OPTIMAL DESIGN OF HIGH-PERFORMANCE INTERIOR PM MOTOR FOR ELECTRIC VEHICLE

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ABSTRACT

Interior permanent magnet synchronous motors (IPMSMs) are widely used in electric vehicles (EVs) due to their electrical and mechanical characteristics. In addition to the magnetic torque generated by the magnets in the IPMSM motors, a higher torque density is achieved by generating reluctance torque resulting from the inductance variation of the rotor on the d-q axes. Therefore, rotor and magnet geometry have significant effects on the motor performance. In an IPM design, it is often desirable to have maximum torque and flux weakening capability, minimum torque ripple, and low rotor harmonic losses. For this reason, rotor geometry is the most important part that affects the overall performance of the motor. In this study, a 100kW, single layer design V-shape structure IPMSM has been designed. The motor is optimized by considering important geometric data such as rotor geometry, magnet dimensions, bridge and flux barrier. Thus, it is aimed to design an optimum IPM traction motor considering efficiency and cost criteria. Also, the study provides design criteria that can meet low leakage flux and low cogging torque requirements for rotor topologies with V-shaped structures. 2D finite element analyzes have been used to verify the theoretically optimized designs.

Keywords: Electric vehicle, interior magnet motor, flux barrier, FEM.

1. INTRODUCTION

Today, designing and using practical, efficient and environmentally friendly products is an inevitable necessity. Electric bicycles, electric motorcycles, and electric cars are among the best examples of these products. In electric vehicles, the torque transferred to the wheels is produced by the electric motor used in the vehicle. Therefore, the performance of the electric vehicles is directly related to the selection of the electric motor used. Synchronous, asynchronous, reluctance, and DC motors can be used in electric vehicles. Although DC motors are easily controlled among these machines, having a commutator and brush cause them to need frequent maintenance. The torque fluctuations of reluctance motors lead these motors to be disadvantageous in this kind of applications. In asynchronous motors, the power density is smaller than permanent magnet brushless motors and limits the use of these machines for high power density applications [1]. The developments in the field of power electronics and the permanent magnet materials accelerated the development of permanent magnet synchronous motors compared to other electric machines. These motors are preferred in many applications in the industry because of their high efficiency, low volume, and high torque/weight ratios [2]. In the literature, permanent magnet synchronous motors (PMSM) with different topologies were compared especially for electric vehicles [3-5]. And also, different rotor structures (spoke-type PMs, tangential-type PMs, U-shape PMs, and V-shape PMs) have been examined for electric vehicles. V-shape rotor structure was found to be superior to others [6]. Also, the V-shape structure has the lowest value in terms of magnet consumption. In W-shape, high efficiency can be obtained in wide speed range [7]. In terms of magnet placement technology, surface mounted permanent magnet motors (SMPMSM) do not have enough overload capacity compared to buried ones. Interior permanent magnet (IPM) motors can be also disadvantageous in terms of production costs because of the need for a high number of stator slots to control their harmonic losses [8]. It was determined that IPM machines give higher efficiency at low speeds, and surface mounted ones give higher efficiency at high speeds [9].

In this study, the design of a 100 kW IPM motor with V-shape rotor for electric vehicles has been performed and optimization of rotor geometry which is aiming different design criteria has been realized. As with other electrical machines, the geometric components that constitute the magnetic circuit in electric motors with high-performance expectations have a significant impact on motor performance. For this reason, the parameters that constitute the rotor geometry of a V-shape IPM motor have been defined as variables. Geometric parameters have been obtained which provide the most suitable designs for maximum power, maximum efficiency/cost ratio, and maximum efficiency criteria. Also, different analyzes and comparative studies have been implemented.

2. ELECTRIC VEHICLES

Electric vehicle (EV) technology has been available since the invention of the car. However, in the early 1900s, the internal combustion engines were more attractive due to their low weight to power ratio and the high energy density of the petroleum used for fuel. Although electric drive systems are superior to the internal combustion system, they were in the background until the 1970s due to the low energy density of the batteries. The oil crisis that occurred in 1970 resulted in an increase in oil prices and attention to the electric vehicles have been reawakened [2].

