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Design and Analysis of Permanent Magnet Brush Less DC Motor

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ABSTRACT

In this paper detailed steps and procedure of design of a 1.0kW, 4-pole, 1800 rpm permanent magnet brush-less DC motor (PMBLDC)has beendiscussed. To satisfy load capability, lifetime, low cost, efficiency etc, the theoretical analysis regardingthe main points of motor design is discussed here. First the design and performance analysis of the machine has been done manually. Then an electromagnetic field analysis using MATLAB and MAXWELL 2-D finite element analysis is introducedtodesign and then to achieve high power density and efficiency.Simulation results are analysed and compared with theoretical values in detail.

Keywords — Electric machines, Permanent Magnet Machines, BLDC Machine, Finite Element Analysis.

I. INTRODUCTION

BLDC motors are almost similar to synchronous motors as per construction, which are power by DC supply and produce an alternating current to drive each phase of the motor through a closed loop controller; it provides pulses ofcurrent to the motor windings to control the speed and torque. BLDC motor is a better choice than Induction motor (IM) due to its high energy density as well as absence of brush contacts when the variable speed drive applications are concerned. The design of the BLDC motor can be optimised if the size and the weight of the motor is minimized and also by reducing the volume of the permanent magnet. Protection of permanent magnet against demagnetising effect of armature current should also be considered during design phase [1].

In BLDC motor operation mainly, close loop current control (in 120^0 mode with hysteresis control) is used because the demagnetising component of the armature current is normally considered to be zero here [2]. So, in thispaper it is considered that the current hysteresis control is used to control the BLDC machine.

II. DESIGN & ANALYSIS OF PMBLDC MOTOR

In this paper, the design and analysis of a 1.0kW maximum power, 220 V DC, 1800rpm, 4 poles, 24 slots permanent magnetic BLDC is discussed. Here the rotor is considered as of SPM type. The stator windingis considered to be distributed winding here. Air-gap between stator along with the magnetic pole and rotor has been selected optimally as this can greatly affect the efficiency and the mechanical space for sleeve of the motor. The technical specifications are presented in Table I.

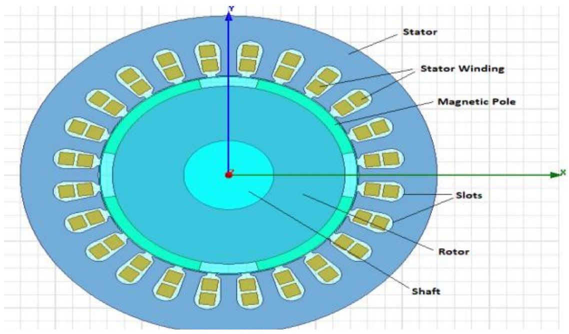

Fig-1 Cross-Section of 1.0kW, 4-pole, PMBLDC Motor

Table I: Technical Specifications of The Motor

Parameters	Specifications	Unit
Rated Output Power	1.0	kW
Maximum Current	70	A
Rated Voltage	220	V
Number of Poles	4	-
Rated Speed	1800	rpm
Number of Stator Slots	24	-
Number of Poles	4	-
Operating Temperature	75	^{0}C

A. Stator Volume and Size

The volume and size of the motor should be designed in such a way that the required torque can be developed effectively. For radial flux motors therelation between developed torque and size of the motor is

$$T = kD^2L_m \quad (1)$$

Where,T is torque, $k$is called the shape dimension ratio of the motor, D is the outer diameter of the rotor, and L_m is the axial length of the rotor.

Further, the size of the rotor, the pole direction length and the inner diameter of the stator are calculated by (2), (3) and (4) respectively.

$$\frac{L_m}{D} = \frac{2a_m}{\phi D\,(D - l_m)} \quad (2)$$

$$L_m = kD \quad (3)$$

$$D_a = D - 2l_g \quad (4)$$

Where,a_m is called rotor mean cross-sectionarea, $l_m$is called the thickness ofthe permanent magnet, D_a is inner diameter of the statorand l_g is length of the air-gap. The diameter of the stator winding is usually decided by the current density and the actual slot area of the stator that are occupied by the windings. The outer diameter of the stator depends upon the thickness of the yoke, which is mainly designed as per the magnetic flux density, as the yoke is also a part of the stator magnetic circuit.

