DESIGNING OF PROTOTYPE SLOTLESS PERMANENT MAGNET BLDC MOTOR WITH HALBACH ARRAY USING ANSYS SOFTWARE AND ITS INVESTIGATION

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Abstract* :This paper presents the developments in the design of Slot less PM brushless DC Motor for higher torque and less cogging effect. The slotless design provides minimum cogging torque, less weight whereas the Halbach array of its extraordinary positions of permanent magnets keeps the magnetic field on any one side of the array and there is no stray field produced. The Matlab coding has been developed for the machine specifications 250Watts, 24Volts, 10.5Amps, 3000Rpm, & 0.67Nm and the output is simulated. The performance characteristics of this special electrical machine are analyzed and verified using Ansys software. Initially, the cad design model of this machine is developed. With the help of the CAD model, the real-time prototype model is developed and then, all the design parameters are validated. The foremost magnitude, back emf is validated perfectly as 0.48volts for 78.12Rpm and 0.4volts for 62.5Rpm using the scope from the prototype model. Finally, the entire design parameters are validated using Ansys, Matlab, CAD in a Prototype model.To avoid risks of failure while developing the motor, a smaller scale of the motor is developed to demonstrate the success of the design including physical dimensions, winding techniques, and Halbach array assembly. The same technique can be used to design higher rating motors.*

***Keywords**: Halbach Array, PMBLDC Motor, Ansys, Cogging Torque, Matlab, CAD.*

1. INTRODUCTION

The AC motors, which are less expensive and rugged, operate in both motoring mode and in generating mode. But, there is a drawback that the presence of commutator and brushes make the motor to operate normally with regular maintenance. To overcome the above limitations of AC motors, Permanent Magnet motors have been developed with variable speed drives. A Brushless DC motors is designed and developed from Permanent Magnet synchronous machine and it operates by the Direct current. The Brushless motors do not require brushes, and they operate using a controller through the electronic commutation method. The BLDC motors have good torque to size ratio, and so high value of torque can be achieved. Further, they have very good dynamic characteristics. The Permanent Magnet BLDC motor develops trapezoidal back Electromotive force voltage and the hall effect sensor method is used to detect the rotor position of the motor. [1]

The BLDC motor is a three phase permanent magnet synchronous motor with the stator having three phase windings and a rotor with permanent magnets. The magnetic material for permanent magnet rotor can be chosen, depending on the magnetic field density required. The ferrite magnets are most normally preferred because of their low cost, and samarium cobalt magnets are used for high torque. In BLDC Motor, brushes and commutators are not needed for their construction. As a result, the problems like sparking in commutators and other problems related to brushes are eliminated. The BLDC motors are electronically commutators and they are operated in three phase supply voltage from inverter unit. [2]The speed of the motor is directly proportional to the applied voltage. By varying the average voltage across the windings, the speed can be altered. This is achieved by altering the duty cycle of the base PWM signal. The use of PWM in power electronics to control high energy with maximum efficiency and power saving is not new but, it is interesting to generate PWM signals using HDL and implementing it in Field Programmable Gate Array. FPGAs are increasingly being used in motor control applications, due to their robustness and customizability.[3]

DC motors have a wide application, due to their low cost, torque-speed characteristics, and their control method. The use of BLDC motor has been increasing in the era of modern technology, due to their high efficiency, silent operation, compact, and high reliability due to the absence of brush and commutator, and low maintenance. Moreover, the higher torque to weight ratio enables them to be used in applications where space and weight are critical factors because they eliminate the problem encountered with the brushes and the commutator. However, the problems are encountered with these motors because of variable speed operation over last decades, continuous technology development in power semiconductors, microprocessors, adjustable speed drivers control schemes and permanent-magnet brushless electric motor production have been combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications. A brushless DC motor is a rotating electric machine with three-phase stator like that of an induction motor. The rotor has surface-mounted permanent magnets. The stator generated flux interacts with the rotor flux, and it defines the torque and the motor's speed.

In the BLDC motor, the speed and position can be controlled by the sensor and sensorless control. However, to reduce the overall cost of actuating devices, sensors are omitted in sensorless control but it needs a complex algorithm. To control the speed of the machine using sensors, the present position of the rotor is needed. The fixed gain PI controller has the limitations of bringing suitable speed only for a limited operating range around the operating point. To reduce the speed oscillation, the voltage across the motor is varied and it can be obtained by varying the duty cycle of the PWM signal. When the phase current and phase voltage in phase, the BLDC motor gets high efficiency by reduced copper and conduction losses.[4] BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment, and instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. BLDC Motors are available in many different power ratings, from very small motors as used in hard disk drives to larger motors used in electric vehicles.[5]

Figure.1. shows the general block diagram of an operation of the BLDC motor. The BLDC motor operates in the closed loop system. The speed of the motor is compared with reference speed and it is fed into the PI controller. Then, the rectifier is used to produce the desired DC voltage and it is given to the inverter for producing three phase supply. The gate signals to inverter are generated by using FPGA motor drive, which produces PWM signals by the use of hall sensor signals from the motor.

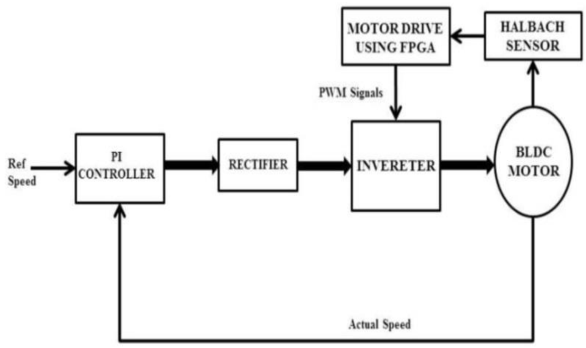


Fig.1.Block Diagram of BLDC Operation

1.1 Existing System and Research Gap

In the existing system, the cost, weight and cogging torque of slotless PM Brushless DC Motor is very high and the developed torque is less. Further, in slotless motor finding out the correct number of poles, slots, magnets and developed torque is a complicated process with respect to specified application because of the absence of Halbach array and the lack of design software.

