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Research Paper

Optimization of Specific Power of Surface Mounted Axial Flux Permanent Magnet Brushless DC Motor for Electrical Vehicle Application

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Abstract: Optimization of specific power of axial flux permanent magnet brushless DC (PMBLDC) motor based on genetic algorithm optimization technique for an electric vehicle application is presented. Double rotor sandwiched stator topology of axial flux permanent magnet brushless DC motor is selected considering its best suitability in electric vehicle applications. Rating of electric motor is determined based on vehicular dynamics and application needs. Double rotor sandwiched stator axial flux PMBLDC motor is designed considering various assumed design variables. Initially designed axial flux PMBLDC motor is considered as a reference motor for further analysis. Optimization of specific power of electric motor for electric vehicle applications is a very important design issue. The Genetic Algorithm (GA) based optimization technique is proposed for optimization of specific power of axial flux permanent magnet brushless DC motor. Optimization with an objective of maximum specific power with the same torque rating is performed. Three-dimensional finite element analysis is performed to validate the proposed GA based specific power optimization. Close agreement between results obtained from finite element analysis and analytical design establishes the correctness of the proposed optimization technique. The performance of the improved motor is compared with the initially designed reference motor. It is analyzed that the specific power of axial flux PMBLDC motor is enhanced effectively with the application of GA based design optimization technique.

Keywords: Axial Flux PM Motor, Design Variables, Computer-Aided Design, FE Analysis, Optimization, Genetic Algorithm.

1 Introduction

LIMITED resources of conventional energy sources and increased carbon emission have evolved the need for alternative energy systems for vehicle transportation. Internal combustion (IC) engines consume fossil fuel and produce nitrogen oxides which are responsible for smog and global warming. Electric mobility concept gained significant attention in recent years. Adoption of electric mobility is in healthy state and expected to see sustainable increase in future also. An electric motor is one of the important elements of the electric vehicle system. Electric motor for electric vehicle (EV) application must possess the following performance parameters [1]:

- High specific power and efficiency;
- High starting torque and fast dynamic response;
- Low voltage rating to reduce battery size and space requirements.

High specific power and efficiency are desirable performance parameters of electric motor applicable in electric vehicle applications. High specific power of electric motor results in an enhanced drive range of electric vehicles [2]. A detailed analysis is carried out for a selection of motor. DC brushed motors suffer from problems related to commutators and brushes. Induction

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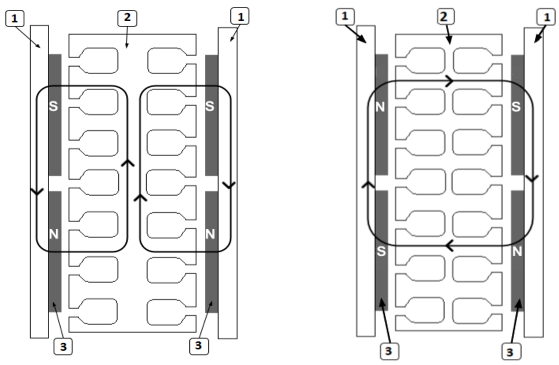
motors have limitations of low power density and low efficiency. Switched reluctance motors have advantages like simple and robust construction, high efficiency along with disadvantages like high torque ripple and complex control. Permanent magnet (PM) motors offer high efficiency compared to other types of electrical motors. PM motors are intrinsically efficient and compact on account of loss-free excitation using permanent magnet [3]. Permanent magnet motors are becoming paramount machines due to many advantages over conventional machines. Permanent magnet motors can be an alternative to induction motor with a transmission mechanism in low-speed high torque applications. Variable-speed permanent magnet motors are increasingly used in a wide range of industrial and commercial applications due to high efficiency, high power density and fast dynamic response. They are more suitable for specific applications where enough emphasis is given on compactness and high efficiency.

