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Design and Performance Analysis of an Interior Permanent Magnet Brushless DC motor using ANSYS Electronics

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ABSTRACT

The paper demonstrates the design process of an Interior permanent magnet brushless D.C motor and the subsequent performance analysis by varying the parameters such as windings, stator and rotor slots, and maximum input current and circuit type. Initially, the stator and rotor set up in the motor are designed as an ANSYS RMXPRT model and it is followed by variation in the design parameters. The model is then analyzed under fixed operating load conditions and based on the simulation results various performance characteristics are deduced. The performance curves establish the relationship between various motor designs-based parameters such as motor torque, efficiency, power with rated speed variations and induced phase voltage with electrical degrees in the motor operating range. This concludes the parametric analysis of the BLDC motor. The second portion of the research deals with the electrical stimulation of the designed PM machine in an ANSYS Maxwell suite. It utilizes a 3-D model of the motor and with the necessary boundary conditions and initial operating inputs delivers a no-load simulation and full-load data set of the electrical motor. The objective behind the simulation is to calculate the value and obtain a characteristic curve for the cogging torque of the motor.

Keywords*— IP Magnet Brushless DC Motor, Performance Characteristics, Cogging Torque, Electrical Simulation, Maxwell Design, ANSYS RMXPRT.*

1. INTRODUCTION

The growing necessity and demand of electrical drivetrain units in the automotive industry have significantly increased the research on the performance of the electric motors in the market. A desire to exceed the performance of the already existing motors has paved the way for upcoming inventions and improvements in the design methodology of a conventional motor setup. Even after such exceptional upgrades in the working and efficiency of the motors, there is still large room for improvement for industrial and automotive applications. I have laid emphasis on the variations in design, which can induce a potential change or improvement in the current BLDC motor operation and furthermore the electrical simulation predicts the torque and power output from the motor setup.

The reason why BLDC motor was inevitable as a subject for research over induction motor is that in spite of the power struggle between automotive companies, the significance of the brushless permanent magnet type motors is untainted and the only possible reason to claim the above-stated fact is the attributes it has to offer. The motor type is highly efficient, compact and lightweight. The embedded interior permanent magnets are placed in slots, which are stamped in the laminations of the rotor. The interior permanent magnet setup is selected for the research work over surface permanent magnet motor due to its high strength and reliability and better anti-demagnetization ability. Moreover, when the magnets are embedded in slots inside the rotor the risk of the magnets being peeled off due to centrifugal forces reduces. The current automotive industry relies more on the BLDC and PMSM type motors due to their high power and torque densities, however, through detailed research work on a modified structure engaging the BLDC and IPM type motors into one I believe a more reliable and efficient electric machine can be obtained. To authenticate the work various performance characteristics shall be provided in this paper linking the performance parameters with the varying operating conditions.

In addition, a parametric analysis is carried out to compare the characteristic curves with variation in parameters and to check the cogging torque in the motors an electrical FEA simulation is initiated. The objective is to evaluate the necessary motor parameters and to get the best possible combination.

2. LITERATURE REVIEW

In-wheel Motor Design for Electric Vehicles, K. Cakir A. Sabanovic, Sabanci University/Faculty of Engineering and Natural Sciences, Istanbul, Turkey. 0-7803-9511-5/06 ©2006 IEEE

The paper demonstrates the design procedure of an “in-wheel motor direct-drive motor” with the objective of replacing the ongoing conventional central drive motor system. This kind of motor setup is used to supply power and speed directly to the individual tires. The author has chosen a switched reluctance motor for the design process. A 3-D model is created and necessary strength analysis is done followed by an electromagnetic Finite element analysis. The analysis is done until the design is converted to a set of consistent dimensions for both mechanical and electromagnetic design. The FEA is followed by a coherency check between the design and analysis to confirm the variations in the results. In this process, all the results of the design and prototype are brought to comparison to check the accuracy of the results obtained. The prototype formed was robust and could be easily installed to an A.C car on the road. However, the power delivered when compared to an I.C engine was significantly lower and the efficiency was dubious as well. This is one criterion, which falls under a future scope and shall be researched upon in detail. In context to the research, the author has laid emphasis on the design and working of the SRM type machine and taking inspiration from this approach, I have referred to a single type of motor, which is an IPM BLDC motor.

