Modelling and Optimization of Interior Permanent Magnet Motor for Electric Vehicle Applications and Effect on Sustainable Transportation

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Abstract. Electric vehicles support low-carbon emissions that facilitate sustainable transportation. This paper explores different design parameters to optimize an interior permanent magnet synchronous motor that contributes to enhancing motor performance hence advancement of sustainable transportation. Various geometry parameters such as magnet dimension, machine diameter, stator teeth height, and number of pole pair are analysed to compare overall torque, power, and torque ripples in order to select the best design parameters and their ranges. Pyleecan, a comparatively new open-source software, is used to design and optimize the motor for electric vehicle applications. It is verified with Motor-CAD software to observe the performance of the Pyleecan software. Following optimisation with NSGA-II algorithm, two designs A and B were obtained for two different objective functions of maximizing torque and minimizing torque ripple and the corresponding torque ripples values of the design A and B are later reduced by 32% and 77%. Additionally, the impact of different magnet grades on the output performances are analysed.

Keywords: Electric Vehicles, IPM Motor, Magnet Grade, Optimization, Permanent Magnet Motor, Torque Ripple

1 Introduction

Electric vehicles (EV) are playing key role for clean energy and total emission reductions that helps sustainable transportation. It is a next-generation mobility technology to meet the global emission reduction targets especially those set out in the Paris Agreement [1] and the European Union (EU). The transition towards electrification of vehicles plays a crucial role in creating a greener and more sustainable future. Compared to classic internal combustion engines (ICE), electric motors used in EVs are significantly more efficient. Due to high efficiency and torque density, A growing proportion of electric vehicles are now based on Permanent Magnet (PM) motors. The most viable solutions in the automotive industry to reduce the environmental impacts of urban mobility, to improve air quality, and to achieve emissions targets is optimization of electric vehicle motors with objectives of high torque and power densities, as well as producing low-cost solutions through materials and mass manufacturing capabilities [2]. Therefore, to ensure the advancement of sustainable transportation highly efficient motor for electric vehicles is a key requirement.

One of the bottlenecks of interior permanent magnet synchronous motor (IPMSM) operation is known as the cogging torque [3]. The interaction between the stator teeth and rotor magnets, and the permeance variations during the magnet rotation lead to the production of cogging torque, which eventually lead to audible noise, vibration, fluctuation in speed, and the introduction of torque ripples. In case of motion control applications, these torque ripples result in significant deterioration of the motor performance and therefore, it is an important aspect to address. Multiple parameters have been identified in the literature [4-7] to have an influence on torque ripples including slot pole combination [8], stator slot opening, slot width, slot height, notch radius [9], airgap length [10], stack length, pole numbers, magnet dimensions, magnet shape and position.

Various studies have explored this issue, and it is understood that one of the most common methods of combating this is by magnet skewing with surface mounted magnets [3],[11]. Magnet skewing involves dividing the magnet into layers and placing them in the rotor in different radial positions that vary by a small angle [12]. The major disadvantage of this method is that it increases cost and manufacturing complexity. Another method of skewing is the stator skewing. However, this complicates automatic winding, and it is not widely popular in mass manufacturing environments.

In order to address the torque ripples issue, an alternative solution has been proposed by optimizing parameters such as number of poles, magnet dimension, stator teeth height, and stator diameter.

The main purpose of this paper is to identify the best component sizing for a given set of requirements and to investigate the trade-offs between torque, power, and torque ripples. A new Open-Source software called Pyleecan is used to analyze the motor characteristics, design and optimize the motor in view of output constraints such as maximum torque and minimum torque ripples. This paper investigates the tradeoffs between objectives of maximizing torque and minimizing torque ripples, ensuring that the 'best possible' physical motor parameters are selected through optimization. The paper ends with a discussion of the advantages and disadvantages of the optimized designs, along with the effect of different magnet grades.

This work adopted the Tesla Model 3 motor [13] as a baseline design which is a light duty passengers' vehicle and employs NSGA-II optimization to investigate the trade-offs between two different objective functions of maximizing torque and minimizing torque ripples. Additionally, the impact of different magnet grades on output performances are analyzed.

2 Methodology

The electromagnetic model of the IPM motor is described at the beginning of this section. After that, the model using Pyleecan software [14] is outlined. The verification of electromagnetic model using Motor-CAD software [15] comes after that. Next, the optimization process, use of different magnet grades and sensitivity analysis are described.

2.1 Electromagnetic Model

The analytical model of Interior Permanent Magnet motor is modelled in the steady state. MATLAB [22] is used for the analytical model based on a 54 slot 6 pole IPM motor from the Tesla Model 3 and verified using two different software Pyleecan and Motor-CAD. The magnetic properties of the chosen magnet materials are provided in [16]. The Magnets are "V shaped". Table 1 gives the initial motor specifications for the baseline design.