PM motors are classified as surface PM (SPM) motors or interior PM (IPM) motors according to the placement of PM on the rotor core. Permanent magnet motors are further classified as radial flux motor and axial flux motor according to the direction of flux in the magnetic circuit of the motor. Flux establishes in the radial direction and current flow in an axial direction in radial flux motor while flux establishes in an axial direction and current flows in a radial direction in axial flux motors. Axial flux motors have salient features like high power density, high efficiency, high torque per ampere and flat shape. Axial flux motors are classified according to numbers and relative positions of stators and rotors respectively. Electric Vehicle application necessitates motor of a flat shape having a low aspect ratio. Considerable dead space in radial flux motor with flat shape adversely affects its torque ability [4]. Axial flux motors are preferred for low aspect ratio. The physical construction of axial flux surface mounted PM motor reveals that dual air-gap sandwiched stator type construction is most compatible in direct drive application in electrical vehicle [5].



1 Rotor core
2 Stator core
3 PM
(a)

1 Rotor core
2 Stator core
3 PM
(b)

Fig. 1 a) NN topology of axial flux motor and b) NS topology of axial flux motor

Double air-gap sandwiched stator axial flux PM motors can be further classified as NN or NS according to the polarity of opposite magnets. NN type topology has two opposite magnets of the same polarity as shown in Fig. 1(a) while NS topology has two opposite magnets of opposite polarity as shown in Fig. 1(b). Ring-type winding is suitable in NN type axial flux motor while drum-type winding is required in NS type axial flux motor. This research work is focused on the NN type double rotor single stator topology.

Motor ratings are determined according to vehicular dynamics and requirements of application [6]. Initial motor design is done based on calculated rating and assumed design variables. Initial reference motor of 250 W, 150 rpm is designed with 48 slots and 16 poles and its performance estimation is carried out subsequently. Computer-Aided Design (CAD) programming is done with two decision making loops. Motor design with high specific power and efficiency is crucial in an automotive application. The entire exercise of design optimization is to optimize specific power of axial flux PMBLDC motor. Optimization of specific power of electric motor enhances the drive range of electric vehicle. Optimization of specific power is carried out using a Genetic Algorithm (GA) technique. Finite Element Analysis (FEA) is carried out to validate CAD-based design and GA based optimized design. Close proximity among results from CAD, GA optimization and FEA establish the correctness of the proposed technique for specific power optimization. The following sections of the paper explain this work carried out and analyze the results obtained.

2 Motor Rating Calculation Based on Vehicle Dynamics

Rating of electric motor for electric vehicle applications depends on application needs and associated dynamics like rolling resistance, gradient resistance, aerodynamic drag, etc.

The force required for driving a vehicle is calculated below.

$$F_{total} = F_r+F_g+F_{ad}+F_a \tag{1}$$

where, F_{total} is total force, F_r is force due to rolling resistance, F_g is force due to gradient resistance, F_{ad} is force due to aerodynamic drag and F_a is accelerating force. F_{total} is the total tractive force that the output of the motor must overcome in order to move the vehicle at a constant speed.

Rolling Resistance Force: Rolling resistance is the resistance offered to the vehicle due to the contact of tires with road. The following equation can be used to calculate force due to rolling resistance.

$$F_r = C_{rr}\times m\times g \tag{2}$$

where, C_{rr} is rolling resistance coefficient, m is mass in kg. and g is acceleration due to the gravity.

Gradient Resistance Force: Gradient resistance of vehicle is the resistance offered to the vehicle while climbing a hill or flyover or while traveling in a downward slope. It can be expressed with the following equation considering α as an angle between the ground and path of a vehicle.

$$F_g = m \times g \times \sin\alpha \tag{3}$$

Aerodynamic Drag Force: Aerodynamic drag is the resistive force offered due to the viscous force acting on the vehicle. It is majorly governed by the shape of the vehicle.

$$F_{ad} = 0.5\, C_d \times A_f \times \rho \times v^2 \tag{4}$$

where C_d is aerodynamic drag coefficient, A_f is frontal area of the vehicle, and ρ is air density.

