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DESIGN OF INTERNAL PERMANENT MAGNET BRUSHLESS DC MOTOR USING ANSYS

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Abstract—Brushless DC (BLDC) Motors are receiving significant attention from industries since the last decade. They are extremely reliable and weightless than other machines of comparable power outputs; also they are suitable for high speed applications such as in CNC milling machines. Although the design procedures of the machine are available as a concatenation of many different sources, the need for an unified, step-by-step design procedure from first principles of electromagnetic is an absolute requirement. The objective of this project is to design an Internal Permanent Magnet Brushless DC (IPMBLDC) Motor. Once it was determined what type and size of material available for stator and rotor, a reasonable size and power output estimated. Using general radial flux concept the design was refined. Software tool, RMxprt of ANSYS is used to build geometry of motor and to calculate basic design parameters, and then this design is taken into Maxwell 2D environment to further analyze it.

Keywords—BLDC motor, ANSYS, Permanent Magnet, Motor Parameters.

I. INTRODUCTION

As its name suggests, a brushless motor is a motor without brushes unlike the conventional DC, Slip Ring Induction and Synchronous motors. Brushless Permanent (BLPM) motors are finding wide applications in industries in recent few years and people are trying to replace rugged Induction motors with BLPM motors. One of the main advantage exhibited by BLPM motors which overcomes IM is that, its torque per ampere doesn't vary during operation and it's easy to control, especially in high precision motion control applications. Another plus point regarding BLPM machines is that, there is nothing like slip as in the case of IM [1] [2]. Fig. 1.1 shows a schematic diagram of a general BLDC motor.

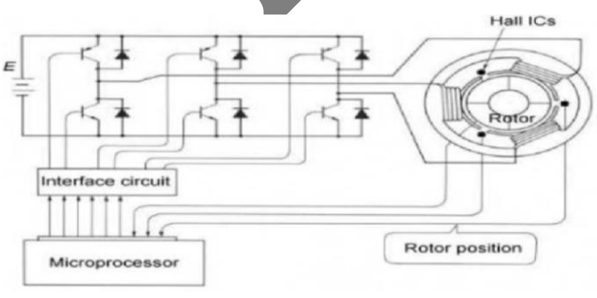

Fig. 1. **Schematic of a BLDC motor [3]**

There are several different configurations of BLDC motors depending upon the position of permanent magnets and stationary coils viz, exterior rotor and interior rotor configuration.

A. *Interior Rotor Motor:*

If an application requires rapid acceleration and deceleration of load then the torque to inertia ratio should be as high as possible. This indicates use of interior rotor motor configuration. This motor has the closest configuration to that of the classical AC motor.

B. *Exterior Rotor:*

If an application requires constant speed at medium to high speed it may make more sense to use an exterior rotor motor. The most common example of this type is hard disk drive motor.

II. FUNDAMENTALS OF MAGNETIC FOR BLDC DESIGN:

A. *Motor size*

This is a very preliminary design requirement before starting design of any motor. The answer for this query is usually given by, Equation (1).

$$T = kD^2L \qquad (1)$$

In this equation, T stands for torque given by motor, k is a constant, D is rotor diameter and L is the axial length of motor. It can be understood from Eq.1 that torque, in turn power output of motor increases if its rotor diameter or axial length are increased. Now if the length of motor gets doubled, power output has to get doubled. On the other hand, if diameter of rotor gets doubled, there is more room for magnets available on rotor because increasing diameter of rotor increases circumference of rotor considerably. Considering this fact, in case of motors used for submersible pump application is having much more axial length compared to their rotor diameter. This is done just to improve power output from motor.

B. *Basics of Magnetic Circuits*

A magnetic field is described by two important quantities, B magnetic flux density, which is magnetic flux available per unit area, whose unit is wb/m^2or Tesla and other one is H magnetic field intensity, which is change in the magnetic field, whose unit is A/m[10]. These two quantities are collinear for all magnetic materials. When magnetic materials are operated at very large operating point, the relation between these two quantities can be stated by Eq.(2), μ is known as permeability of the material.

$$B = \mu H \quad (2)$$

Magnetic circuit analysis plays around two fundamental equations, one relates magnetic flux density to magnetic flux (B to ∅) and the other one relates field intensity to magneto motive force (H to MMF). Now the total flux in a given volume can be given as integration of all flux densities in the given area, it is given by Eq. (3), where A is cross sectional area. This forms first fundamental equation.

