Electromagnetic Performance Analysis of Outer Halbach Magnet Rotor Brushless DC Motor 150kW

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Abstract

In this paper, an outer rotor electric bike brushless DC motor of 200 KW for Electric Vehicles is investigated with different magnet topologies. Magnetic angle and Halfbach arrangement are varied to evaluate their electromagnetic torque, forces, and temperature distribution. The power and torque density and efficiency performance have been also studied and compared with IPM motors with the same geometry and power drives. This study for applying an auto-design program is to find out suitable permanent magnetic parameters and winding size after iterations. This program allows us to estimate the magnetic flux density, electromagnetic torque, and ripple torque via a finite element magnetic method (FEMM). To reduce the cogging torque ripple and harmonic order of Back EMF, the magnet angle and Halbach topology will be validated by the FEM simulation. The simulated results are also compared with the measured results from the experimental test system.

Keywords
Brushless DC motor, Special Power Electric Engineering (SPEED), Finite element method (FEM).

1. Introduction
An external rotor brushless (BL) DC motor for the electric vehicle has been proposed by many publications about the maximum efficiency, and torque performances. Such as the Raymond (2002) proposed the Response Surface Methodology that is process and product optimization using designed experments; the Annette (2007) developed performance evaluation BLDC for electric bicycles: the power, torque, and speed characteristics have been investigated by a function of load, speed; the Yang with an optimal design procedure for a rim motor would make electric powered wheelchairs foldable, light, fuel-efficient; Xie (2012) developed the optimal design of transverse flux machine for high contribution of permanent magnet; Lee (2015) has a design and comparison of multistage axial flux permanent magnet machines, Chung (2015) developed the method of a 20-pole- 24-slot with consequent pole rotor. This paper aims to provide an optimal design of an outer motor 200kW as an electric vehicle. The objective of the optimal design of this Outer rotor BLDC motor is to improve the output characteristics of the motor and to have a stator form to facilitate automatic winding. The response surface methodology is developed for the optimal design and the 2-D model is used for electromagnetic field analysis. It is designed to have cost-effective fabrication. For the rotor part, a solid core is used to save cost according to the lamination process. For the stator part, an optimal design is performed to form a stator core and to facilitate automatic winding. The finite element method (FEM) is applied to the required electromagnetic field analysis during the design process.

2. Specification of in-wheel motor
The design specifications of the in-wheel motor are summarized in Table 1. They are considered as meeting the requirements of the battery and the controller as well as the own performances of the E-bike. The rated output power of the in-wheel motor was experimentally settled as 150kW by considering the weight of the E-car and the capacity of the battery.

Table 1. Specifications of in-wheel motor

Parameter	**Value**		**Unit**
Pole Number	24	24	
Back Iron Thickness	3	2	mm
Magnet Thickness	1.5	1.2	mm
Magnet Arc [ED]	135	120	
Magnet Segments	3	1	
Banding Thickness	0	0	
Slot Number	27	27	
Armature Diameter	120	120	mm
Tooth Width	5	3.5	mm
Slot Depth	15	9	mm
Slot Corner Radius	0	0	
Slot Opening	1.8	1.8	mm
Tooth Tip Depth	0.75	0.75	mm
Tooth Tip Angle	15	15	
Airgap	0.5	0.5	mm
Sleeve Thickness	0	0	
Axle Dia	58	58	mm
Number Strands in Hand	4	4	
Phases:	3	3	
Turns:	12	12	

To automate an armature winding, the specifications of restrictions on the automatic winding machine should be checked. The maximum diameter of a strand of wire that can be caught by a needle of the automatic winding machine and the maximum number of strands that the automatic winding is available are considered as design specifications. The dimensions of the in-wheel motor are limited by the size of the wheel. Therefore, the slot open width of the stator is also limited by the needle of the automatic winding machine because the needle moves around the entrance slot.