Accelerating Force: It can be expressed with the following equation.

$$F_a = m \times a = m \times \frac{dv}{dt} \tag{5}$$

The vehicle has a laden weight of 150 kg. and a maximum speed of 25kmph. It should attain a top speed in 09 sec. Vehicle parameters considered in the present work are given in Table 1.

According to vehicle dynamics and application requirements, calculated rated and maximum power are 250 W and 803.4 W, respectively while calculated rated and maximum torque are 15.91 N.m. and 58.32 N.m., respectively.

3 Axial Flux Dual Air Gap PMBLDC Motor Design

Design of electric motor includes finalization of topology, calculation of dimensions and performance estimation.

View of double rotor single stator axial flux motor is shown in Fig. 2. Permanent magnets are mounted on the surface of the rotor core. Flux emanates from PM crosses air-gap and travels via stator back iron and then returns to the rotor. Surface PM topology is usually selected in case of low or medium speed applications. Interior PM topology is preferred in case of high-speed application where the centrifugal force on PM is considerable. Neodymium (Nd) sintered PM is used to realize high torque ability and high efficiency as Nd sintered PM offers maximum remanence & energy density [4].

Table 1 Vehicle parameters.

Parameter	Symbol	Value
Rolling resistance coefficient	C_{rr}	0.011
Vehicle weight	m	150 kg
Air density at 25°C	ρ	1.177 kg/m^3
Grade angle	α	0 degree
Frontal area	A_f	0.9 m^2
Aerodynamic drag coefficient	C_d	0.7
Gravitational coefficient	g	9.81 m/s^2

Outer radius (R_o) and inner radius (R_i) are the main dimensions of axial flux motor as shown in Fig. 3. Outer radius can be calculated from the following equation.

$$R_0 = \sqrt{\frac{3T}{2\,\eta\, N_c\, N_m\, N_{spp}\, K_w\, B_g\, I_s}} \tag{6}$$

Inner radius can be calculated from the outer radius and assumed diametric ratio,

$$R_i = \frac{R_0}{K_r} \tag{7}$$

Dimensions of iron sections like stator back iron, rotor back iron and stator teeth are calculated according to magnetic flux and assumed flux density in that section respectively. Weight of a particular motor section can be calculated by the product of volume and material density. Following are equations to determine the volume and weight of various motor sections.

$$V_{sc} = 0.9\left[\pi(R_o^2 - R_i^2)\times \left(2(W_{sbi} + d_s) - N_s(d_s \times w_{sb})(R_o - R_i)\right)\right] \tag{8}$$

$$W_{sc} = V_{sc} \times \rho_i \tag{9}$$

$$V_{cu} = \left[A_{ss} \times S_f \times N_s (R_o - R_i)\right] \tag{10}$$

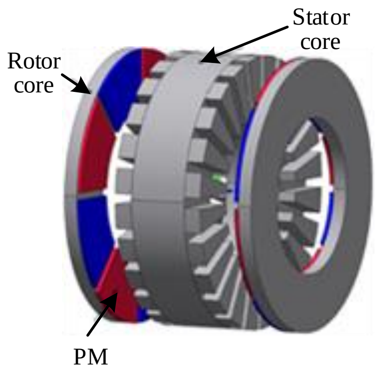


Fig. 2 Dual air-gap axial flux PMBLDC motor.

