Optimization Design of Surface-mounted Permanent Magnet Synchronous Motors Using Genetic Algorithms

Trinh Truong Cong¹, Thanh Nguyen Vu¹ *, Gabriel Pinto² and Vuong Dang Quoc¹

¹Laboratory of High-Performance Electric Machines (HiPems); School of Electrical and Electronic Engineering; Hanoi University of Science and Technology, No1, Dai Co Viet street, Hai Ba Trung District, Hanoi, Viet Nam
²Universidade do Minho - Departamento de Eletrónica Industrial (DEI), Campus de Azurém - 4800-058 Guimarães, Portugal

Abstract

The permanent magnet synchronous motor (PMSM) has gained widespread popularity in various industrial applications due to its simple structure, reliable performance, compact size, high efficiency, and adaptability to different shapes and sizes. Its exceptional characteristics have made it a focal point in industrial settings. The PMSM can be categorized into two primary types based on the arrangement of the permanent magnets (PM): interior permanent magnet (IPM) and surface-mounted permanent magnet (SPM). In the IPM, the magnets are embedded into the rotor, while in SPM, they are mounted on the rotor's surface. The utilization of PMs eliminates the need for excitation currents due to their high flux density and significant coercive force. This absence of excitation losses contributes to a notable increase in efficiency. In this study, a multi-objective optimal design approach is introduced for a surface mounted PMSM, aiming to achieve maximum efficiency while minimizing material costs. The optimization task is accomplished using a genetic algorithm. Furthermore, the motor designs are simulated using the finite element method (FEM) to assess and compare designs before and after the optimization process.

Keywords: Permanent magnet synchronous motor (PMSM), Surface-mounted permanent magnet synchronous motor (SPMSM), genetic algorithm (GA), finite element method

Received on 10 November 2023, accepted on 08 January 2024, published on 16 January 2024

Copyright © 2024 T. T. Cong et al., licensed to EAI. This is an open access article distributed under the terms of the CC BY-NC-SA 4.0, which permits copying, redistributing, remixing, transformation, and building upon the material in any medium so long as the original work is properly cited.

doi: 10.4108/ew.4864

*Corresponding author. Email: thanh.nguyenvu@hust.edu.vn

1. Introduction

The permanent magnet synchronous motor (PMSM) is widely employed in diverse industrial applications due to its simplicity, reliability, compact size, high efficiency, and its ability to be adapted to various shapes and sizes [1]. Particularly, in the low speed, the PMSMs have extensive usage in fields such as ship propulsion, lifting, mining, and oil field exploitation [2], [3]. The PMSMs can be classified into two main types based on the arrangement of the permanent magnet: interior permanent magnet (IPM), where the magnets are embedded into the rotor, and surface-mounted permanent magnet (SPM), where the magnets are mounted on the rotor's surface. The PMSMs are excited by permanent magnets (PMs) rather than excitation currents due to their high flux density and significant coercive force. This characteristic eliminates excitation losses, resulting in a substantial increase in efficiency [4]. The three primary magnet materials used in the PMSMs are ferrite, samarium-cobalt (SmCo), and neodymium-iron-boron (NdFeB).

For high-torque applications, the fractional-slot concentrated winding is commonly employed. The term fractional-slot winding refers to a situation where the number of slots per pole per phase is a non-integer value and less than one. When each coil of the winding is wound around a single tooth of the stator, it is referred to as a concentrated winding. Motors with this type of winding have drawbacks, including slightly lower winding factor and higher harmonic content in the magnetomotive force (MMF), distribution compared to integral slot machines [5], [6]. Therefore, the motor must be designed with a suitable
combination of the number of pole pairs and slots based on its intended applications.

The genetic algorithm (GA) is an heuristic search frequently employed for generating effective solutions to optimization and search problems. Inspired by natural evolution, the GA utilizes techniques such as inheritance, mutation, selection, and crossover to generate solutions for optimization problems. Its versatility makes it a powerful tool for global optimization and analysis of large datasets [7]. Numerous researchers have utilized the genetic algorithm to explore optimal designs for the PMSMs [8]-[10]. However, the discrete variation of variables and their lack of complete correlation with each other and other parameters can lead to changes in output power after the optimization process.