Table 2. Parameter of armature winding

Parameter	**Material**	**Weight (kg)**	
Stator Lam (Back Iron)	M350-50A	2.208	2.208
Stator Lam (Tooth)	M350-50A	1.334	1.334
Stator Lamination [Total]		3.543	3.543
Armature Winding [Active]	Copper (Annealed)	0.9311	0.9311
Armature EWdg [Front]	Copper (Annealed)	0.07692	0.07692
Armature EWdg [Rear]	Copper (Annealed)	0.07692	0.07692
Armature Winding [Total]		1.085	1.085
Wire Ins. [Active]		0.03266	0.03266
Wire Ins. [Front End-Wdg]		0.002698	0.002698
Wire Ins. [Rear End-Wdg]		0.002698	0.002698
Wire Ins. [Total]		0.03805	0.03805
Impreg. [Active]		0.09729	0.09729
Impreg. [Front End-Wdg.]		0.1806	0.1806
Impreg. [Rear End-Wdg.]		0.1806	0.1806
Impreg. [Total]		0.4585	0.4585
Slot Wedge		0.03456	0.03456
Slot Liner		0.00885	0.00885
Rotor Lam (Back Iron)	Mild Steel	0.7469	0.7528
Rot Inter Lam (Back Iron)		0	0
Rotor Lamination [Total]		0.7469	0.7528
Magnet	N30UH	0.2598	0.3091
Axle [Active]		1.649	1.649

Axle [Front]		0.02144	0.02144
Axle [Rear]		0.02144	0.02144
Axle [Total]		1.692	1.692
Bearing [Front]		0.002297	0.002297
Bearing [Rear]		0.002297	0.002297
Total		7.326	7.381

2. Modeling of electromagnetic problem

An auto-design program of the BLDC motor was used as the optimal design process for the rotor and stator core design. The basic theory has been explained in some papers. The detailed process has been displayed in the diagrammatic form shown in figure 1.

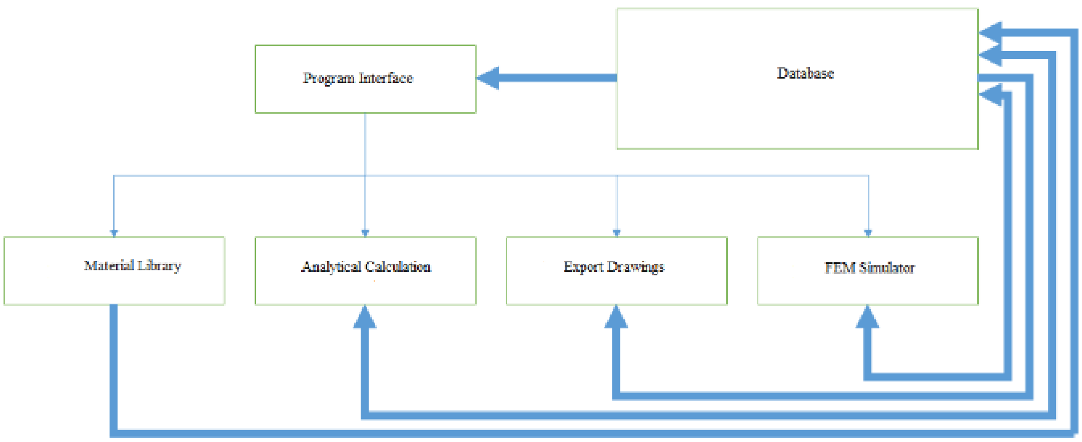

Figure 1. The diagrammatic program

The program is divided into three main parts: analytical calculation, exporting drawing and magnetic stimulation. There are also some supporting parts including the material library which also associate with the FEM library.

Many analytical steps have been implemented to define the torque and electromagnetic parameters as:

$$T = \frac{\pi}{2} D^2 L_{stk} \sigma \tag{1}$$

where T is the electromagnetic torque, D is the rotor diameter, L_{stk} is the stack length and $\sigma = \frac{L}{D}$ is defined from 0.2 to 0.25 for the outer rotor.

The interface links to the database, material library as well as calculation results. When the system receives the main parameters for motors, calculations will be then executed. The results will be stored in the database in a format.

