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Design Optimization of a Permanent Magnet Brushless DC motor for Power Density Enhancement for a Particular Application

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ABSTRACT

Nowadays, the Permanent Magnet, Brushless DC (PMBLDC) motors are extensively used in various real-time applications like Navigation systems, aerospace systems, and domestic areas because of its various advantages like high efficiency, precise control, smoother operation, and wide range of speed control. In this perspective, the design of an efficient PM BLDC motor is necessary. The conventional design aspects of PM BLDC motor on the electrical side leads to the development of cogging torque. To overcome this effect, the proposed paper describes a unique methodology by considering various mechanical parameters of the motor on the stator side. Along with the design aspects of the motor, it also represents the Genetic Algorithm and Grey Wolf Optimization algorithms for the identification of various design parameters in an optimal way to achieve maximum efficiency in turn to enhance the power density of the motor. The proposed algorithms are implanted using MATLAB.

Key words: Brushless DC motor, Efficiency, Optimal parameters.

1. INTRODUCTION

In general, the design of the PMBLDC motor will start from the output power requirement of the corresponding application. Based on the given specifications of the motor, the next step is to select the number of phases and poles. In general, the number of phases is three, whereas as the number of poles depends upon the number of slots since the number of poles and slots implies the winding factor coefficient. The winding factor coefficient should be nearer to unity. So the designer needs to select the optimal values of poles and slots.

Selecting too many numbers of poles leads to the accommodation problem for a given volume. Then the designer needs to identify the speed range of operation. Then the designer needs to establish the relationship between electrical and mechanical speeds via the number of poles.

In the design aspect of the PMBLDC motor, the rotor is basically the permanent magnet. Hence the efficiency and power density can be enhanced by optimizing the mechanical and electrical parameters. Then the designer needs to identify the volume of the motor by considering its bore diameter and axial length.

In the design, one should also consider the magnetic flux linkages by establishing the magnetic circuit since the torque capability can be enhanced by maximizing the flux component.

The structure of the permanent magnet BLDC motor basically depends on various internal parameters [1]. These parameters should be within the specified limits [6]. The basic design depends on the following equation

$$T = KD^2L \tag{1}$$

Where T is Torque
K is constant
D is the rotor diameter
L is the axial rotor length

In the design of the PMBLDC motor, the designer needs to assume some of the parameters are constant. In the formulation of the final model, the designer needs to assume these variables are constants only.

The various parameters in the design are the number of poles, the number of slots, winding coefficient, stator inner and outer diameters, rotor radius, stator radius, back iron thickness, etc. [10].

The final model is developed in terms of diameter, magnetic thickness, winding thickness, pole arc to pole pitch ratio, number of pole pairs, magnetic flux density, etc. [2].

2. DESIGN CONSIDERATIONS OF PMBLDC MOTOR

The basic design equations of a Permanent Magnet, Brushless DC motor [8], are given by

Mechanical Speed $\omega_m = \frac{S_r \Pi}{30}$ Rad/ Sec (2)

Electrical Speed $\omega_e = \frac{N_m \omega_m}{2}$ Rad/Sec (3)

Fundamental Frequency $f_e = \frac{\omega_e}{2\Pi}$ Hz (4)

Number of slots $N_s = N_{sp} N_{ph}$ (5)

Slot Pitch $\theta_{se} = \frac{\Pi}{N_{sm}}$ Rad (6)

Skew factor $K_s = \left[1 - \frac{\theta_{se}}{2\Pi}\right]$ (7)

3. INTRODUCTION TO OPTIMIZATION PROCESS

Optimization is one of the important areas in the design of permanent magnet brushless DC motor. It is an iterative procedure, and the process will be continued till we reach the desired band of targeted values.

A. Constructing the Mathematical Model of the Objective function

The optimization procedure will start with the final target output. Accordingly, the objective function is formulated by considering all the parameters which are involved in the process and the limitations of the objective parameters.

The objective of the present paper is to minimize the power joule losses of the proposed Permanent Magnet Brushless DC motor so that the power density of the motor can be enhanced [1], [3] by considering the volume of the machine into account.

In this case, the design approach of the Permanent Magnet Brushless DC motor is initiated from the fundamental parameters and then expanded the model towards the output in such a way that all the constraints of the design parameters [9] are involved with limitations.