Table 1. Initial motor specifications

Number of pole pairs	6
Stator outer diameter (mm)	232.1
Stator inner diameter (mm)	151.5
Rotor outer diameter (mm)	148
Rotor inner diameter (mm)	70
Stack length (mm)	135
Airgap (mm)	0.85
Number of Slot	54
Magnet material	N40 UH
Rated RMS current (A)	800
Rated Speed (RPM)	17900

The steady state voltage equations for d and q axes of an IPMSM are presented by equations (1) and (2) [17].

$$v_q = R_s i_q + w_e \lambda_m + w_e L_d i_d \quad (1)$$

$$v_d = R_s i_d - w_e L_q i_q \quad (2)$$

where v_q, v_d , i_q, i_d are q and d axis voltages and currents, L_q, L_d are q and d axis inductances, Rs shows phase resistance, ω_e is electrical frequency and λ_m is permanent magnet flux linkage. The electromagnetic torque developed for an IPM motor can also be found as, [17]

$$T_{em} = \frac{3p}{2}\left[\lambda_m i_q + \left(L_d - L_q\right)\right] i_d i_q \quad (3)$$

where, p is the number of pole pairs.

2.2 Pyleecan Model

A Python-based open-source software Pyleecan (PYthon Library for Electrical Engineering Computational ANalysis) [14] is used to verify the analytical design. The software includes object-oriented modelling of 2D machines and multi-objective optimization [18]. In this study, the Graphical User Interface of this software is used to model the IPM motor, where the design parameters of the machine are defined in their respective sections. The electromagnetic model of the motor is then simulated using the magnetic and electrical modules in the software is used to simulate and observe the output performance of the machine. The Pyleecan model of the IPM motor is shown in Fig. 1.

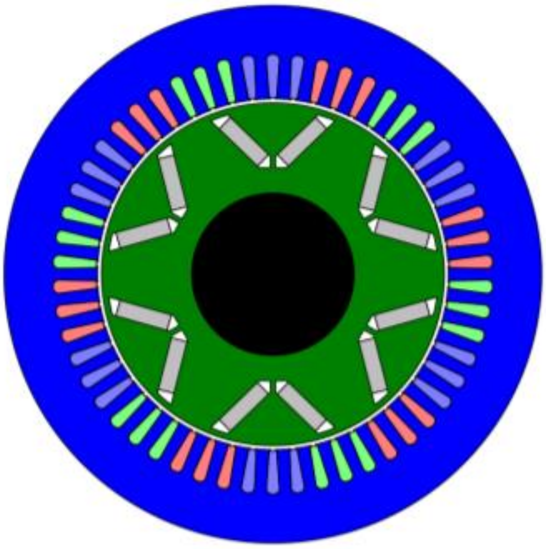

Fig. 1. IPM motor design in Pyleecan

The air gap flux density of the Pyleecan model differs by only 3% from the analytical design, which gives good validity of the model.

The overall torque of the above simulated motor is 402 Nm and the power is 167 kW. The output of the above simulated motor is given in Fig. 2. It can be observed that there is a high fluctuation in torque of 30.57 Nm, which is the peak-to-peak value of the torque ripples.

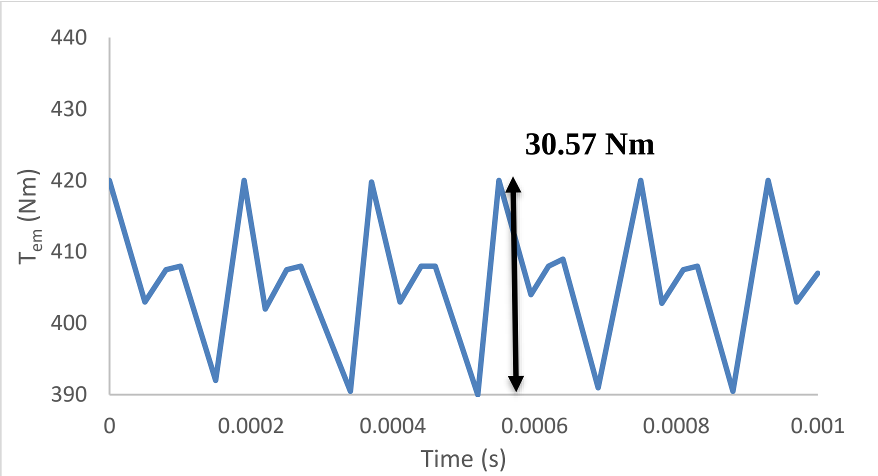

Fig. 2. Motor output with torque ripples

2.3 Motor-CAD Model

The electromagnetic model of the IPM motor again verified using Motor-CAD software [15] to observe the performance of the comparatively new open-source software Pyleecan. Fig. 3 shows the developed electromagnetic model using Motor-CAD.

