DESIGN OF BRUSHLESS DC MOTOR FOR ELECTRIC VEHICLE

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ABSTRACT

In this project, an analytical method to design a brushless DC (BLDC) motor is developed. The main dimension, stator, and rotor parameters were calculated by using the existing magnet to achieve the required torque and speed. The magnet assembly, gap, and rotor saturation webs are considered for the design, and also flux leakage coefficient and selected working point of a permanent magnet were used. An advanced equivalent magnetic circuit was developed to verify the total flux leakage and the quiescent operating point based on design parameters. Key design method points are considered and analyzed. An electromagnetic field analysis based on Ansys maxwell and the finite element method (FEMM) were used in the design to verify the equivalent magnetic circuit and to optimize the BLDC motor parameters. Then by using these calculated values, the 3D model of the motor is constructed in the SOLIDWORKS software. Then the electrical and mechanical designs are combined, and the BLDC motor is developed and simulation is carried out using Ansys Maxwell. In this paper, the simulation results show that an analytical method carried out to design a brushless DC (BLDC) motor can be used to optimize the design of motor parameters which are in good agreement with calculated values.

Keywords: Brushless DC (BLDC) motor, Electric Vehicles, FEM, Ansys Maxwell.

ABBREVIATION

BLDC Brushless DC
EV   Electric Vehicle
OD   Outer Diameter
ID   Inner Diameter

I.   INTRODUCTION

An electric vehicle is an automobile that is propelled by one or more electric motors, using energy stored in rechargeable batteries—the first practical electric vehicles produced in the 1880s. From 2008, a renaissance in electric vehicle manufacturing occurred due to advances in electric motors, batteries, and the

desire to reduce greenhouse gas emissions and improve urban air quality.[1] Electric Vehicles have several benefits over conventional internal combustion engine automobiles, including a significant reduction of local air pollution, as they do not directly emit pollutants such as particulates, volatile organic compounds, hydrocarbons, carbon monoxide, ozone, lead, and various oxides of nitrogen.[2]
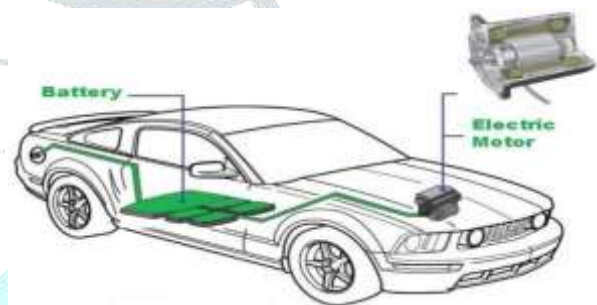

Fig 1: Schematic diagram of an EV motor arrangement

Electric vehicles are not something new to this world, but with the technological advancement and increased concern on controlling pollution has given it a tag of future mobility. The core element of the EV apart from Electric Vehicle Batteries, which replaces the Internal Combustion engines, is an Electric motor.[3] The rapid development in the field of power electronics and control techniques has created a space for various types of electric motors used in Electric Vehicles. The electric motors used for automotive applications should have characteristics like high starting torque, high power density, excellent efficiency, etc.[4]

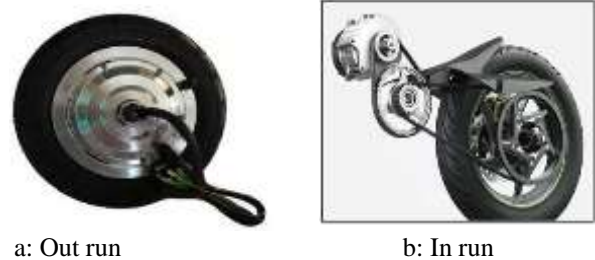a: Out run   b: In run

Fig 2. BLDC Motor

The permanent magnet brushless dc motors (PMBLDCM) are either of outer rotor motor or inner rotor motor as shown in fig 2. The outer rotor motor consists of magnets on the outer body of the motor, and the inner body includes windings that are excited from the external supply. In the case of the inner rotor motor, the windings are placed on the outer body, and magnets are provided on the inner body of the motor.[5] So while designing the BLDC motors, the type of rotor plays an important role. As the name indicates that 'brushless DC motors, no brushes are used for construction. Therefore, for reduced size, the required parameters can be achieved, such as high torque, high speed, increased reliability, reduced noise, and longer lifespan. Hence from the above parameters, these motors are employed to the electric vehicles, which act as a prime mover for the car. Before manufacturing the motor, the various characteristics are analyzed using FEMM and Ansys maxwell software for the better performance of the motor, and it is designed using different drawing software such as auto cad for 2D drawing and solid works for 3D drawing.[6][7][8]