After identifying the objective function, one should analyze the objective of the proposed model [11].

Then one should select the appropriate software tool to simulate the proposed model.

B. Genetic Algorithm Optimization

The genetic algorithm optimization is one of the familiar optimization processes. It is basically an iterative process, and the process will start by selecting the population randomly.

In this case, the population basically means the generation. In each generation, the objective function will be evaluated, and the fitness will be identified [12].

The next generation parameters are formulated by adopting some changes in the current population [15], [16] and the process will be continued until one can arrive at the target with a specified tolerance, as shown in figure.1.

The main steps in the Genetic Algorithm are

Step: 1 Initialize the population

Step: 2 Selection

Step: 3 Crossover

Step: 4 Mutation

The flow chart of the proposed Genetic Algorithm is illustrated in figure 1.

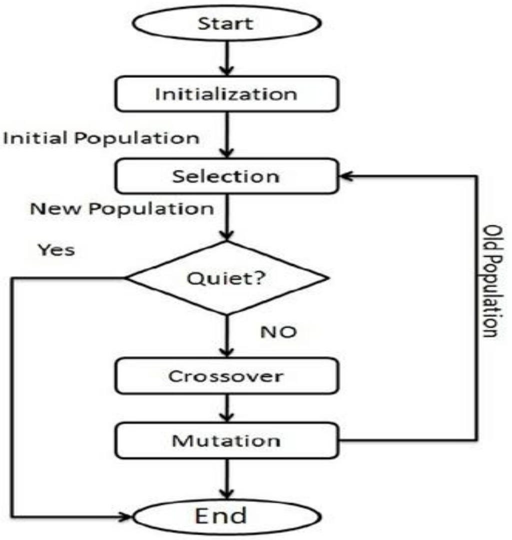

Figure 1: Flow Chart of Genetic Algorithm

C.Grey Wolf Optimization Algorithm

A Grey wolf optimization algorithm is also one of the important algorithms in the optimization area. This follows the hunting behavior of wolfs. The optimization process starts from the initial level and continues up to the last level.

The leadership in this process is subdivided into four classes of wolfs. They are Alpha (α), Betas (ß), Omega (ω), and Delta (δ).

The hierarchy of wolfs will start starts from alpha and moves towards delta [13].

The main steps in the Grey Wolf Optimization are

Step: 1 Social Hierarchy
Step: 2 Encircling Prey
Step: 3 Hunting
Step: 4 Attacking Prey
Step: 5 Search for Prey

The flow chart of the Grey Wolf Optimization Algorithm is illustrated in figure 2.

The optimization process starts from the social hierarchy of the wolf and continues up to search for prey. If the final objective parameter values are within the specified limits, then the process will be terminated; otherwise, it will again start and continues till one can reach the target.

This process will start from Tracking and continues up to attack towards the prey.

In this case the objective function is formulated to minimize the joule loss of the machine so that one can enhance the power density by considering its volume into account.