Design of A New Dual Rotor Radial Flux BLDC Motor with Halbach Array Magnets for an Electric Vehicle. B. V. Ravi Kumar* and K. Siva Kumar†, Member, IEEE Department of Electrical Engineering, Indian Institute of Technology Hyderabad (IITH), Hyderabad-502285, INDIA. 978-1-4673-8888-7/16/$31.00 ©2016 IEEE

The author has designed a dual rotor radial flux BLDC motor and it has the additional functionality of a HALBACH array of magnets. This inclusion is done with the motive of delivering high torque and power density. The dual rotor set up in an electrical motor is suitable for the new generation electric vehicles and therefore it is used in this research work. The HALBACH array arrangement utilizes an auxiliary magnet between the main or the primary magnets. The author has followed a sequence of operations, which initiates the selection of the magnetic material followed by the sizing of the motor and magnetic analysis using FEA. The electrical design and performance analysis is done to assess the operating condition of the motor. Various performance characteristic curves have been plotted to establish the relationship between variables and operating conditions. In the final stage, a comparative analysis between DR – HA BLDC motor and the DR BLDC motor is carried out to check the results and the parameters which are assessed are torque and power density. The inference from this research work has been the subject of magnet positioning and its significance in load-bearing and power generation.

Design of High-Power Permanent Magnet Motor with Segment Rectangular Copper Wire and Closed Slot Opening on Electric Vehicles. Jae-Hak Choi, Yon-Do Chun. Pil-Wan Han, Mi-Jung Kim, Dae-Hyun Koo, Ju Lee, and Jang-Sung Chun. Electric Motor Research Centre, Changwon, 641-120, Korea. 0018-9464/$26.00 © 2010 IEEE.

This paper deals with high power brushless DC motor used for traction in a 48-volt golf cart system. In the design process, the stator has segmented rectangular copper windings to maximize output power within its limited dimension. The parameter such as efficiency and current density is compared for two design approaches, which is a closed slot opening and a slot pole combination. The results obtained show an increase in power density per volume of 120% compared to a commercial motor with round winding coils at similar efficiency. The result satisfies the objective behind the motor design. What we inferred from the research work is that there exists a direct relation between cogging torque and output power. The more we decrease the cogging torque more decline in output power is observed up until a critical point. This happens due to the dependence of the cogging torque on the length of the slot opening and in my research work, this fact has been considered.

Design and Prototyping of 3-Phase BLDC Motor Y.B. Adyapaka Apatya, Aries Subiantoro, and Feri Yusivar* Electrical Engineering Department, Universitas Indonesia, Depok 16424, Indonesia. 978-602-50431-1-6/17/$31.00 ©2017 IEEE.

This research paper deals with the designing and prototyping of an interior permanent magnet BLDC motor. During the designing process, the structure of an interior rotor permanent magnet is selected for use in the process. A software-based FEA simulation follows the designing process. Various parameters such as stator resistor, inductance, and the back EMF constants were used to evaluate the results of design and prototype motor. The author has also performed parameter testing to evaluate stator resistance, D-axis stator inductance, q-axis stator inductance and back EMF constant of the prototype permanent magnet BLDC motor. In conclusion, the author has discovered that the anomaly between the design and prototype was caused due to the incompatibility of material used for the construction of the motor. The evaluation results highlight the fact that constituent materials influence the electromagnetic properties of the motor. Therefore, materials selection along with rotor positioning has been emphasized a lot in this research work as these parameters impact the performance of the BLDC motor. Since this work directly relates to the work highlighted in my research paper, therefore, the concept of designing is considered but due to the unavailability of any monetary funds, a prototype has not been made for research work.

3. DESIGN METHODOLOGY

The design involves an RMXPRT model of the BLDC motor. The permanent magnets are embedded in the laminations inside the rotor slots while the poly-phase armature winding is embedded in the stator whose number of poles is the same as that of a rotor. The stator poly-phase winding is connected to a power supply that is D.C in nature. The connection is made through a switched circuit to produce a rotational magnetic field in the air gap. The conduction sequence of the switched circuit depends on the position of the rotor magnetic field. The attempt is to make the stator magnetic field orthogonal to the rotor magnetic field. The function of the switched circuit is the same as the commutator in the conventional dc electric machine.