II. DESIGN OF BLDC

2.1 Main Dimension Calculation

- The main dimensions are calculated by considering the number of poles, required torque, and existing magnet dimension.
- The length of the stack is taken the same as that of magnet length.
- The bore diameter is calculated by using equation 1

$$w_o = (D^2 L_i) / T_m \dots\dots\dots\dots\dots(1)$$

Where, D=bore diameter, L_i=stack length, T_m=torque, w_o=coefficient ($20\mu \ m^2/kg$ to $25 \ \mu \ m^2/kg$)
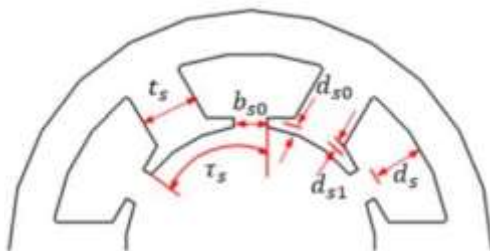
2.2 Stator Calculations

Fig 3: Stator parameters

Typically, the experienced equations are used to determine the stator slots' size. Fig 3 shows the schematic structural view of the stator slots considered for the design. [5]

- $T_s = (\pi * D) / S$ .... (2)

where S= number of slots and T=tau(slot pitch)
- Width of the slot t_s,
  $0.4 \ T_s \leq t_s \leq 0.6 \ T_s$
  - $b_s = T_s - t_s$

- The height of the slot had been calculated using d_{so}, d_{s1}, and d_s.
  - To find d_s, we have $3 \ t_s \leq d_s \leq 7 \ t_s$
  - $d_{s0} = (0.005 \ to \ 0.05) * b_s$
  - $d_{s1} = (0.002 \ to \ 0.005) * b_s$
  - Therefore, **Total height= $d_s + d_{s0} + d_{s1}$**

- The minimum distance from OD to the slot is 20mm to 25mm.
  Therefore, **ID of stator is= OD - (2* height of slot) - (2*minimum distance from OD to slot)**
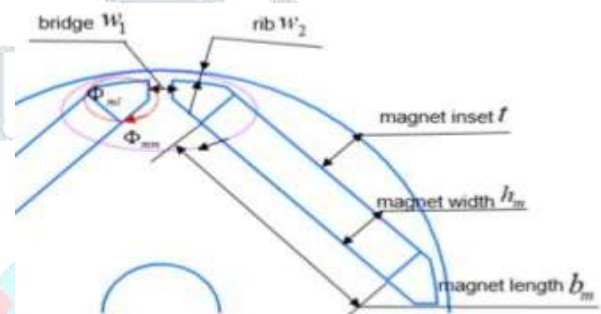
2.3 Rotor Calculations

Fig 4: Rotor parameters

The air gap is selected as per requirement which should not vary above 1mm

Therefore, **OD of rotor = ID of stator – (2*airgap)**

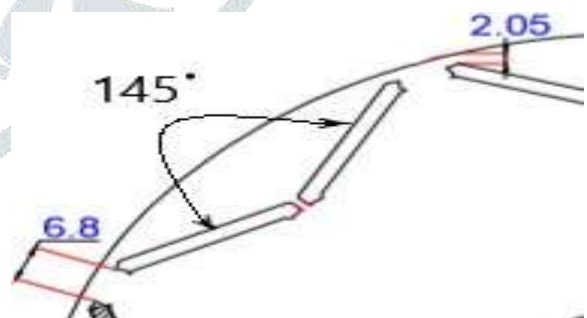The dimension of the shaft is selected as per the requirement.

Fig 5: Two magnet embedded type

- As shown in fig 5 the pole is two magnets embedded type; thus the angle between them is **145°**
- The maximum distance from the OD of the rotor to a magnet (Rib) should not vary from **2mm to2.5mm**.