1.2 Proposed work

In this proposed research, initially, Excel software has been used to validate the number of slots, pole pairs, and thickness of the permanent magnet by performing more number of iterations. In the second step, Matlab analytical coding is developed and simulated for calculating the speed, torque, current, voltage and back emf, of the slotless PM BLDC motor. In the third step, Ansys software has been used to analyze the various performance characteristics of PM BLDC motor. In the fourth step, the CAD model has been designed for developing the prototype model. After that, both the analytical and hardware output results are verified in the single point of contact which means that the back emf has been validated in the prototype model for satisfying the entire design parameters. Finally the expected output is achieved from the hardware that is suitable for space craft applications.

1.3 Future Work

We have started the preliminary work for designing and development of 5HP, 48Volts, 800Rpm compact slotless permanent magnet brush less dc motor for various defence applications with the help of proto type machine.

2. EVALUATION OF POLES AND SLOTS

The number of poles and virtual slots have been validated by performing various iterations using Excel Software and analytical calculations. Finally, the total numbers of poles and slots are determined as 12 and 36 for the required torque and speed of PM BLDC Motor. As per the analytical calculation the peak flux density 1.13 tesla is produced for 12 poles that is denoted in fig.2.

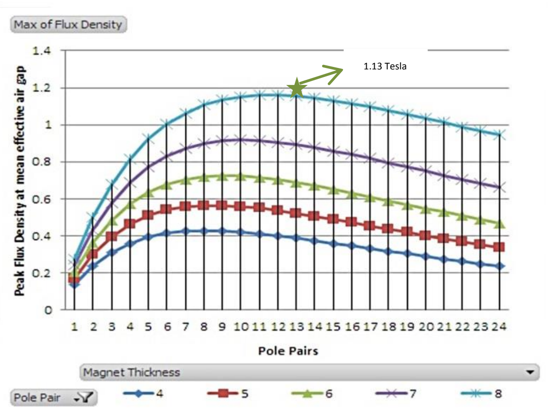


Fig. 2. Evaluating Pole Pair and Slots for flux density at mean efficiency airgap

3. ANALYTICAL MODELING OF PMBLDC MOTOR

The PMBLDC motor is modeled in the 3-phase *abc* variables.

$$v_{an} = Ri_a + t\psi_a + e_{an} \quad (1)$$

$$v_{bn} = Ri_b + t\psi_b + e_{bn} \quad (2)$$

$$v_{cn} = Ri_c + t\psi_c + e_{cn} \quad (3)$$

where v_{an}, v_{bn}, v_{cn} are phase voltage and may be designed as *:*

$$v_{an} = v_{ao} - v_{no} \;, v_{bn} = v_{bo} - v_{no},$$

$$v_{cn} = v_{co} - v_{no} \quad (4)$$

where v_{ao}, v_{bo}, v_{co} and v_{no} are 3-phase and the neutral voltages are referred to the zero reference potential at the center-point of DC link. R is the resistance per phase of the stator winding, t is the time differential operator and $e_{an}, e_{bn},$ and e_{cn} are phase to neutral back emfs.

The $\psi_a, \psi_b,$ and ψ_c are total flux linkage of phase windings *a*, *b* and *c*, respectively. These values can be expressed as:

$$\psi_a = L_s i_a - M(i_b + i_c) \quad (5)$$

$$\psi_b = L_s i_b - M(i_a + i_c) \quad (6)$$

$$\psi_c = L_s i_c - M(i_a + i_b) \quad (7)$$

where L_s and M are the self and mutual inductances, respectively. The PMBLDC motor has no neutral connection and hence, this results in:

$$i_a + i_b + i_c = 0 \quad (8)$$

Substituting equation (8) into equations (5), (6) and (7) ,the flux linkages are given as:

$$\psi_a = i_a(L_s + M), \psi_b = i_b(L_s + M)$$

$$and \;\; \psi_c = i_c(L_s + M) \quad (9)$$

By substituting equation (9) in volt-ampere equations (1), (2), and (3) and rearranging these equations in a current derivatives, state space form becomes

$$ti_a = 1/(\;L_s + M)\,(v_{an} - Ri_a - e_{an}) \quad (10)$$

$$ti_b = 1/(\;L_s + M)\,(v_{bn} - Ri_b - e_{bn}) \quad (11)$$

$$ti_c = 1/(\;L_s + M)\,(v_{cn} - Ri_c - e_{cn}) \quad (12)$$

The developed electromagnetic torque may be expressed as:

$$T_e = (e_{an}i_a + e_{bn}i_b + e_{cn}i_c)/\omega_r \quad (13)$$

Substituting

$$e_{an} = k_b f_a(\theta_r)\omega_r, \quad e_{bn} = k_b f_b(\theta_r)\omega_r \;\text{,and}$$

$$e_{an} = k_b f_c(\theta_r)\omega_r$$

$$T_e = k_b[f_a(\theta_r)i_a + f_b(\theta_r)i_b + f_c(\theta_r)i_c] \quad (14)$$

where ω is the rotor speed in electrical rad/sec. The mechanical equation of motion in speed derivative form can be expressed as:

$$t\omega_r = (P/2)(T_e - T_l - B\omega_r)/\mathrm{J} \quad (15)$$

where P is the number of poles, T_l is the load torque in N-m, B is the frictional coefficient in N-ms/rad, and J is the moment of inertia, kg-m^2.

The derivative of the rotor position (θ_r) in state space form is expressed as:

$$t\theta_r = \omega_r \qquad (16)$$

The potential for the neutral point with respect to zero potential (v_{no}) is needed to be considered to avoid balance in the applied voltage and to simulate the performance of the drive.