Table II: Physical Dimensions Of The Stator

Parameters	Specifications	Unit
Inner Diameter of Stator	75	mm
Outer Diameter of Stator	120	mm
Length of Stator Core	65	mm
Stacking Factor of Stator Core	0.95	-
Type of Steel	M19_24G	-
Slot Area	82.102	mm^2
No. of Parallel Branches	1	-
No. of Conductors per Slot	50	-
Average Coil Pitch	5	-
Type of Coils	21	-
No. of Wires per Conductor	1	-
Wire Diameter	1.024	mm

In this motor, flux crosses in the radial direction from the rotor to the stator. It consists of inner rotor and outer stator configuration. The air-gap inductance is significantly increased due to the presence of ferromagnetic material at the rotor surface,asthe use of rectangular magnets is supported by the interior permanent magnet rotor. Also, it counts a reluctance component to the developed torque.

Table III: Physical Dimensions Of The Rotor

Parameters	Specifications	Unit
Length of Rotor	65	mm
Inner Diameter	26	mm
Minimum Air Gap	0.5	mm
Stacking Factor of Iron Core	0.95	-
Type of Steel	M19_24G	-
Polar Arc Radius	37	mm
Max. Thickness of Magnet	3.5	mm
Width of Magnet	38.8	mm
Type of Magnet	XG196/96	-

B. Stator Slot Size

The size of the stator slots is normally determined by standard equations. Fig-2 shows the schematic structural view of the stator slot considered here.

$$\tau_s = \frac{\pi D}{S} \quad (5)$$

$$0.4\tau_s \leq b_s \leq 0.6\tau_s \quad (6)$$

$$3t_s \leq h_s \leq 7t_s \quad (7)$$

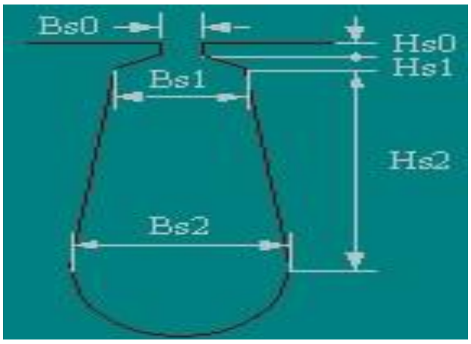

Fig-2: Dimension of Stator Slot

C. Winding arrangement

The mode of operation of a 3-ph star-connected motor is usually 120^0 conduction mode in time domain by means of a 3-ph inverter, so that at any instant any two phases would invariably get excited. There are various options for pole and slot combinations and for winding layouts, so, proper assumptions are required to find optimum windings configurations. Following are the assumptions, that are considered here:

a) The motor has three phases. (Modification of the material in this chapter for other phase counts follows in a straightforward fashion).

b) Each and every slot should be filled optimally. The number of slots should be the multiple of the number of phases, i.e., $N_s = kN_{ph}$. Usually,the slot number should be multiple of 3 for a3-ph motor.

c) The stator winding should be restricted as a double layer winding, so in each slot there should be 2 coils sides.

d) Windings should be balanced so that the back emf of any two phases should be 120^0 offset from the back emf of third phase.

e) For convenience, consider number of slots in stator per phase per poleas less than or equal to two.The number of slots per phase per pole is representedby $N_{spp} = N_s/N_{ph}/N_m$. Itis a general assumption for BLDC motor design and almost all motors of different rating follow it. If N_{spp} is supposed to be greater than two, the winding layout becomes complicated by the motor performance does not increases significantly.If a motor has fewer number of magnet poles, then to reuse the stator lamination, N_{spp} is kept greater than 2.

f) Finally, all stator coils should have same resistance and inductance, hence theyshould have the same number of turns and all span the same number of slots.

Table IV: 3-PH, 2-Layer Winding Arrangement

	Phase	Turns	In Slot	Out Slot
Coil_1	A	25	1T	6B
Coil_2	A	25	2T	7B
Coil_3	-C	25	3T	8B
Coil_4	-C	25	4T	9B
Coil_5	B	25	5T	10B
Coil_6	B	25	6T	11B

Phase-A axis (elec. degrees): 90
Angle per slot (elec. degrees): 30
First slot Center (elec. degrees): 0