- Due to 145° displacement, the bridge can be calculated from designing in the AutoCAD software or any relevant software.
- The bridge is varied depending on the number of poles.

2.4 Magnetic Calculation

- Area of the magnet, $A_m=2wl+2lh+2hw$
- Standard values of the NdFeb magnet
  - Remanent flux density, $B_r = 1.28\ T$
  - Coercive factor, $H_c = 923\ kA/m$
- Maximum flux density B_m,

  $B_m = (0.7\ to\ 0.95) * B_r$
- Maximum magnetic field intensity H_m,

  $H_m = B_m / \mu_o$
- Remanent flux Φ_r, $\Phi_r = B_r * A_m$
- Coercive magnetic force, $F_c = H_c\ L_m$
- Main flux Φ_m, $\Phi_m = B_m\ A_m$
- Mmf drop F_m, $F_m = H_m\ L_m$
- Airgap flux Φ_g, $\Phi_g = \Phi_m - \Phi_L$
- Leakage coefficient, $F_{lkg} = \Phi_g / \Phi_m$

Where, L_m=length of the magnet, Φ_m=main flux Φ_L=leakage flux, and Φ_g=gap flux

2.5 Winding Calculation

The required winding for the motor has been calculated coil span= no of slots / 2p

Offset= $(2/3) * (N_s/2p)$

Total no of conductors in a slot, Z= $4aN_{Ph}$

Where, p = pair of poles, N_s = No of slots, a = No of parallel paths, and N_{Ph} = No of phases

LAP winding is preferred as it has to withstand high current.

Considering double-layer LAP winding, 12 slots, and 2 pairs of poles, coil span=3, offset=2, and Z=24. The winding scheme and winding diagram are obtained as shown in fig 6 and fig 7 respectively.

Fig 6: winding scheme

AA|bb|CC|aa|BB|cc|AA|bb|CC|aa|BB|cc|

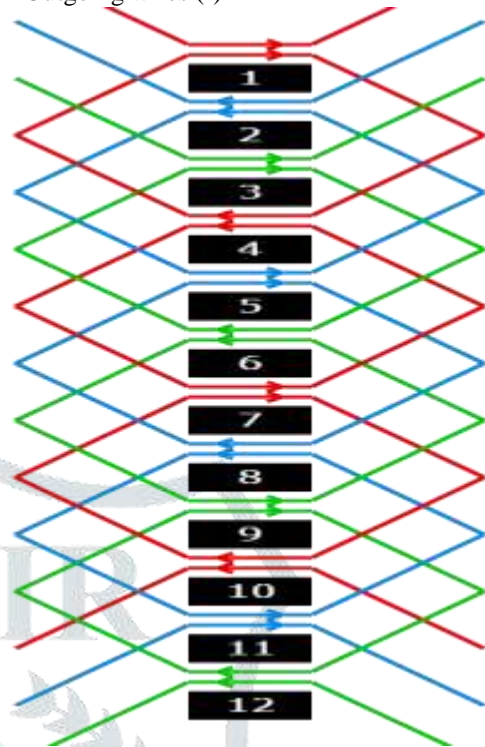ABC: Incoming wires (+)
abc: Outgoing wires (-)

Fig 7: Winding Diagram

III. SOFTWARE USED AND DESIGN CONSIDERATION

3.1 FEMM

The finite element method (FEM) is a numerical procedure that can be applied to obtain solutions to a variety of problems in engineering and science. Steady, transient, linear, and nonlinear problems in electromagnetics, structural analysis, and fluid dynamics may be analyzed and solved with it. Its main advantage is its capability to treat any type of geometry and material inhomogeneity without a need to alter the formulation of the computer code that implements it providing geometrical fidelity and unrestricted material treatment.

3.2 ANSYS MAXWELL

Designers of electrical machines and generators can enhance Ansys Maxwell with Ansys RMxprt, a template-based design 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 hundreds of "what if" analyses in a matter of seconds.

