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Design & Prototype development of 2.2 kW Axial Flux PCB Stator Motor

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Abstract: Axial flux permanent magnet motors are gaining more interest due to short axial length and higher torque density, what makes them difficult is the manufacturing and assembly process. PCB stator motor is a novel and innovative type of axial flux permanent magnet motor where copper traces are etched in PCB to form a stator, multi layers of PCB can be utilized to form a single stator, making it easier for assembly and mass production. Compared to the conventional permanent magnet type of electric motors, this construction eliminates the iron core, as a result there is a reduction of weight, cogging torque and increase in efficiency. The motor performance is comparable to traditional motors with improved reliability, reduced noise and increased power density. This paper presents the design and prototype development of 2.2 kW, Axial flux PCB stator motor with dual rotor single stator (PCB) configuration for IE5 efficiency. PCB stator is made up of 12 coils (virtual slots) with all phases spread in single layer, concentric type of winding arrangement has been incorporated and stacked up to 8 layers (series and parallel connections) with 6 Oz of copper etched on it. Rotor with N-S pole type configuration with 16 poles has been used. Analytical design and finite element analysis have been used to model and evaluate motor performance theoretically and results are presented. The motor offers very low inductance as it eliminates the core, the current ripple will be very high for low switching frequencies. Several techniques have been examined and adding series inductors has been proposed.

Keywords: PCB, FR4, PCB Stator, AFPM, AFPMSM, Axial Flux, Dual Rotor AFPM, Power density

1. Introduction

Based on the orientation of the flux in air gap flux density, motors are classified as radial flux and axial flux. Axial flux PM Motors are attractive because of the high-power density, less weight and highly efficient. Axial flux PM Motor offers different orientation. One-stator–two-rotor motors are called TORUS-type AFPM motors, and two-stator– one-rotor motors are called axial-flux internal rotor (AFIR)- type AFPM motors [2]. PM Motors are highly efficient due to PM excitation. By utilizing the dual rotor single stator axial flux topology and PM excitation, the concept of removing iron in dual rotor axial flux topology was studied. PCB Stator construction is by etching the copper coils directly onto the PCB, we eliminate the heavy steel core and copper windings. This reduces the size and weight by half and by removing the iron in magnetic path, the cogging torque, torque ripple & acoustic noise also reduces. This results in a significant increase in efficiency. The PCB FR4 offers high insulation properties and is easily manufacturable. When the core and copper are replaced by copper traces etched in PCB it offers many advantages for the manufacturing and quality aspects. The PCB board can be easily made with advanced automation techniques. The coefficient of thermal expansion of the FR4 and copper are equivalent which helps in reduction of thermal induced stress failure, where quality and reliability is ensured. There are certain challenges which are associated with this type of motors are with low inductance. Hence different techniques are studied and incorporated to make this motor run. In PCB stator disc-type motor, the effective conductor width should be taken into full consideration to lower eddy loss, especially for high-speed motors [7]. It is important to study the effect of eddy currents (skin and proximity) due to its operation at high frequency [8]. In this paper a 2.2 kW, 3000 RPM single stator sandwiched between two rotor type of topology motor is designed for IE5 efficiency and prototyped. The details of the design and prototype are discussed in further sections. The challenges and advantages associated with this type of motor are also addressed.

2. Motor Specification

The proposed motor specification is listed in Table 1. In this design, fractional slot PM, 12 Stator slots and 16 Poles combination is used. The performance was evaluated using analytical analysis and then FEA is performed to check the output torque, ripple & flux density.

Table 1. Motor Specification

S. No	Parameters	Values	Units
1	Rated Speed	3195	rpm
2	Rated Power	2.2	kW
3	Max Speed	4900	rpm
4	Rated Current [Irms]	5A	A
5	PCB Stator Diameter [OD]	325	mm
6	PCB Stator Inner Diameter [ID]	150	mm
7	Stack Length [Lstk]	53	mm
8	PCB Thickness	7	mm
9	Air gap [g]	2	mm
10	Magnet Thickness	6	mm
11	Copper thickness	6	Oz
12	No of Layers in PCB	12	Nos
13	Track Width	2.8	mm
14	Efficiency [%]	89.5	%

The PCB Stator motor works on the principle of short path for magnetic flux is made possible by sandwiching rotors with magnets around a thinly printed circuit board stator as shown in figure1.

