w} = \begin{bmatrix}
0.169621 & 0.000111356 & -8.54 \times 10^{-4} & 0.000776 & -0.0091472 & 0.00136 \\
-12.0105 & -8.54 \times 10^{-4} & -0.00349691 & 0.173456 & 0.0422674 & 0.0519655 \\
2.25442 & 0.000776053 & 0.173456 & 0.00518288 & -0.176384 & -0.0308659 \\
10.631 & -0.0091472 & 0.0422674 & -0.176384 & 0.0103776 & 0 \\
1.56996 & 0.0013602 & 0.0519655 & -0.0308659 & 0 & 0.000179296 \\
\end{bmatrix}
\]

where \(\Delta x\) represents the variation of a variable and the range of the value of this variable is \((x_{\text{max}}, x_{\text{min}})\). When the \(R_e\) changes from 10 to 100%, for the design parameters discussed, the rates of change for the objective functions are shown in Figure 11. According to the sensitivity results the parameters \(D1\), and \(O1\) shows larger impact on the value of frequency and power factor than magnet dimensions \(w\) and \(t\). Considering the changes of efficiency and power factor, the sensitivity of undertaken design parameters of PMSM can be ranked as follows: the parameter \(O1\) is more sensitive followed by \(D1\), \(Rib\), \(t\) and \(w\) on the response of efficiency. Similarly the parameter \(D1\) is more sensitive followed by \(O1\), \(t\), \(Rib\) and \(w\) on the response of power factor. Results also reveal that the parameters \(D1\) and \(t\) have positive sensitivity on efficiency and other parameters have negative sensitivity. The magnet width \(w\) has positive impact on the power factor and other parameters have negative impact on the power factor.

6 Experimental validation

The experiment on 1.07 kW PMSM having a rated speed of 4000 rpm, mechanically coupled with a DC generator was performed for validation of PMSM model designed in ANSYS Maxwell software. The experimental set up and circuit diagram are shown in Figure 12. In the experiments, three speeds viz., 2700, 3000, and 3300 rpm were selected and the corresponding line voltage, line current, and input power at 25% load, 50% load, 75% load, full load, and 110% load were measured. All the measurements of current, voltage, input power, and power factor were made using Fluke 1738 Power Logger. The PMSM is loaded indirectly by loading the mechanically coupled DC generator using lamp loads. The generated EMF and armature current of DC generator are also measured using voltmeter and ammeter, respectively. The generated EMF and armature current values were used to calculate the output power.
Performance parameters such as efficiency and torque were calculated using Eqs. (6) and (7), respectively.

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$  \hspace{1cm} (6)$$

$$T = \frac{P_{\text{out}}}{2\pi N}$$  \hspace{1cm} (7)$$

where $P_{\text{out}}$ is the output power of PMSM and $P_{\text{in}}$ is the input power to the PMSM. $N$ is the speed of motor in rpm. These results were compared with the experimental results for validating the performance of the PMSM in Table 4.

Table 4 compares line currents for phase A ($I_a$), phase B ($I_b$), and phase C ($I_c$) obtained experimentally with simulation results. The percentage difference between experimental and simulation results of line current for phase A at 2700 rpm was found to be 9.26% while at the same speed for phase B and C were 7.17 and 9.74%, respectively. The minimum difference of 0.624% was seen for a speed of 3300 rpm in phase C. In other cases except for phase A, the percentage difference lies below 8%. A higher percentage difference in experimental and simulation line currents is seen in phase A. This may be due to low current measured in phase A as compared to the current measured in phase B and phase C. As the same equipment was used for measuring current in all three phases, this difference was may be because of improper functioning of current transformer (CT) used in the equipment for measurement of current in phase A. This conclusion is made from repeated recording of experimental data for same speed, and a similar type of result was obtained each time. Another possible reason for difference in measured current and

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Speed (rpm)</th>
<th>Phase</th>
<th>Simulation current (A)</th>
<th>Experimental current (A)</th>
<th>% Difference (absolute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2700</td>
<td>A</td>
<td>6.064</td>
<td>5.55</td>
<td>9.261</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>6.387</td>
<td>6.88</td>
<td>7.166</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>6.273</td>
<td>6.95</td>
<td>9.741</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>A</td>
<td>5.936</td>
<td>5.11</td>
<td>16.164</td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>6.053</td>
<td>6.28</td>
<td>3.615</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>6.146</td>
<td>6.35</td>
<td>3.213</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>3300</td>
<td>A</td>
<td>5.983</td>
<td>4.75</td>
<td>25.958</td>
</tr>
<tr>
<td>8</td>
<td>B</td>
<td>5.954</td>
<td>5.61</td>
<td>6.132</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>C</td>
<td>5.893</td>
<td>5.93</td>
<td>0.624</td>
<td></td>
</tr>
</tbody>
</table>
simulation current for phase A may be because of unbalanced loading. This conclusion is drawn after comparing the currents of the three phases for different load levels and different speed. The current in phase A is lesser in each case as compared to the current in phase B and phase C.