3.3 FLOWCHART

The design process of the BLDC motor is more complicated compared to the surface permanent magnet motor. The leakage path of a BLDC motor usually includes saturable magnetic bridges and webs. These bridges and webs are designed to provide integrity to the rotor. These bridges and webs introduce magnetic short circuits and complicate the design and analysis of the BLDC motor. The coefficient of flux leakage F_{lkg} varies because of saturable magnetic bridges and webs. Figure 8 shows the whole design process. A coefficient of the flux leakage F_{lkg} and a selected working point of the permanent magnet is used for the initial design of BLDC motor. The value of the coefficient of flux leakage F_{lkg} and the working point of permanent magnet will be calculated after the rough parameters are determined based on our equivalent magnetic circuits model. Structural parameters will be adjusted using a computer-aided tool. We provide the initial BLDC motor parameters design size mathematical model, and a much smaller torque angle than that in traditional designs at rated load and thus has higher overloading handing capability and improved efficiency. After that, electromagnetic analysis and FEM simulation can be performed to optimize the design parameters.
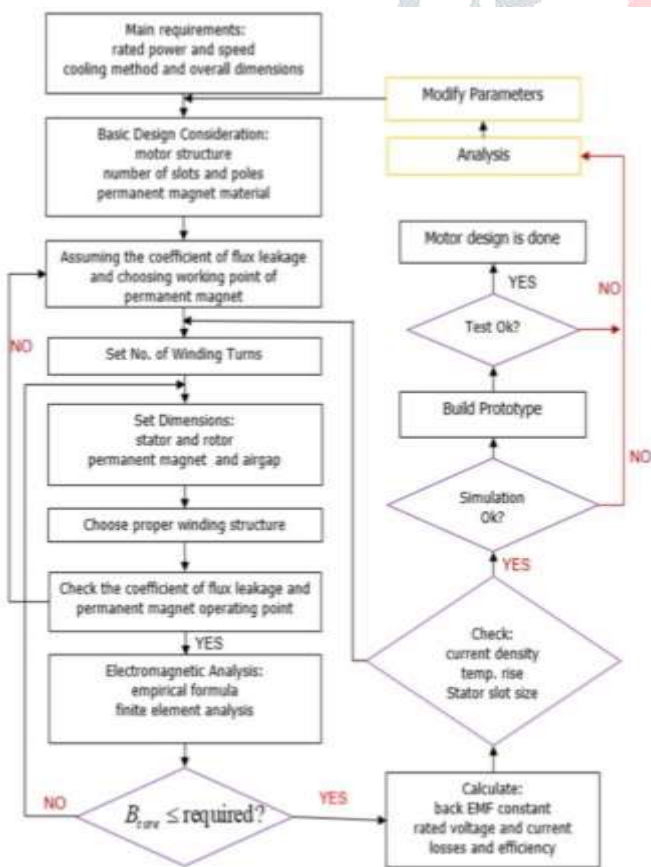

Fig 8: Flow chart for design

IV. SIMULATION AND RESULT DISCUSSION

4.1 FEMM

FEMM simulation is carried out to know the magnetic flux density and magnetic field intensity.
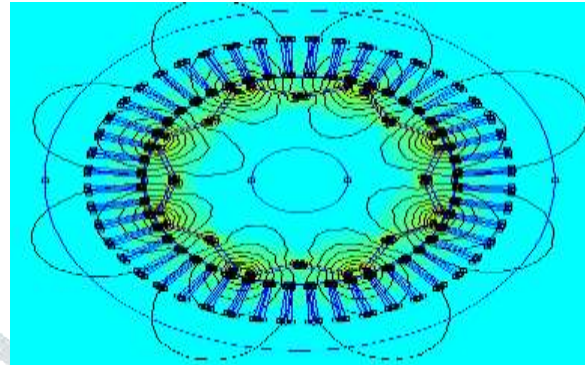