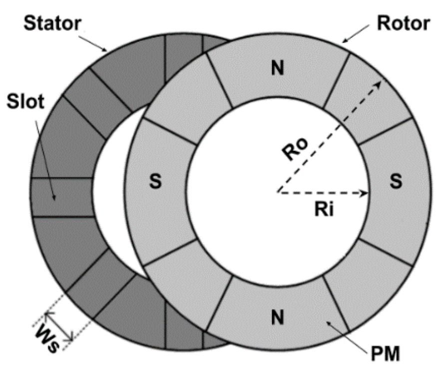


Fig. 3 Main dimensions of axial flux PMBLDC motor [R-III].

$$W_{cu} = V_{cu} \times \rho_{cu} \tag{11}$$

$$V_{rbi} = 2 \times L_{cr} \times \pi (R_o^2 - R_i^2) \tag{12}$$

$$W_{rbi} = V_{rbi} \times \rho_i \tag{13}$$

$$V_{pm} = 2\pi (R_o^2 - R_i^2) L_m - 2(R_o - R_i) L_m \tau_f N_m \tag{14}$$

$$W_{pm} = V_{pm} \times \rho_{pm} \tag{15}$$

$$W_{total} = W_{sc} + W_{cu} + W_{rbi} + W_{pm} \tag{16}$$

The equation of total motor weight is derived in terms of design parameters. Motor weight depends on various design variables like average air-gap flux density, ampere loading, packing factor, winding factor, diametric ratio and maximum flux densities in various magnetic sections. Motor weight can be calculated from the following equation.

$$\begin{aligned} W_{total} = \; & k_i \left[\pi (R_o^2 - R_i^2) \times (2W_{sbi} + 2d_s) - N_s d_s w_{sb} (R_o - R_i) \right] \rho_i \\ & + \left[A_{ss} S_f N_s (R_o - R_i) \right] \rho_{cu} \\ & + \left[2\pi (R_o^2 - R_i^2) L_m - 2(R_o - R_i) L_m \tau_f N_m \right] \rho_{pm} \\ & + \left[2L_{cr} \pi (R_o^2 - R_i^2) \right] \rho_i \end{aligned} \tag{17}$$

The above equation is selected as an objective function to be optimized. Parameters of motor design are presented in Table 2.

4 Design Optimization Based on Genetic Algorithm

Design of motor is an analytical exercise to be performed based on the specification and assumed design variables. Design variables are assumed considering materials availability and typical requirement of application [7]. Design of electric motor comprises determination of main dimension, design of stator, design of rotor and prediction of performance [8]. The flow chart of computer-aided design program is shown in Fig. 4. CAD program corrects assumed design variables if predicted performance differs from the expected performance of the motor. The computer-aided design program for Axial Flux surface mounted PMBLDC motor is developed incorporating decision making loops. Performance improvement of the motor is a crucial design issue for energy conservation, environment protection and sustainable development. Specific power is one of the important performance parameters of electric motors particularly designed for an application having dimensional constraint.

Optimization of electric motor design is required to

Table 2 Description of design parameters.

Parameter	Definition	Parameter	Definition
T	Torque	N_m	No. of rotor poles
K_r	Diametric ratio	A_{SS}	Area of slot
η	Efficiency	S_f	Space factor
N_C	Coils conducting simultaneously	V_{SC}	Volume of stator core
N_m	Number of poles	ρ_i	Density of iron
N_{spp}	No. of slots per pole per phase	W_{SC}	Weight of stator core
K_w	Winding factor	V_{cu}	Volume of copper
B_g	Air-gap flux density	ρ_{cu}	Density of copper
I_S	Slot ampere loading	W_{cu}	Weight of copper
W_{sbi}	Weight of stator back iron	V_{rbi}	Volume of rotor back iron
d_s	Depth of slot	ρ_i	Density of iron
N_S	No. of stator slots	W_{rbi}	Weight of rotor back iron
w_{sb}	Width of slot bottom	V_{pm}	Volume of permanent magnet
L_{cr}	Length of rotor core	ρ_{pm}	Density of permanent magnet
l_m	Length of magnet	W_{pm}	Weight of permanent magnet
τ_f	Magnet spacer	W_{total}	Total weight