3.1 RMXPRT model – ANSYS Electronics

Table 1: Model design parameters

Parameters	Motor Design
Number of Poles	8
Types of magnets	embedded
Number of Windings	3
Number of slots	48
Rotor position	Inner rotor
Transistor & Diode drop	0.8 V
Load angle or trigger	0
Voltage	240 V
Rated speed	4000 RPM
Rated current	18 amps
Efficiency	96%

3.2 Design Flowchart

The process initiates with specifying the design aspects of the motor allocating the poles in stator and rotor and setting up the voltage and input current. The setup is followed by entering the value for motor dimensions i.e. stator and rotor inner and outer diameter. Slots and winding types are entered and the value of air gap length follows. The selection of magnet is important for better conduction and high strength magnetic field. Some of the used magnets are Ferrite, Alnico, Samarium Cobalt, and Neodymium Ferrite Boron. Once we input the values, a solution setup needs to be set up with values of rated voltage, rotational speed and operating temperature of the motor. This is followed by the analysis and results.

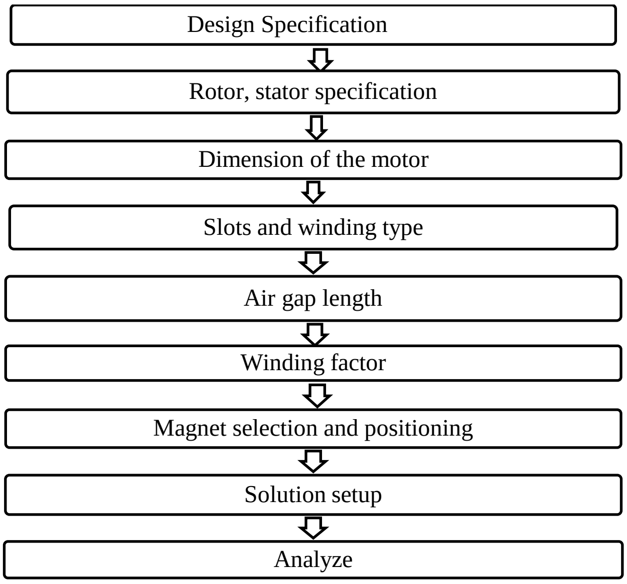

Fig. 1: Design flowchart

Table 2: Stator specification

Parameters	Motor design-stator (inch)
Outer Diameter	8
Inner Diameter	5
Length	4
Stacking Factor	0.93
Steel type	M19-24G
Number of slots	48
Skew Width	0
Number of branches	3

Table 3: Rotor specification

Parameters	Rotor Specification (inch)
Outer Diameter	4.75
Inner Diameter	1.5
Length	3.8
Steel	M19 -24G
Stacking factor	0.93
Pole type	2

The model of the IPM BLDC motor was made in ANSYS electronics suite and later the FEA simulation is carried out in MAXWELL 2D.

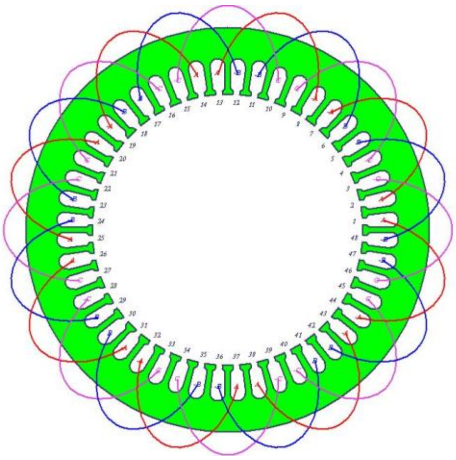

Fig. 2: Connected stator coil setup

The stator coil was not connected during the analysis stage. The diagram just shows the coils connected in the designing phase when the values to stator slots and coil pitch were allocated.