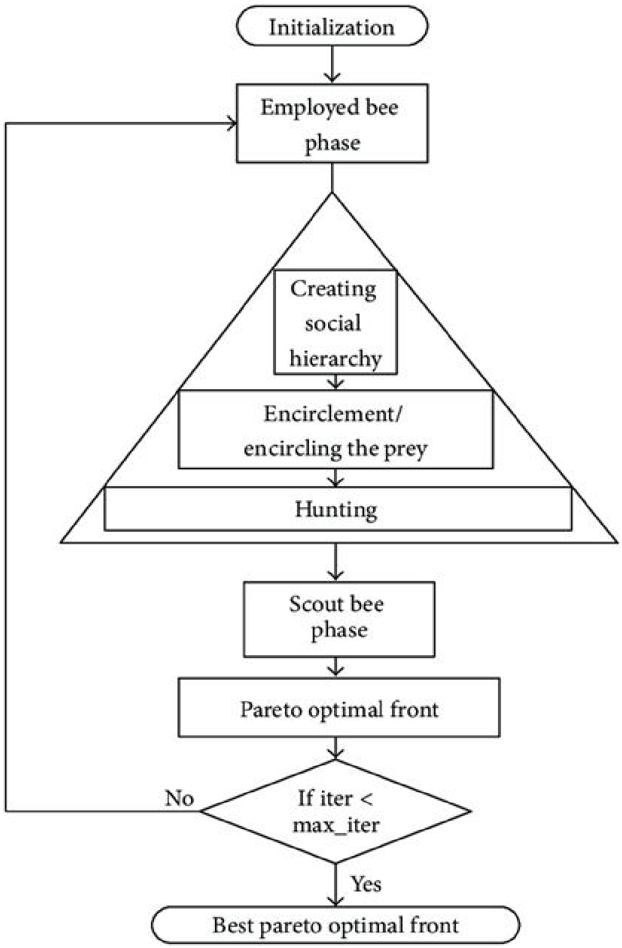

Figure 2: Flow Chart of Grey Wolf Optimization Algorithm

4. MATHEMATICAL MODELLING

A PM BLDC motor is proposed to design with the following design parameters as shown in table 1.

Table 1 :. Specifications of Proposed PMBLDC motor

Parameters	Specified Value
Output power	350 W
Number of poles	6
Number of slots	18
Rated speed	2000 RPM
K_w	1

Because of the limitations on the electrical side, the present paper gives a unique model with various optimum values on the stator side parameters.

The proposed paper presents the formulation of the objective function by considering the design parameters into account in order to enhance the power density of the permanent magnet brushless DC motor.

The various design parameters are considering for the optimization of joule loss minimization, the volume of the magnet, and the volume of the active parts [2], [4].

Three objective functions are used by considering the design variables like bore diameter (D), motor form factor (λ), motor electric loading (E_{ch}), etc. [5].

The constraints of the objective function for the proposed model for joule loss minimization, the volume of the magnet, and volume the active parts with minimum and maximum limits are illustrated in the table.

The motor mathematical model [14] is given as

Bore diameter is given by

$$D = \frac{P \Delta P}{\Pi} \tag{8}$$

Where ΔP =Polar Pitch=100 mm,

Motor form factor λ is given as

$$\lambda = \frac{D}{L} \tag{9}$$

Where L is the Axial Length

Motor electric loading is given as

$$E_{ch} = K_r E J_{cu}^2 \tag{10}$$

Where k_r=Filling Factor=0.70;
E is winding Thickness
J_{cu} is the Current density

Inter pole leakage coefficient K_f is given as

$$K_f = 1.5P\beta\left[\frac{e+E}{D}\right] \tag{11}$$

Where β is pole arc to pitch ratio
e is the mechanical air gap

No load magnetic flux density B_e is given as

$$B_e = \frac{2l_a P}{D\log\left(\frac{D+2E}{D-2(l_a+e)}\right)} \tag{12}$$

Where P is the magnetic remanency =0.90 T
l_a is magnetic thickness

Electromagnetic torque Γ_{em} is given as

$$\Gamma_{em} = \frac{\Pi}{2\lambda}(1-K_f)(\sqrt{K_r \beta E_{ch} E} D^2 (D+E) B_e \tag{13}$$

E_{ch} = Electric Loading

Using flux conversation law, the stator and iron magnetic flux density B_{fer} is given as

$$B_{fer} = \frac{\Pi \beta B_e D}{4PC} \tag{14}$$

C is the stator and rotor Yoke thickness

Finally joule losses P_L is given as

$$P_L = \Pi \rho_{cu} L(\lambda L + \left[\frac{K_f B_{fer} 4CD \log\left(\frac{D+2E}{D-2(l_a+e)} \right)}{3\beta^2 \Pi l_a M} - e \right] K_r E J_{cu}^2) \tag{15}$$

Where ρ_{cu} is the copper resistivity

The total magnet volume is

$$V_m = \frac{\Pi D}{\lambda}\left[\frac{4CPB_{iron}}{\Pi \beta B_e} + \frac{E_{ch}}{K_r J_{cu}^2} - e - l_a \right]\left[\frac{\Pi \beta B_e}{2PB_{iron}} + \frac{DK_f}{1.5P\beta} + B_e D \log\left(\frac{D+2E}{D-2(l_a+e)} \right) \right] \tag{16}$$

The volume of the active parts

$$V_a = \left[\frac{\Pi \beta B_e D^2 \log\left(\frac{D+2E}{D-2(l_a+e)} \right)}{2P\lambda} \right]\left[\frac{4CPB_{iron}}{\Pi \beta B_e} - 2\left[\frac{K_f D}{1.5P\beta} - \frac{E_{ch}}{J_{cu}^2} \right] - l_a \right] \tag{17}$$