This can be obtained as follows:

Substituting equation (8) in the volt-ampere equations (1), (2), & (3) and adding them together it gives:

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = R(i_a + i_b + i_c) + (L_s + M)(ti_a + ti_b + ti_c) + (e_{an} + e_{bn} + e_{cn}) \qquad (17)$$

Substituting equation (11) in equation 1, 2 and 3 the following equations is obtained:

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = (e_{an} + e_{bn} + e_{cn})$$

Thus $v_{no} = [v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})]/3$

The set of differential equations mentioned in equations (10), (11), (12), (15) and (16) defines the developed model in terms of the variables $i_a, i_{b,} i_c, \theta_r, \omega_r$ and time as an independent variable.

4. MATLAB AND SIMULATION RESULTS

Figure 3 shows the functional block and operation of three phase permanent magnet BLDC motor. The Matlab block diagram has been developed for 24V, 3000Rpm, 0.67Nm, and 10.4Amperes, PMBLDC Motor. The block consists of three phase inverter which is a voltage-source configuration with constant voltage Vdc. The BLDC motor operates in many modes (phases), but the most common and popular is the 3-phase. This motor has been constructed with its drive unit, stator windings, permanent magnets located on the rotor and hall sensors. The gate pulses of the inverter switch are generated by hall sensor signals from rotor and the inverter converts the supply dc voltage into input three AC supply. The three arms carry two switches to inverter. Each arm is delayed by an angle 120^{o} and the switching of each switch occurs to 60^{o} angle interval.

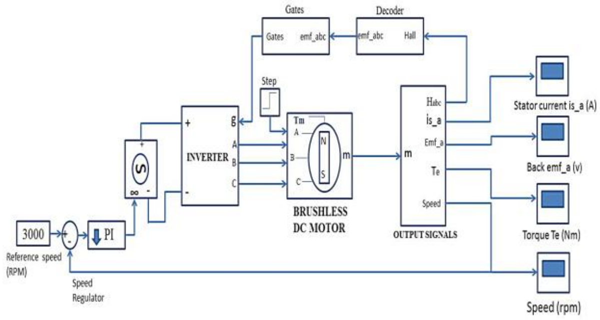


Fig. 3.Matlab Block Diagram of BLDC Motor

The speed control closed loop system uses PI regulator to develop the torque reference for the current control of the system. The purpose of controller is to maintain the closed loop system of machine and the reference speed is set so that the corresponding speed of the motor will be maintained for complete operation. The feedback controller, which is used, will make the entire system unresponsive to disturbance and changes into the factors, if it is properly designed. When the motor is in operating condition, the rotor's magnetic field and the number of turns in the stator windings remain constant. The only factor, that affects the back emf, is the angular velocity or rotor speed. As the speed increases, back emf increases as well. The potential difference across a winding can be described by subtracting the back emf and the dc supply voltage per phase. While the motor is working at the rated speed, the potential difference between back emf and DC supply voltage will be adequate for the motor to draw the rated current and to distribute the rated torque.

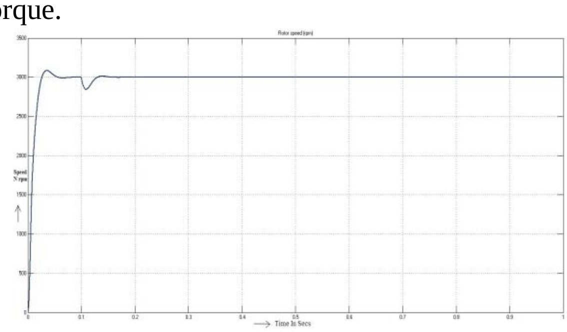


Fig. 4.Speed developed by the motor

Figure.4. Presents the speed developed by the motor under running condition by using Matlab.

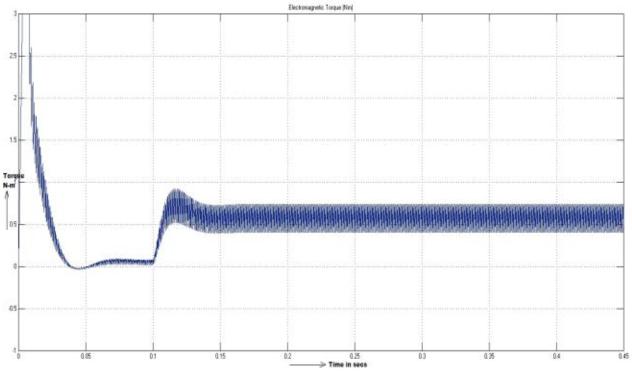


Fig. 5.Torque Developed in the motor

Figure .5 Depict the torque developed by the motor with respect to speed under running conditions.

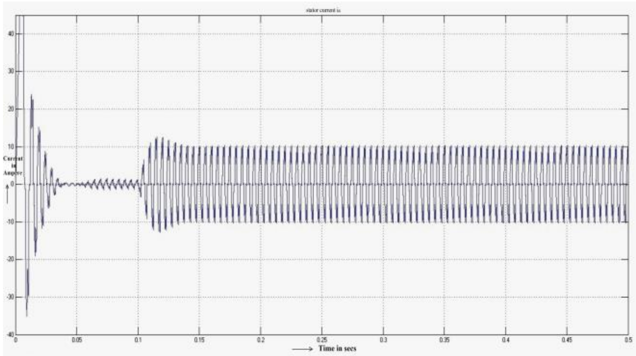


Fig. 6. Stator Current of motor

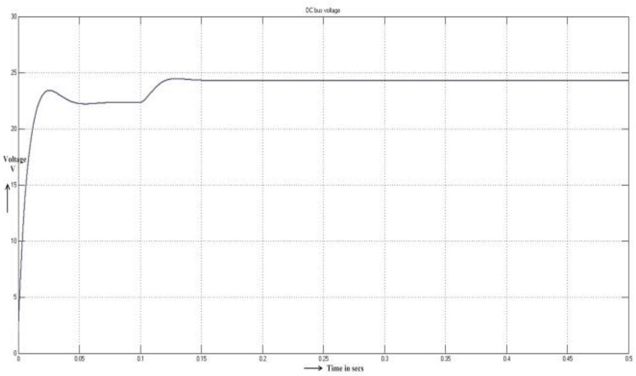


Fig. 7. DC 24Volt applied to the motor

Figure.6. and Figure.7 Illustrate the corresponding simulation waveforms of the stator current of 10.4A and the voltage 24V.