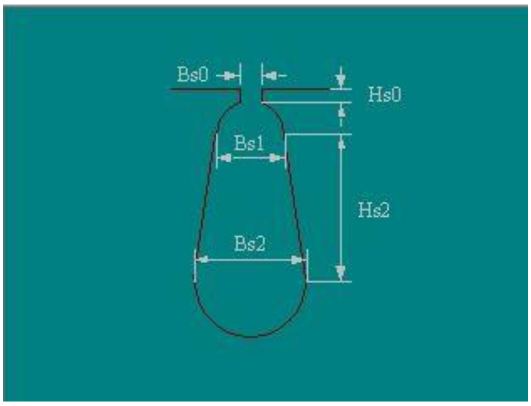

Fig. 3: Stator slot and its dimensions

The values taken are as follows: (Inch)
Tooth width – 0.042*1.2
Hs0 -0.028
Hs2 – 0.72
Bs0 – 0.080

The parallel arrangement of a tooth is selected with whole-coiled windings. The number of slots on the winding is taken as 28.

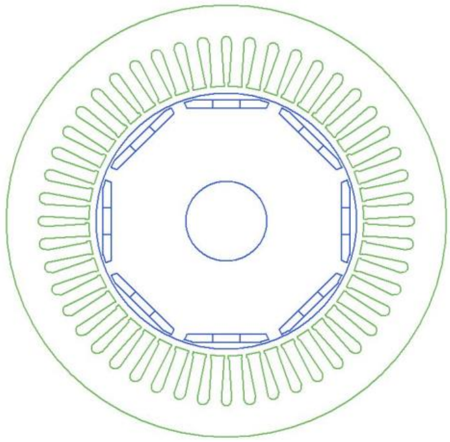

Fig. 4: IPM BLDC motor setup RMXPRT model.

The value of the rotor pole parameters are as follows: (inches)
Embrace - 0.7
Bridge – 0.05
Rib – 0.5
Magnet – NdFe30
Magnet width – 0.5
Magnet thickness -0.15
The values used in solution setup –

The parameters used for the solution setup are as follows:
Load type – constant power
Rated horsepower – 10 HP
Rated voltage – 356 V (240 *pi*sqrt (2)/3)
Rated speed – 4000 RPM
Operating temperature – 75 Celsius.

Based on the solution set up an analysis of the DC machine is carried out which provides no-loaded, full –load and steady-state value of the electric parameters.

4. OBSERVATION

Based on the analysis of the RMXPRT model of the IPM BLDC motor setup the following results are obtained:

STEADY STATE PARAMETERS	
Stator Winding Factor:	0.965926
D-Axis Reactive Inductance Lad (H):	0.00166995
Q-Axis Reactive Inductance Laq (H):	0.00235879
D-Axis Inductance L1+Lad(H):	0.00328556
Q-Axis Inductance L1+Laq(H):	0.0039744
Armature Leakage Inductance L1 (H):	0.00161561
Zero-Sequence Inductance L0 (H):	0.00161561
Armature Phase Resistance R1 (ohm):	0.370923
Armature Phase Resistance at 20C (ohm):	0.305114
D-Axis Time Constant (s):	0.00450215
Q-Axis Time Constant (s):	0.00635925
Ideal Back-EMF Constant KE (Vs/rad):	0.480268
Start Torque Constant KT (Nm/A):	0.509468
Rated Torque Constant KT (Nm/A):	0.132833

Fig. 5: Steady-state parameters –Software analysis electrical solution

Average Input Current (A):	0.383452
Root-Mean-Square Armature Current (A):	0.129965
Armature Thermal Load (A^2/mm^3):	0.0124976
Specific Electric Loading (A/mm):	0.218898
Armature Current Density (A/mm^2):	0.0570933
Frictional and Windage Loss (W):	26.2077
Iron-Core Loss (W):	98.7876
Armature Copper Loss (W):	0.0187956
Transistor Loss (W):	0.204055
Diode Loss (W):	0.00307356
Total Loss (W):	125.221
Output Power (W):	11.0694
Input Power (W):	136.291
Efficiency (%):	8.12189
Rated Speed (rpm):	6988.71
Rated Torque (N.m):	0.0151251
Locked-Rotor Torque (N.m):	242.526
Locked-Rotor Current (A):	476.107

Fig. 6: Full load magnetic output data

Now to carefully asses the dependency of these results on certain parameters another solution setup is added and certain changes were brought in the design.