The various constants are

ρ_{cu} =0.018 μΩ-m,

$K_f < 0.30$,

B_{fer}=1.5,

B_{iron}=Iron Magnetic flux density=1.50 T,

$E_{ch}=10^{11}$A/M,

$e_{min}=10^{-3}$

Table 2 : Lower and Upper limits for Joule losses

S. No	Parameter	Lower Limit	Upper Limit
1	Iron axial length -L(m)	4×10^{-3}	500×10^{-3}
2	Magnet thickness- l_a(m)	1×10^{-3}	50×10^{-3}
3	Winding thickness-E(m)	1×10^{-3}	50×10^{-3}
4	Stator and rotor yoke thickness- C(m)	1×10^{-3}	50×10^{-3}
5	Mechanical air gap- e(m)	10^{-3}	5×10^{-3}
6	Ratio: Polar arc to Polar pitch-β	0.8	1
7	Current density-J_{cu}(A/m^2)	1×10^5	1×10^7
8	Form factor-λ	1	2.5
9	Diameter-D(m)	0.01	0.5

Table 3: The volume of Active parts and Volume of Magnet

S. No	Parameter	Lower Limit	Upper Limit
1	Diameter-D(m)	0.01	0.5
2	Form factor-λ	1.0	2.5
3	Magnet thickness-l_a(m)	0.003	0.05
4	Winding thickness-E(m)	0.001	0.05
5	Stator and rotor yoke thickness-C(m)	0.001	0.05
6	Ratio: Polar arc to Polar pitch-β	0.8	1.0
7	Number of pole pairs-P	1	10
8	Magnetic flux density-B_e	0.1	1.0
9	Current density-J_{cu}(A/m^2)	10^5	10^7
10	Inter pole leakage coefficient -K_f	0.01	0.5
11	Mechanical air gap- e(m)	0.1×10^{-4}	5×10^{-4}

5. RESULTS

The optimum values for Joule losses, Volume of the active parts, and Volume of the magnets using Genetic Algorithm Optimization are illustrated in table 4, table 5, and table 6.

The optimum values for Joule losses, Volume of the active parts, and Volume of the magnets using the Grey Wolf Optimization technique are illustrated in table 7, table 8, and table 9.

The design procedure adopted in the proposed paper for a PMBLDC motor with two different design models. They are Genetic Algorithm and Grey Wolf Optimization techniques.

Both the design procedures give maximum power output; the minimum volume of the active parts and minimum volume of the magnet further leads to an enhanced power density of the permanent magnet brushless DC motor.

From the comparisons of the proposed methods, i.e., from table 10, table 11, and table 12, the optimum values of the mechanical air gap in the volume of active part and volume of the magnet in the Genetic Algorithm are zero. In contrast, in Grey Wolf Optimization, the values are finite.

The practical design of the permanent magnet brushless DC motor with zero air gap is not physically realizable. So in this aspect, the Grey Wolf Optimization is better Optimization when compared to the Genetic Algorithm in this case.

This paper presents an optimal procedure in terms of various mechanical and electrical parameters to get an efficient and high power density PMBLDC motor with various design parameters.

The Genetic Algorithm and Grey Wolf Optimization Algorithms were implemented using MATLAB.

A. GENETIC ALGORITHM

Table 4: Optimum Vales for Joule Loss

S.NO	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Iron axial length -L(m)	4×10^{-3}	500×10^{-3}	**0.458**
2	Magnet thickness- l_a(m)	1×10^{-3}	50×10^{-3}	**0.046**
3	Winding thickness-E(m)	1×10^{-3}	50×10^{-3}	**0.05**
4	Stator and rotor yoke thickness- C(m)	1×10^{-3}	50×10^{-3}	**0.018**
5	Mechanical air gap- e(m)	10^{-3}	5×10^{-3}	**0.05**
6	Ratio: Polar arc to Polar pitch-β	0.8	1	**0.977**
7	Current density-J_{cu}(A/m^2)	1×10^5	1×10^7	**100002.442**
8	Form factor-λ	1	2.5	**1.005**
9	Diameter-D(m)	0.01	0.5	**0.469**