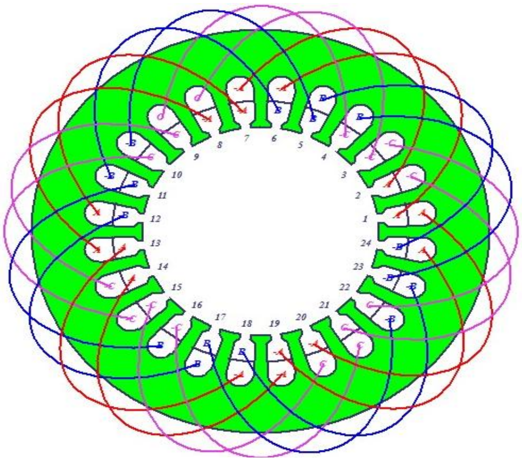

Fig-3: Winding Arrangements

D.Size of the Permanent Magnet

It is commonly assumed that the shape of a magnet determines the direction of its magnetization. These assumptions may be true in some cases, but magnetization direction is determined by the fixture used to magnetize the magnets. In any case, the magnetization direction has less impact on motor performance as the magnet pole count increases [3].

The design of permanent magnet should be optimum because its width and thickness would directly affect the performances of a BLDC motor.To determine the size of the permanent magnet, (8) and (9) are used to calculate height and width respectively [9].

$$h_m = \frac{K_s K_\alpha \alpha_m}{(1-\alpha_m)} \delta \quad (8)$$

$$b_m = \frac{2\delta_0 B_{\partial 1} \tau_1}{\pi \alpha_m B_r K_\phi} \quad (9)$$

where α_m is the operating point of the permanent magnet, δ is length of air gap, K_s is the saturation factor of the motor, generally its value range from1.05 to 1.3, K_α is the structure factor of the rotor, generally its value range from0.7 to 1.2,$B_{\partial 1}$ is the peak value of the air gap fundamental wave, B_r is the residual flux density,K_ϕ is the air gap flux waveform factor, this is related to the pole arc coefficient.

Table V: Permanent Magnet Data

Parameters	Specifications	Unit
Coercive Force	690	kA/m
Residual Flux Density	0.96	Tesla
Maximum Energy Density	183	kJ/m^3
Demagnetized Flux Density	0.585937	Tesla
Recoil Coercive Force	690.015	kA/m
Recoil Residual Flux Density	0.867073	Tesla

E. Pull Out Torque

Pull-out torque, in case of transient overload condition, is the maximum torque that a motor can be operatedwithout affecting the synchronism. Ignoring the effects of the stator resistance of the torque, general power angle equation [4] is used to obtain the pull-out torque

$$T = \frac{mp}{\omega_s^2}\left[\frac{E_{PM}U}{L_d}sin(\delta_a) + \frac{U^2}{2}\left(\frac{1}{L_q} - \frac{1}{L_d}\right)sin(2\delta_a)\right] \quad (10)$$

where $m$is the phase number, p is the pole pairs, $\omega_s$is the angular frequencyof the stator current, L_d and L_q are the d-axis inductance and q-axis inductance, E_{PM} is the back EMF, induced by the flux linkage of permanent magnet and δ_a is thepower angle.

Because of the increase in back EMF due to the increase in thickness of the magnets, the d-axis inductance decreases; as a result,thetorque developing capability of the PMBLDC motor increases. As a result,the pull-out torque would be increased, and the rated torque can be obtained at comparatively lower load condition [5].

III. DETERMINATION OF ELECTRICAL PARAMETERS

A. Determination of self-inductance

The d-axis and q-axis inductance can be determined by (11) and (12) respectively.

$$L_d = L_l + \frac{3}{2}(L_1 + L_2) \quad (11)$$

$$L_q = L_l + \frac{3}{2}(L_1 - L_2) \quad (12)$$

Where, L_l is the leakage inductance
and air-gap Reluctance,

$$R_g = \frac{2(l_g + l_m)}{\mu_0 A} \quad (13)$$

B. Resistance of stator winding

$$P_{ph} = \frac{\rho L_{mt} T_{ph}}{conductor \quad area} \quad (14)$$

Where, L_{mt} is the length of mean turn, T_{ph} is the operating temperature (75^0C)

C. Torque and cogging torque

Rated torque of BLDC motor = 1000W/147.4 (rad/s) = 6.7838 Nmand peak to peak cogging torque 0.6651 N-m i.e. 9.8 % of ratedtorque. The torque at rated speed and with rated load condition are shown in Fig.11.

