# Weight Optimization of Axial Flux Dual Air-Gap Permanent Magnet Brushless DC Motor for Electrical Vehicle

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*Abstract:* This paper presents weight optimization of axial flux dual air-gap permanent magnet brushless dc motor based on genetic algorithm optimization technique for an electric vehicle application. First, the initial motor design is carried out as per calculated motor rating based on vehicle dynamics and application requirements. Design of a permanent magnet motor is a complex and nonlinear process involving various design variables. Genetic algorithm based optimization technique is proposed for weight minimization of axial flux permanent magnet brushless dc motor. Optimization with an objective of minimum motor weight is performed. Three-dimensional finite element analysis is executed to authenticate the proposed genetic algorithm based weight optimization. The optimization technique is elucidated with necessary flowchart. Close agreement between results obtained from finite element analysis and analytical design establishes the correctness of the proposed optimization technique. It is analysed that the weight of dual air gap axial flux PMBLDC motor is reduced considerably using GA based design optimization.

*Keywords*: Axial Flux PMBLDC motor, Computer Aided Design, FE Analysis, Optimization, Genetic Algorithm

## 1. Introduction

Depletion of conventional energy sources and increased carbon emission have evolved the need for alternate energy system for vehicle transportation. Use of internal combustion(IC) engine consumes fossil fuel and produces nitrogen oxides which are responsible for smog and global warming. Electric mobility concept gained significant attention in recent years. 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]:

- Low weight and high efficiency;
- High torque at low speed and low torque at high speed, fast dynamic response;
- Low voltage rating to reduce battery size and space requirements.

Low weight and high efficiency result in an enhanced drive range of motor [2]. Detailed analysis is carried out for a selection of motor. DC brushed motors suffer from problems related to commutators and brushes. Induction 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 rotor core. Permanent magnet motors are further classified as radial

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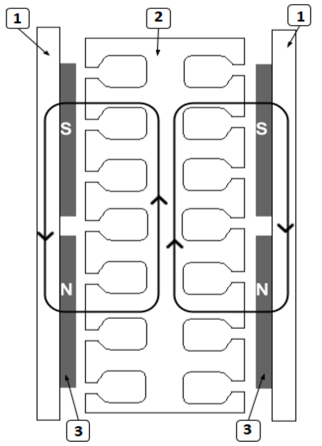
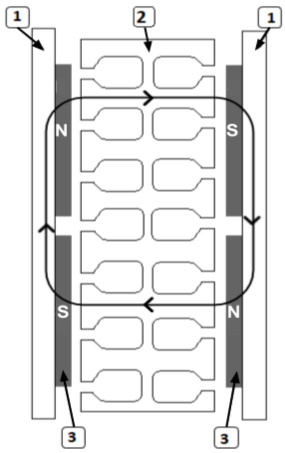
flux motor and axial flux motor according to the direction of flux in the magnetic circuit of the motor. Flux establishes in the radial direction and current flow in an axial direction in radial flux motor while flux establishes in an axial direction and current flows in a radial direction in axial flux 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 affect its torque ability [4]. Axial flux motors are preferred for low aspect ratio. The physical construction of axial flux surface mounted PM motor revels 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)

Figure 1. (a) NN topology of axial flux motor (b) NS topology of axial flux motor

[R-I] 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 Figure.1 (a) while NS topology has two opposite magnets of opposite polarity as shown in Figure.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 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 minimum weight and expected efficiency is crucial in an automotive application. The entire exercise of design optimization is to minimize motor weight resulting in an enhanced range of drive. Weight optimization 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 weight optimization. Following sections of paper explain this work carried out and analyze the results obtained.

## 2. Motor Rating Calculation Based on Vehicle Dynamics [R-II]

Rating of electric motor for electric vehicle application depends on application requirements and dynamics like rolling resistance, gradient resistance, aerodynamic drag, etc.
The force required for driving a vehicle is calculated below.

$$F_{total}=F_r+F_g+F_{ad}+F_a \quad (1)$$

where, $F_{total}$ =Total force, $F_r$= force due to rolling resistance, $F_g$= force due to gradient resistance, $F_{ad}$=force due to aerodynamic drag and $F_a$ = accelerating force
$F_{total}$ is the total tractive force that the output of 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. Following equation can be used to calculate force due to rolling resistance.

$$F_r=C_{rr}*m*g \quad (2)$$

where, $C_{rr}$= coefficient of rolling resistance, $m$= mass of vehicle in kg. and $g$= acceleration due to gravity

*Gradient Resistance Force:* Gradient resistance of vehicle is the resistance offered to 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.

$$F_g = m* g *\sin \alpha \quad (3)$$

*Aero-dynamic 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.

$$F_{ad} = 0.5\, C_d*A_f*\rho*v^2 \quad (4)$$

Where $C_d$ aerodynamic drag coefficient, $A_f$ frontal area of vehicle and $\rho$ air density.

