Torque Performance Analysis of Bldc Motor for Electric Motorcycle By Halbach And Skewing Rotor

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Abstract

A Permanent magnet BLDC motor has been designed with different rotor configurations based on the arrangement of the permanent magnets such as step skewing Halbach continuous ring/sinusoidal array. Rotor magnet arrangement configuration strongly influences the torque and efficiency performance of permanent magnet electric motors. This paper is to compare and evaluate different rotor configurations for PM BLDC motors with parallel/radial and Halbach continuous ring/sinusoidal array permanent magnets. Many applications for electric drives or electric aircraft prefer surface-mounted permanent magnet design due to its ease of construction and maintenance. A finite element method has been used for the analysis and comparison of different geometry parameters and rotor magnet configurations to improve efficiency and torque performance. This paper describes a comprehensive design of a three-phase PMBLDC motor with 15 kW for an in-wheel electrical drive. An FEA simulation of the PMBLDC motor has been implemented to evaluate their designs. In this paper, the step-skewing and Halbach magnet array are applied to the PM surface-mounted Brushless DC Motor for eliminating torque ripples. To observe the skewing rotor effect, the rotor slayers are skewed with different angles and a Halbach sinusoidal/continuous ring array. With a determined skewing angle, the cogging torque is eliminated theoretically, and back EMF harmonics are also analyzed. After several design validation, a suitable design will be selected for pilot manufacture.

Keywords

Permanent Magnetic Brushless Direct Current, Finite Element Method, Ansys Maxwell, SPEED software, Magnetic flux density.

1. Introduction

Permanent magnet (PM) brushless DC motors-PMBLDC have been widely used because of their attractive features like compactness, low weight, high efficiency, and easy assembly (P. Ji 2003, Yeji 2020). Many applications for electric drives or electric aircraft prefer surface-mounted permanent magnet design due to its ease of construction and maintenance (Islam 2009, Ravi 2016, Bommadevara 2018, Anusha 2021). Two innovative designs of Outer rotor PMBLCD Motor have been introduced in papers (Park 2020, Yang 2021, Zhang 2021, Park 2020). However, more specific and detailed torque performance is still being developed more useful results in torque improvement in this study. The reliability of the BLDC motor is high since it easy to mount a permanent magnet and robust structure. Different rotor configurations are available for PMBLDC motors with surface-mounted PM design with interior or exterior rotors, and interior PM design with buried magnets due to specific strengths and weaknesses (Bommadevara 2018, Anusha 2021). Among these the radial-flux motor, the surface-mounted type with different magnet arrangements has been used for electrical drives. This paper introduces high efficiency and low torque ripple through the novel design of the rotor of BLDC 15kW-Z36P12. The electromagnetic performance of the PMBLDC with 36 stator slots and 12 rotor poles is compared and discussed in this paper.