In 1997, Toyota was developed the Prius which was the first modern hybrid electric vehicle. Then Honda Insight and Honda Civic hybrid electric vehicles were produced. Generally, there are three different drive technology in EVs. First one is a battery-powered electric vehicle (all-electrical), the second one is classic internal combustion vehicles and the third one is hybrid electric vehicles with more than one drive unit. Figure 1 shows the principle of three types of structures.

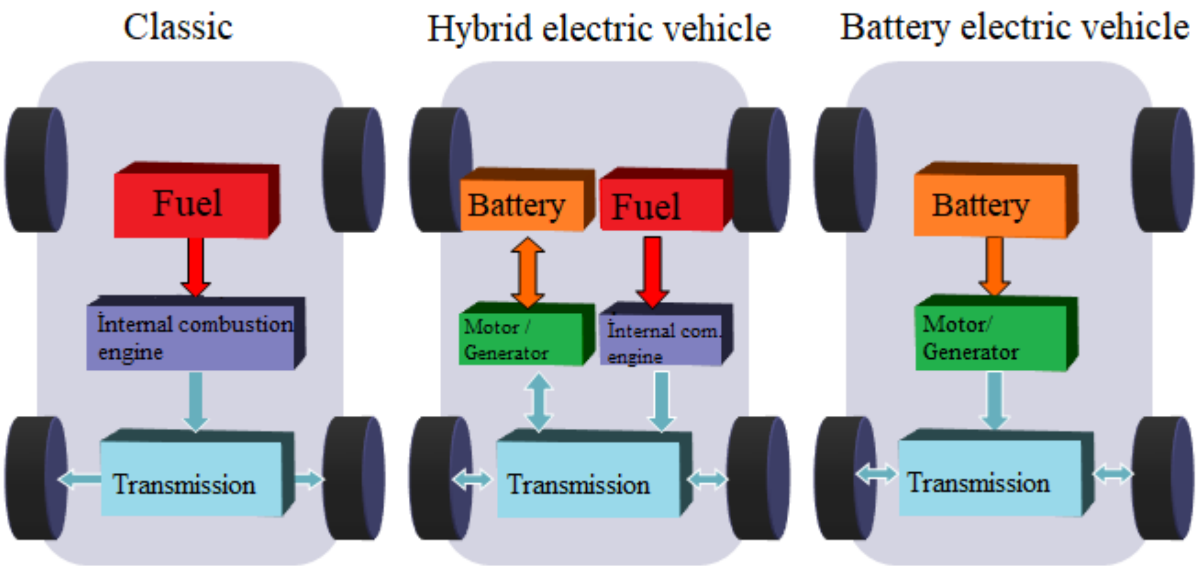


Figure 1. Details of Vehicles According to Drive Unit and Operation [2].

In the battery electric vehicles (BEV), the wheels are driven by electric motor. In this structure, the power of the electric motor is only supplied by the batteries. Since BEV do not use fossil fuels, they do not release emissions. Furthermore, fuel and maintenance costs are also lower than others [10-12] In the hybrid electric vehicle (HEV), in addition to the all-electric system, an internal combustion engine has been added. In this type of vehicles, fuel efficiency is significantly increased and emission values are reduced compared to conventional vehicles [13,14].

3. DESIGNED INTERIOR PM MOTOR

The designed motor has an internal rotor and V-shape buried structure. In the PMSMs, there is no rotor winding losses because the rotor magnetic field is obtained from magnets instead of rotor conductors. Moreover, PMSMs are preferred in many areas because of their high power and torque density [15-17]. Despite the high cost of rare earth magnets, permanent magnets (PM) are preferred especially for high efficiency and power density applications [18]. There are already different types of PM materials in the industry.

PMs consist of iron, nickel and cobalt alloys. PMs have a wide BH curve, high magnetic remanence and coercive force [19]. The maximum energy product value (BHmax) of a magnet is expressed by the product of the magnetic field intensity (H) and the magnetic flux density (B). In the study, high-temperature NdFeB type magnets with high BHmax are preferred. The characteristics of the initial design are given in Table 1.