D. Losses and efficiency

The Eddy current loss and hysteresis loss can bedetermined by (15) and (16) respectively.

$$P_e = \frac{\Pi^2 f^2 B_m^2 t^2}{6\rho \times mass \ density} \text{ W/kg} \quad (15)$$

$$P_h = \frac{k_h f B_m^k}{mass \ density} \text{ W/kg} \quad (16)$$

Efficiency at rated load(1.0 kW) = 88.6%.

Table VI: Steady State Parameters

Parameters	Specifications	Unit
Stator Winding Factor	0.933013	-
D-Axis Reactive Inductance L_d	0.0112432	H
Q-Axis Reactive Inductance L_q	0.0112432	H
Armature Leakage Inductance L_l	0.00256797	H
Zero-Sequence Inductance L_0	0.00179613	H
Armature Phase Resistance R_{ph}	1.52936	Ohm
Rated Torque	6.78379	Nm
Cogging Torque	0.66505	Nm
Output Power	1000	W
Input Power	1160.031	W
Total Loss	160.031	W
No-Load Speed	1777.2	rpm
Rated Speed	1408.06	rpm
Efficiency	88.6	%

IV. PERFORMANCE ANALYSIS

In this work, ageneral assumption-based program has been constructed andresults have been obtained after 24 iterations. Using 2-D finite element analysis (FEA) using Maxwell software,performance characteristics of the motor have beenobtained. The magnetic fluxdensity and the field intensity under the no-load condition and the distribution of flux line within the motor are shown in Fig-3, Fig-4 andFig-5 respectively.Itcan be seen that the flux has never been crossed the saturationlevel within the motor. Fig-6 shows the run time temperature profile of the motor at no-load condition.

The flux density distribution in theair-gap is nearly sinusoidal, and it can be anticipated with parallel magnetisation. Fig-7 shows the Cogging Torque & Flux Density.The transient parametersare importantparameters because of the power limitations; Fig-8 & Fig-9 shows the currents and induced voltages respectively. Fig-10 shows the running torque and Fig-11 is the input current, output torque, power and efficiency with respect to rotor speed. It can be seen that the maximum efficiency can be obtained at a speed of 1545.39 rpm but maximum output power can be obtained at a speed of 734 rpm and maximum torque can be achieved at a speed of 77.27 rpm.