Figure. 1 E-Bike for Viettel Shipper

2. Radial and Halbach Magnet Arangerment

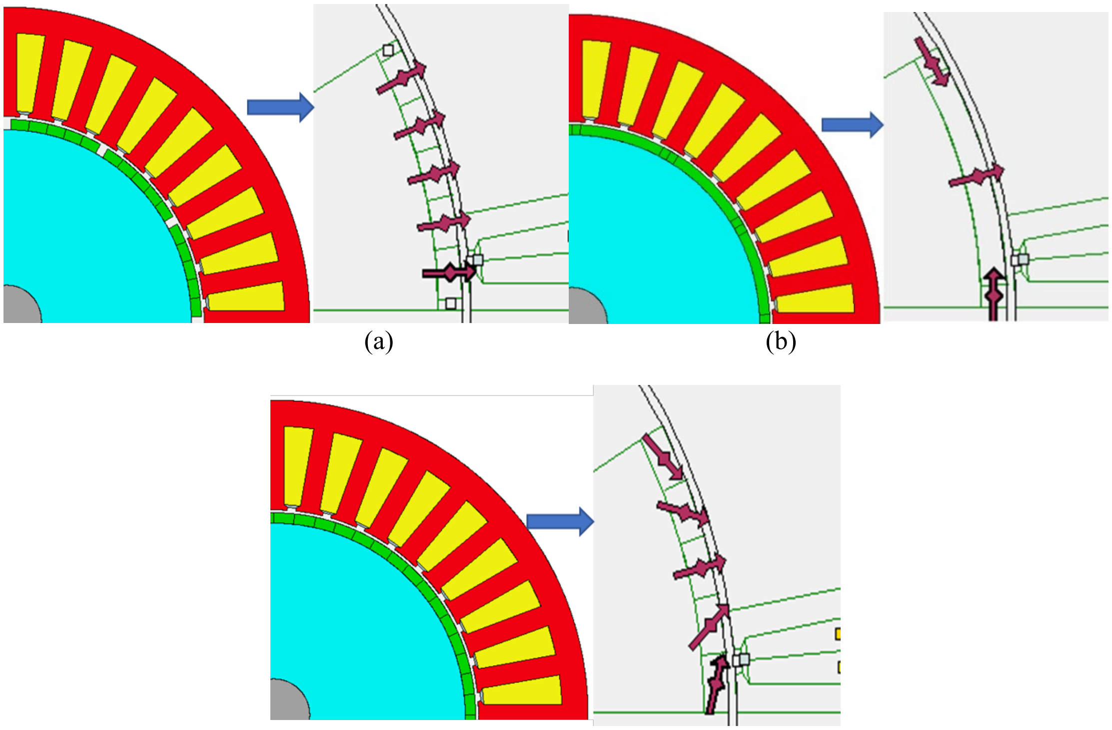
The design requirements are low cost, overload capacity, high efficiency, and reliability. For electric vehicle applications, high efficiency and torque density is the priority of this design. With those requirements above, a layout of the BLDC motor was calculated by SPEED software shown in Figure 1. The geometry specifications of the motor used for the analysis are listed in Table 1.

Table 1. Technical requirement of PMBLDC Motor

No	Parameters	Unit
1	Outer diameter	218 mm
2	Rotor diameter	142 mm
3	Slot length	52 mm
4	Normal Torque	80 Nm
5	Maximum Torque	150 Nm
6	Speed	3600 rpm

The motor length, diameter, and height are calculated based on motor requirements. All dimensions of the motor will be calculated, including the stator slot, rotor slot, and airgap. The stator slot size is calculated mainly based on stator winding which depended on power, current, and experience coefficients.

The geometry dimensions of the motor are saved in the database in matrix form. When the export command is generated, the drawing process will be executed. The program was developed by MATLAB DXF library. For drawing circle lines, and rotating objects of stator slots, 2D modeling is implemented for geometrical formulas of circle lines. The algorithm must satisfy both requirements: ensure the shape of these lines is similar to the desired curve and use the least points as much as possible. Using the minimum number of lines will help the system doesn’t have to store a lot of data, which will result in slowing down speed and difficulties when exporting the drawings to another software. On the other hand, rotating and mirror is also difficult task in programming. The strategy, using the loop function to redraw several times and using a trigonometric function with angle steps, is applied and returns good results.
Three-rotor topologies of radial, Halbach continuous ring, and sinusoidal array have been designed in figure 2. The embrace magnet angle is from 155^{o} to 165^{o} with a radial magnet array while the embrace magnet angle of the Halbach continuous ring/sinusoidal array is 180^{o} but the Halbach segment ratio is changed.



(a) (b)

(c)

Figure 3. BLDC Motor p =12, Z = 36 ; Radial magnet (a), Halbach continuous ring magnet (b); Halbach Sinusoidal magnet (c)

The rotor and stator cores for the three topologies have the same weight of components. Especially, magnetic weight is kept the same. Magnet thickness is 3.5 mm for Halbach design and 4mm for Radial design. Those thicknesses are available from magnetic supplies.