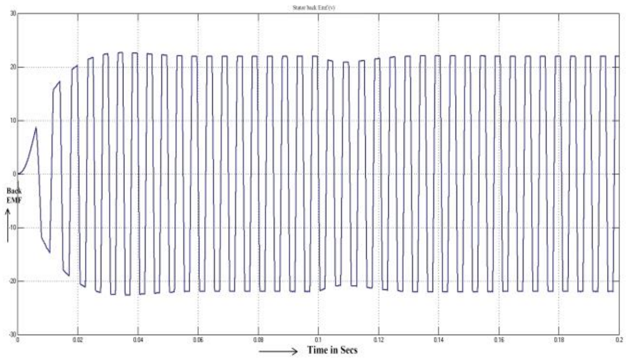


Fig. 8. Back EMF produced in motor

Figure.8 Portray the value of back emf produced by the motor at no load condition, it reads the back emf of 22V.

5. ANALYSIS USING ANSYS SOFTWARE

The basic design parameters obtained from the analytical result is used to model the machine in Finite Element Analysis method. Two dimensional FE analysis has been carried out, as the machine is axis symmetric. Commercial FE software package RmXprt and Maxwell 2D is used for the analysis. The output results matches with finite element analysis results and analytical results. By using ANSYS software, the following output performance characteristics curve has been obtained.

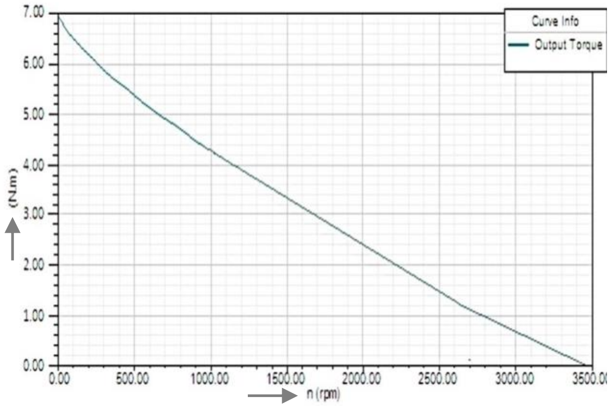


Fig. 9. Relation between Torque and Speed curve

Figure.9 shows the relation between torque and speed characteristics of BLDC motor.

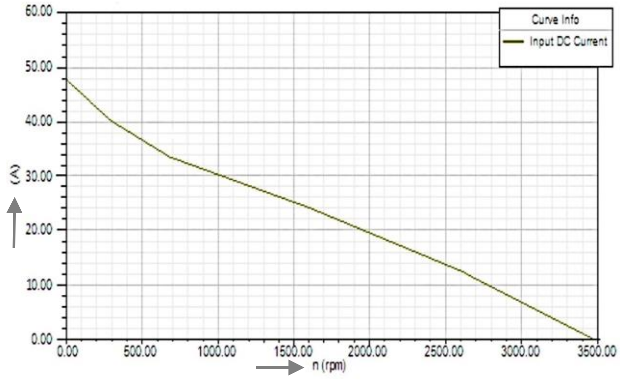


Fig. 10. Current produced at the rated Speed of Motor

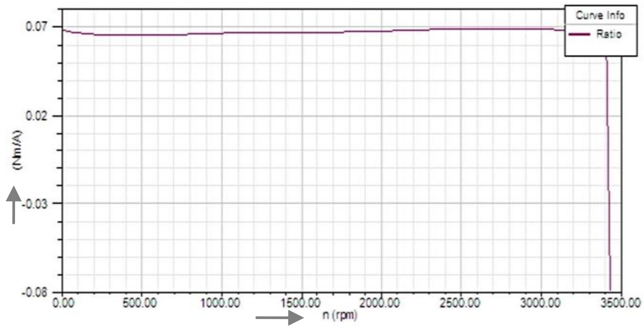


Fig. 11. Torque(Nm) Produced at 1 Ampere of current

Figure 10. shows the relation between current and speed of the motor using Ansys software and the torque produced per current has been shown in Figure 11 which reads the torque value 0.064Nm for 1 Ampere current at the speed of 3000 Rpm. The torque 0.7Nm obtained for the rated current 10.4 Ampere.

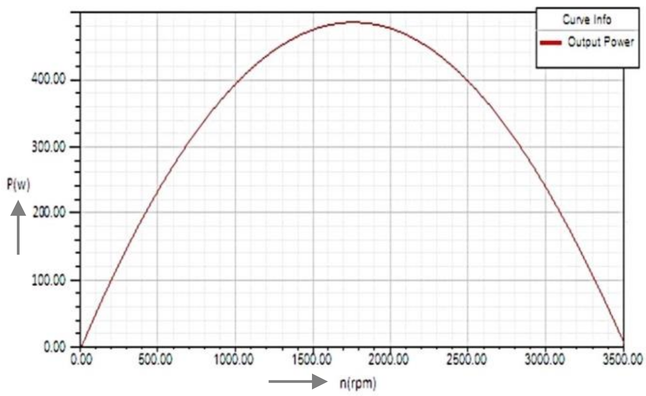


Fig. 12. Power and speed Characteristics curve

Figure. 12. Explains the relation between power and speed characteristics curve which is simulated by using Ansys software.