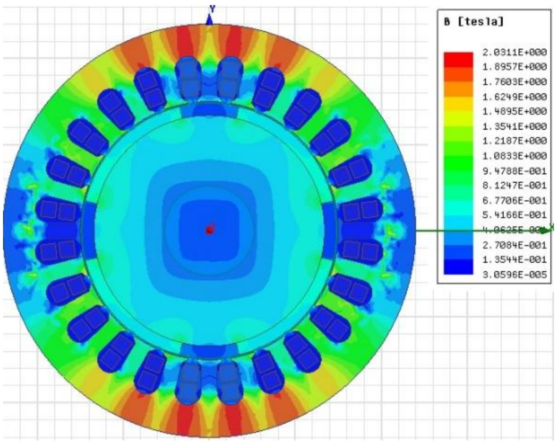

Fig-3 Flux Density

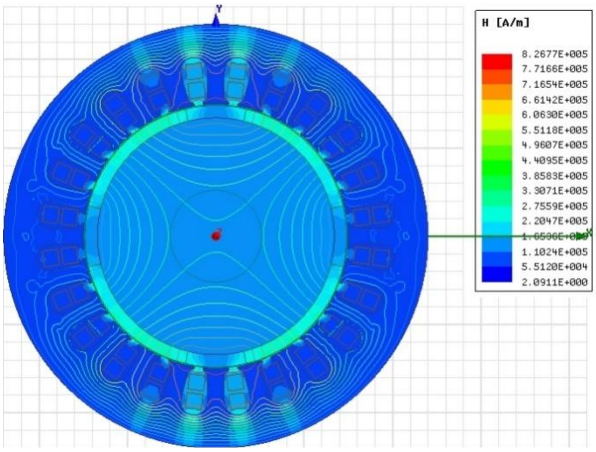

Fig-4 Magnetic Field Intensity

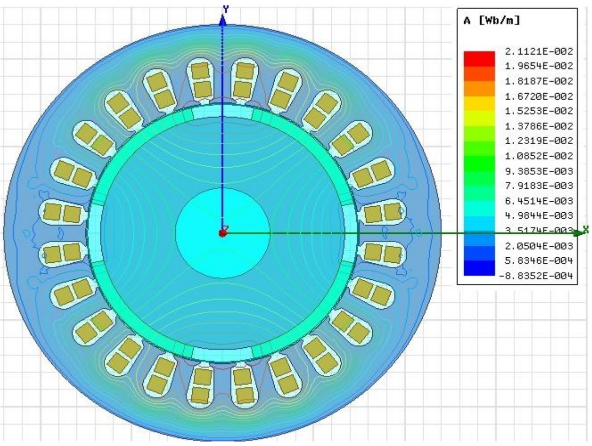

Fig-5 Distribution of Flux Lines

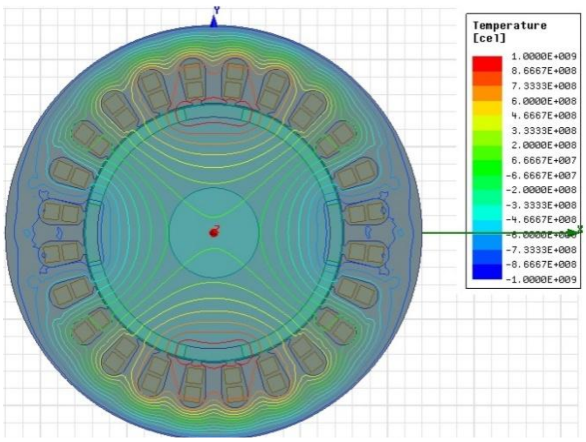

Fig-6 Run Time Temperature Profile

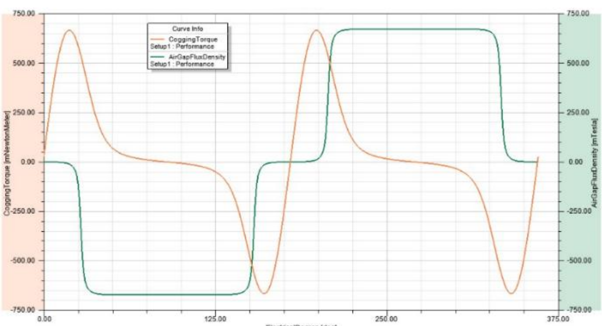

Fig-7 Cogging Torque & Flux Density

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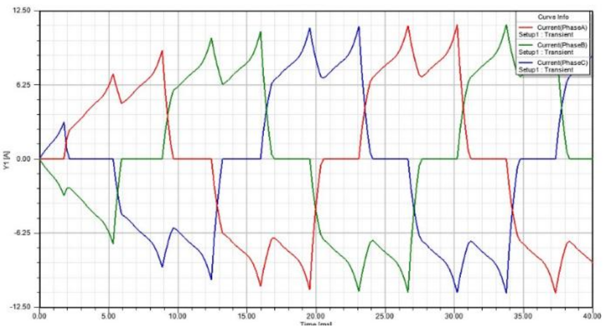