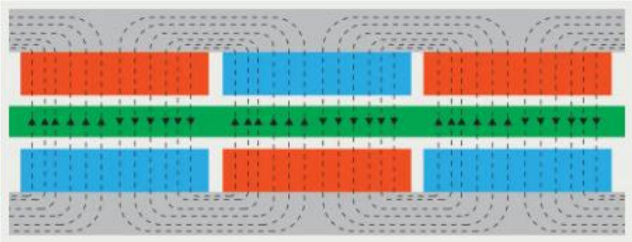


Figure 1. PCB Stator Motor, Blue & green – Magnets, Green – PCB board, Grey – Back iron

3. Sizing of Motors

The Sizing of motors are established using the analytical equation by assuming the air gap flux density. Axial flux motors are high power density motors, Power is directly proportional to cube times of diameter. Slight increase in diameter will have output power increase by cube times.

$$P_{out} \propto D^3$$

The topology selected for this design is a single stator (PCB) dual rotor. The required torque is obtained by establishing the required air gap flux density in air gap. Once the air gap flux density is finalized, the outer diameter can be obtained using the below mentioned analytical equation.

$$Td = \frac{\pi}{2} k_D k_w {D_{out}}^3 B_g * AC * Cos\,\emptyset. [5]$$

There are several research papers discuss about the derivation of outer diameter and inner diameter, out of which Split ratio, which is found to be feasible, by assuming the split ratio Kd – ratio of inner to outer diameter, both OD & ID are obtained analytically.

$$Kd = \frac{ISD}{OSD} \leq 1$$

The required air gap flux density is established in air gap using the sizing of magnets.

4. Stator (PCB) Design

The stator design includes winding design & PCB design. There are different methods of winding connections that are studied as shown in figure 2. [1, 4]. Out of all the methods, concentric type winding connection is simpler and produces more back emf and torque. In this design concentric type with equal width is used considering the highest flux linkage, highest induced voltage, and torque.

The PCB is a flat board made of insulating material such as fiber glass with conductive path etched in it can be single layer or multilayer depending on the circuit connection. The winding connections can be done with all phases in one layer of PCB or One phase in one layer & connect to different layers to become a single stator unit. In this design, it is a star connected circuit with all the phases etched in one layer as shown in figure 3. The first four layers are in series connected parallel to the next four layers. Totally there are eight layers PCB board is constructed.

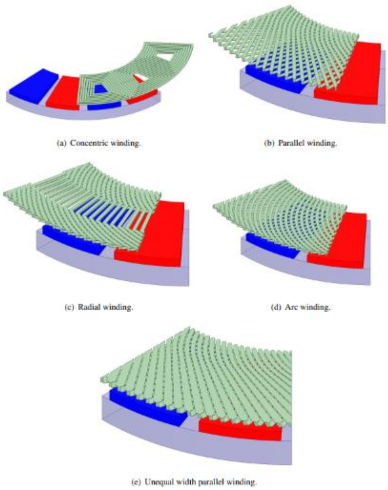


Figure 2. Different types of winding schematics [4].

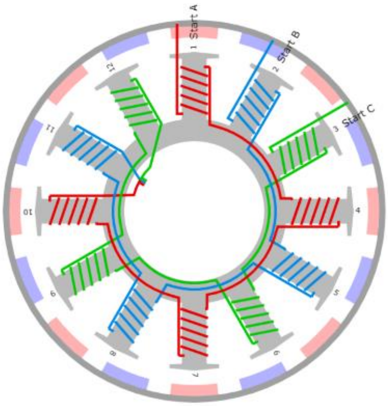


Figure 3. Winding layout connection star circuit – all phases in one layer

The number of turns for the design is sixteen turns & copper track width is 2.8 mm & thickness is 6 Oz.

$$N_c < \frac{1}{2}\left(\frac{r_o - r_i}{Wc} + 1\right) \text{ [3].}$$

The current density can be reduced by connecting the circuit with 2 Parallel connections. The layer-to-layer connection is established through 'via's.' In this design we have used through hole via and blind / buried via. Using thermal via for a parallel multilayer PCB winding can achieve a higher current carrying capacity in combination with heat sink. [6].