Table 5: Optimum Vales for Volume of Active Parts

S. No	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Diameter-D(mm)	0.01	0.5	**0.016**
2	Form factor-λ	1.0	2.5	**2.376**
3	Magnet thickness-l_a(m)	0.003	0.05	**0.043**
4	Winding thickness-E(m)	0.001	0.05	**0.024**
5	Stator and rotor yoke thickness-C(m)	0.001	0.05	**0.006**
6	Ratio: Polar arc to Polar pitch-β	0.8	1.0	**0.989**
7	Number of pole pairs-P	1	10	**2**
8	Magnetic flux density-B_e	0.1	1.0	**0.63**
9	Current density-J_{cu}(A/m^2)	10^5	10^7	**9150980.287**
10	Inter pole leakage coefficient -K_f	0.01	0.5	**0.481**
11	Mechanical air gap- e(m)	0.1×10^{-4}	5×10^{-4}	**0**

Table 6: Optimum Vales for Volume of Magnet

S. No	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Diameter-D(m)	0.01	0.5	**0.03**
2	Form factor-λ	1.0	2.5	**1.167**
3	Magnet thickness-l_a(m)	0.003	0.05	**0.046**
4	Winding thickness-E(m)	0.001	0.05	**0.032**
5	Stator and rotor yoke thickness-C(m)	0.001	0.05	**0.003**
6	Ratio: Polar arc to Polar pitch-β	0.8	1.0	**0.961**
7	Number of pole pairs-P	1	10	**3**
8	Magnetic flux density-B_e	0.1	1.0	**0.638**
9	Current density-J_{cu}(A/m^2)	10^5	10^7	**4171726.927**
10	Inter pole leakage coefficient -K_f	0.01	0.5	**0.186**
11	Mechanical air gap- e(m)	0.1×10^{-4}	5×10^{-4}	**0**

B. GREY WOLF OPTIMIZATION ALGORITHM

Table 7: Optimum Vales for Joule Loss

S. No	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Iron axial length -L(m)	4×10^{-3}	500×10^{-3}	**0.5**
2	Magnet thickness- l_a(m)	1×10^{-3}	50×10^{-3}	**0.04798**
3	Winding thickness-E(m)	1×10^{-3}	50×10^{-3}	**0.05**
4	Stator and rotor yoke thickness- C(m)	1×10^{-3}	50×10^{-3}	**0.03476**
5	Mechanical air gap- e(m)	10^{-3}	5×10^{-3}	**0.05**
6	Ratio: Polar arc to Polar pitch-β	0.8	1	**0.8**
7	Current density-J_{cu}(A/m^2)	1×10^{5}	1×10^{7}	**10000000**
8	Form factor-λ	1	2.5	**1.2399**
9	Diameter-D(mm)	0.01	0.5	**0.02254**

Table 8: Optimum Vales for Volume of Active Parts

S. No	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Diameter-D(mm)	0.01	0.5	**0.5**
2	Form factor-λ	1.0	2.5	**1**
3	Magnet thickness-l_a(m)	0.003	0.05	**0.05**
4	Winding thickness-E(m)	0.001	0.05	**0.05**
5	Stator and rotor yoke thickness-C(m)	0.001	0.05	**0.00721**
6	Ratio: Polar arc to Polar pitch-β	0.8	1.0	**1**
7	Number of pole pairs-P	1	10	**1**
8	Magnetic flux density-B_e	0.1	1.0	**1**
9	Current density-J_{cu}(A/m^2)	10^5	10^7	**7930100.0048**
10	Inter pole leakage coefficient -K_f	0.01	0.5	**0.5**
11	Mechanical air gap- e(m)	0.1×10^{-4}	5×10^{-4}	**0.0002791**

Table 9: Optimum Vales for Volume of Magnet

S. No	Parameter	Lower Limit	Upper Limit	Optimum Value
1	Diameter-D(mm)	0.01	0.5	**0.5**
2	Form factor-λ	1.0	2.5	**1**
3	Magnet thickness-l_a(m)	0.003	0.05	**0.05**
4	Winding thickness-E(m)	0.001	0.05	**0.006139**
5	Stator and rotor yoke thickness-C(m)	0.001	0.05	**0.001**
6	Ratio: Polar arc to Polar pitch-β	0.8	1.0	**1**
7	Number of pole pairs-P	1	10	**1**
8	Magnetic flux density-B_e	0.1	1.0	**1**
9	Current density-J_{cu}(A/m^2)	10^5	10^7	**9935416.1404**
10	Inter pole leakage coefficient -K_f	0.01	0.5	**0.0621**
11	Mechanical air gap- e(m)	0.1×10^{-4}	5×10^{-4}	**0.000359**