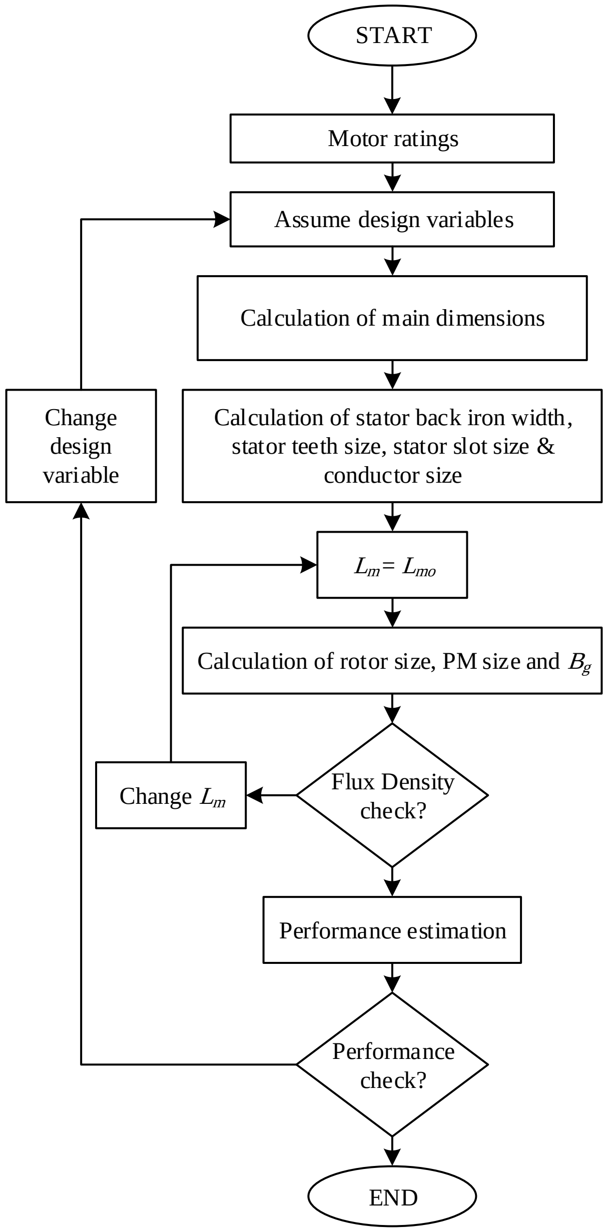


Fig. 4 Flowchart of CAD program for axial flux PMBLDC motor.

ensure the performance parameter [9]. In this paper, the investigation is focused on enhancing the specific power of axial flux motor with a GA based optimization technique. GA is found the most suitable optimization technique in nonlinear problems having many design variables[10]. Design of electrical machine is also nonlinear problem involving many variables. Flowchart of the GA based optimization technique is shown in Fig. 5. GA mimics problem solving strategy based on Darwin's principle of evaluation and survival of fittest. Generate population, selection, crossover, and mutation are four key stages of the GA based optimization technique. Definition of an engineering problem and its volume govern the size of the population [10].

GA starts with selection of influential design variables with upper and lower bound. Population is a set of different chromosomes randomly generated from range of design variables. The entire population is first sorted according to the fitness they have in selection process. The fitness here is dependent on the value of the fitness function. The chromosome with highest specific power is given fitness of "2" others are given "1" and the chromosome with lowest specific power is given fitness "0". The selection process aims at retaining the chromosomes with the high specific power and discards the chromosome with lowest specific power. This is done by first arranging the chromosomes in the descending order of their specific power from highest to lowest; this is followed by creating two copies of the topmost chromosome and single copies of others at the same time keeping the population size constant. This leads to a new population with 2 copies of topmost chromosome and the lowermost chromosome being discarded from the population. The process of crossover ensures that sufficient diversity is maintained during the entire process of genesis. This process ensures that in spite of multiple copies of the same chromosome being present in the population, there is a diversity created in the population every time a generation progresses forward. The mutation process introduces sudden and random changes in the original string/chromosome. This process is introduced because in natural genesis, mutation sometimes brings about positive change in the traits leading to a better offspring.