Table 1. Parameters of the Initial Design.

Parameter		Value	Unit
Rated output power		100	kW
Supply voltage		425	V
Rated frequency		300	Hz
Rated speed		4500	rpm
Number of poles		8	-
Number of slots		48	-
Stator	Outer diameter	245	mm
	Inner diameter	170	mm
	Length	120	mm
	Material	M210-35A	-
	Coil pitch	5	-
Rotor	Outer diameter	168.5	mm
	Inner diameter	110	mm
	Material	M210-35A	-
Magnet	Material	N40UH	-

2D and 3D models of the initial design are given in Figure 2. In order to see the motor structure in more detail, the motor is given in a split structure.

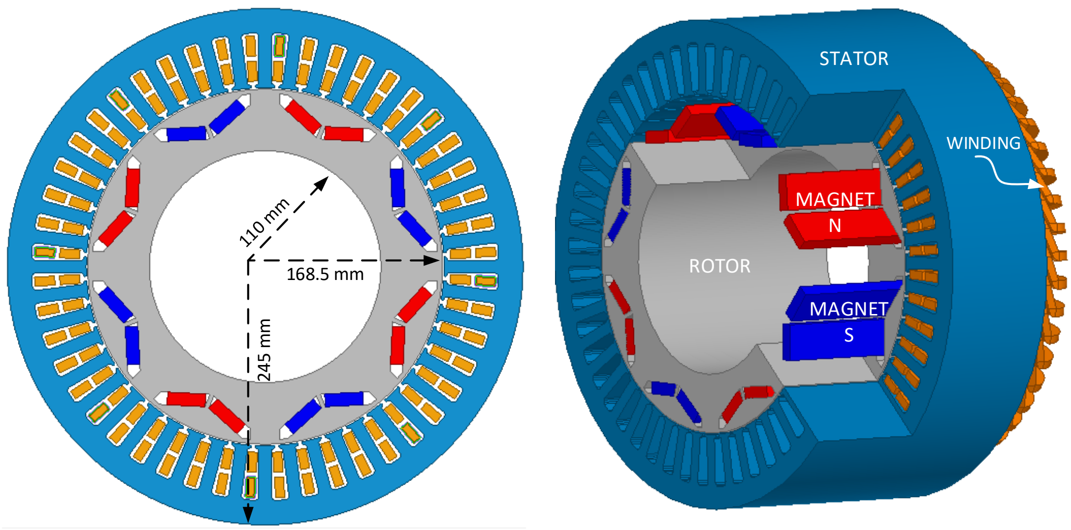


Figure 2. 2D and 3D View of Initial Design.

Some criteria should be taken into account when designing an electrical machine. These criteria can be classified as low-cost design, efficient design, balanced design and high-power density design. In this study, motor designs with different rotor geometries have been performed considering maximum power, maximum efficiency/cost ratio and maximum efficiency criteria. In PM machines, the most important component of the cost is the magnet material. For this reason, total magnet weight needs to be optimized in order to obtain low-cost design. In some specific applications, instead of the best efficiency, maximum output power may be at the forefront due to the requirement of a low-volume motor. On the other hand, designs aimed to get higher efficiency often bring about an increase in motor costs. For this reason, maximum efficiency/cost ratio can be the most important criterion to be taken into account for a motor especially used in EV applications. In order to provide the three criteria mentioned above, the parameters of the rotor geometry are defined as a variable. For the analysis studies, the upper and lower limits of these variables have been determined within the mechanical limitations and are given in Table 2.

Table2. Defined Variables and Their Values for the Rotor Geometry.