$$\emptyset = BA \quad (3)$$

Now the second fundamental equation is given by, Eq. (4), where F is magneto motive force, whose unit is A and l is length of material, whose unit is m.

$$F = Hl \quad (4)$$

Substituting Eq. (3) and Eq. (4) into Eq. (2) and rearranging the terms gives us Eq. (5)

$$\emptyset = PF \quad (5)$$

In Eq. (5), P is known as permeance of material and it is given as Eq. (6), whose unit is wb/A or henries H. Materials having higher permeability have higher permeance and promote greater flux flow through them.

$$P = \mu \frac{A}{l} \quad (6)$$

Eq. (5) is analogous to general Ohm's law, which is I = GV. Flux ∅ is analogous to current I, MMF is analogous to potential difference V and conductance G is analogous to permeance P. Inverse of permeance is known as reluctance R, it is given in Eq. (7).

$$R = 1/P = l/\mu A \quad (7)$$

Now in terms of reluctance, Eq. 2.5 can be re-written as,

$$F = \emptyset R \quad (8)$$

Eq. 1.8 is analogous to ohm's law, but current flow through resistance constitutes energy dissipation while flux through reluctance constitutes energy storage.

C. Sources of magnetic field

There are two sources of magnetic fields one is an electromagnet in which a wire is wrapped around a soft iron piece and other one is a permanent magnet.

D. Concept of Flux Linkage

The way in which electrical energy gets converted into mechanical energy is very closely dependent upon how much flux gets created because of magnetic field, also the way in which this flux links with the materials available in its vicinity.

III. DESIGN PROCEDURE FOR BLDC MOTOR

The approach here is to begin with basic motor physical constraints and magnetic circuit describing flow of flux, from which operating point is to be decided. Then motor dimensions and current required to generate specific motor output power at rated speed with desired back emf is to be found [4].

A. Radial flux topology

Radial flux topology is most commonly used strategy in motor construction. With reference to Fig. 3.1, some of the strengths and weaknesses can be given as,

1) Strengths

- Rotor-Stator attractive forces are balanced around the rotor so there is no net radial force on rotor.
- Heat produced by the stator winding is readily removed because of the large surface area around the stator back iron.
- Except for skewing, the rotor and stator are uniform in the axial direction.
- The rotor is mechanically rigid and easily supported on both ends.

2) Weaknesses

- For a surface mounted magnet rotor, it is not possible to use rectangular shaped magnets; at least one surface must be arced.
- If the motor is to operate at high speeds, some means of holding the magnets to the rotor are required, thus sleeve or strapping adds to the air gap length.
- The air gap is not adjustable during or after motor assembly.
- The adhesive bonding the rotor magnets to rotor back iron forms another air gap since it is nonmagnetic.

IV. MOTOR DESIGN:

In this focuses on basic design of motor in RMxprt™ of Ansys Maxwell. Fixed parameters available from below Table used as input to this software. A brief introduction to RMxprt is given here first, and then details about design are given.

A. RMxprt™

ANSYS RMxprt is a template-based design tool. Designers of electrical machines and generators can enhance their design with this tool. Together Maxwell and RMxprt create a truly customized machine design flow to meet market demand for higher efficiency, lower cost machines. Using classical analytical motor theory and equivalent magnetic circuit methods, RMxprt can calculate machine performance, make initial sizing decisions, and perform many analyses in a matter of seconds. RMxprt can then automatically set up the complete Maxwell project (2-D/3-D) including geometry, materials, boundary conditions including the appropriate symmetries, and excitations with coupling circuit topology for rigorous electromagnetic transient analysis. Design sheets list all the relevant input and calculated parameters and a graphical display of waveforms, such as current, voltage, torque, and back emf. It uses classical electric-machine theory in combination with a magnetic circuit approach to calculate performance.

B. Stator design

Table I. shows analysis setup parameters for design. Based on these parameters RMxprt will solve for other parameters. The diameter of lamination available is stator outside diameter.

TABLE I. GENERAL INPUT PARAMETERS

SR.NO.	PARAMETER	VALUE
1	Rated Output Power(W)	500
2	Rated Voltage(V)	230
3	Number of Poles	4
4	Given Rated Speed(rpm)	3000
5	Frictional Loss(W)	10
6	Windage Loss(W)	2

TABLE II. STATOR DATA

Sr.	PARAMETER	VALUE
1	Number of	12
2	Outer	108
3	Inner Diameter	62
4	Length of	55
5	Number of	110
6	Average Coil	4
7	Stator Slot Fill	40.6927

The stator parameters are shown in Fig. 4.1 and Table 4.2 shows parameters.