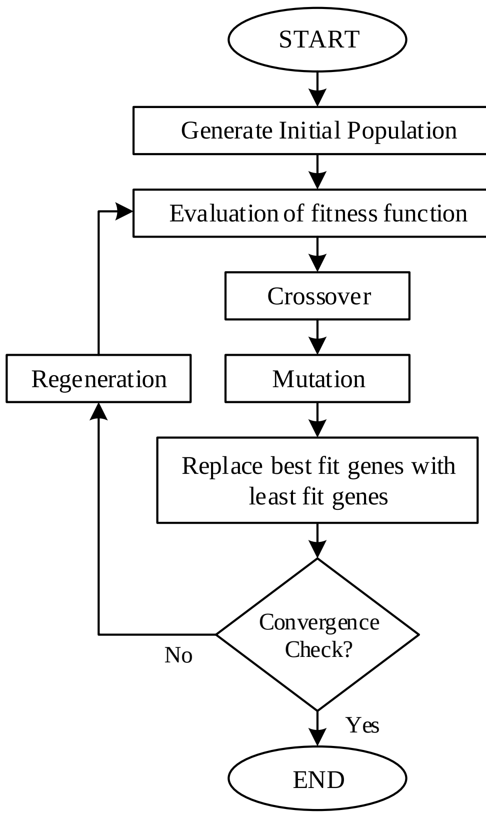


Fig. 5 Flowchart of GA based optimized CAD program.

5 Results and Analysis

Based on the parametric analysis, primary design variables for optimization are scrupulously identified. To access the effect of design variables on axial flux motor output, a parametric analysis was performed. Selection of design variables is primarily influenced by availability of materials and manufacturing limitations. Constraints introduced in analysis are dimensional in nature.

Table 3 indicates primary design variables with lower to upper band and variables assumed in initial CAD. Table 4 illustrates each chromosome's 1x5 array for proposed optimization.

Using the GA technique, the specific power of the motor is optimized. Effect on specific power of number of design variables is shown in Table 5. It is observed that the fitness function i.e. septic power is improved as the number of design variables is increased.

Optimum specific power of 33.06 W/kg. is converged with GA based design optimization. Optimized findings are reached in 89 generations. Fig. 6 shows the convergence of objective function with the GA based optimization technique.

Relative performance of the CAD and GA based optimized design on per unit basis is shown in Fig. 7.

Table 3 Range of design variables.

Design Variables	Description	Range	
		Minimum	Maximum
X_1	Air gap flux density (B_g)	0.4 T	0.9 T
X_2	Slot electrical loading (I_s)	100 A	400 A
X_3	Stator diametric ratio (K_r)	1.3	2.5
X_4	Max. current density (I_{max})	4 A/mm^2	10 A/mm^2
X_5	Packing factor (k_{cp})	0.4	0.7

Table 4 Representation of chromosome.

B_g	I_s	K_r	I_{max}	k_{cp}

Table 5 Effect of number of variables on specific power.

Variables	Specific power
B_g , J_{max}	25.38 W/kg
B_g , J_{max} , k_{cp}	25.66 W/kg
B_g , K_r , J_{max} , k_{cp}	29.37 W/kg
B_g , I_s , K_r , J_{max} , k_{cp}	33.06 W/kg

The CAD-based initial design is considered as the reference. It is analyzed that GA based unconstraint design with 5 variables results in optimum specific power of 33.06 W/kg. It is evident that the optimized solution is better in comparison to the initial design of the axial flux motor. Increased specific power results in reduced motor weight and increased torque density as an outcome of optimization. The overall mass of the electric vehicle is reduced due to the reduction in motor weight. Any improvement in specific power i.e. reduction in motor weight results in enhanced drive range. Efficiency of the electric motor is slightly compromised but the overall performance of the electric vehicle is improved. Improvement of specific power is of high significance in applications with space constraints like electric vehicle, elevator, etc. The cost of motor reduces as material requirement reduces due to reduced weight of axial flux motor.