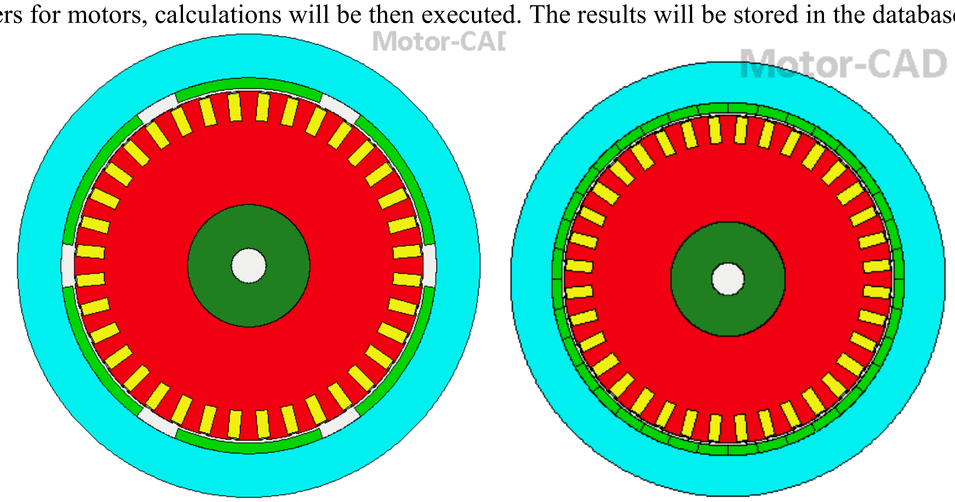

Figure 2. Normal (a) and Halbach outer Motors

A special power electric engineering software is used for simulating to obtain the magnetic flux density, electromagnetic torque curves, and the outline of the inner stator as shown in Figure 3.
The winding editor has been implemented by the SPEED software. An optimal winding will affect directly to the efficiency and torque value (Fig. 4).