The design changes include:

- The control type is changed from D.C type to Chopped current control (CCC).
- Maximum current = 20 Ampere and minimum current = 18 Ampere.
- The orientation of the winding is changed and the coil pitch is changed from **3** to **7.**
- Slot value of stator set to **9.**
- The slot figure modified.
- Number of strands in the machine set to 1 from 0
- Rib **-0.5**, Bridge – **0.1**

The intention is to measure the variation of the torque and power characteristics curves with variation in the air gap between magnets and certain winding changes.

Modified RMXPRT model:

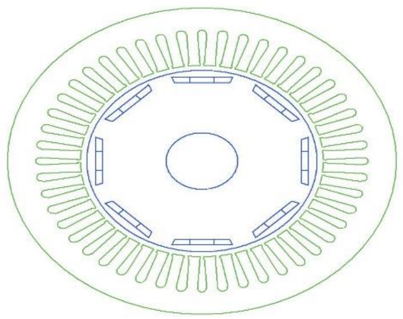

Fig. 7: Modified Design of IPM BLDC motor

Comparative analysis of the performance curves:

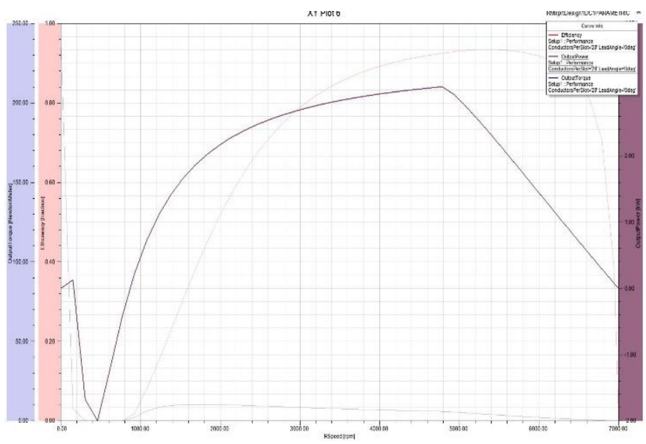

Fig. 8: Efficiency, power & torque vs speed – Case 1

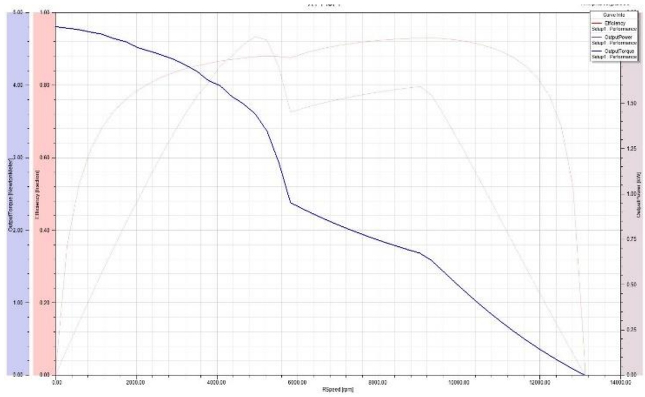

Fig. 9: Efficiency, power, and torque vs speed – Case 2

The variation in the efficiency torque and power with speed as we bring about a change in the air gap and coil pitch is evident. It can be observed with the performance curves. The value of efficiency of the motor remains almost constant at 0.84 but the output torque does fluctuate with an increase in the speed of the motor from 0 to 4000 RPM. Now comparing the Induced phase voltage in both the cases:

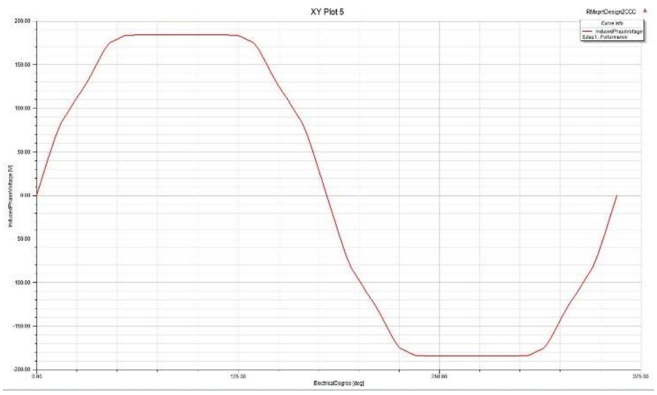

Fig. 10: Induced phase voltage vs electric degree –Case 1 & 2

As per the results, the value of induced phase voltage remains unchanged with the variations in both the cases and thus we obtain a similar performance curve.

The following observations are taken into account:

- The value of output torque declined rapidly with an increase in the air gap.
- The rapid decline in air- gap flux density.
- No significant impact on the d-axis inductance.
- The major change observed in the q-axis inductance along with the rotor.

- Cogging torque reduces significantly.
- The output power dips in the first case and low RPM and then rises significantly however with the increase in the bridge and decrease in rib the value of power increases initially and starts dropping beyond 4000 RPM in steps.

5. COGGING TORQUE ANALYSIS

The torque present due to the interaction between the permanent magnet of stator and rotor slots in an IPM BLDC machine is known as cogging torque. The presence of cogging torque in addition to the electromagnetic torque and reluctance torque induces vibration, acoustic noise, speed ripples, and position inaccuracy, which hampers the motor performance at low speeds and low loads.

In order to accurately calculate the value of cogging Torque, the process followed involves solving a parametric sweep in Magnetostatic (the input parameter being the angle between rotor and stator). The method adopted might not lead to excellent results, as the error due to the mesh will be different for each position (the mesh will change for every row).

Therefore, the steps followed will have a particular sequence and it will be carried out in accordance with the design presented in the initial stage. Another approach that is preferred in this research is by using a transient solver with motion. In the simulation process, the rotor is moved at the speed of 1 degree/s. Therefore, the mesh remains unchanged for all the positions due to the Band object: the mesh inside the Band object will rotate with the rotor. Due to this, each time step will be independent of the other. The adaptive mesh will not be used therefore the simulation time will be shorter.

STEP 1: Simulation at NO –LOAD

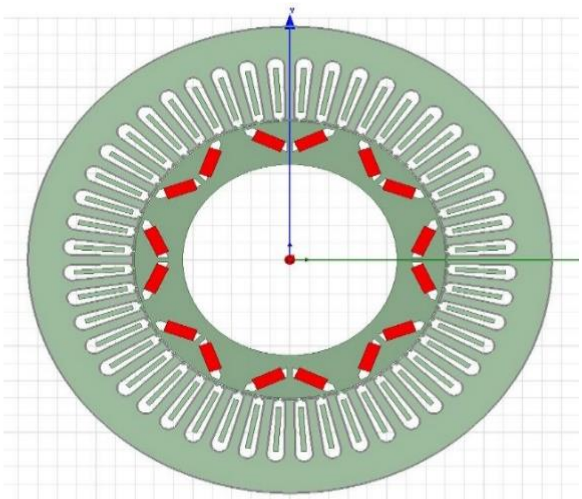

Fig. 11: Maxwell Design with Lap coil arrangement

The meshing operation and calculation setup of the analysis of the motor at full-load are done. To carry out this operation in ANSYS electronics a MAXWELL 3D model of the motor is made and static and dynamic analysis is carried out with appropriate input parameters and master-slave and Vector potential boundary conditions.

The Maxwell model is first reduced in size for adaptive meshing and application of initial boundary conditions. This resulted in a plot of magnetic flux strength highlighting the magnetic flux densities at all faces of the rotated motor setup.