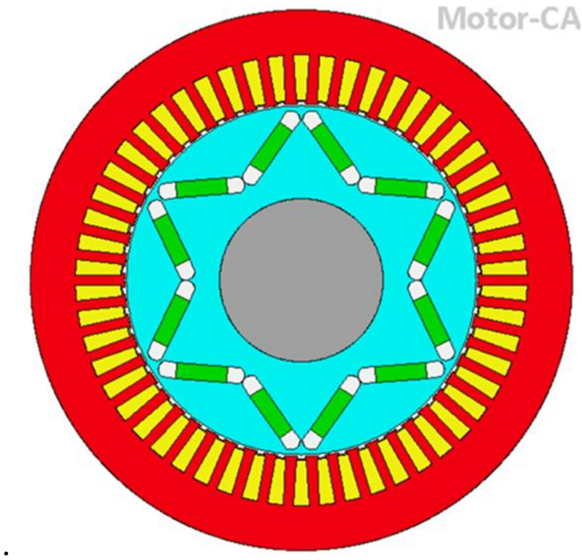

Fig. 3. IPM motor design in Motor-CAD

Output results of Motor-CAD model shows good validity of Pyleecan model. Fig. 4 gives the Torque Speed characteristics of the IPM motor for different model.

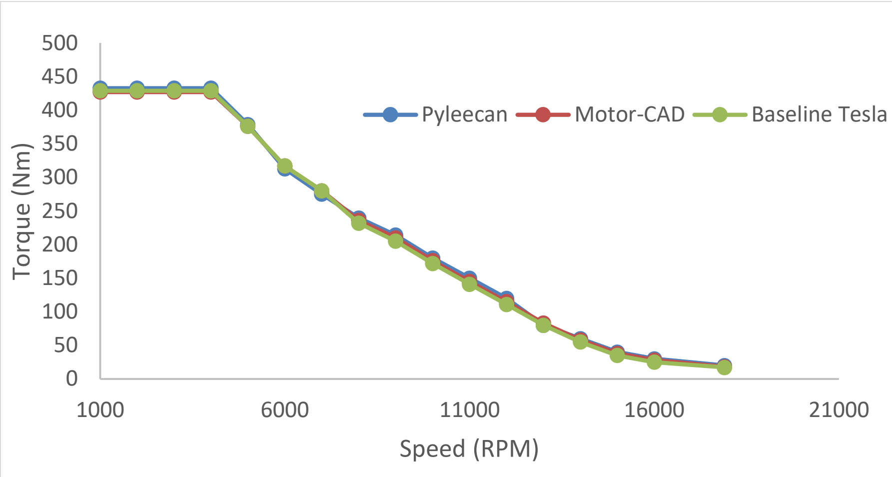

Fig. 4. Torque Speed characteristics of the IPM motor for Baseline Tesla, Pyleecan and Motor-CAD model

2.4 Optimization

To optimize the IPM motor, the Pyleecan software [14] is used. This software utilizes one of the most efficient algorithms in the realm of multi-objective optimizations, the NSGA-II algorithm [19]. In this study, it is particularly suitable due to its speed and accuracy. A random initial population is generated in this optimization method and the goal is to narrow down designs that meet the objective of the optimization and rank them. From the population, the offsprings are generated through selection, crossover, and mutation. This process repeats until the algorithm terminates [20].

To maximize the torque and minimize the torque ripple, optimal designs can be given as [21]

$$Design\ A = maxF_1(x) \tag{4}$$

$$Design\ B = minF_2(x) \tag{5}$$

Where *x* boundary limits and constraints for the optimization.

Table 2. Boundary limits for the independent variables

Independent variables	LB	UB
Number of pole pairs	6	8
Stator teeth height (mm)	15	30
Stator outer diameter (mm)	115	120
Magnet length (mm)	15	25
Magnet width (mm)	4	8.5

In this study, magnet height, magnet width, stator teeth height, number of pole pair, and stator diameter is chosen as independent variables for the optimization. The size of population is set as 52 and the number of generations as 8. Table 2 shows the lower boundaries (LB) and the upper boundaries (UB) for the independent variables.

2.5 Different Magnet Grades

The output performances were analyzed by replacing baseline magnet grade N40UH with different magnet grades of same temperature range. Different magnet grades are used to see the effect on motor performances for the same amount of magnet. Table 3 shows different Neodymium magnet grades that were used for this analysis.

Table 3. Different magnet grades [16]

Magnet grade	Remanent flux density(T)
N30UH	1.13
N35UH	1.21
N40UH	1.29
N42UH	1.31

3 Results and Discussions

Table 4 gives the results of the optimization process for optimal design A (maximum torque) and B (minimum torque ripple). Design A gives a small reduction in torque ripples and an increase in torque and power by increasing magnet width, stator diameter, teeth height and reducing magnet length while maintaining the number of pole pair. Whereas, design B has increased pole number, stator diameter, teeth height and reduced magnet length while magnet width is maintained.