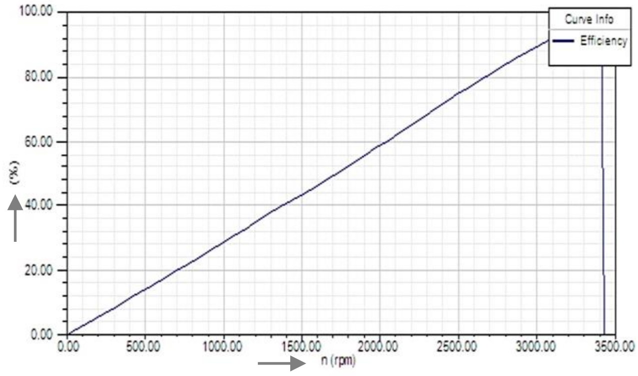


Fig. 13. Efficiency versus Speed characteristics curve

Figure 13. Describes the efficiency of the motor with respect to speed.

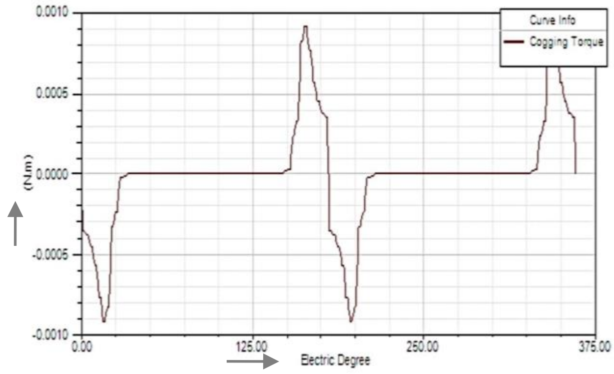


Fig. 14. Cogging torque developed in motor

Figure14. Focuses the magnitude of cogging torque produced by the motor and it is very minimum.

6. HARDWARE DETAILS / EXPERIMENTAL VALIDATION

The Results obtained from Matlab simulations the design parameters finalized by using Ansys software and the model developed by the Cad have been validated through a real time hardware implementation.

Table.1 Motor Specification

Motor Type	Slot-less using Hal-bach array
Rotor Type	Internal with shaft output
Rated Power	250 W
Rpm(Rated Max)	3000 RPM
Torque (Rated)	0.67 Nm
Voltage	24 V
Current	10.5 A
No.of Slots	36
No.of Poles	12
Stator Outer Radius	58.3MM
Rotor Outer Radius	54.4MM
Axial Length	25MM

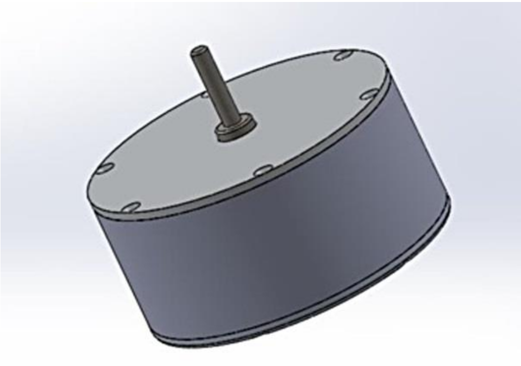


Fig. 15. CAD model of 250 Watts slot-less motor using Halbach array rotor

The cad model of 300watts slot-less using halbach array rotor has been developed after validating the design parameters by using analytical calculations as per the Table.1 and it is shown in figure 15. CAD is mostly used for meticulous engineering of three dimensional models or two dimensional drawings of real components, but it is also used for the overall engineering development from conceptual design and layout of products, through strength and dynamic analysis of assemblies from definition of manufacturing schemes of devices.

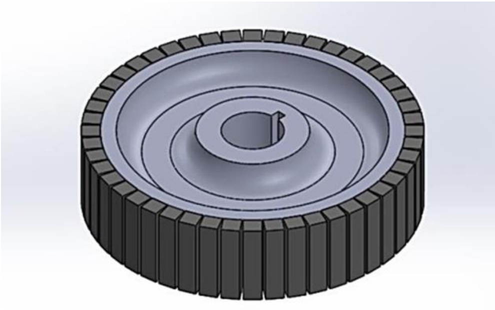


Fig. 16.CAD model of the rotor using Halbach array

Figure.16. shows the CAD model of the rotor using Halbach array. Samarium cobalt is used as permanent magnet in the rotor. It deals motor design details that are linked with the magnetic field distribution in a motor. Perfect prediction of the magnetic flux density distribution within the air gap is an important factor. Samarium Cobalt magnets exhibit good corrosion resistance compared to Neodymium magnets. For most of the applications, coating or plating is not required, but it should be considered when operating in environments that are acidic, and have high moisture, or vacuum. Coatings and metal platings can be applied to increase the ability of the magnet. Low environmental reactivity makes Samarium Cobalt (SmCo) magnets as good materials for Medical and Aerospace applications. Samarium Cobalt rare earth magnets are extremely resistant to demagnetization and they can operate at temperature up to 500^{O}F (260^{O}C).

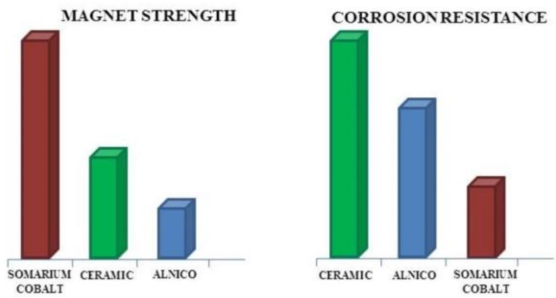


Fig. 17. Comparison of magnetic materials

Figure.17 shows the bar chart of strength of magnet and corrosion resistance for various magnetic materials. Here, the samarium cobalt is chosen because of the above merits.