Initial CAD-based design is carried out with an assumption of various design variables. Assumed design variables are specific magnetic loading 0.75 T, specific ampere slot loading 140 A, diametric ratio 1.75, maximum current density 4.0 A/mm^2 and conductor packing factor 0.4. With the application of the GA based optimization technique, the various design variables have been selected with an objective of optimum specific power of axial flux PMBLDC motor. The optimized design variables are specific magnetic loading 0.55 T, specific ampere slot loading 200.67 A, diametric ratio 1.85, maximum current density 5.78 A/mm^2 and conductor packing factor 0.49.

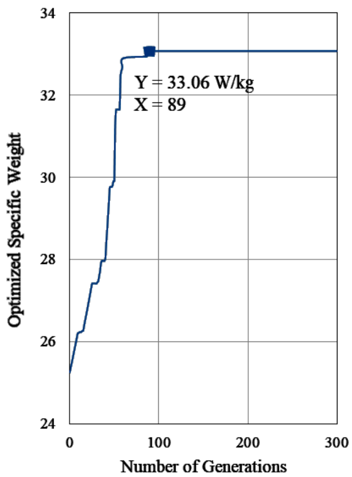


Fig. 6 Optimized weight vs. number of generations.

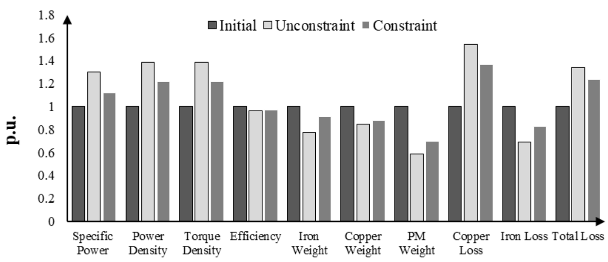


Fig. 7 Relative performance of CAD and GA based optimized design.

Improved motor design is carried out considering the abovementioned optimized design variables. Specific electric loading is increased and specific magnetic loading is reduced compared to initial CAD-based design hence the number of conductors per slot is increased and the weight of core is reduced along with. The number of slots has remained the same, only slot size is increased to accommodate more number of conductors per slot. Permanent magnet requirement is also reduced due to reduced specific magnetic loading. The copper requirement is increased but the permanent magnet requirement is reduced along with. Reduction of permanent magnet requirement results in to cost reduction of the motor. Motor inductance increases due to the increase in the number of conductors per slot. Table 6 shows that the specific power of the motor is improved with the GA based optimized design compared to CAD-based design.

6 Finite Element Analysis

Motor design and its optimization is analytical work hence its validation is necessary to establish the correctness of it. Application of the finite element technique requires less time for modeling and analysis, and provides precise results [11]. Finite element modeling and analysis is well established and universally accepted tool for performance analysis of electric machines [12]. Finite element (FE) motor model is prepared based on design information obtained from initial CAD and GA based optimized design. Axial flux motor geometry necessitates three dimensional (3-D) finite element modeling and analysis. Three-dimensional finite element analysis (FEA) is carried out to validate CAD and GA based constraint design. Magnetic field calculations are carried out at no-load condition to obtain flux density profile of motor. Flux density profile and torque profile of CAD-based initially designed motor are shown in Figs. 8 and 9, respectively.

Table 6 Comparison of CAD and GA based design.

Parameters	CAD-based design	GA based optimized design	
		Unconstraint	Constraint
Specific power [W/kg]	25.25	33.06	28.40
Efficiency [%]	88.16	84.75	85.75
Outer diameter [mm]	182	177	184.8
Inner diameter [mm]	104	95.2	97
Number of cond/slot	26	34	30
Axial length [mm]	90	68.4	71.5

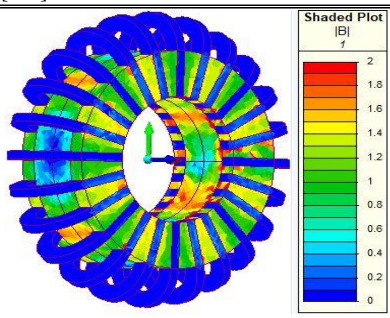


Fig. 8 3-D flux density distribution of the CAD-based AFPMBLDC motor.