Table 4. Optimization results

	Baseline	Design A	Design B
Number of pole pairs	6	6	8
Stator teeth height (mm)	18.8	19.2	22
Stator outer diameter (mm)	116.05	117	120
Magnet length (mm)	25	24	22
Magnet width (mm)	7	8	7
Torque (Nm)	402	417	380
Torque Ripples (Nm)	30.57	20.74	6.88
Power (kW)	167	173	148

Design B significantly reduced torque ripples, but it is accompanied by a small reduction in torque and power.

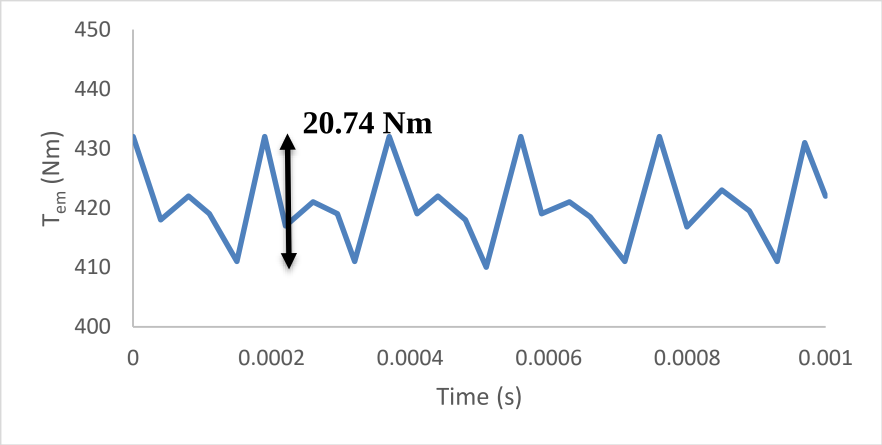

Fig. 5. Torque and torque ripple of Design A

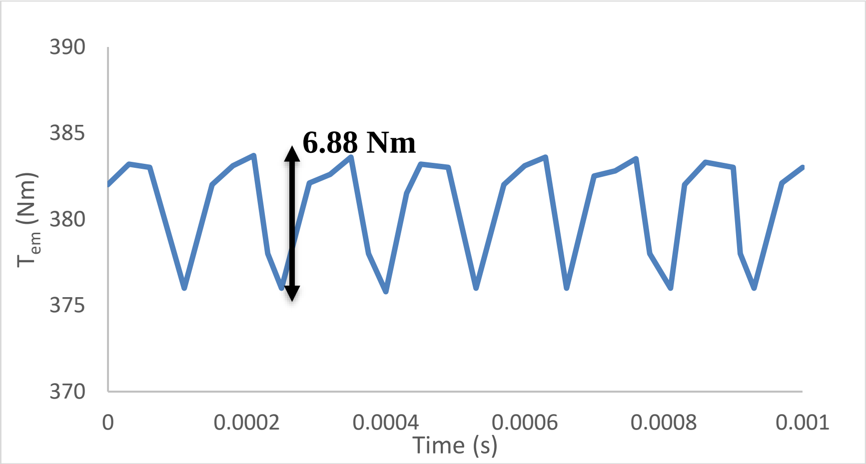

Fig. 6. Torque and torque ripples of Design B

Fig. 5 and Fig. 6 shows the torque ripple of design A and design B. Table 5 illustrates that, for same amount of magnet, replacing the magnet grade increase torque and power with increasing magnet grade.

Table 5. Effect of different magnet grades

Magnet Grade	Design A		Design B	
	Torque(Nm)	Power (kW)	Torque(Nm)	Power (kW)
N30UH	381	152	341	126
N35UH	390	158	354	134
N40UH	417	173	380	148
N42UH	425	175	389	154

4 CONCLUSION

This paper optimized IPM motor for electric vehicle and explored the effects on sustainable transportation. This paper presented the issue of cogging torque and its effect on the performance of interior permanent magnet motors. The optimization yielded two designs whose performances are compared in terms of the overall torque, torque ripples, and power. This demonstrated that the design B with increased pole number, stator diameter, teeth height, and reduced magnet length had a superior performance in terms of torque ripples, which is reduced by 77% compared to that of the initial design. Furthermore, analysis was extended to the performance of designs based on different magnet grades and their respective results were compared. It can be seen that for the same amount of magnet, replacing the magnet grade increase torque and power with increasing magnet grades. It is also shown that optimization of EV motor to maximize torque and to minimize torque ripples can improve the performance of EV which can play an important role to fulfil the requirements of sustainable transportation. Further research can be performed on cost of energy and different motor topologies to see the effect on EV.

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