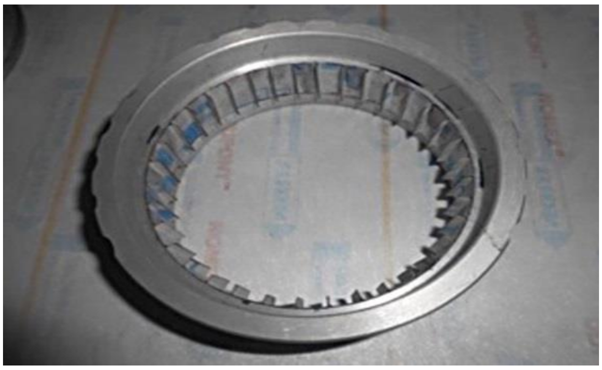


Fig. 18. Casing with arrangements to hold the stator coil

Figure.18 shows the casing with arrangements to hold the stator coil. The stator casing is prepared in Figure 18. Using Class F insulation sheet, 36 rectangular slots of dimensions 10 mm x 3 mm are prepared and they are pasted on the inside of the casing. These will hold the coils in place.

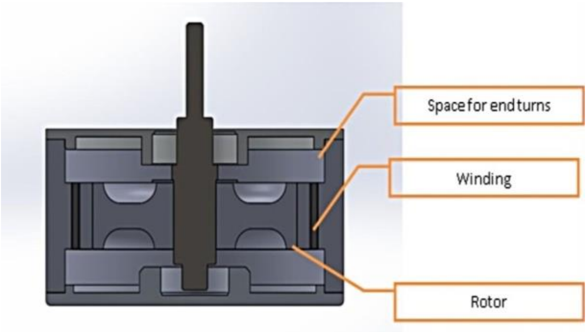


Fig. 19.Cross Section of 250 watts slot-less BLDC motor

The Cross Section of the 250 watts slot-less motor using Halbach array rotor is presented in Figure19. It indicates various parts like rotor, winding, shaft and space for end turns. A cross-sectional vision portrays a cut-away segment of the part and it is another way to illustrate unseen internal parts in a device.

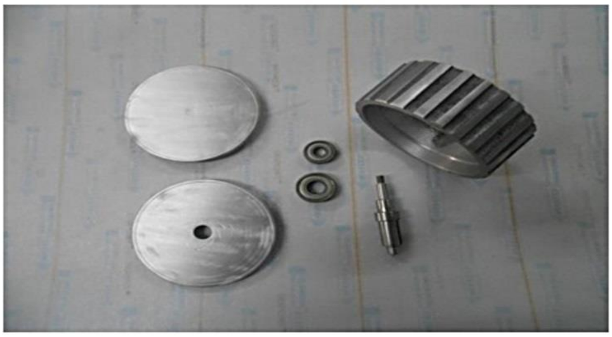


Fig. 20. Parts of the slot-less motor after machining

Figure. 20 represent various parts like stator casing, bearings, end cover and shaft, of slot-less PMBLDC Motor after machining for the present requirements.

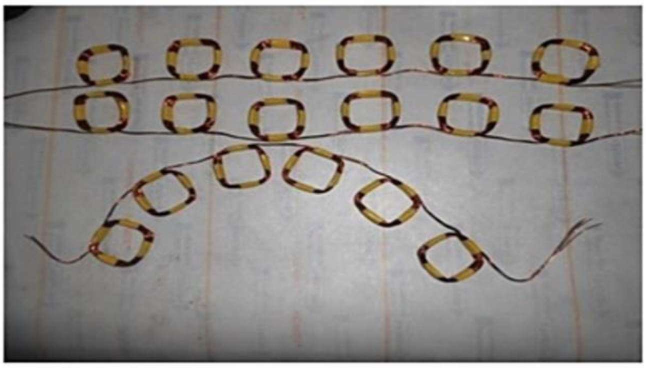


Fig. 21. Winding connection

Figure 21 shows the winding connections of slot less PMBLDC motor. It is possible to validate the number of turns/slot. By accurately calculating the number of turns, current density will be improved by increasing the number of parallel wires. Slotless motors reveal no cogging torque, and hence, there is no necessary for exploiting fractional pitch windings or the equivalent of fractional slot construction. In addition, it is general to place coils side-by-side in the circumferential direction rather than forming two layers in the radial direction. As a result, slotless motors normally have full pitch windings and one coil per pole per phase. It is the equivalent of one slot per pole per phase.

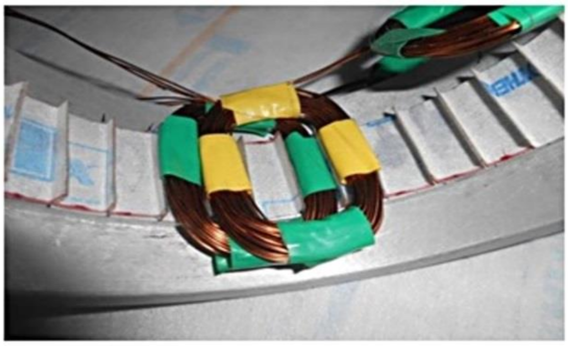


Fig. 22. Windings onto the motor casing

Shown in Figure 22. The windings are placed onto the motor casing and the coil is impregnated with resin. Due to overlapping phase wires, the space required for end turns (3mm) are not enough to accommodate 7 turns x 4 parallel wires. Therefore, a new set of coils has been wound for 7 turns x 2 parallel wires. As a thumb rule, there should be at least 2 times x winding thickness as additional space for the end turns (i.e., 6 mm instead of 3 mm). Between the time of placing the coils in the casing and resin impregnation, the coils need to be held firmly in place (by means of pins).