The CAD schematic of the developed PCB board is shown in the figure. 4.

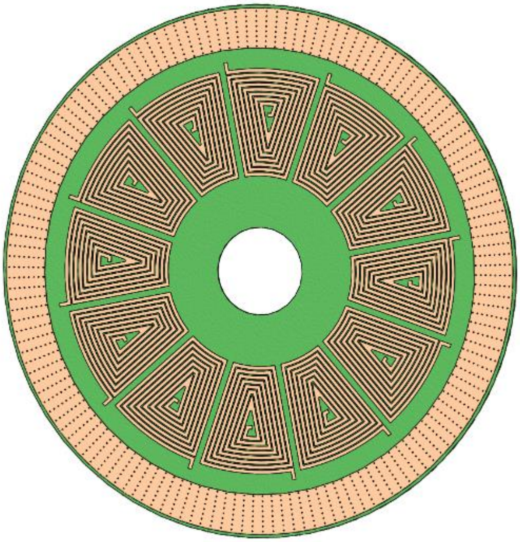


Figure 4. CAD Layout of PCB Board layer

When all the phases are spread in a single layer, the clearance between coils and clearance between phases are important to withstand the dielectric breakdown voltage requirements. Coil to coil clearance – 5.125 mm & Interturn clearance – 1 mm. Since PCB board material FR4 possess high insulation properties, it is important to select the right material to cater to all the insulation requirements. The selected FR4 base material is S1000 -2 M & Tg value of the board – 180 degrees & Surface finish – ENIG Coating. The stack up chart for each layer is shown in figure 6.

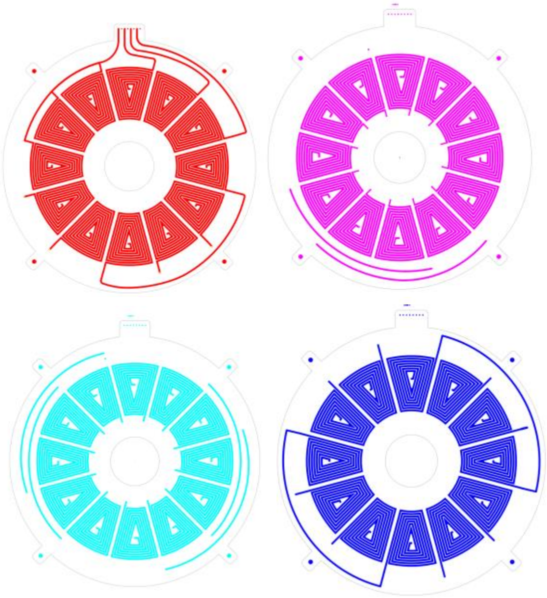
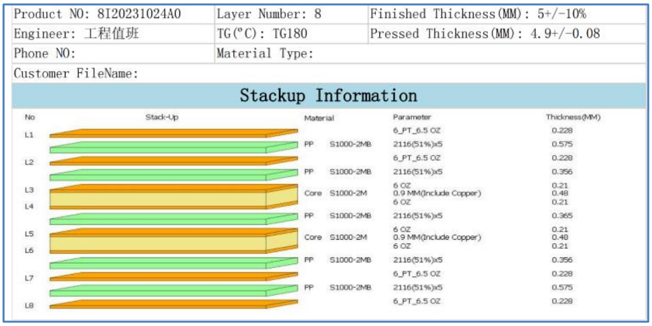


Figure 5. RED- 1st layer, PINK – second layer, Cyan – 3rd layer, Blue- 4th Layer.