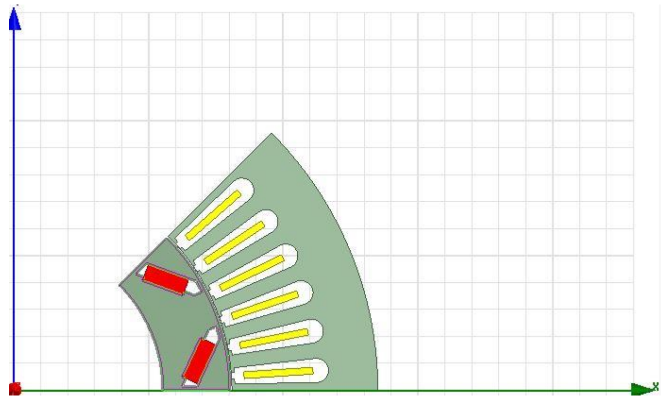

Fig. 12: Cut section for electrical simulation

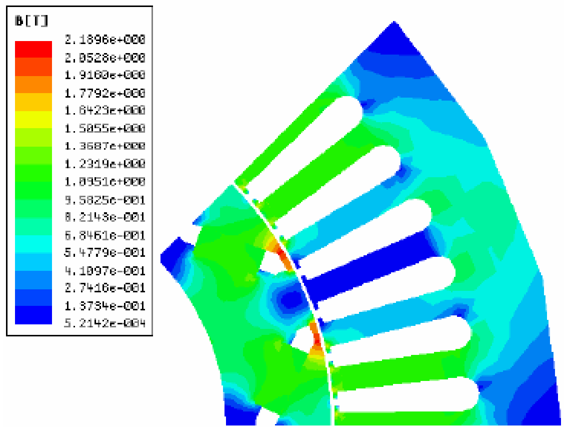

Fig. 13: Magnetic flux density at the face of the cut-section

The model highlights the maximum value of the magnetic flux density obtained at the face of the magnet at a no-loaded condition. However, for cogging torque, we are considering the solution setup of full –load motor condition with variations in the calculation.

STEP -2 Variation in FULL-LOAD DATA:

- The rotor is moved at 1 Degree/sec.
- One pole pair takes 7.5 mechanical degrees.
- Solving over 15 in order to have two periods.
- The time step is set to 0.125 s to have a very smooth curve.
- Lowering the nonlinear residual to 1e-4.

Selecting the parameters to a plot that involves torque and time we get a curve showing the value of cogging torque relevant to this design i.e. **1.82 Nm.**

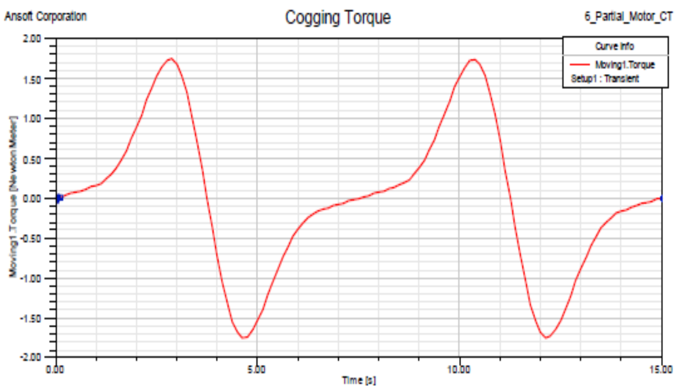

Fig. 14: Cogging Torque vs Time relation

The cogging torque can be expressed by the integration of the normal and tangential magnetic flux components within the air gap. [1]. We can also consider this design aspect of the machine by relating the parameters of pole shoe variation and magnetic span angle to the cogging torque.

6. CONCLUSION

The research paper covers all the aspects pertaining to the designing and solution-based analysis of an Interior permanent magnet DC brushless motor. It also assesses the performance of the motor and the dependency on the positioning of rotor magnets. The variation of torque and induced phase voltage by the change in the magnet width and spacing is highlighted with performance curves. A major discovery would be the reduction in air gap flux density and cogging torque with changing rib and bridge in the rotor slots.

In addition, the simulation with full-load data in ANSYS electronics suite with the objective of calculating the cogging torque was successful and thus by reducing the angular speed of the movement of the rotor along with keeping a smaller time step resulted in a complete simulation with the lesser error. However, many aspects of motor design and performance testing are untouched by this paper due to a lack of information and resources. The non – availability of funds and limited access to the labs have limited my research to only computer designing. Therefore, a lot of further progress could be made and a variety of design approaches can be tested to assess the performance of an IPM BLDC motor.

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