Electrical Parameter Design and Optimization of Permanent Magnet Synchronous Machine Drive

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Abstract. Due to the need to replace fossil fuels with cleaner alternatives, the advancement of electric mobility has accelerated. Based on this, the electric train has been successfully developed and reached the condition. However, logistics and commercial vehicles still need to be sufficiently developed due to the electrical machine efficiency, weight, size, and control technology of the machines. This can be overcome by optimizing the dimensions of machines like winding diameter, length, and magnetic properties. In this study, we discussed various loss assessments, optimized winding size, and examined the mechanical properties of machines, including speed and torque. To examine the efficiency, speed, and torque characteristics of a machine, mathematical calculations are first done. The analytical model is validated through COMSOL, later the speed-torque characteristics are validated using a Simulink/MATLAB model.

1 Introduction

High-speed electric vehicles are rapidly increasing because they are replacing fuel vehicles and are emission-free. In general, there are different types of electrical machines are used for electric vehicles. The selection criteria depend on the requirement of speed, torque, efficiency, manufacturing cost, machine lifetime, maintenance and recycling capability [1-3]. However, high-speed electrical machines have constraints in machine design. Mainly, the electrical machines have constraints of rotor construction design. Secondly, the machine causes high power losses during high-speed operating conditions due to the higher operating frequency. The high operating frequency also generates the possibility of damage to the machine [4-6].

Generally, the losses of the machines are classified as mechanical losses, magnetic losses, and winding losses. The losses that occur at high-speeds are known as AC or high-frequency losses [7],[8]. Many machine design and optimization techniques have been developed to mitigate or eliminate the losses. DC machines are not recommended for electric vehicles due to their lower efficiency and maintenance of carbon brushes and losses [9]. Generally, induction motors and permanent Magnet synchronous Machines (PMSM) are referred to for high-speed applications. The construction difference between the induction machine (IM) and PMSM is rotor winding. The IM has rotor slots to modify the speed of the machine.

The PMSM windings has the permanent magnets for constant speed applications. Generally, IMs are preferred for high-speed applications with high torque because of their robust construction and simple design [10]. The PMSM is used for low and medium-speed applications. Rotor windings of PMSM motors are modified to ensure the maximum speed of electrical applications. Interieur permanent magnet (IPMs) provides high speed due to the high mechanical integrity property of the machine [11]. However, the mechanical design and optimization process does not consider high-frequency power losses. Optimizing the conductor's diameter will minimize the electrical machines' high-frequency losses [12-14]. Iron losses due to high-speed operating conditions are reduced by reducing the thickness of laminations of windings. High current density will improve the speed-torque characteristics of electrical machines. However, this will increase the iron losses of electrical machines. To reduce iron losses, high cooling techniques are required. The cost of PMSM is 20% higher than the IM due to the presence of permanent magnets. However, the overall system cost is less for the same power level due to the higher efficiency of PMSM. The maximum efficiency of the PMSM has constraints with speed and torque ratio [15],[16].

The machine's efficiency is different for the full speed and torque range. It depends on the many parameters, mainly based on the construction of the electrical machine [17]. The PMSM has the higher efficiency during the rated speed operating range, and the IM has the maximum efficiency during the high-speed operating range. Some electrical vehicle

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companies use both machines in electric vehicles. For example, Tesla uses the IM in the front-wheel drive and the PMSM in the rear-wheel drive. This method has the advantages of both machines during variations in speed [16] [17].

The Fig. 1 shows the parameter exchanges between the COMSOL and MATLAB software. This work focuses on the analysis and design process of PMSM electrical machines for the speed Torque characteristics. Also analysis the power loss of the machine. This analysis will be helpful for the design process of the electrical machines.

![Fig. 1. Co-simulation used for PMSM model](image)

The paper is organized as follows: in section II, we analyze the design and optimization of PMSM and section III, we discuss the power losses of the electrical machines; in section IV, we discuss modelling considerations of PMSM using the COMSOL. In section V, we present the simulation results; and section VI concludes the results.