Table 10: Comparison of Optimum Vales for Joule Loss

S. No	Parameter	Optimum Value Using Genetic Algorithm	Optimum Value Using Grey Wolf Optimization
1	Iron axial length -L(m)	**0.458**	**0.5**
2	Magnet thickness- l_a(m)	**0.046**	**0.04798**
3	Winding thickness-E(m)	**0.05**	**0.05**
4	Stator and rotor yoke thickness- C(m)	**0.018**	**0.03476**
5	Mechanical air gap- e(m)	**0.05**	**0.05**
6	Ratio: Polar arc to Polar pitch-β	**0.977**	**0.8**
7	Current density-J_{cu}(A/m^2)	**100002.442**	**10000000**
8	Form factor-λ	**1.005**	**1.2399**
9	Diameter-D(m)	**0.469**	**0.02254**

Table 11: Comparison of Optimum Vales for Volume of Active Parts

S. No	Parameter	Optimum Value Using Genetic Algorithm	Optimum Value Using Grey Wolf Optimization
1	Diameter-D(mm)	**0.016**	**0.5**
2	Form factor-λ	**2.376**	**1**
3	Magnet thickness-l_a(m)	**0.043**	**0.05**
4	Winding thickness-E(m)	**0.024**	**0.05**
5	Stator and rotor yoke thickness-C(m)	**0.006**	**0.00721**
6	Ratio: Polar arc to Polar pitch-β	**0.989**	**1**
7	Number of pole pairs-P	**2**	**1**
8	Magnetic flux density-B_e	**0.63**	**1**
9	Current density-J_{cu}(A/m^2)	**9150980.287**	**7930100.0048**
10	Inter pole leakage coefficient -K_f	**0.481**	**0.5**
11	Mechanical air gap- e(m)	**0**	**0.0002791**

Table 12: Comparison of Optimum Vales for Volume of Magnet

S. No	Parameter	Optimum Value Using Genetic Algorithm	Optimum Value Using Grey Wolf Optimization
1	Diameter-D(m)	**0.03**	**0.5**
2	Form factor-λ	**1.167**	**1**
3	Magnet thickness-l_a(m)	**0.046**	**0.05**
4	Winding thickness-E(m)	**0.032**	**0.006139**
5	Stator and rotor yoke thickness-C(m)	**0.003**	**0.001**
6	Ratio: Polar arc to Polar pitch-β	**0.961**	**1**
7	Number of pole pairs-P	**3**	**1**
8	Magnetic flux density-B_e	**0.638**	**1**
9	Current density-J_{cu}(A/m^2)	**4171726.927**	**9935416.1404**
10	Inter pole leakage coefficient -K_f	**0.186**	**0.0621**
11	Mechanical air gap- e(m)	**0**	**0.000359**

6. CONCLUSION

Optimum design of permanent magnet brushless DC motor is investigated in this paper. Three objective functions were considered by the use of the Genetic Algorithm and Grey Wolf Algorithm. By performing the optimization of these three objective functions gives minimization of the total loss of motor and maximizing power density of motor, respectively.

The minimization of the joule losses leads to the enhancement of efficiency and performance of the machine. The minimization of the volume of a magnet and active parts leads to a decrease in the weight of machines and losses. Ultimately these objectives combine leads to enhancement of Power density of a Permanent Magnet Brushless DC motor. The objective functions is formulated by using various parameters like bore diameter (D), motor form factor (λ), motor electric loading (Ech) etc.. By using the Grey wolf optimization technique, the practical motor design is more reliable when compared to the Genetic Algorithm Optimisation technique.

7. FUTURE SCOPE

The present paper proposes the complete design procedure by considering some of the key parameters of a PMBLDC motor for a particular application. Further, one can enhance the power density of the motor by changing the mechanical structure of the motor so that the actual design of the motor is easy.

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