Fig 9: Flux density plot

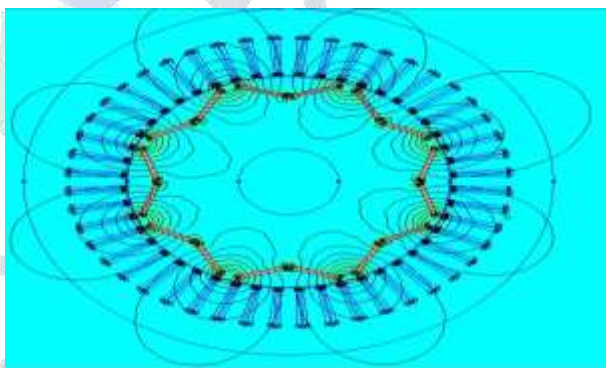

Fig 10: The result of the flux density plot
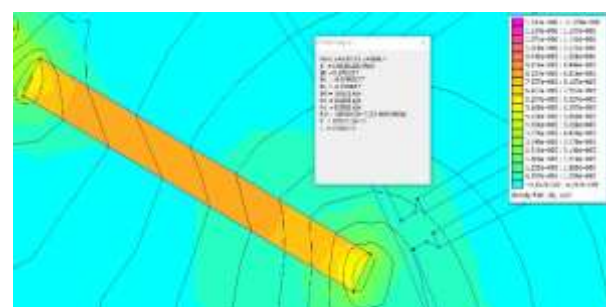

Fig 11: Field intensity plot

Fig 12: The result of the field intensity plot

For example, the value of B_m and H_m should be equal or lesser than the calculated value, hence as shown in the above result from fig 9 to 12, field intensity and flux density are compared with the calculated values as listed in table 1.

Table 1: Comparative result

Parameters	Theoretical value	Analyzed value
Flux density (B_m)	0.896 T	0.427 T
Field intensity (H_m)	713.014 kA/m	703.502 k A/m

- These values are lesser than the calculated value; hence the performance of the machine is good.
- Otherwise, while running, the motor becomes unbalance, and a large current flows to the motor than the rated current which leads to the burning or damage of the windings.

4.2 Ansys Maxwell

The simulation is done in Ansys maxwell to study the different characteristics of the calculated values of the motor.
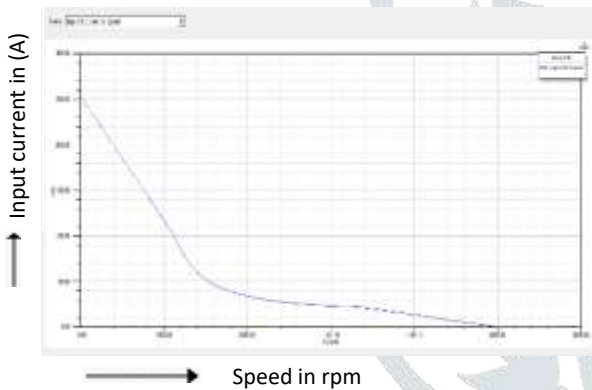

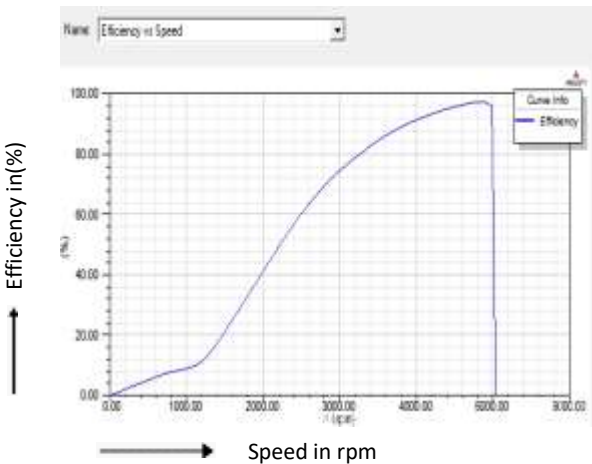Fig 13: Input current vs. Speed
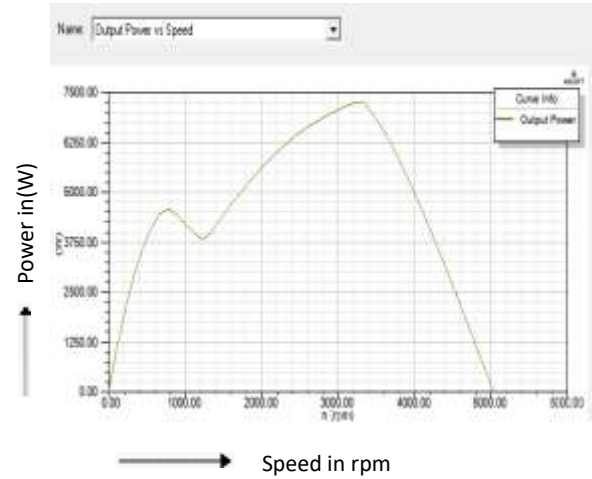