## 2 Design and Optimization of PMSM

The machine design is mainly based on the stator and rotor machines. By changing the inner and outer diameter of the stator and rotor, we can optimize the design of electrical machines. The stator slots we can design, and the rotor slots are PM magnets. By changing the diameter of the machine, we can reduce the machine losses. D1 and D2 are the inner and outer diameters of the machine.

The efficiency of the machine also depends on the diameter of the winding, and the torque equation is given here. The nominal current ($I_n$) of the PMSM machine is given in the equation (1).

$$I_n = \frac{P_n}{\sqrt{3}V_L \cos \phi_n}$$  

The nominal torque($T_n$) of the machine is given in (2)

$$T_n = \frac{P_n}{n_n \pi}$$  

In the above equations, $P_n$ is the line power of the torque, $V_L$ is the line voltage of machine and $\cos \phi_n$ is the power factor.

### A. Rotor Design

The rough estimation of the PM materials is given in (3).

$$V_m = \frac{P_n}{f_B i H_c}$$  

### B. Stator Design

The stator design of the PMSM machine is almost the same as that of the induction machine. The stator design of the machine mainly depends on the inner (D1) and outer diameter (D2) and the stack aspect ratio of the machine. The inner and outer diameter of the PMSM machine has been correlated in (4)

$$D_1 = D_2 \cdot 0.61$$  

The stack aspect ($\lambda$) ratio of the machine has been calculated in (5).

$$\lambda = \frac{L}{\pi D_1}$$  

The airgap power ($S_{ag}$) of the machine in (6)

$$S_{ag} = \frac{K_e P_n}{n_n \cos \phi_n}$$  

### C. Stator winding design

The number of per pole ($q$) and per phase of the stator has been calculated in (7). $N_s$ is the synchronous speed of the machine.

$$q = \frac{N_s}{2 \pi m}$$  

The electrical angle ($\alpha_e$) of the neighboring slots has been calculated in (8).

$$\alpha_e = \frac{2 \pi P}{N_s}$$  

The design and optimization of electrical machines are mainly based on the machine's efficiency, power losses, and compact size and weight. The accuracy of the calculation of the magnetic losses has been verified by the season number by using (9)

$$S_{ag} \cdot 60 \frac{D_1^2}{L n_1} = k_f k_w \pi A_1 B_{ag}$$  

$A_1$ is the cross section of the winding. Bag is the air gap flex density. $K_i$ and $K_w$ are the winding constants.

## 3 Loss Analysis of electrical machines

The machine losses are calculated to calculate the efficiency of the machine. The major the magnetic, mechanical and winding losses.

### A. Magnetic Losses

The magnetic losses of PMSM are high compared with induction machines due to the presence of permanent magnets. Generally, magnetic losses vary with the operating temperature of electrical machines. Magnetic losses are given in (10):

$$P_m(t) = \frac{l_{act}}{\sigma_m} \sum_{i=1}^{n_t} j_{B_{ref},(t)}^2 S_i$$  

Where, $P_m$ is the magnetic losses of the machine, $l_{act}$ length of the conductor, $\sigma_m$ is the conductivity of the magnets, $j_{B_{ref},(t)}$ is the current density, $S_i$ is the area of mesh. The current density is derived from the following (11): where $A_i$ is area of the machine $S_{i}$ is the area of magnet.
\[ J_{M,i(t)} = -\sigma_M \left[ \frac{\partial A_{zi}}{\partial t} - \frac{1}{3M} \sum_{i=1}^{N} \frac{\partial A_{zi}}{\partial t} S_i \right] \] (11)

B. Mechanical Losses

Mechanical losses are high during the high speed operating conditions of the machine. In order to reduce this loss, high design and optimization process is required. Mechanical losses (P_mec) is the combination of bearings losses and windage losses is given in (12):
\[ P_{\text{me}} = P_{\text{bearing}} + P_{\text{windage}} \] (12)

Bearing losses (P_{bearing}) depend on the lubricants on the bearing, speed and load of the machine. To reduce the bearing losses, the diameter of the bearings has to be appropriately optimised. The bearing losses can be calculated from the (13):
\[ P_{\text{bearing}} = 0.5N\mu F D_{\text{bearing}} \] (13)

Where N is the speed of the machine, \( F \) is the load applied to the bearings, and \( D \) is the inner diameter of the bearings.