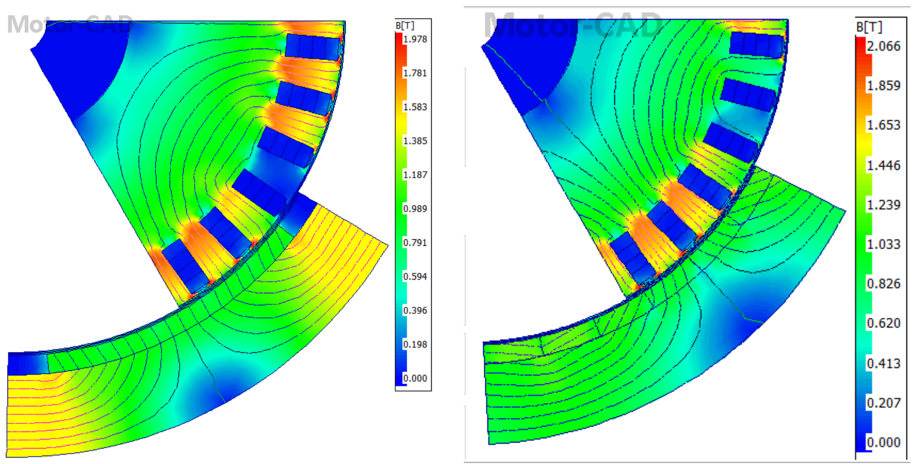

Figure 3. Normal (a) and Halbach Flux density

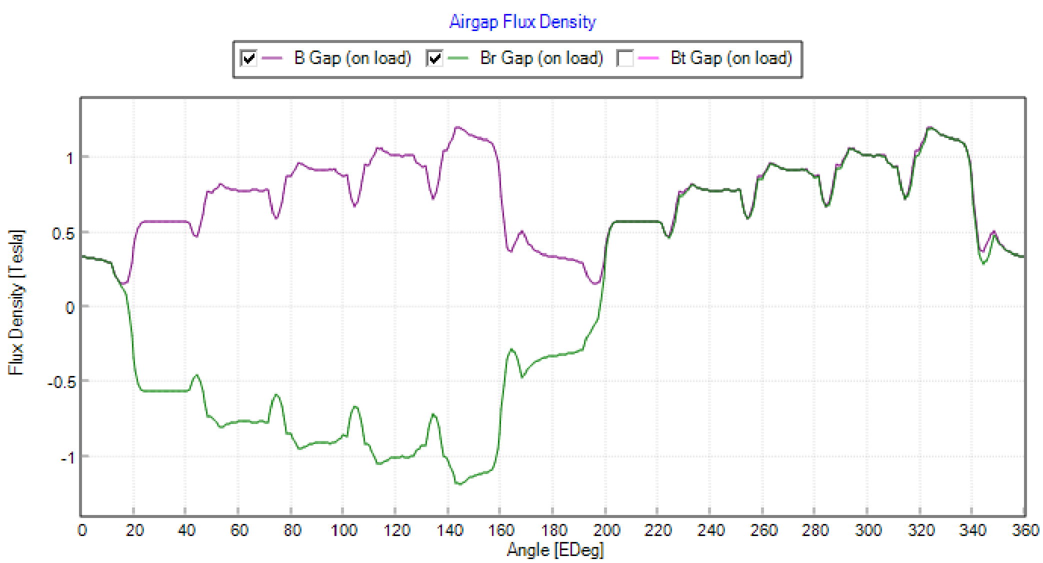

Figure 4. Normal Flux density in air gap

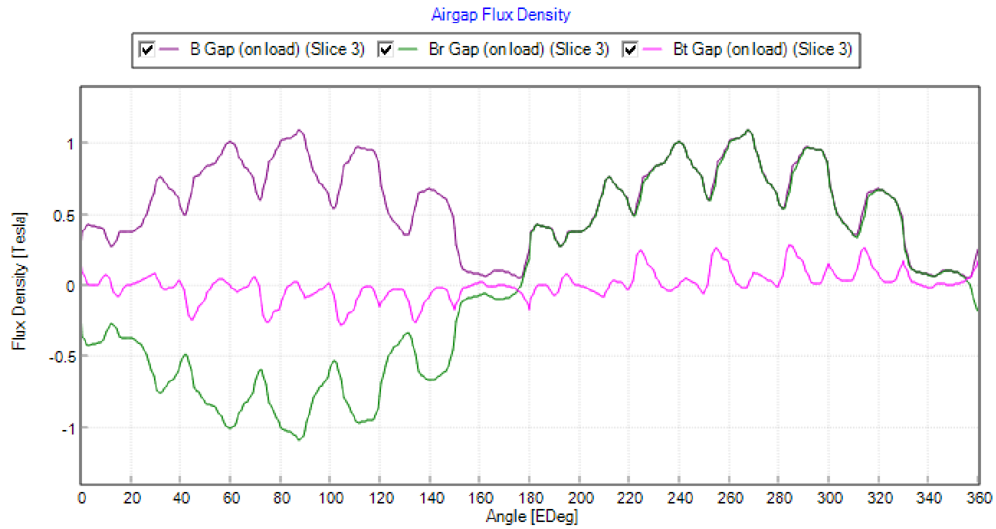

Figure 5. Halbach Flux density in air gap

The permanent magnets for the BLDC motor are NdFe45 inserted in the out ring. There are 60 permanent magnets with dimensions of 15x50x2.5 mm. The dynamic torque, current and voltage have been also evaluated under different operation conditions. The phase current, electromotive force (EMF), and torque waveforms at a base speed of 5000rpm are shown in Figures 6 and 7.