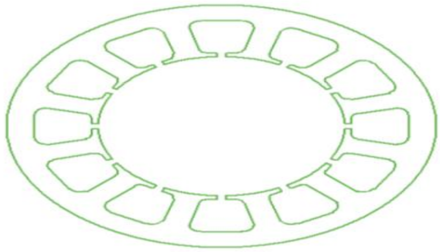

Fig. 2. **Stator data**

C. Slot parameters

Details about slot dimensions are given in Fig. 4.2 and Table 4.3.

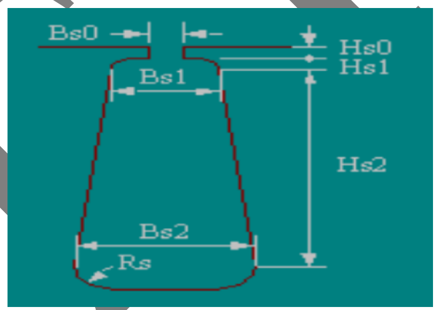

Fig. 3. **Slot Dimensions**

TABLE III. SLOT DIMENSIONS

Sr. No.	PARAMETER	VALUE
1	hs0(mm)	1.5
2	hs1(mm)	1.0
3	hs2(mm)	9.4
4	bs0(mm)	2.5
5	bs1(mm)	11.4777
6	bs2(mm)	16.8367
7	rs(mm)	3

V. PARAMETRIC SOLUTION

Rmxprt has one tool called parametric solution by which software can be requested to solve one parameter with respect to another parameter. Here conductors per slot (cps) were solved in a given range in order to get the number at which maximum efficiency and output power at rated speed can be fetched. Results are shown in Fig. 3 and Fig. 4.

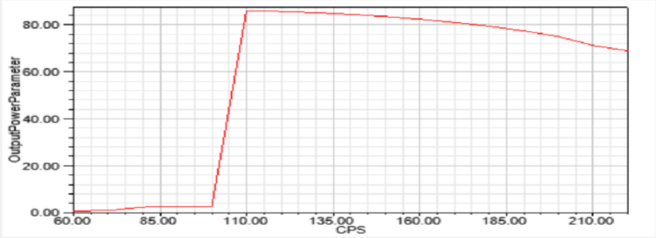

Fig. 4. **Parametric solution of output power v/s cps**

Fig. 5. **Parametric solution of efficiency v/s cps.**

A. Rotor design

Rotor has internal permanent magnets as shown in Fig. 4.5. This rotor pole template is available in RMxprt. Only the magnet dimensions and rotor outside diameter are to be input.

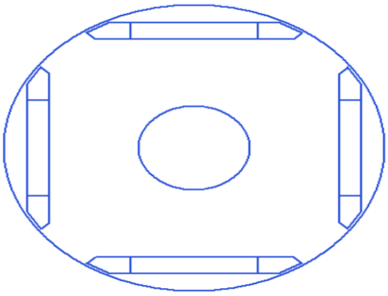

Fig. 6. **Rotor geometry**

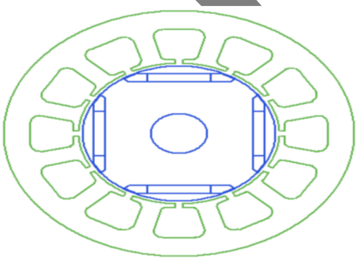

Fig. 7. **Cross section view of motor**

Following figures represent some of the plots got after simulating design in RMxprt. Only important plots are given here.

TABLE IV. ROTOR PARAMETERS

Sr. No.	PARAMETER	VALUE
1	Minimum Air Gap (mm)	1
2	Inner Diameter (mm)	18
3	Length of Rotor(mm)	110
4	Stacking Factor of Iron Core	0.95
5	Type of Steel	M43-26G
6	Bridge (mm)	0.5
7	Rib (mm)	10
8	Mechanical Pole Embrace	0.6
6	Max. Thickness of Magnet	3.5
7	Width of Magnet(mm)	20
8	Type of Magnet	NdFe30