Fig-8 Transient Currents

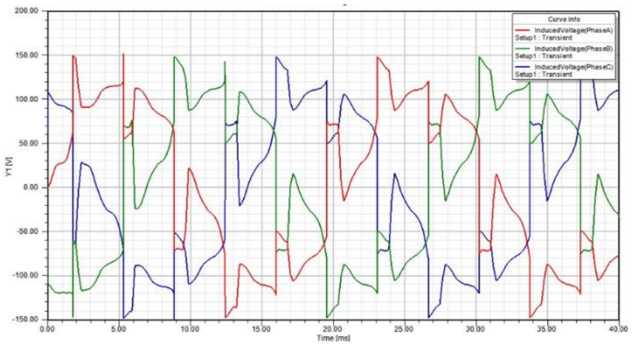

Fig-9 Transient Induced Voltages

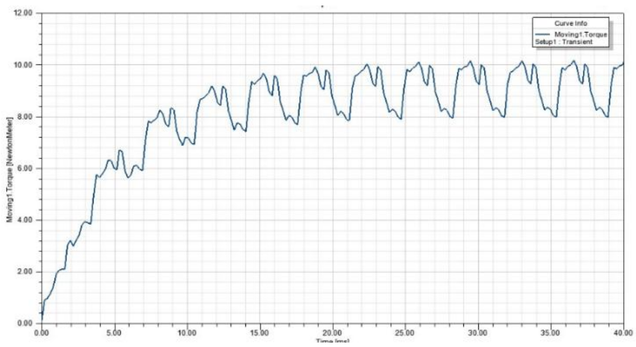

Fig-10 Running Torque

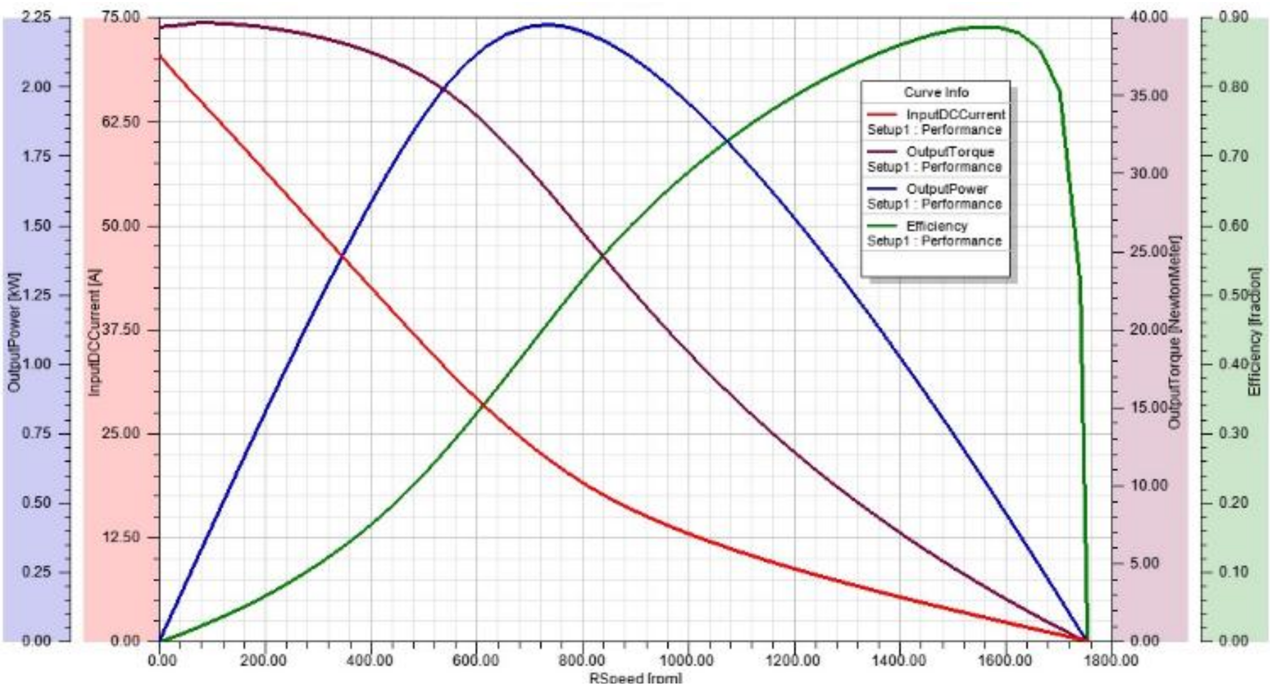

Fig-11 Performance Analysis of the Motor with respect to Rotor Speed

Table VII: kW, 4-pole Permanent Magnet Brush-Less DC Motor Performance Data Table

S. No.	Rotor Speed [rpm]	Input DC Current [mA]	Output Torque [Nm]	Output Power [kW]	Air Gap Torque to DC Current Ratio	Efficiency [fraction]
1	0	70505.215	39.33616	0	0.559002	0
2	38.6348	67631.589	39.459935	0.159648	0.584584	0.01073
3	77.2697	65012.656	39.636524	0.320725	0.610849	0.022424