In this study, a surface-mounted permanent magnet synchronous motor (SPSM) employing NdFeB N35 magnets is designed. Subsequently, the genetic algorithm is applied to determine the optimal dimensions that achieve maximum efficiency while minimizing material costs (such as electrical steel, copper, and magnets) with power conservation.

2. Analytical model of SPMSM

The rotor volume, expressed as the product of \( D^2 \) and \( L \), plays a crucial role in determining the motor’s dimensions, where \( D \) represents the inner diameter of the stator and \( L \) denotes the active length of the machine. Several methods have been proposed to calculate this parameter [11]-[13]. However, to determine the rotor volume, a coefficient concept that depends on the cooling systems, as presented in [14], is employed.

\[
\frac{D^2 L}{T_e} = V_0, \quad (1)
\]

where \( T_e \) is the motor torque.

Typically, for motors with an output power of up to 10 hp and air cooling, the specific volume (\( V_0 \)) ranges from 5 to 7 \( \text{in}^3/\text{ft-lb} \). On the other hand, for motors with a power greater than 10 hp and water or liquid cooling, the specific volume is typically between 2 and 5 \( \text{in}^3/\text{ft-lb} \).

The magnet is a critical component of the PMSM, as it generates the magnetic field in the air gap. In this paper, NdFeB N35 magnets are utilized. The fundamental flux density in the air gap can be determined using the following equation:

\[
B_g = \frac{4}{\pi} \sin \left( \frac{\rho_{pm}}{2} \right) B_m, \quad (2)
\]

where \( \rho_{pm} \) represents the electrical angle of the PM, and \( B_m \) is the flux density of the magnet. The thickness of the magnet can be calculated as:

\[
h_m = \frac{\mu_r g}{B_r \cdot 4 \sin \left( \frac{\rho_{pm}}{2} \right) B_g \pi} - 1, \quad (3)
\]

where \( \mu_r \) is the permeability of the magnet and \( g \) is the length of air gap. The model for separating iron losses can be categorized into three components: hysteresis loss, eddy current loss, and additional loss.

\[
P_{Fe} = p_h + p_e + p_a = k_h f B_m^a + k_e f^2 B_m^2 + k_a f^1.5 B_m^{1.5} \quad (4)
\]

In this design, the additional loss, which accounts for a small portion of the motor iron loss [15], is disregarded. The motor design in this paper utilizes the M530A-50A (European standard EN 10106-1996) non-oriented electrical steel. For the non-oriented model, the parameter \( \alpha \) ranges from 1.6 to 1.8, while the values of \( k_h \) and \( k_e \) for the M530A-50A steel can be found in [16].

The iron loss encompasses the total loss occurring in the stator, rotor, and teeth of the motor. It can be calculated using the loss separation method, as follows:

\[
P_{Fe} = p_{stator} M_{stator} + p_{rotor} M_{rotor} + p_{tooth} M_{tooth}. \quad (5)
\]

As previously mentioned, the PMSM is excited by permanent magnets instead of excitation currents, resulting in the absence of copper loss in the rotor. Therefore, the copper loss in the PMSM is solely attributed to the stator winding. The calculation for copper loss is as follows:

\[
P_{Cu} = Q_s I^2 R, \quad (6)
\]

where \( Q_s \) is the number of slots, \( I \) is the phase current and \( R \) is the resistance of the winding in each tooth.