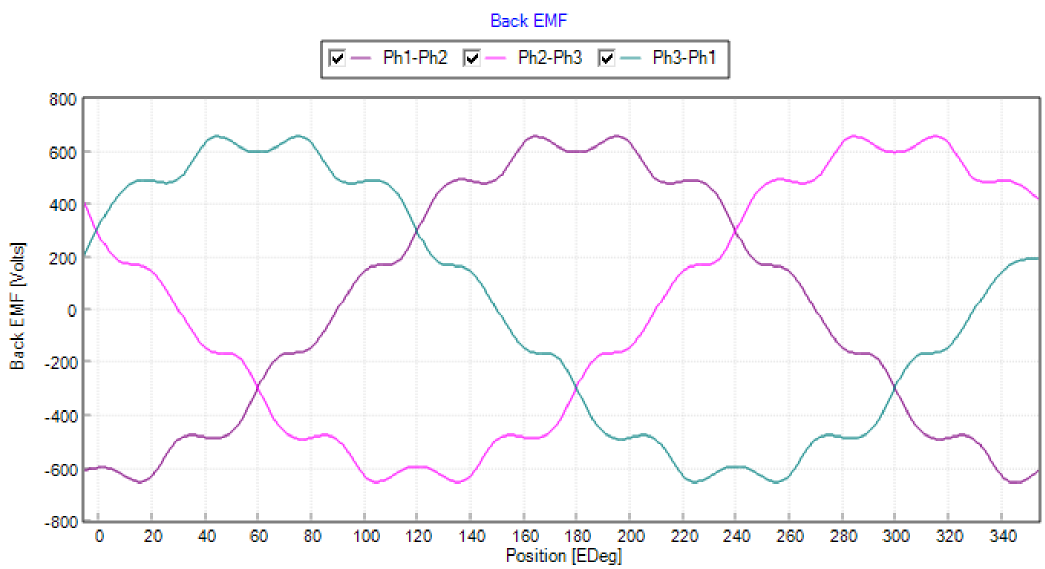

Figure 6. Normal Back EMF waveform

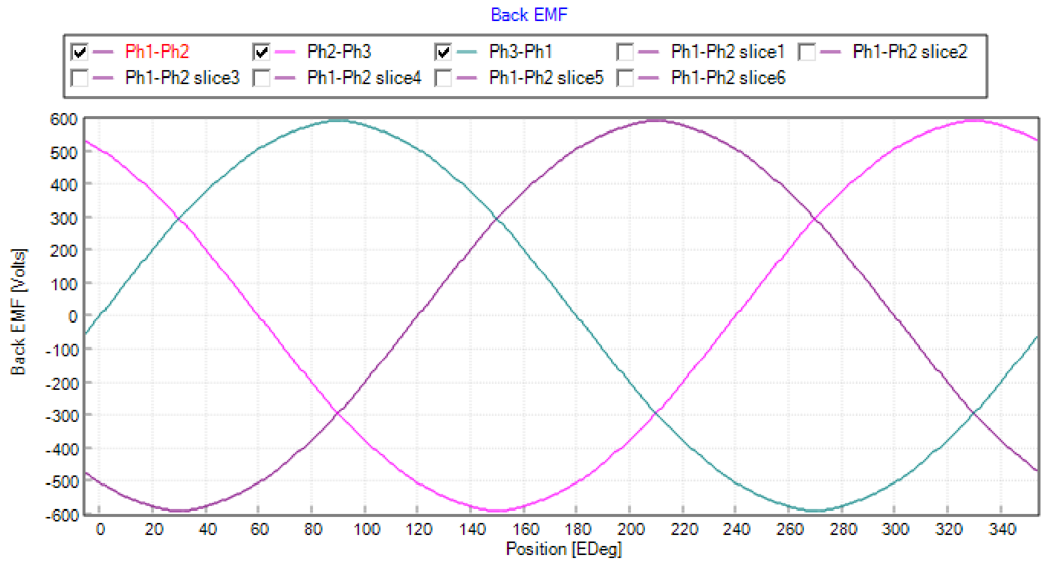

Figure 7. Halbach Back EMF waveform

The torque and speed characteristics are the most important curves of the BLDC motor. Based on the motor specification, the torque, speed, efficiency, and DC link current have been validated with speeds from 0 to 10000. The input voltage from the batteries is 270 VDC. The DC current supplied by three phases is from 0 to 450A. Electromagnetic torque waveforms of two motors have been plotted in figure 8&9