Table 2. Component weight of three topologies

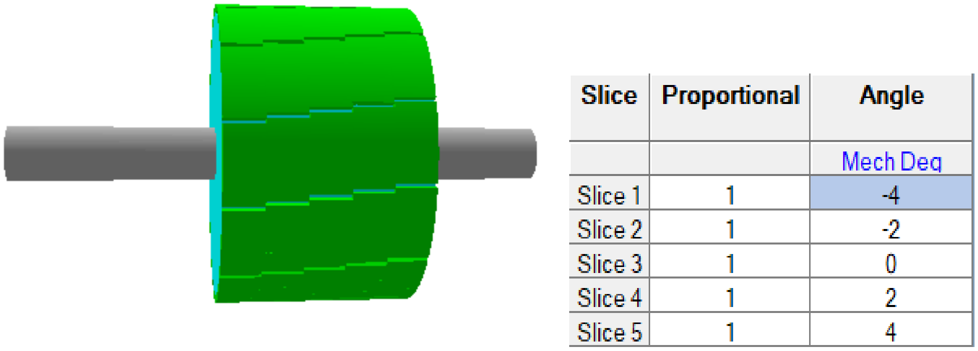
Parameters	**Material**	**Radial Array (kg)**	**Halbach Continuous Array (kg)**	**Halbach Sinusoidal Array (kg)**
Stator Lam (Back Iron)	M350-50A	2.193	2.193	2.193
Stator Lam (Tooth)	M350-50A	2.759	2.759	2.759
Stator Lamination [Total]		4.952	4.952	4.952
Armature Winding [Active]	Copper (Pure)	1.795	1.795	1.795
Armature EWdg [Front]	Copper (Pure)	1.453	1.453	1.453
Armature EWdg [Rear]	Copper (Pure)	1.453	1.453	1.453
Armature Winding [Total]		4.7	4.7	4.7
Wire Ins. [Active]		0.042	0.042	0.042
Wire Ins. [Front End-Wdg]		0.034	0.034	0.034
Wire Ins. [Rear End-Wdg]		0.034	0.034	0.034
Wire Ins. [Total]		0.11	0.11	0.11
Impreg. [Active]		0.1521	0.1521	0.1521
Impreg. [Front End-Wdg.]		0.2387	0.2387	0.2387

Impreg. [Rear End-Wdg.]		0.2387	0.2387	0.2387
Rotor Lam (Back Iron)	M350-50A	4.926	4.972	4.972
Rotor Inter Lam (Back Iron)		2.24E-05	2.27E-05	2.27E-05
Rotor Lamination [Total]		4.926	4.973	4.973
Magnet	N30UH	0.5589	0.5628	0.5628
Shaft [Active]	Iron (Pure)	0.1932	0.1932	0.1932
Shaft [Front]	Iron (Pure)	0.2511	0.2511	0.2511
Shaft [Rear]	Iron (Pure)	0.1352	0.1352	0.1352
Shaft [Total]		0.5795	0.5795	0.5795
Flange Mounted Plate		7.158	7.158	7.158
Total		15.73	15.78	15.78

Three PMBLDC motors with Step-skewing and Halbach magnet arrays are drawn in figure 2. The magnet thickness of the conventional design is 4mm and has an electric angle of 150^0 while the Halbach magnet array with a thickness of 3.5mm and 165 electric embraces. The total weight of the novel design of the Halbach magnet is lower with the same magnet weight in table 2.

3. Step Skewing Rotor Design

Step skewing slices of the rotor are used frequently in BLDC motors for eliminating this cogging torque. With the optimum skew angle of that slice, cogging torque can be eliminated theoretically. Skewed slots for the rotor slices are illustrated in figure 6.