The total loss is the sum of the iron loss and the copper loss, which is given as below:

\[
P_{loss} = P_{Fe} + P_{Cu} \quad (7)
\]

3. Optimization method

The diagram of the optimization process using genetic algorithm is presented as:

![Figure 1. Main steps of a multi-objective genetic algorithm.](image)
The optimization of Permanent Magnet Synchronous Motors (PMSMs) involves a multi-objective problem with numerous variables and constraints. The selection of variables is critical as it directly impacts the output results. In this study, a careful consideration led to the inclusion of seven variables in the optimization process. These variables include the inner stator diameter ($y_1$), air gap length ($y_2$), height of the stator yoke ($y_3$), height of the rotor yoke ($y_4$), width of the tooth ($y_5$), current density ($j$), and the number of turns per tooth ($n$). The variables $y_1$, $y_3$, $y_4$, and $y_5$ are associated with iron loss and steel volume, whereas $y_2$, $j$, and $n$ pertain to magnet dimensions and copper loss. All seven of these variables have the potential to influence both the motor's dimensions and its losses, ultimately leading to variations in the objective functions. Table 1 provides the upper and lower boundaries for each variable:

**Table 1. Upper and lower boundaries of optimization variables.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower boundary</th>
<th>Upper boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_1$ (mm)</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>$y_2$ (mm)</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>$y_3$ (mm)</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>$y_4$ (mm)</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>$y_5$ (mm)</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>$j$ (A/mm$^2$)</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>$n$ (turns)</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

The proposed constraints must be precisely formulated in order to ensure that the optimization results meet all the operational requirements of the Permanent Magnet Synchronous Motor (PMSM). This research paper focuses on three parameters, namely the stator volume, rotor volume, and magnet volume, each accompanied by an equality constraint. The winding's slot fill factor is maintained within the range of 0.45 to 0.55. Additionally, references [17]-[20] provide a typical range for the flux density values of the stator yoke, rotor yoke, and tooth of the PMSM, resulting in four inequality constraints. The objective functions must be established, specifically the minimization of total loss ($P_{loss}$) and material cost ($C$). The material cost encompasses the expenses associated with electrical steel, copper, and magnets, which can be described as follows:

$$ C = c_{Fe} M_{Fe} + c_{Cu} M_{Cu} + c_{m} M_{m} = c_{Fe}(M_{stator} + M_{rotor} + M_{teeth}) + c_{Cu} M_{Cu} + c_{m} M_{m}, \quad (8) $$

where $c_{Fe}$, $c_{Cu}$, $c_{m}$ are the cost per kilogram of electrical steel, copper, and magnet respectively. The mass of the different parts of the motor in (8) is calculated as:

$$ M_{stator} = K_1 \frac{4K_2y_3y_5 - 4y_5^2}{x_1^2} \quad (9) $$

$$ M_{rotor} = $$

$$ K_1 \left( y_1 - 2K_1y_3 \right)^2 - (y_1 - 2, K_4y_2 - 2y_4)^2 \cdot \frac{1}{y_1^2} \quad (10) $$

$$ M_{teeth} = K_1 \left[ \frac{\pi}{4} (K_2y_1 - 2y_4)^2 \right. $$

$$ - Q_s \left[ \left( K_2 - \frac{1}{2} \right) y_1 - y_3 \right] $$

$$ - K_3 \left( K_2 + \frac{1}{2} \right) y_1 - K_7 $$

$$ y_3 - y_5 + K_7 $$

$$ + K_9 $$

$$ h_w \left( K_7 y_1 \right) $$

$$ - y_5 \right) \right] \quad (11) $$

$$ M_{Cu} = $$

$$ \frac{K_{10}}{x_6} 2j \left( y_5 + \frac{V_{rotor}}{x_1^2} \right) $$

$$ + \frac{K_9}{\sqrt{n}} \left( \left( \frac{K_2 - y_1 - y_3 - K_5}{\sqrt{1 + a^2}} \right) \frac{y_7}{K_9} \right) \quad (12) $$

$$ M_m = 10y_m M_m. 10^{-9}. \quad (13) $$

Where the factors $K_1, K_2, K_3, K_4, K_5, K_6, K_7, K_8$ and $K_9$ are respectively given as:

$$ K_1 = \frac{\pi}{4} 10^{-6} y_{Fe} V_{rotor} $$

$$ K_2 = \frac{V_{stator}}{V_{rotor}} $$

$$ K_3 = \frac{\mu_s}{\beta_m} \quad + 1, $$

$$ K_4 = \frac{1}{4} \left( K_2^2 - 1 \right) - \frac{K_3 + 1}{2} . K_5 $$

$$ K_5 = h_w + h_{so}, $$

$$ K_7 = \frac{2K_6}{K_5}, K_6 = h_{so} b_{so} $$

$$ \frac{1}{2} h_w a_{wo} + \frac{\mu_s}{\beta_m} K_9, K_9 = 1,095 \left( \frac{\beta_1}{\pi} \right) \quad K_{10} = \frac{y_{Cu}}{10^{-n}}. $$