Parameter	Value
Magnet thickness	from 5 mm to 8 mm, step = 1 mm
Magnet width	from 20 mm to 40 mm, step = 1 mm
R_{ib}	from 10 mm to 15 mm, step = 1 mm
O2	from 5 mm to 13 mm, step = 1 mm

Defined variables are shown on the rotor the motor geometry in Figure 3. R_{ib} is the distance between magnet barriers and O2 is the distance between the magnets and rotor inner diameter. In addition, magnet width and thickness are defined as other variables

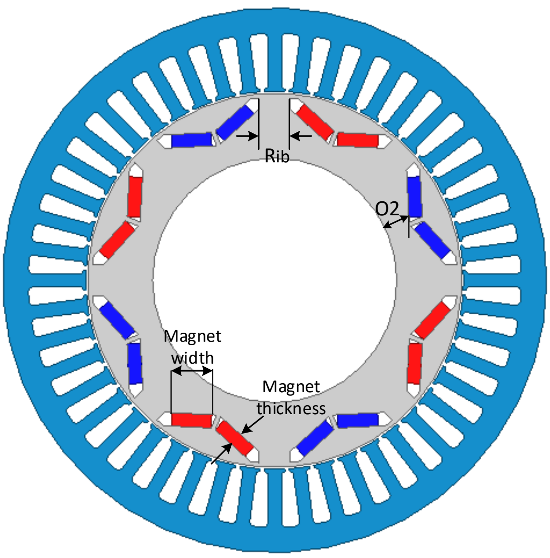


Figure 3. View of Defined Variables on the Rotor Geometry.

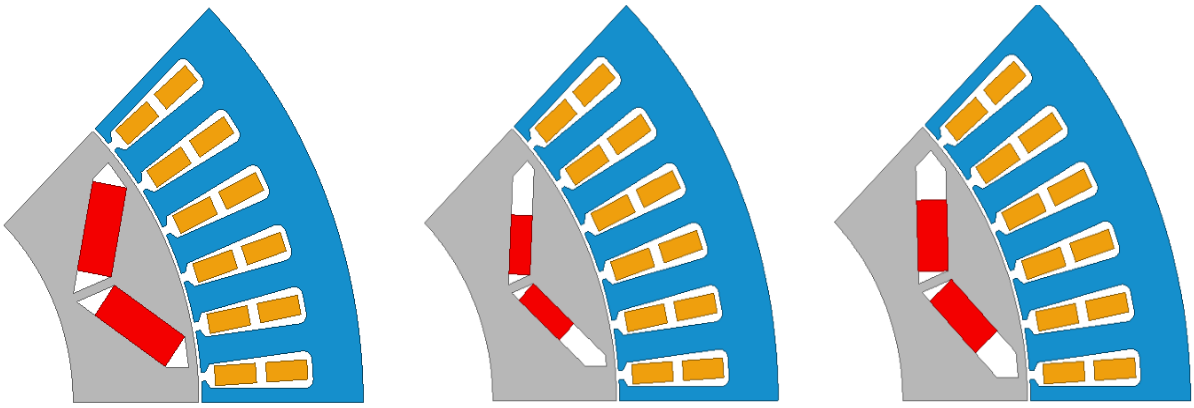
4. ANALYSIS RESULTS

Parametric solution method used in optimization of electric motors is a result oriented, fast and practical. In this method, geometric parameters of the motor are defined as a variable. By determining the lower and upper limits of the variable, the analysis is carried out in the desired solution steps. The solution range directly affects solution accuracy and analysis time. As the step sensitivity increases, analysis time will be longer as expected [20]. In the study, a total of 4536 different analysis have been performed. This number varies according to the sensitivity of the variables. Since the general trend of geometric variables is the primary target, the steps for the solutions have been expressed in 1mm intervals. According to analysis results, the maximum output power, the highest efficiency/cost ratio and the best efficiency design have been obtained and given in Table 3.

Table3. Obtained Parameters Satisfying the Given Design Criteria.

	Maximum output power (Design A)	Maximum efficiency/cost ratio (Design B)	Maximum efficiency (Design C)
Parameter	**Value**	**Value**	**Value**
Magnet thickness	8 mm	5 mm	7 mm
Magnet width	40 mm	26 mm	31 mm
R_{ib}	5 mm	9 mm	9 mm
O2	15 mm	15 mm	10 mm

By using symmetrical boundary conditions, 1/8 symmetrical view of the three different motors which have been optimized is given in Figure 4. Solution time was reduced by the boundary conditions applied to the motor model.