Slice	Proportional	Angle
		Mech Deg
Slice 1	1	-4
Slice 2	1	-2
Slice 3	1	0
Slice 4	1	2
Slice 5	1	4

Figure 3. Rotor step-skewing slides

Cogging torque can be calculated from stored energy in the air gap. Variation of the co-energy gives the cogging torque (Dosiek 2006):

$$T_c = \frac{dW}{d\theta}, \tag{1}$$

where T_c is the cogging torque, $\partial\theta$ is the displacement with a mechanical degree, ∂W is the stored co-energy in the air gap.

Cogging torque is periodic along the air gap. By using this periodicity feature, the Fourier series of the cogging torque can be obtained:

$$T_{skew}(\theta) = \sum_{i=1}^{\infty} K_{sk} . T_i . \sin(iC_p\theta_m + \theta_i), \tag{2}$$

where K_{sk} is the skew factor which is 1 for non-skewed motor laminations. C_p is the least common multiple between the number of pole and the number of stator slots, T_i is absolute value of the harmonics, θ_m is the mechanical angle between stator and rotor axis while motor is rotating and represent to the phase angle K_{sk}, that is skew factor, the defined by:

$$K_{sk} = \frac{Sin(\frac{iC\pi\alpha_{sk}}{N_S})}{iC\pi\alpha_{sk}/N_S}, \tag{3}$$

where α_{sk} is the skew angle and Ns is the number of the slide. The skew angle is given in Equation (6).

Average values of load torque are nearly same values for Even one slot pitch skewed motor results in terms of average load torque are coherent with the non-skewed motor model. The relative torque ripples can be calculated as follows:

$$T_{ripple} = \frac{(T_{max}-T_{min})}{T_{avg}} \tag{4}$$

If increasing skew angle, the torque ripple is reduced but the average torque will be down also, so for optimal torque performances, the ratio of magnetic pole/stator slots needs to increase.

Table 3. Design parameters of PMBLDC Motor

Parameters	**Values**	**Unit**
Stator Bore	142	mm
Tooth Width	7	mm
Stator Slot Depth	36	slot
Tooth Tip Depth	1	mm
Slot Opening	3	mm
Magnet Angle	155-165	degrss
Pole Number	12	pole
Magnet Thickness	3.5-4	mm
Housing Dia	228	mm
Stator Lam Dia	218	mm
Stator Bore	142	mm
Airgap	1	mm

Two PMBLDC motors with Step-skewing and Halbach magnet arrays are drawn in figure 3. The magnet thickness of the conventional design is 4mm and has an electric angle of 150^0 while the Halbach magnet array with a thickness of 3.5mm and 165 electric embraces. The total weight of the novel design of the Halbach magnet is lower with the same magnet weight.

4. Electromagnetic Performance Analysis

The program can be easily applied for several designs to investigate torque, torque ripple, and efficiency performance. The program can also be linked to some optimized function to choose the best solution for a specific objective. The comprehensive performances have been analyzed in table 4. The highest efficiency and lowest torque ripple of the Halbach Continuous Skewing are 93.913% and 5.65%. The Halbach continuous skewed rotor with 5 slices is optimized by a control current of 150A with 100VDC.

Table 4. Electromagnetic Performance Comparison of PMBLDC Motor

Parameters	**Radial Array**	**Halbach Continuous**	**Halbach Sinusoidal**	**Halbach Continuous skewing**	**Unit**
Maximum torque possible (DQ)	121.74	129.74	121.32	130.55	Nm
Average torque (virtual work)	106.44	112.08	106.05	111.52	Nm
Average torque (loop torque)	105.78	111.41	105.39	110.86	Nm
Torque Ripple (MsVw)	29.034	23.951	6.5158	6.0037	Nm
Torque Ripple (MsVw) [%]	26.059	21.392	6.154	5.6509	%
Cogging Torque Ripple (Ce)	19.344	26.761	0.064419	0.096562	Nm
Cogging Torque Ripple (Vw)	18.311	24.508	0.092116	0.060309	Nm
The speed limit for constant torque	1377.9	1371.7	1443.8	1437.5	rpm
Electromagnetic Power	16688	17587	16631	17501	Watts
Input Power	17649	18547	17589	18454	Watts
Total Losses (on load)	1132.8	1131.3	1083.8	1123.3	Watts
Output Power	16516	17416	16505	17331	Watts
System Efficiency	93.581	93.9	93.838	93.913	%