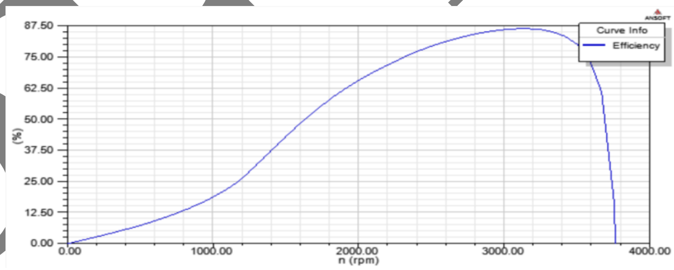

Fig. 8. Plot showing efficiency v/s speed

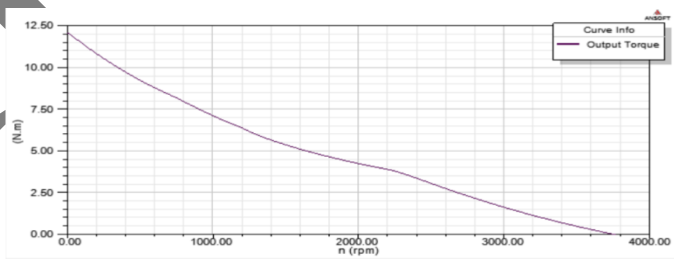

Fig. 9. Plot showing Torque v/s speed

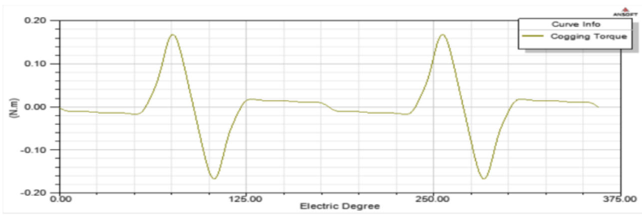

Fig. 10. Plot showing Cogging torque in two teeth

TABLE V. OTHER PARAMETERS OF MOTOR

SR. NO.	PARAMETER	VALUE
1	Residual Flux Density (Tesla)	1.1
2	Coercive Force (kA/m)	838
3	Maximum Energy	230.45
4	Relative Recoil Permeability	1.0446
5	Demagnetized Flux Density(T)	0.2023
6	Recoil Residual Flux Density(T)	1.1
7	Recoil Coercive Force (kA/m)	838
8	Total Net Weight(kg)	3.5834
9	Air-Gap Flux Density(T)	0.4931
10	Average Input Current(A)	2.5322
11	RMS Armature Current(A)	2.3209
12	Armature Thermal	70.319
13	Specific Electric Loading(A/mm)	15.728
14	Armature Current	4.4708
15	Frictional and Wind age Loss(W)	12.107
16	Iron-Core Loss(W)	20.521
17	Armature Copper Loss(W)	45.618
18	Transistor Loss(W)	3.7336
19	Total Loss(W)	82.292
20	Output Power(W)	500.11
21	Input Power(W)	582.40
22	Efficiency(%)	85.870
23	Rated Speed(rpm)	3020.0
24	Rated Torque(N.m)	1.5813

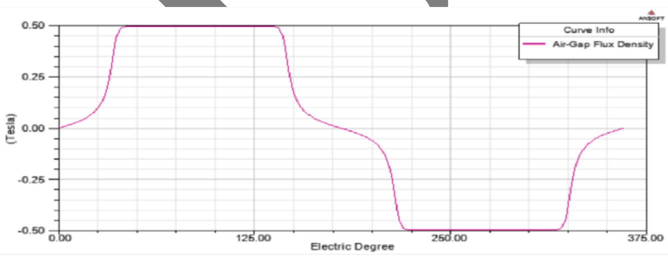

Fig. 11. Plot showing air gap flux density

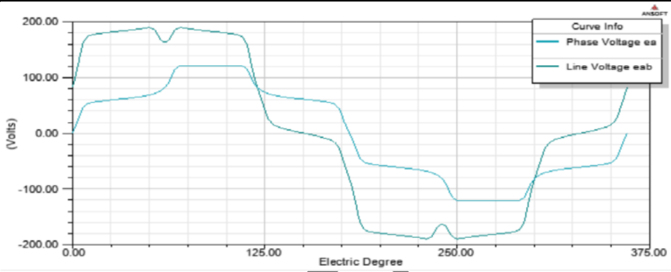

Fig. 12. Plot showing Induced coil voltages

VI. MAXWELL 2D SIMULATION

RMxprt gives crude motor design and performance based on given input dimensions. In order to check performance of motor thoroughly, it is necessary to run a finite element simulation in software like Maxwell in 2D. The geometry prepared in RMxprt is taken into Maxwell 2D environment. There software itself creates meshing which is necessary for FEA, also it automatically chooses boundary conditions in which geometry is to be solved. Winding excitations are also assigned automatically here and software itself decides symmetry in geometry and accordingly does operations and shows motor, like shown in Fig.12.