The effect of speed on line current is shown in Figure 13. Figure shows that both experimental and simulation line currents linearly decreases with speed. The lowest current was seen in phase A both in experimental and simulation results. The line current in phase B and phase C were very close to each other both in experimental and simulation results.

The efficiency of the PMSM was measured by experimental analysis and was compared with the efficiency results obtained in ANSYS Maxwell after simulation as shown in Figures 14 and 15. The absolute percentage difference of experimentally calculated efficiency and simulation efficiency for 2700 rpm was 0.85% whereas at 3000 and 3300 rpm, the absolute percentage differences came out to be 0.89 and 0.84%, respectively. The efficiency of PMSM of same capacity and slightly different capacities at different operating speed available in literature [37, 40–45] are included for comparison. The variations in efficiencies observed are due to difference in PMSM capacities and operating conditions. The results of 1.07 kW capacity or near to 1.07 kW capacity operated at investigated speed are found to be very close to the present results. This shows the wide application of designed PMSM over a wide range of speed with efficiency much better than that of induction motor. This shows that PMSM can effectively be used in applications requiring higher efficiency over a wide range of speeds such as in electric vehicles, aircraft engine starter and even in cutters and grinders.

The experimental and simulation load torque for different speeds under full load are compared in Figure 16 which reveals that the difference between experimental and simulation load torques decreases as the speed increases. The maximum difference of 4.89% was observed at 2700 rpm while at other two speeds the percentage differences were less than 1%. Due to significant improvement
of efficiency and power factor in the optimized PMSM, the designed PMSM is more suitable for low load and high speed applications such as blowers, material handing equipments, home appliances and robotics [46, 47]. The designed permanent motor synchronous machine can also be suitable for hybrid vehicles of low power capacity [41].

7 Conclusions

In this study, the Taguchi method and response surface method were used to determine the magnet and rotor size for optimal PMSM efficiency and power factor. The following conclusions are drawn from simulation and experimental observation:

1. L16 orthogonal array (OA) was used in Taguchi method to optimize the magnet width w and thickness t, and magnet position parameters i.e., D1, O1, and Rib. On the basis of the results of S/N ratio for power factor and efficiency the optimum solutions are found as w = 20 mm, t = 7.38 mm, D1 = 64 mm, O1 = 23 mm and Rib = 0.5 mm for design of 1.07 kW capacity PMSM.

2. The result of the different performance parameters of designed PMSM is achieved in ANSYS Simplorer. The PMSM designed in ANSYS Maxwell was co-simulated with the drive system designed in ANSYS Simplorer.

3. The parameters D1 and O1 shows larger impact on the frequency and power factor than magnet dimensions w and t. O1 is more sensitive followed by D1, Rib, t and w on the response of efficiency whereas D1 is more sensitive followed by O1, t, Rib and w on the response of power factor.

4. The validation of the simulated results of 1.07 kW PMSM designed in ANSYS Maxwell software and the drive system in ANSYS Simplorer software was compared with the experimental results. All experiments were conducted on 1.07 kW PMSM similar to the optimized one at three speeds viz., 2700, 3000, and 3300 rpm and the corresponding line voltage, line current, and input power at 25% load, 50% load, 75% load, full load, and 110% load were measured to calculate performance parameters.

5. The percentage difference between experimental and simulation results of line current for phase A, B and C at 2700 lies below 10%. At higher speeds the percentage difference is found to be less than 7% except phase A. The absolute percentage difference of experimentally calculated efficiency and simulation efficiency for 2700, 3000 and 3300 rpm were 0.85, 0.89 and 0.84%, respectively.

6. The proposed methodology made use of efficient computational resource, i.e., RMxprt tool of the ANSYS Maxwell software for obtaining the real time solutions. Designing the machine in RMxprt saves a lot of simulation time as compared to other tools. The model designed in RMxprt can be easily converted to 2D model in ANSYS.

7.1 Future scope

The sensitivity of the controller and optimization technique may be taken as a future scope of study for the performance enhancement of permanent magnet synchronous motors.

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