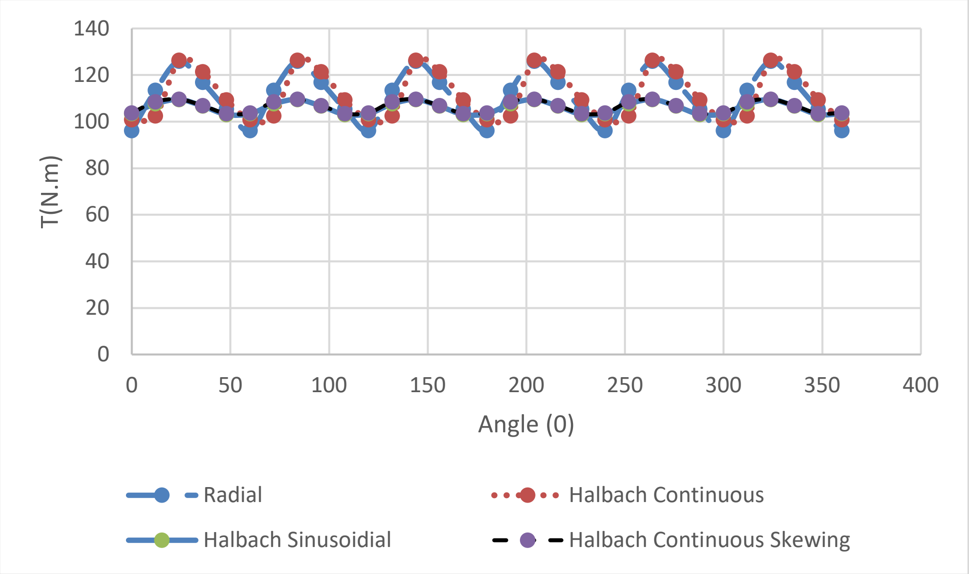


Figure 4. Torque waveforms.

To verify the radial and Halbach continuous skewing, sinusoidial magnet array, the torque and torqure ripple of the halbach prototype was investigated in figure 4.

Figure 5 shows the torque versus speed. One can see that the Halbach continuous skewing has the best torque performance.