Fig. 23. Assembling rotor

Figure 23 and 24 portray the assembling rotor by pasting 48 magnets (12x4 = 48) in a Halbach array method

Fig. 24. Machine Prototype

7. MACHINE TOPOLOGY AND HALBACH ARRAY

Table 2. Parameters for Slot-less, Core-less, 250 Watts Motor Prototype using Halbach Array

Description	Value
Watts Rating	250 W
Voltage	24 V
Amps	10.5 A
Rated Speed	3000 RPM
Number of Slots	36
Number of Poles	12
Air gap	1 mm
Magnet Type	Samarium Cobalt (Sm_2Co_{17})
Magnet Arrangement	Halbach Array
Number of magnets per pole	4
Number of main magnets per pole	3
Number of flux focusing magnets per pole	1
Dimension of a single magnet	6 mm width x 6 mm thickness x 25 mm length
Total number of magnets	12×4 = 48 magnets
Slot Dimensions	10 mm width x 3 mm thickness x 25 mm length
Winding Technique Employed	Single layer lap winding / Integer Winding
Stator Dimensions	140 mm OD x 110 mm ID x 60 mm Length
Stator Material	Fiber Reinforced Polymer
Rotor Dimensions	108 mm OD x 96 mm ID
Rotor Material	Aluminium
Shaft Dimension	20 mm diameter
Shaft Material	EN8

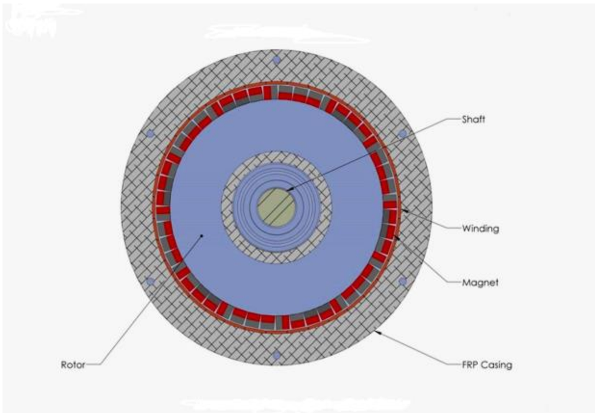


Fig. 25.Motor Topology

Fig.25. Shows the Motor topology of 36 slots, 12poles slotless, coreless BLDC Motor.

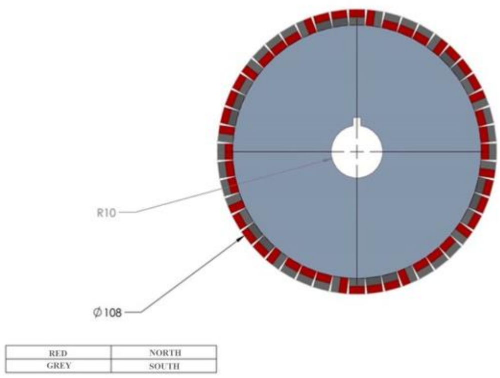


Fig. 26. Rotor with halbach array

Fig.26 shows the rotor with halbach array arrangements. The red color denotes the north pole and grey color denotes south pole.

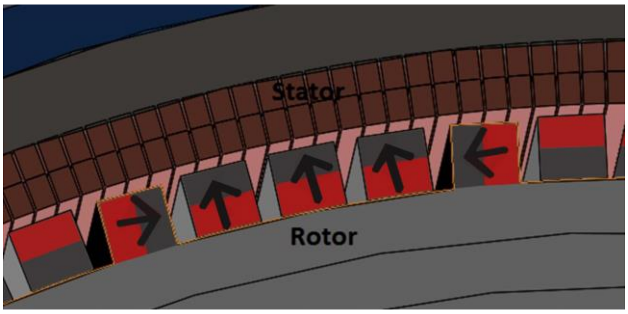


Fig.27. Magnetization direction in motor design

Fig.27. shows the magnetization directions of main magnet and halbach array magnet.

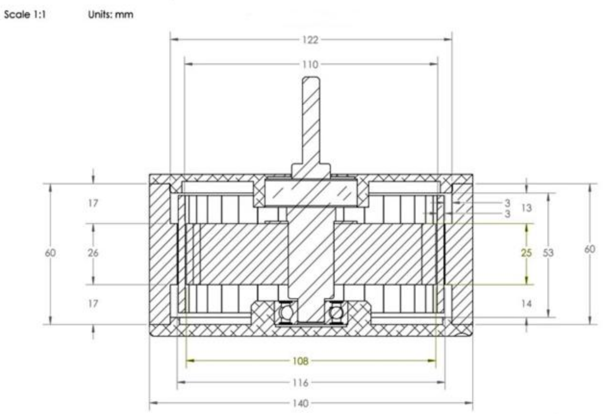


Fig. 28.Cross sectional view of coreless BLDC motor with dimensions

Fig.28 shows the overall dimensions of coreless BLDC motor.

8. EXPERIMENTAL SETUP

8.1 No Load Condition

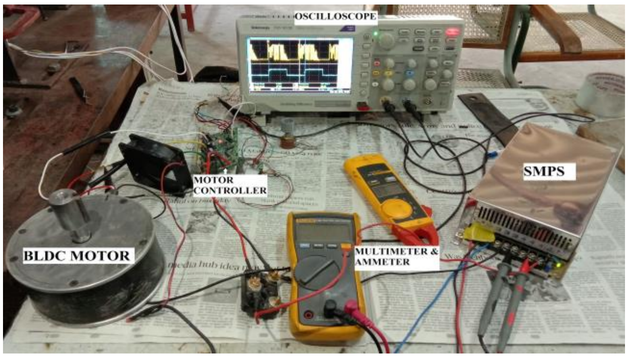


Fig.29 Experimental setup of BLDC motor at No load condition.

Input Voltage: 24VDC
No Load Current: 2A
Hertz: 362
RPM = 362×120/12 = 3620 RPM

Fig.30..Speed of the motor at no load condition

8.2 Load Condition

Motor was coupled with a Permanent Magnet DC Generator of same rating and a resistive load acted on the alternator to load the motor.