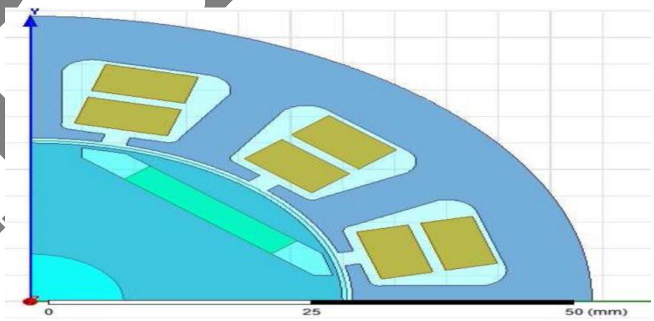

Fig. 13. Sector of Motor in Maxwell 2D

Following are some analysis done in Maxwell 2D by running the simulations and saving fields at an appropriate step time. Fig. 13 shows lines of flux in the stator and rotor and Fig. 14 shows field intensity in stator and rotor and Fig. 15 shows flux density in stator and rotor back iron.

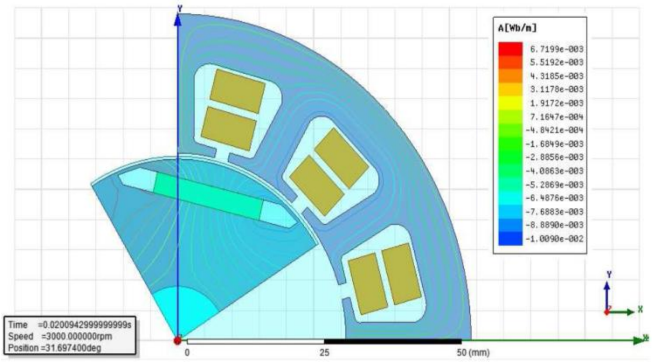

Fig. 14. **Flux lines in stator and rotor when rotor is moved**

Following are some important plots obtained after simulating motor in Maxwell 2D.

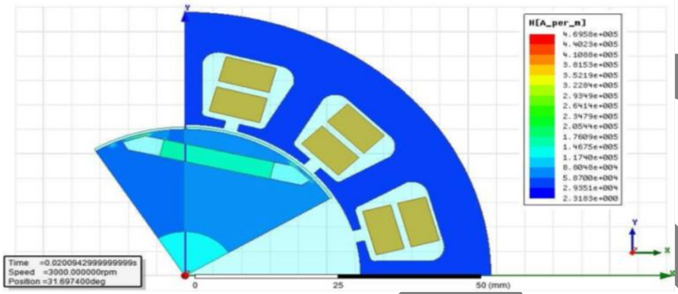

Fig. 15. **Field Intensity in stator and rotor when rotor is moved**

A. Design by increasing width of magnet

Above motor is able to give around 500Watt power output. The main reason for getting such low output power is the lesser width of magnet used on rotor. Ultimately magnets available on rotor are the source of magnetic field on rotor side. Also the flux output from magnet depends upon magnet volume. In order to double the output from same geometry of motor, only magnet width needed to be increased. It is tried to increase width of magnet from 20 mm to 28 mm keeping all other geometrical dimensions same and modifying slot somewhat. It is then seen that, motor output becomes almost double also the torque ripples are reduced because as magnet width increases, magnet covers more area of rotor and flux through air gap becomes more uniform. The air gap flux density also increases which in turn helps to improve motor power output. At the same time efficiency has been compromised little bit as armature conductors losses will increase. Table 4.6 shows some of the improved parameters after increasing width of magnet. From following torque plot it is seen that here motor is able to give higher power output at lesser torque ripples than that of earlier design. Just by increasing magnet width, it is possible to improve motor performance.