Fig 14: Efficiency vs. Speed
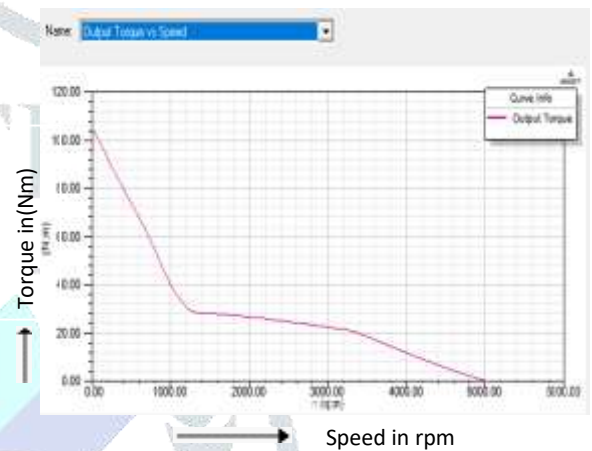

Fig 15: Output power vs. Speed

Fig 16: Torque vs. Speed

The following results are achieved by simulating in the Ansys maxwell which is shown in table 2 and table 3.

Table 2: No load operation

Data:	No-Load Operation		
	Name	Value	Units
1	Stator-Teeth Flux Density	1.50479	tesla
2	Stator-Yoke Flux Density	1.42896	tesla
3	Rotor-Yoke Flux Density	0.288503	tesla
4	Air-Gap Flux Density	0.622988	tesla
5	Magnet Flux Density	0.961163	tesla
6	Stator-Teeth Ampere Turns	59.854	
7	Stator-Yoke Ampere Turns	29.8812	
8	Rotor-Yoke Ampere Turns	2.86803	
9	Air-Gap Ampere Turns	393.895	
10	Magnet Ampere Turns	-486.311	
11	Start Armature Reactive AT	1458.9	
12	Leakage-Flux Factor	1.26981	
13	Stator Yoke Correction Factor	0.478969	
14	Rotor Yoke Correction Factor	0.809387	
15	No-Load Speed	5092.33	rpm
16	Cogging Torque	2.18486e-012	NewtonMeter

Table 3: Full load operation

	Name	Value	Units
1	Average Input Current	22.3887	A
2	RMS Armature Current	25.8507	A
3	Armature Thermal Load	850.231	
4	Specific Electric Loading	34148	A_per_meter
5	Armature Current Density	24.8984	
6	Frictional and Windage Loss	5.01139	W
7	Iron-Core Loss	0.0140819	W
8	Armature Copper Loss	1564	W
9	Transistor Loss	112.147	W
10	Diode Loss	22.8176	W
11	Total Loss	1703.99	W
12	Output Power	7251.49	W
13	Input Power	8955.48	W
14	Efficiency	80.9726	
15	Rated Speed	3321.09	rpm
16	Rated Torque	20.8506	NewtonMeter
17	Locked-Rotor Torque	105.146	NewtonMeter
18	Locked-Rotor Current	253.368	A
19	Maximum Output Power	7251.49	W

Data: Full-Load Operation

4.3 SOLIDWORKS

The SOLIDWORKS CAD software is a mechanical design automation application that lets designers quickly sketch out ideas, experiment with features and dimensions, and produce models and detailed drawings.

3D model in SolidWorks

As per the design the 3D model is constructed in the SolidWorks as shown in fig 17

Fig 17: 3D model in SolidWorks

CONCLUSION

In this project, an analytical method is introduced to design the BLDC motor. The dimensions of the stator, rotor are calculated with the equations. The magnetic properties are calculated with the existing magnet. Then the theoretically obtained values are compared with the simulation result. The magnetic properties are obtained by simulating in the FEMM software so that maximum flux density and maximum field intensity does not exceed the theoretical value. Other properties such as no-load performance, full load performance, torque, speed, output power, and their characteristics have been analyzed using Ansys maxwell software, and the result is obtained. After analyzing, the 3D model of the motor is designed in the SOLIDWORKS software. The simulation results show that an analytical method carried out to design a brushless DC (BLDC) motor can be used to optimize the design of motor parameters which are in good agreement with calculated values. Further BLDC motor can be developed for the designed values and the performance of the motor can be verified experimentally.

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