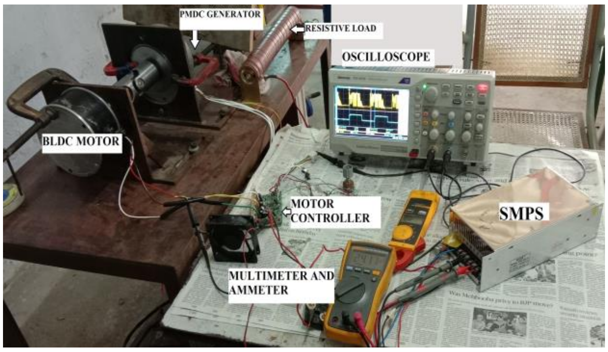


Fig.31. Experimental set up of BLDC Motor at Load condition

Iteration 1:
Test Condition: Load motor up to 10.5 A and record speed in RPM.
Recorded RPM:
Hertz: 316.4 Hz
RPM = 316.4 ×120 /12 = 3164 Rpm at load of 10.5 A
Torque Derived= 0.68 Nm

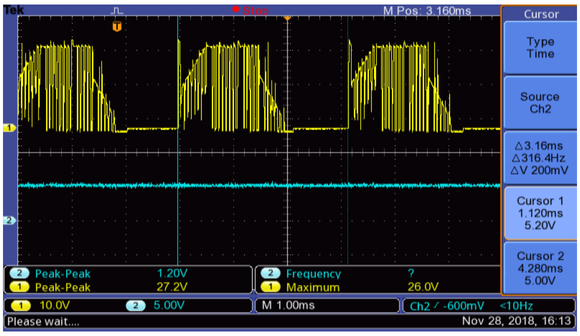


Fig.32 .Speed of the motor for 10.5A current at load condition

Iteration 2:

Test Condition: Load motor up to 9.5 A and record speed in RPM

Recorded RPM:

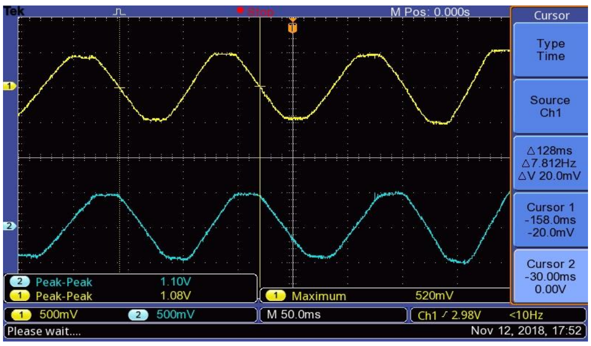
Frequency of the speed sensors installed on the alternator: 268.8 Hz

RPM = 268.8×120/10 = 3225 rpm at load of 9.5 A

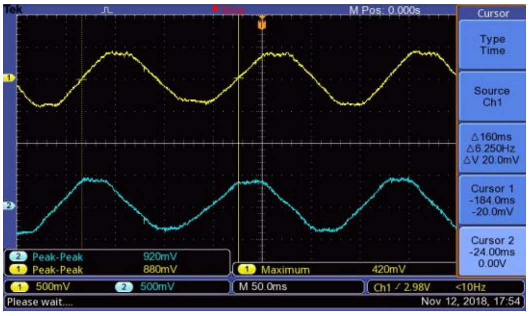
Torque Derived = 0.61 Nm

Fig.33.Speed of the motor for 9.5A current at load condition

8.3 Back Emf Generation



(a)



(b)

Fig. 34. Back Emf from 250 Watts (24V) Prototype (a) Phase 1 and 2 (b) phase 1 and 3

From the oscilloscope readings we infer the following:-

Sample 1:

Sample Run Frequency: 7.812 Hz

Back emf Voltage: 480 mV

Sample Run RPM = (7.812 ×120)/12

= 78.12 RPM

Calculated RPM at 24V (Bemf)

= (24000/480)×78.12

= 3906 RPM

Sample 2:

Sample Run Frequency: 6.25 Hz

Back emf Voltage: 400 mV

Sample Run RPM = (6.25×120)/12

= 62.5 RPM

Calculated RPM at 24V (Bemf)

= (24000/400)×62.5

= 3750 RPM

Table 3.Investigations on Proto type(BLDC MOTOR 250 Watts, 10.5Amps, 24Volts)

SL. No.	**Parameters**	**Values Measured from Proto type model**
1	Losses 1.Copper Loss	9%(22.5Watts)
	2.Core Loss	NIL
	3.Bearing Loss & Windage Loss	1%(2.5Watts)
2	Efficiency	90%
3	Power Factor	Power Factor is closed to unity because of DC Machine.

Table 4. Comparison of Cost and Performance for Slotted and Slotless Machine

Parameters	Slotted machine	Slotless machine
Cost	9000 INR Per Machine	12000 INR per Machine(Cost will be reduced if produced more number of machines)
Performance	Less Performance because of more cogging torque , More coreloss and lesser efficiency	Higher Performance due to Zero cogging torque Nil coreloss and More efficiency

Table 5.Comparison of weight for Slotted and Slotless Machine

Description	250 watts Slotted	250 Watts Slot-less, Core-less
Stator with housing	1.503 Kg (Aluminium Housing)	0.468 Kg (FRP Housing)
Rotor	0.5 Kg (8 Pole IPM)	0.557 Kg (Halbach array)
End Plates (2 Nos)	0.33 Kg (Cast Aluminium)	0.334 Kg (Cast Aluminium)
Bearings (2 Nos)	0.061 Kg	0.061 Kg
Miscellaneous	0.017 Kg	0.017 Kg
Total	**2.42 Kg**	**1.435 Kg**

9. CONCLUSIONS

The elevated torque and moderate speed are achieved in a novel slotless PM brush less dc motor with halbach array especially used for space craft applications. In addition, this machine structure forms coreless and extends more torque to inertia ratio. Analytical coding has been developed for the proto type machine and the output results are simulated. The design parameters are determined using ansys software. The entire machine model is developed using cad software. With the help of cad model and ansys software, the real time proto type model has been developed for space craft applications. Expected Back emf of the BLDC machine is measured from the proto type and all the design parameters like current, voltage, speed, torque are validated. Both the simulation and hardware outputs coincide. The similar method can be used to design higher end machines.

10. ACKNOWLEDGEMENT

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