Windage loss (P_{windage}) is the combination of air gap losses (P_{windage,1}) and end surface rotor losses (P_{windage,2}). Windage loss is expressed in equation (14). The air gap losses and end surface rotor losses can be calculated from the equation (15) and equation (16)
\[ P_{\text{windage}} = P_{\text{windage,1}} + P_{\text{windage,2}} \] (14)
\[ P_{\text{windage,1}} = \frac{1}{32} K C_m \pi \rho D_{\text{out},r}^4 N^3 \] (15)
\[ P_{\text{windage,2}} = \frac{1}{64} C_m \rho (D_{\text{out},r}^5 - D_{\text{out},r}^6) N^3 \] (16)

K is roughness coefficient, \( \rho \) is lubricant coefficient, \( D_{\text{out}} \) is the outer diameter of the rotor, \( l_{\text{act}} \) is actual length of the rotor.

C. Winding Losses

Winding losses (P_{winding}) is the combination of skin effect losses (P_{skin}) and proximity losses (P_{proximity}). This loss also called as high frequency loss. Winding loss equation is given in equation (17)
\[ P_{\text{winding}} = P_{\text{skin}} + P_{\text{proximity}} \] (17)

Skin losses are calculated from the skin resistance \( (R_{\text{skin}}) \) of the conductor and rms current \( (I_{\text{rms}}) \) value of the conductor. The skin resistance mainly depends on the length of the conductor \( (l) \) and diameter of the conductor \( (d) \).
\[ p_{\text{skin}} = R_{\text{skin}} I_{\text{rms}} \] (18)

The proximity loss of the conductor depends on time period (inverse frequency), length of the conductor \( (l) \), conductors conductivity \( (\sigma) \) and magnetic field \( (B) \) of the conductor.
\[ p_{\text{proximity}} = \frac{1}{T} \int_0^T n I_{\text{rms}} dB \frac{dB}{dt} dt \] (19)

The winding losses consume significant losses for the machine. The skin and proximity losses can be controlled by optimizing the diameter and length of the conductor.

While optimizing the machine dimension for the high-speed machines, the variations should be less than 5 %. Less variation minimizes the maximum efficiency. For example, if we increase the machine dimension variations to 6 %, the stator core loss will increase to 35 %, reducing the system's overall efficiency.

D. Modelling Considerations

The Co Simulink model is the concept of integrating the two software to extract the required output. Here, the COMSOL multi-physics modelling is integrated with the MATLAB model. In COMCOL, a finite element model is used to analyze and optimize the mechanical parameters of the PMSM. This analyzed value is fed back to the MATLAB Simulink model. Again, this value fed back to the COMSOL model.

The PMSM model material is given in Fig.2. The motor is considered as a 2D machine to assess the flux density of PMSM effectively. Also, the two pole pairs with eight slots. The rare earth permanent magnet is regarded with its remanent flux density.

In order to determine the maximum magnetic flux density of the machine, soft iron permanent magnetic material is considered. The air gap is considered and windings are considered as distributed type. The modelling mesh must be fine enough to calculate the air gap area. The mesh modeling of machine is given in Fig.3.

The analytical phase resistance of the stator material has been considered as
\[ R_{ph} = \frac{Q L + D_2 \Pi}{M A_1' \text{slot} N \rho_{cu}} \] (20)

A' slot is the cross sectional area of one slot filled with copper, \( Q \) is slot number, \( L \) is motor active length, \( M \) is number of phase and \( N \) is windings turn number.
5 Simulation results and analysis

The high speed PMSM motor speed torque characteristics are analyzed and compared with existing PMSM machine. The simulation parameter values are given in Table I. The Same parameters are used for both the PMSM machine. Both machines are tested in MATLAB/Simulink for maximum power of 40 kW and Maximum rotational speed of 1200 rpm. The magnetic field characteristics and loss analysis of PMSM are analyzed and optimized in COMSOL – FEA. The output speed torque characteristics of the PMSM machines are validated and compared in the MATLAB Simulink.