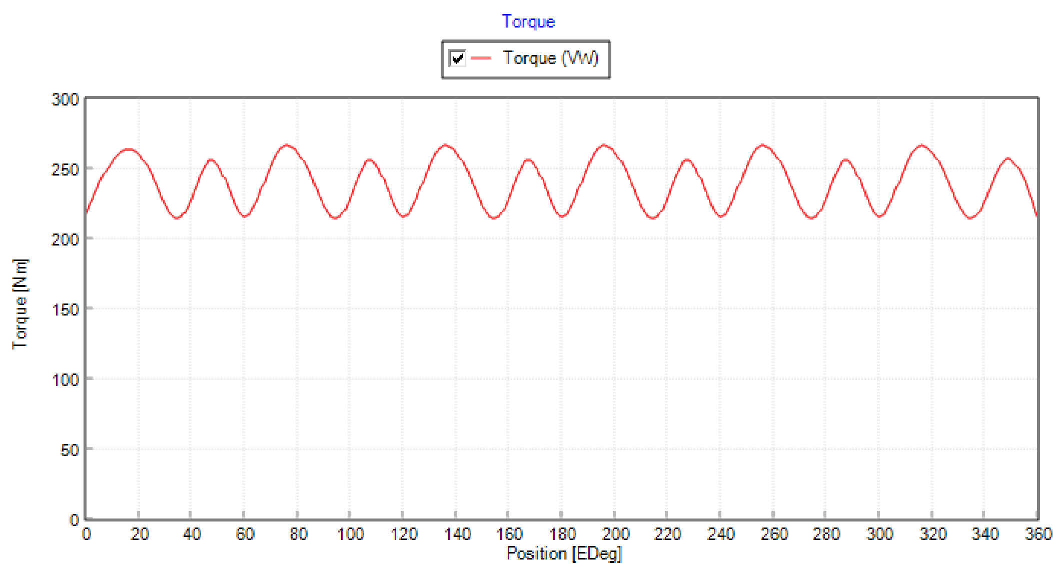

Figure 8. Normal torque waveform

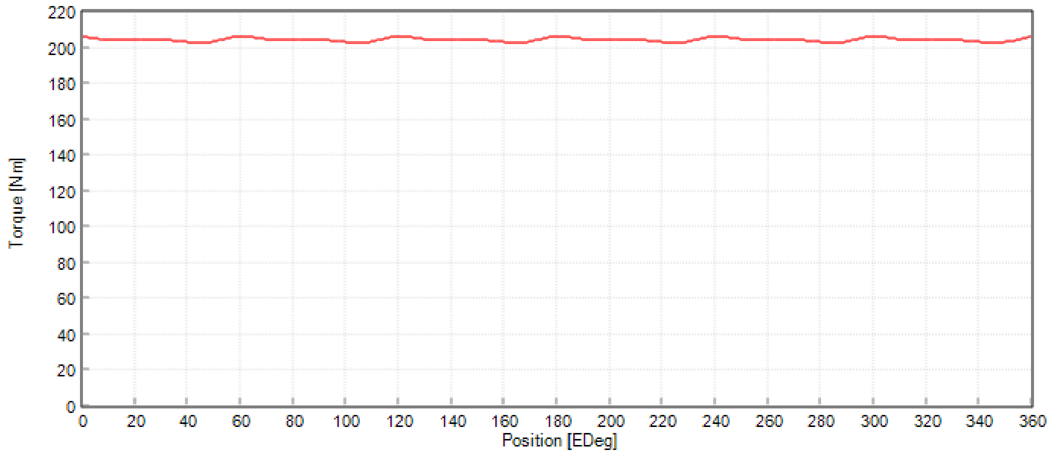

Figure 9. Halbach torque waveform

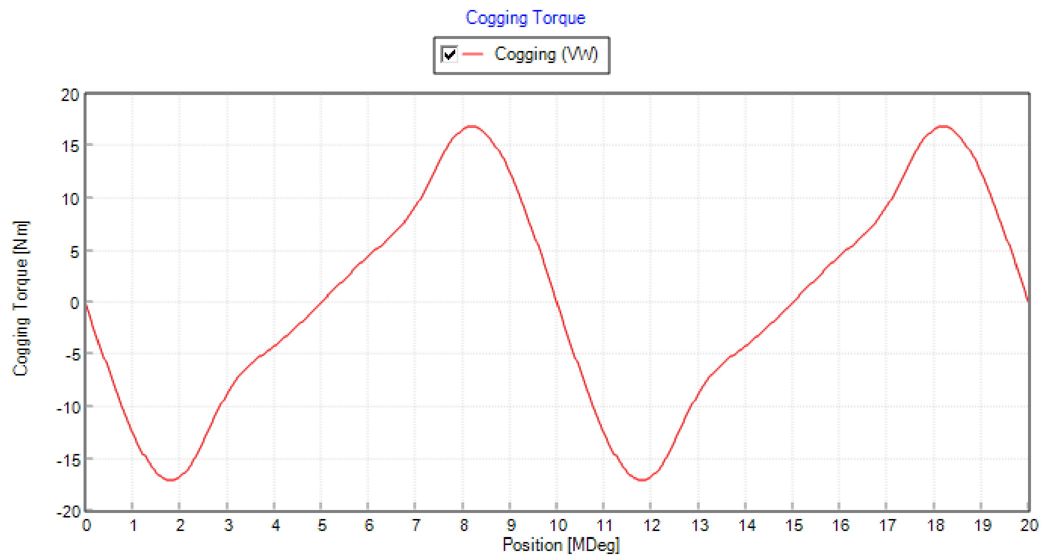

Figure 10. Normal cogging torque waveform

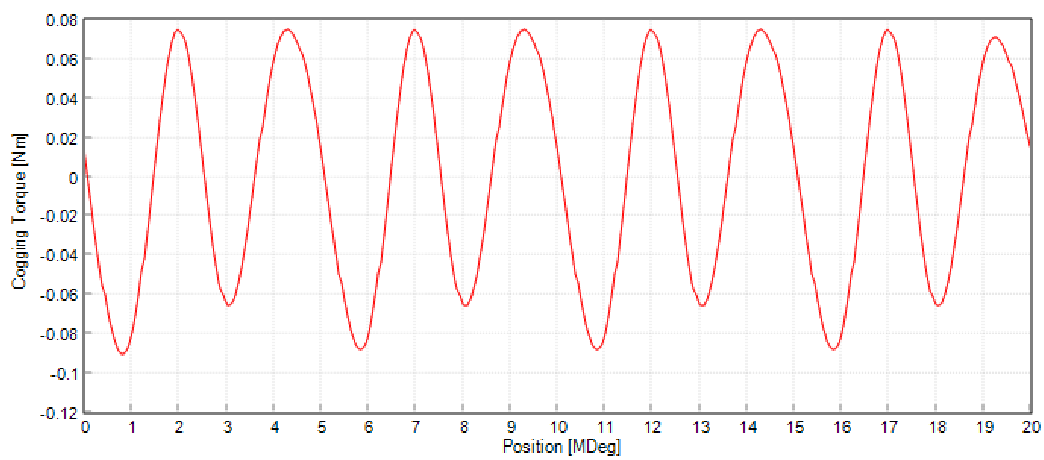

Figure 11. Halbach cogging torque waveform

The maximum efficiency of the BLDC motor can obtain 98% at the speed of 5000 rpm and torque of 255 N.m. The maximum power is 152kW. The output power, efficiency, current and speed vs torque are reported in the below tables

Table 3. Electromagnetic results

Maximum torque possible	245.36	203.69	Nm
Average torque (virtual work)	242.11	203.78	Nm
Average torque (loop torque)	241.21	202.55	Nm
Torque Ripple (MsVw)	32.079	3.6244	Nm
Torque Ripple (MsVw) [%]	13.241	1.7777	%
Cogging Torque Ripple (Vw)	23.168	0.157	Nm
No load speed	6569.2	7108.9	rpm
Electromagnetic Power	1.52E+05	1.28E+05	Watts
Input Power	1.55E+05	1.30E+05	Watts
Total Losses (on load)	2958.1	2559.8	Watts
Output Power	1.52E+05	1.28E+05	Watts
System Efficiency	98.086	98.035	%

Table 4. Total loss results

Armature DC Copper Loss (on load)	1415	1415	Watts
AC Copper Loss (Hybrid)(Total)	690.6	449.7	Watts
Magnet Loss (on load)	250.9	308.6	Watts
Stator iron Loss [total] (on load)	594.3	381.6	Watts
Rotor iron Loss [total] (on load)	6.872	4.581	Watts
Total Losses (on load)	2958	2560	Watts

The maximum efficiency is about 98%. The input and output power, speed, and DC link current vs torque have been carried out by FEM simulation. The load torque is increased by 5 N.m for each step, and the power meters are recorded at all palters for further analysis.

5. Conclusion

The results of power, torque, and efficiency performances obtained by the FEM are successfully checked to be close to the measured results. The BLDC motor has been also successfully manufactured and tested by the dynamic test bench. This is very difficult to test the dynamic performance of the full torque, current, and power for starting mode because of the mechanical coupling of the E-car and torque sensors. This design can be improved after doing the experimental test. For this application, the torque needs to be increased by 10% to improve the starting torque.

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Biographies

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