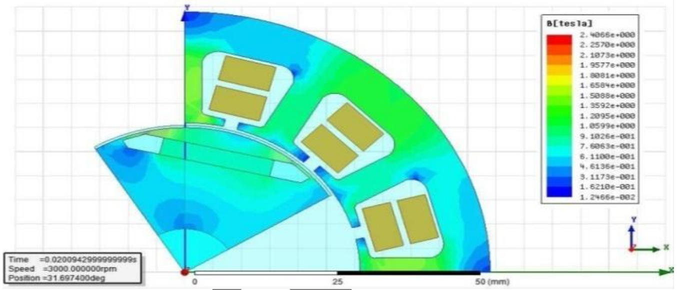

Fig. 16. **Flux density in stator and rotor when rotor is moved**

TABLE VI. PARAMETERS AFTER INCREASING MAGNET WIDTH

Sr.No.	PARAMETER	VALUE
1	Air-Gap Flux Density(T)	0.578026
2	Average Input Current(A)	5.72171
3	RMS Armature Current(A)	6.04715
4	Armature Current	11.6488
5	Frictional and Wind age	8.07468
6	Iron-Core Loss(W)	21.7535
7	Armature Copper Loss(W)	275.097
8	Transistor Loss(W)	9.36732
9	Total Loss(W)	315.782
10	Output Power(W)	1000.21
11	Input Power(W)	1315.99
12	Efficiency (%)	76.0043
13	Rated Speed(rpm)	2189.24
14	Rated Torque(N.m)	4.36285

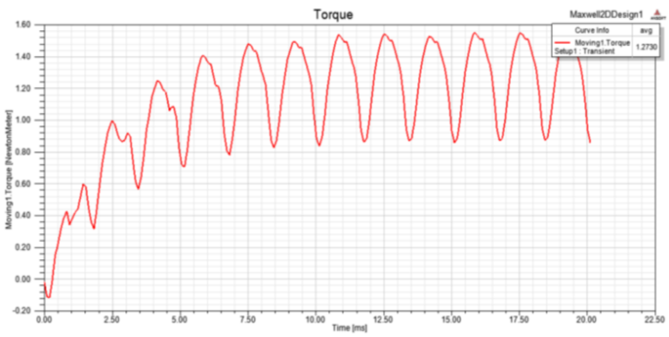

Fig. 17. **Motor Torque**

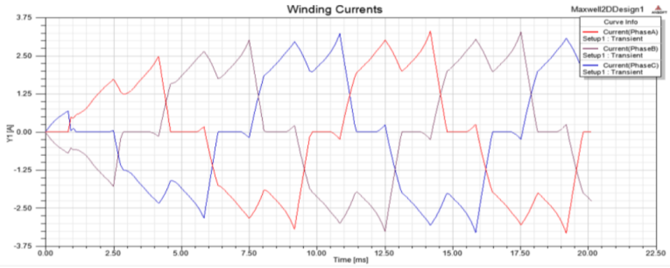

Fig. 18. Motor winding currents

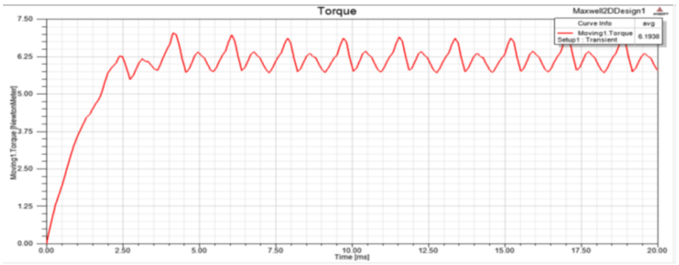

Fig. 19. Torque output of motor when magnet width is increased

VII. CONCLUSION

This paper has demonstrated an approach to brushless DC motor design and to analyze it. It is seen that as per given dimensions of laminations and magnet, the motor is able to give a power of around 500 Watt with considerably lesser torque ripples. RMxprt tool of ANSYS solves basic motor design equations and gives crude design data. This data should not be considered as optimized motor design parameters. It is necessary to undergo simulation through Finite Element Analysis tool of ANSYS that is Maxwell 2D. According to this design, motor gives considerably good efficiency at rated speed and torque. Also ripples in torque are within limits and currents in winding are not exceeding beyond rated value. it can be concluded here after doing this project that, it is not always necessary that results obtained from RMxprt should match up with the results got by simulating same model in Maxwell 2D. Another point to be noted here that, in case of internal permanent magnet motor, width of magnet plays important role in deciding torque ripples. Magnet should cover maximum area so that flux coming from magnet should cover maximum air gap area. Again it is worth to be noted that, there is a limit of power which a motor using a particular size magnet will produce. As seen here, a magnet with width of 20 mm is able to give 500 Watt of power at lower armature current density and at considerably good efficiency. It is seen that output power of motor increases considerably but at the cost of some compromise with efficiency. A parametric solution has been run to check optimized value of conductors per slot which can give almost 1000 Watt of power output at considerable efficiency. It is seen that as width of magnet increases, air gap flux density and motor output power increases. Also a ripple in torque gets reduced as air gap flux becomes more uniform.

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