In construction there is no difference in the machine. But rotor coil and stator windings of the PMSM has been changed in the diameter and core length of the machines.

The magnetic flux density of the PMSM is given in the Fig. 4. It has high flex density. The magnetic field is related to the magnetic characteristics of the inner rotor diameter and also the outer rotor diameter. The diameter of the rotor is based on the conductivity of the conductor.

Table 1. Parameter of High-Speed machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (kW)</td>
<td>40</td>
</tr>
<tr>
<td>Maximum rotational speed (rpm)</td>
<td>1200</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
<td>80</td>
</tr>
<tr>
<td>Number of slots per pole per phase</td>
<td>2</td>
</tr>
<tr>
<td>DC link voltage (V)</td>
<td>500</td>
</tr>
<tr>
<td>Maximum rms current per phase (Amp)</td>
<td>445</td>
</tr>
<tr>
<td>Windings</td>
<td>Distributed-series</td>
</tr>
<tr>
<td>Maximum current density (A/mm²)</td>
<td>15</td>
</tr>
<tr>
<td>Number of pole pair</td>
<td>4</td>
</tr>
<tr>
<td>Flux density (T)</td>
<td>1.2</td>
</tr>
<tr>
<td>Lamination Thickness</td>
<td>0.35</td>
</tr>
</tbody>
</table>

From equations 10 and 11, the machine dimensions are optimized for the PMSM in Table II.

Table 2. Optimized machine dimensions value

<table>
<thead>
<tr>
<th>Machine dimensions</th>
<th>Reference machine</th>
<th>Optimized value</th>
<th>Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Outer Diameter</td>
<td>200.0 mm</td>
<td>198.1 mm</td>
<td>0.9 %</td>
</tr>
<tr>
<td>Stator Inner Diameter</td>
<td>126.0 mm</td>
<td>124.6 mm</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Rotor Outer Diameter</td>
<td>125.0 mm</td>
<td>123.9 mm</td>
<td>0.16 %</td>
</tr>
<tr>
<td>Rotor Inner Diameter</td>
<td>120.0 mm</td>
<td>53.4 mm</td>
<td>0.15 %</td>
</tr>
<tr>
<td>core length</td>
<td>120.0 mm</td>
<td>116.8 mm</td>
<td>2.75 %</td>
</tr>
<tr>
<td>Volume of machine</td>
<td>1450.0 cm³</td>
<td>1425.4 cm³</td>
<td>1.64 %</td>
</tr>
</tbody>
</table>

From Table II, we can infer that the volume of the machine has been reduced. The speed and torque characteristics of existing PMSM is given in Fig. 7 and
Fig. 8. And the speed and torque characteristics of proposed PMSM is given in Fig. 9 and Fig. 10. From the figure Fig. 9, it has clearly shows the high starting torque compared to the existing system. In Fig. 10, the proposed machine has the high speed compared with existing machine for the same power rating. And also from the losses analysis, the proposed PMSM has less losses with existing machine. From the table II, the volume the PMSM machine also reduced with proposed system.

6 Conclusion
The inner and outer diameter and core length of electrical machines are designed and optimized. The iron and winding losses of the three-phase PMSM machine are examined. This research demonstrates how the dimensions of electrical machines are planned, optimized, and compared to traditional machines. The PMSM machine's size-based design ensures a smaller overall machine footprint. The losses analysis of the PMSM machines are analysed using the COMSOL. The torque and speed characteristics of the PMSM are examined using the optimized values and compared to the same conventional rating of PMSM using the MATLAB/Simulink tool. As soon as the machine attained its rated speed, it suggests that the optimized PMSM torque and speed has been recommended for the high power Electrical Vehicle applications. The super conducting material analysis will be made for the proposed machine in the future.

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