The other parameters $V_{stator}, V_{rotor}, V_m, B_{rm}, B_{m}, h_w, h_{so}, b_{so}, y_{Fe}, y_{Cu}$ and $y_m$ represent the volume of stator, rotor, magnet, the operating remanence of the magnets at working temperature, the flux density above the magnets, the wedge height, the tooth tip depth, the opening width of the semi-closed slot; the mass density of electrical steel, copper, and magnet respectively.

The cost function becomes:

$$ C = f_1(x) = f_1(y_1, y_2, y_3, y_4, y_5, y_6, y_7). \quad (14) $$

The loss component parts of each part of the core is calculated as:

$$ p_{stator} = \frac{K_{11}}{(y_2y_3y_5^2)^{1.6}} + \frac{K_{12}}{(y_2y_3y_5^2)^{2}}. \quad (15) $$

$$ p_{rotor} = \frac{K_{11}}{(y_2y_3y_5^2)^{1.6}} + \frac{K_{12}}{(y_2y_3y_5^2)^{2}}. \quad (16) $$
where:

\[
K_{11} = k_h f \left( \frac{B_m V_m (K_3 - 1)}{V_\text{rotor} K_j} \right)^{0.6},
\]

\[
K_{12} = k_e f^2 \left( \frac{B_m V_m (K_3 - 1)}{2 V_\text{rotor} K_j} \right)^2,
\]

\[
K_{13} = k_h f \left( \frac{\pi B_m V_m (K_3 - 1)}{q_\phi V_\text{rotor} K_j} \right)^{0.6},
\]

\[
K_{14} = k_e f^2 \left( \frac{\pi B_m V_m (K_3 - 1)}{q_\phi V_\text{rotor} K_j} \right)^2.
\]

The parameters \( f \) and \( K_j \) are the frequency stacking factor of the iron lamination, respectively. The resistance of the winding in each tooth is given as:

\[
R = 2K_{15} n \left( \frac{y_5 + V_\text{rotor}}{y_1^2} \right) + \frac{K_9}{\sqrt{n}} \left( \frac{x_7}{\text{floor} \left( \frac{K_2 - 1}{2} y_1 - y_3 - K_5 \right)} \right) \sqrt{1 + a_1^2}
\]

where \( K_{15} = \frac{\rho_{\text{Cu}}}{10^3} \) and \( \rho_{\text{Cu}} \) is the electrical resistivity of copper. The minimum of total loss means the maximum efficiency. By combining equations (5), (6), (7) together, the total loss function becomes:

\[
P_{\text{loss}} = f_2(x) = f_2(y_5, y_2, y_3, y_4, y_5, y_6, y_7)
\]

### 4. Numerical and optimal results

The test problem is a practical SPMSM given in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>2200</td>
<td>W</td>
</tr>
<tr>
<td>Terminal voltage</td>
<td>380</td>
<td>V</td>
</tr>
<tr>
<td>Number of slots</td>
<td>12</td>
<td>Slot</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>5</td>
<td>Pole</td>
</tr>
<tr>
<td>Rated speed</td>
<td>600</td>
<td>rpm</td>
</tr>
</tbody>
</table>

The distribution of flux density \((B)\) on the stator and rotor before optimization \((\text{top})\) and after optimization \((\text{bottom})\) is pointed out in Figure 2. It can be seen that before optimization, the value of \(B\) is observed to be 2.185 (T), which subsequently increases to 2.208 (T) after the optimization process. This means that there is a slight increase in the flux density on the tooth, but the total loss decreased as a result. This change will not have any adverse effects on the motor's operational parameters.
The pareto front plot of the objective functions is also presented in Figure 6. It is evident that the two objective functions exhibited inverse changes, indicating that a smaller total loss corresponded to a larger material cost, and vice versa. By examining the scatter plot of the Pareto front, we selected the minimum value for the sum of the two objective functions as the basis for calculating the motor parameters.