Product NO: 8I20231024A0	Layer Number: 8	Finished Thickness(MM): 5+/-10%
Engineer: 工程值班	TG(°C): TG180	Pressed Thickness(MM): 4.9+/-0.08
Phone NO:	Material Type:	
Customer FileName:		

Stackup Information

No	Material		Parameter	Thickness(MM)
L1			6_PT_6.5 OZ	0.228
	PP	S1000-2MB	2116(51%)x5	0.575
L2			6_PT_6.5 OZ	0.228
	PP	S1000-2MB	2116(51%)x5	0.356
L3	Core	S1000-2M	6 OZ	0.21
			0.9 MM(Include Copper)	0.48
L4			6 OZ	0.21
	PP	S1000-2MB	2116(51%)x5	0.365
L5	Core	S1000-2M	6 OZ	0.21
			0.9 MM(Include Copper)	0.48
L6			6 OZ	0.21
	PP	S1000-2MB	2116(51%)x5	0.356
L7			6_PT_6.5 OZ	0.228
	PP	S1000-2MB	2116(51%)x5	0.575
L8			6_PT_6.5 OZ	0.228

Figure 6. PCB board stack up details

The PCB board consists of eight layers (4 layers parallel to four layers) and thickness of 4.8 mm, whose stack up details are shown in figure. 6 The CTI of PCB board is 400 Volts.

5. Rotor Design

The rotor design involves the magnet arrangement in both the rotors. The magnets in DE and NDE side of rotors are arranged in N- S type. N45SH magnet grade is used to get the required air gap flux density. To minimize the torque ripple, magnets are arranged in radial spacing in bottom and top side.

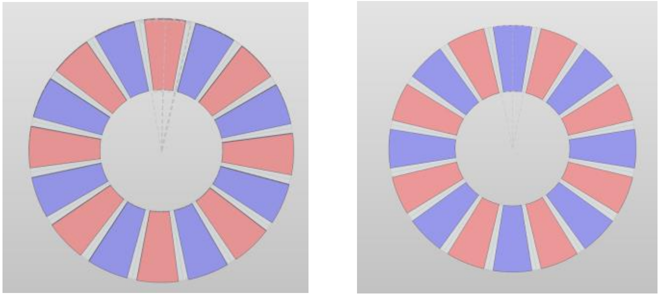


Figure 7. Arrangement of both rotors

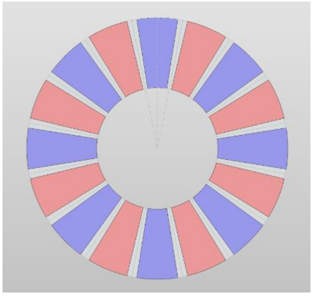


Figure 8. Radial spacing of magnet in rotor

6. FEA Results

The motor is modelled in FEA tool, and assumptions are included in analysis of the motor. Simulation carried out with sinusoidal and inverter circuit.

1. Air gap flux density
2. No load Back EMF
3. Flux density
4. Torque Output

6.1 Air gap flux density

The air gap flux density was found to be 0.52 T and due to absence of stator slot opening, there is no dip and harmonics associated with it.

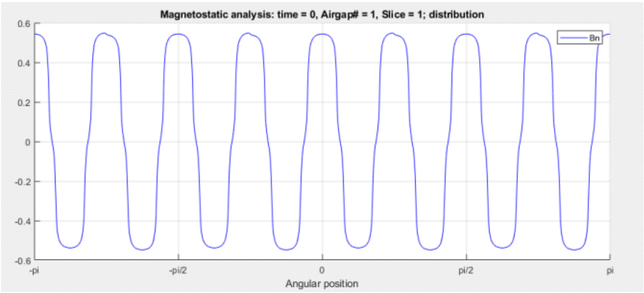


Figure 9. Air gap flux density plot

6.2 Flux Density

The flux density of the rotor back plates are shown in figure. The rotor yoke thickness is lesser, the leakage losses increase, and output of the motor will reduce. Hence the rotor yoke saturation was kept under 1.2T at load condition.