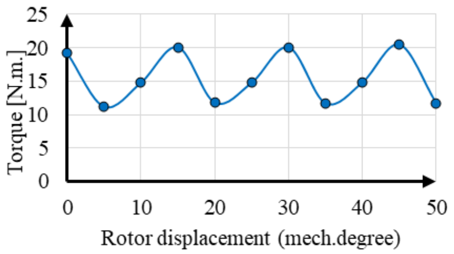


Fig. 9 Torque profile for CAD-based motor design.

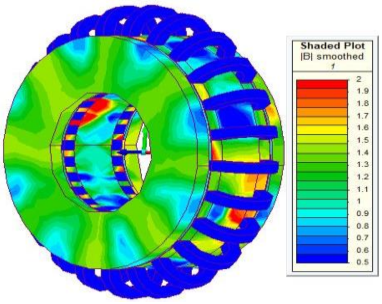


Fig. 10 3-D flux density distribution of the GA-based optimized AFPMBLDC motor.

Flux density profile and torque profile of GA based optimized axial flux permanent magnet brushless DC motor are shown in Figs. 10 and 11, respectively.

Electromagnetic torque developed at different rotor positions is determined and based on that torque profile of the motor is obtained. It is analyzed that the flux densities established in stator back iron, stator teeth, rotor core, and air gap are very near to the assumed flux densities in the respective section. The average torque obtained from FEA is very close to CAD-based designed motor torque and GA based optimized motor torque. Torque developed from FEA is slightly less by 2.45% and 2.89% with reference to CAD and GA based optimizations, respectively. This marginal difference is attributed due to pragmatic formulas and nonlinear characteristic of core materials. Comparative analysis between results obtained from CAD and GA based optimization are shown in Table 7.

7 Conclusion

Design optimization of axial flux sandwiched stator double rotor surface mounted PMBLDC motor is presented in this paper. Dual rotor sandwiched stator topology of axial flux motor is the best suited for electric vehicle application. Design optimization is carried out with an objective of the optimum specific power of the electric motor. Optimized specific power results into compactness and enhanced drive range. Unconstraint, as well as constraint design optimization of axial flux PMBLDC motor using GA technique, is proposed. Specific power of 250 W, 150 rpm axial flux PMBLDC motor is effectively improved with this proposed optimization technique. Specific power is increased from 22.25 W/kg. to 33.06 W/kg. using unconstraint design optimization and to 28.40 W/kg

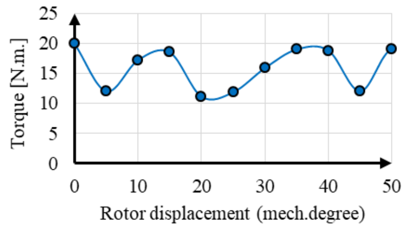


Fig. 11 Torque profile for GA based optimized (constraint) motor design.

Table 7 Validation of Designed Axial Flux PMBLDC Motor.

Motor parameters	CAD-based design		GA based constraint design optimization	
	CAD	FE	GA	FE
Average Torque [N.m.]	15.91	15.52	15.91	15.45
Air gap flux density [T]	0.75	0.76	0.55	0.67
Stator core flux density [T]	1.5	1.66	1.5	1.45
Stator teeth flux density [T]	1.7	1.75	1.7	1.66
Rotor core flux density [T]	1.5	1.60	1.5	1.46
Phase inductance [mH]	17.4	17.9	22.2	23.1

using constraint design optimization. At the end, three-dimensional finite element analysis (FEA) is performed to validate design optimization. It is analyzed that there is close agreement between results from FEA and GA based constraint as well as unconstraint design optimization. Accuracy of GA based design optimization is established based on the results of FEA.

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