4	115.905	62370.677	39.593108	0.480561	0.636028	0.035022
5	154.539	59705.306	39.495792	0.639173	0.662792	0.048661
6	193.174	57020.454	39.355853	0.796136	0.691546	0.063465
7	231.809	54319.027	39.171173	0.95088	0.722538	0.07957
8	270.444	51606.652	38.938115	1.102759	0.755998	0.09713
9	309.079	48892.372	38.655262	1.251141	0.792182	0.116317
10	347.714	46190.464	38.311323	1.39501	0.831075	0.137278
11	386.348	43503.639	37.897396	1.533264	0.872888	0.160202
12	424.983	40825.652	37.405742	1.66471	0.918103	0.185346
13	463.618	38156.109	36.825273	1.787866	0.967123	0.212985
14	502.253	35512.191	36.131027	1.90034	1.019577	0.243238
15	540.888	32926.76	35.295817	1.999212	1.074269	0.275986
16	579.523	30446.31	34.294672	2.081256	1.128907	0.310719
17	618.157	28126.005	33.114637	2.143619	1.180083	0.346431
18	656.792	25945.976	31.805754	2.187572	1.22879	0.383239
19	695.427	23903.042	30.394779	2.213498	1.274782	0.420924
20	734.062	22008.534	28.900808	2.221628	1.316635	0.458836
21	772.697	20268.745	27.348465	2.212945	1.353062	0.496273
22	811.332	18681.263	25.76522	2.189076	1.383291	0.532638
23	849.966	17286.411	24.201659	2.154148	1.404459	0.566432
24	888.601	16038.791	22.670055	2.109542	1.418215	0.597852
25	927.236	14906.987	21.181256	2.056698	1.426019	0.627131
26	965.871	13867.64	19.741045	1.996723	1.429042	0.654474
27	1004.51	12903.915	18.352807	1.930561	1.428187	0.680048
28	1043.14	12003.49	17.017651	1.858964	1.42409	0.703948
29	1081.78	11155.295	15.736478	1.782679	1.417522	0.726389
30	1120.41	10351.852	14.506766	1.702066	1.408749	0.74737
31	1159.05	9586.546	13.327315	1.617602	1.398179	0.766985
32	1197.68	8854.203	12.196247	1.529662	1.386081	0.785278
33	1236.31	8150.143	11.111173	1.438525	1.372683	0.802287
34	1274.95	7470.492	10.069732	1.344434	1.35816	0.818027
35	1313.58	6812.067	9.069549	1.247591	1.342609	0.832474
36	1352.22	6171.662	8.108148	1.148147	1.326149	0.845615
37	1390.85	5547.655	7.184102	1.046364	1.308751	0.857335
38	1429.49	4936.93	6.29445	0.942252	1.290446	0.867536
39	1468.12	4338.374	5.438013	0.836049	1.271077	0.875955
40	1506.76	3749.475	4.612031	0.72772	1.250422	0.882209
41	1545.39	3168.906	3.815033	0.617399	1.228003	0.885592
42	1584.03	2595.494	3.045569	0.505196	1.20284	0.884743
43	1622.66	2028.078	2.302174	0.391197	1.172819	0.876774
44	1661.3	1466.286	1.584385	0.275637	1.132644	0.854467
45	1699.93	910.785	0.892665	0.158909	1.063983	0.793068
46	1738.57	361.65	0.226744	0.041282	0.838208	0.518853
47	1752.64	175.734	0	0	0.434717	0

CONCLUSION

Brushless motors have some major advantages as compared to brushed motors, such as, high power to weight ratio, high speed, and also the introduction of electronic control. Now a days BLDC motors have various applications such as computer peripherals, hand-held power tools, and vehicles ranging from model aircraft to automobiles.

In this paper,the design and analysis of a 1.0 kW permanent magnet BLDC motor has been proposed. The proposed designof the motor is optimised and simultaneously verified with the help of 2-D finite element analysis. The results, obtained by finite element analysis are found to be similar to the designed parameters.

REFERENCES

[1]. Hanselman Duane, "Brushless permanent magnet motor design", 2nd edition, Magna Physics Publishing, ISBN: 1-881855-15-5, 2003.
[2]. H. M.Yang, J. W. Cha, B. H. Baik, B. Kwon, "Design and Analysis of High Speed BLDC Motor for Centrifuge", 18th International Conference on Electrical Machines and Systems (ICEMS), Thailand, Oct'2015.
[3]. A.K. Sawhney, "Electrical Machine Design", Dhanpat Rai and Co., 6th edition, 2006
[4]. C.C. Hwang, P.L. Li, C.T. Liu, C. Chen, "Design and analysis of a brushless DC motor for applications in robotics", IET Electric Power Appl., Vol. 6, Issue 7, pp. 385–389, 2012.
[5]. Pinaki Mukherjee, Mainak Sengupta, "Design, Analysis and Fabrication of a Brush-less DC Motor", IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2014