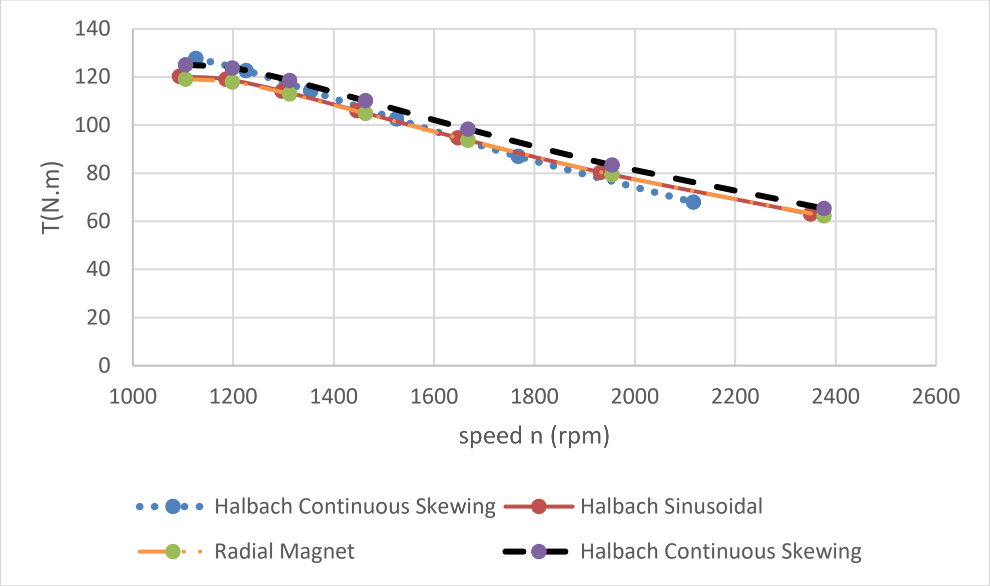


Figure 5. Torque vs speed curves

5. Thermal Analysis by Finite Element Method

The finite element method (FEM) has been used to solve overheating temperatures of IM based on Iron and copper losses, mass transport, heat transfer, and fluid flow. For solving the thermal problem, an analytical model is combined with a finite element method such as Motor-CAD. it has a finite element solution for the stator winding only. The thermal study of the test motor by FEM is to determine the temperature distribution in the case of a steady state at any point of the induction motor.

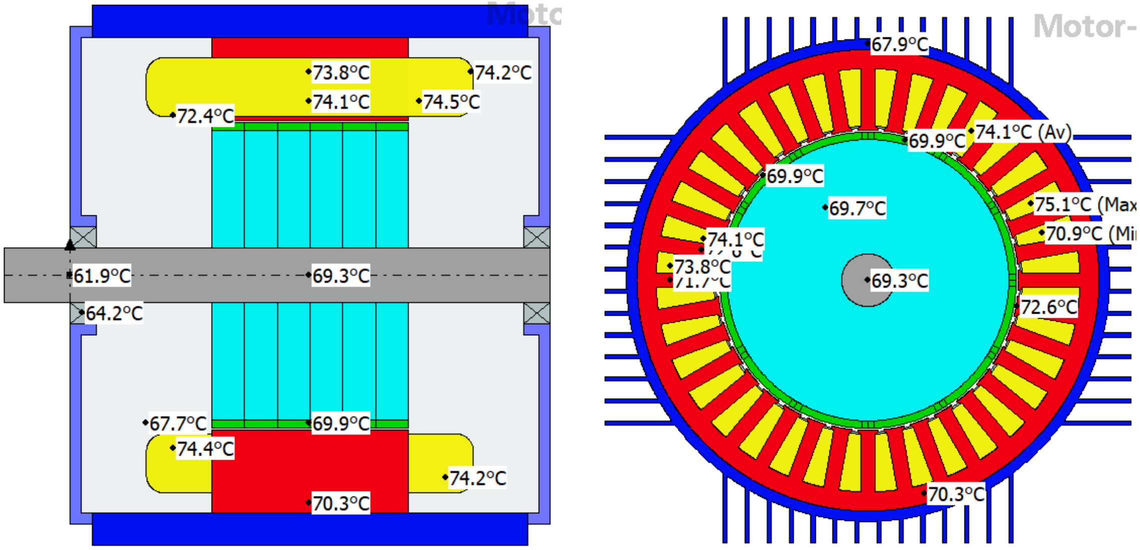


Figure 6. Radial and Axial view of the test motor temperature distribution

The temperature of each component of the test motor has been determined at an ambient temperature of 40 ºC. The losses of the test motor induction are used as the heat sources (stator and rotor copper losses, stator and rotor core losses in figure 5.

6. Conclusion

The paper has presented a comprehensive design of a PMBLDC motor for electric vehicles. The design was calculated by the analytical method. Four topology designs have been evaluated for electromagnetic characteristics by FEM. Particularly, radial and Halbachmanent magnet array rotors with skewed slides were carried out to compare efficiency, torque, and cogging torque. The torque ripple is minimum with a skew angle of 5.6%. The best Halbach continuous skewing magnet array is determined by a 5-slices angle of 10 degrees. For electrical drive, the PM surface-mounted motor is easy to arrange Halbach and skewing structures. A thermal analysis of a PMBLDC motor has been performed successfully by approach method based on analytical and FEM simulation under full-load steady-state conditions.

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