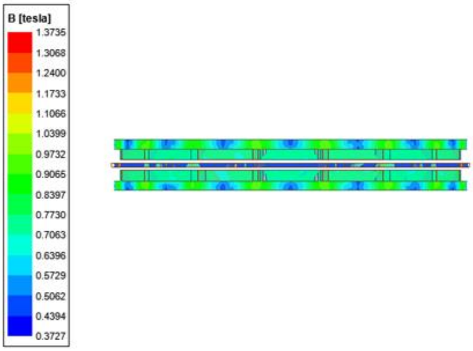


Figure 10. Flux density Plot

6.3 No Load Back EMF

The three-phase back emf is shown in figure 8. Which matches with analytical design. The shape of the back emf is sinusoidal. As there are no eddy current losses in rotor due to the rotor end plates are designed with low carbon steel not with laminated core, the rotor back iron material comparison is made with non-magnetic steel and magnetic steel and found 36% reduction in magnitude of the phase back if nonmagnetic steel is used.

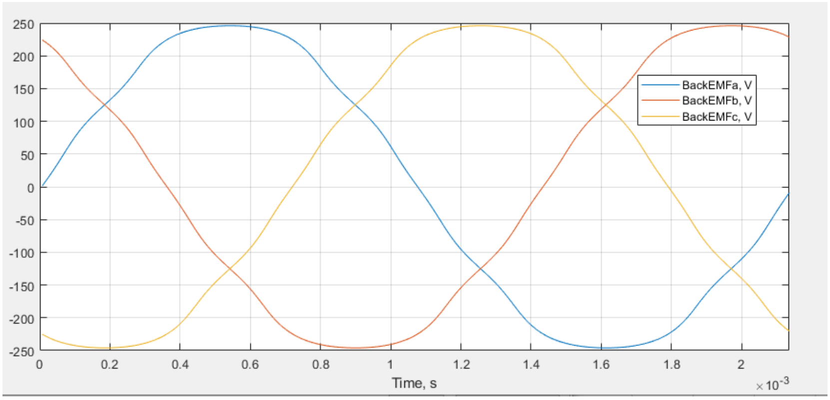


Figure 11. Air gap flux density plot

6.4 Torque Output

The simulation was carried out using the sinusoidal current excitation and the torque output is 7.25 N-m as shown in Figure. 12. The torque ripple was found to be 5% at rated condition.

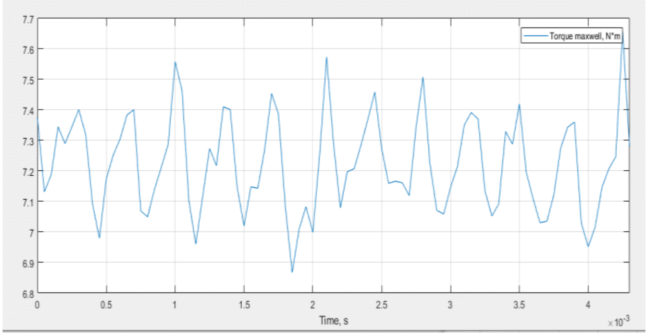


Figure 12. Torque output at rated load condition

When the FEA is performed with dynamic analysis with inverter circuit, it is found that due to low inductance the current ripples are higher, and it affects the torque output. The torque ripples are higher due to rapid rise and fall of pulses due to low inductance. The solution to this problem was addressed by adding a series inductance in circuit. A 700 micro henry inductance is added.

7. Prototype Model

7.1 PCB Stator

The developed PCB stator is as shown in figure. 13. It is an 8-layer board with 4.9 mm thickness.

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The developed PCB stator is as shown in figure. 13. It is an 8-layer board with 4.9 mm thickness.

Figure 13. Prototyped PCB Stator

Figure 14. Surface mount magnet with Rotor

8. Conclusion

This paper presents the concept design and prototype details of 2.2 kW AFPM motor with PCB as stator. Analytical design was made, and performance was evaluated using FEA tools. The proposed design meets IE5 design requirements. The FEA results indicate low cogging torque and ripple. The prototype was developed with an 8-layer board and 6 Oz copper thickness with track width of 2.8 mm. The challenges include the low inductance of motor, which is found during simulation, which should be overcome by adding the inductance to the motor, which is planned during the testing of the motor.

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Conflict of interest

The Authors have no conflicts of interest to declare that they are relevant to the content of this article.

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