The optimization results on main parameters of the SPMSM is given in Table 3. The torque ripple percentage decreased by 2.82%, going from 9.26% to 6.44%. Additionally, the motor's efficiency improved from 94.298% to 94.835%. The power factor remained relatively stable, while the total material cost decreased from 358.02$ to 342.8$. Furthermore, the torque output becomes smoother after optimization, indicating a decrease in torque ripple. Although there is a slight increase in the flux density on the tooth, it does not adversely affect any motor parameters during operation. These positive outcomes highlight the favorable comparison between the optimized design and the original configuration.

Table 3. Optimization results on main parameters of the SPMSM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before optimization</th>
<th>After optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator outer diameter (mm)</td>
<td>221.8</td>
<td>218.12</td>
</tr>
<tr>
<td>Stator inner diameter (mm)</td>
<td>135</td>
<td>133</td>
</tr>
<tr>
<td>Tooth width (mm)</td>
<td>12.3</td>
<td>13.4</td>
</tr>
<tr>
<td>Slot height (mm)</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Magnet thickness (mm)</td>
<td>2.45</td>
<td>2.45</td>
</tr>
<tr>
<td>Magnet electrical angle</td>
<td>126</td>
<td>122</td>
</tr>
<tr>
<td>Active length of iron core (mm)</td>
<td>134</td>
<td>138.6</td>
</tr>
<tr>
<td>Number of turns</td>
<td>85</td>
<td>81</td>
</tr>
<tr>
<td>Conductor diameter (mm)</td>
<td>1.55</td>
<td>1.64</td>
</tr>
<tr>
<td>Slot fill factor</td>
<td>0.52</td>
<td>0.55</td>
</tr>
<tr>
<td>Torque Ripple (%)</td>
<td>9.26</td>
<td>6.44</td>
</tr>
</tbody>
</table>
Power factor | 0.93 | 0.93  
Shaft torque (Nm) | 35.3 | 35  
Efficiency (%) | 94.3 | 94.8  
Material cost ($) | 358 | 342.8

**Figure 7.** Thermal equivalent circuit after optimization.

**Figure 8.** Radial view result of the thermal model after optimization.

**Figure 9.** Axial view result of the thermal model after optimization.

**Figure 10.** Temperature distribution in the stator slot after optimization.
The model of thermal equivalent circuit after optimization is presented in Figure 7. Figures 8 and 9 show the radial and axial view results of the thermal model after optimization already given in Figure 7. The Temperature distributions in the stator slot and in in the rotor and PM after optimization are pointed out in Figures 10 and 11. Based on the obtained results from Figure 7 to Figure 11, the maximum temperature of the motor is reduced from 78.4°C to 73.2°C due to a reduction of the total losses. Although these two values of the maximum temperature are both still in the safe threshold for the operation of the motor, but they once again demonstrate the correctness and effectiveness of the motor optimization model.

5. Conclusion

This research paper focuses on the design of a SPMSM using a multi-objective optimization approach that incorporates a genetic algorithm. The dimensions of a 2.2 kW SPMSM with a fractional-slot concentrated winding were computed. The main objective of the optimization process was to minimize two crucial factors: total loss and material cost. To validate the effectiveness of the selected variables and constraints in the optimization method, the motor's efficiency was evaluated using the FEM. The results obtained indicate that the optimized design significantly reduces material costs compared to the original design while maintaining the desired efficiency level, but it also brings about desirable changes in other parameters such as cogging torque and torque ripple. Future work could involve the development and optimization of additional goal functions, such as torque output, cogging torque, and torque ripple. Other optimization methods such as particle swarm optimization, cultural algorithm, bee algorithm, and more, could be attempted to tackle the optimization problems and achieve even better results.

Acknowledgements

This research is funded by Hanoi University of Science and Technology (HUST) under project number T2022-PC-008.

References