Design A Design B Design C

Figure 4. Views of A, B and C Designs.

The performance of the motors for Design A, Design B, and Design C has been given in Table 4. Design A is the design that fulfils maximum power criteria. The motor geometry which provides maximum output power criteria need a higher magnet consumption so this leads to higher cost as expected. Design C has the highest efficiency among the solutions. Design B is the design that which fulfils maximum efficiency/cost ratio. In all design variations, 100 kW output power is the minimum requirement to be a valid design.

For this reason, designs that cannot provide this output power have not been taken into consideration even if they have lower costs or higher efficiency. Since the cost function has been expressed directly as the amount of magnet consumption, Design B has been considered to be the most suitable candidate for electric vehicle applications.

Table 4. Motor Performances Satisfying the Proposed Criteria.

	Efficiency (%)	Total magnet consumption (kg)	Maximum output power (kW)
Design A	94.31	2.27	234
Design B	95.65	0.92	102.8
Design C	97.91	1.54	147.4

The motor models which successfully passed the analytical design and optimization criteria have been subjected to finite element analysis. The finite element method (FEM) is a method in which an approximate solution of general differential equations in a specified region has been performed. With this method, heat transfer, solid and liquid mechanics and electromagnetic problems can be solved. The use of FEM in electrical machines gives the designer a great advantage both time and economy. In addition, electrical and electromagnetic parameters of the machine have been analyzed with high accuracy rate with this method. [17, 21]. The magnetic flux density distribution for the obtained three designs have been given in Figure 5.

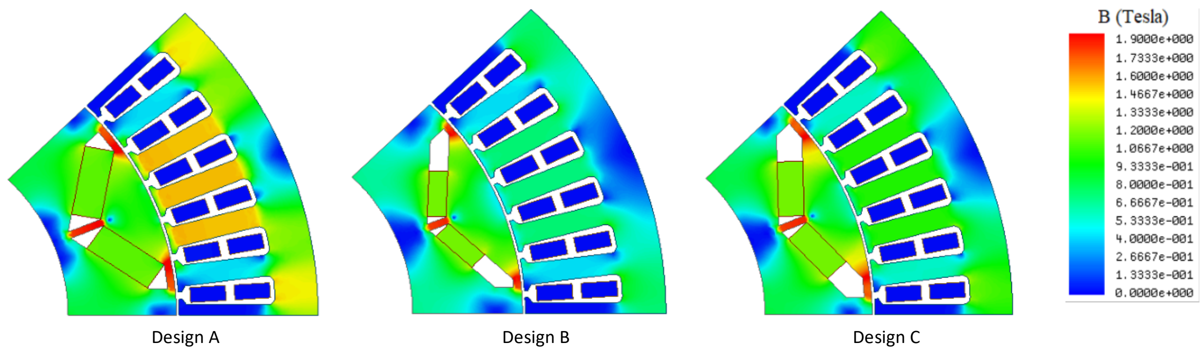


Figure 5. 2D Magnetic Flux Density Distributions for Design A, B, and C.

When the magnetic flux densities are examined, the flux density increases partly as the magnet thickness increases due to decreasing core cross section. It is seen that when considering the M210-35A core material, the flux values fulfil the requirements.

5. CONCLUSIONS

This paper has presented the design details and rotor geometry optimization which fulfils different design criteria of interior permanent magnet synchronous motors for electric vehicles. Motor models have been created which provide the best efficiency, highest output power, and best efficiency/cost ratio criteria by using a parametric approximation method. The performances of three different designs have been obtained with the help of finite element analysis. Considering the results of the study, it has been seen that designs targeting maximum output power result in high cost and relatively low efficiency. In addition, it has been observed that providing the highest efficiency criteria alone would not be the right approach and would usually result in very high costs. It has been seen that the maximum efficiency/cost ratio criterion is the most appropriate approach. The uncertain fluctuation in magnet prices leads to an increase of the studies that focus on the reduction of the magnet consumption. In the systems fed by the battery, efficiency is the most important performance value. As a result, the study provided a geometry-based optimization approach to the studies that can be performed to achieve maximum efficiency with minimum cost.

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