Table 1. Vehicle Parameters

| Parameter | Symbol | Value |
|---|---|---|
| Rolling resistance co-efficient | $Crr$ | 0.011 |
| Vehicle weight | $m$ | 150 kg |
| Air density at 25° C | $\rho$ | 1.177 kg/m$^3$ |
| Grade angle | $\alpha$ | 0 degree |
| Frontal area | $A_f$ | 0.9 m$^2$ |
| Aero dynamic drag co-efficient | $C_d$ | 0.7 |
| Gravitational co-efficient | $g$ | 9.81 m/s$^2$ |

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

$$F_a = m * a = m * \frac{dv}{dt} \quad (5)$$

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

## 3. Axial Flux Dual Air Gap PMBLDC Motor Design

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

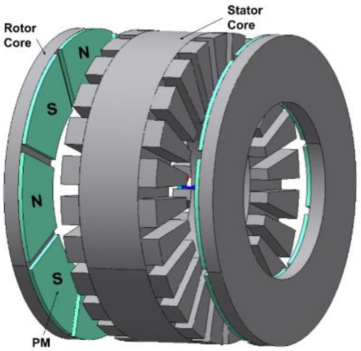



Figure 2. Dual Air-Gap Axial Flux PMBLDC Motor

View of double rotor single stator Axial Flux motor is shown in Figure 2. Permanent magnets are mounted on the surface of rotor core. Flux emanates from PM crosses air-gap and travels via stator back iron and then returns to 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 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]. Polyphase winding wound on slotted stator produces a rotating magnetic field.

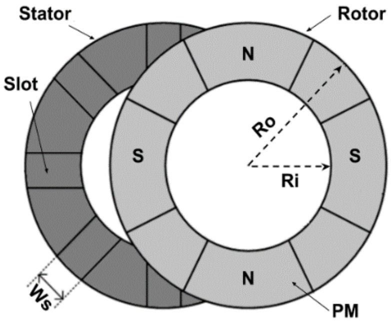



Figure 3. Main Dimensions of Axial Flux PMBLDC Motor R-III

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

$$R_0 = \sqrt{\frac{3*T}{2*\eta*N_c*N_m*N_{spp}*K_w*B_g*I_s}} \quad (6)$$

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

$$R_i = \frac{R_0}{K_r} \quad (7)$$

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 particular motor section can be calculated by product of volume and material density. Following are equations to determine the volume and weight of various motor sections.

$$V_{sc} = 0.9 * (\pi(R_o^2 - R_i^2) * (2(W_{sbi} + d_s) - N_s(d_s * w_{sb})(R_o - R_i)) \quad (8)$$

$$W_{sc} = V_{sc} * \rho_i \quad (9)$$

$$V_{cu} = [A_{ss} * S_f * N_s(R_o - R_i)] \quad (10)$$

$$W_{cu} = V_{cu} * \rho_{cu} \quad (11)$$

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

$$W_{rbi} = V_{rbi} * \rho_i \quad (13)$$

$$V_{pm} = [(2\pi(R_o^2 - R_i^2) * L_m) - ((R_o - R_i) * L_m * \tau_f * N_m * 2)] \quad (14)$$

$$W_{pm} = V_{pm} * \rho_{pm} \quad (15)$$

$$W_{total} = W_{sc} + W_{cu} + W_{rbi} + W_{pm} \quad (16)$$

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 |
| $\eta$ | Efficiency | $S_f$ | Space factor |
| $N_c$ | Coils conducting simultaneously | $V_{sc}$ | Volume of stator core |
| $N_m$ | Number of poles | $\rho_i$ | 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 | $\rho_{cu}$ | 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 | $\rho_i$ | 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 | $\rho_{pm}$ | Density of permanent magnet |
| $l_m$ | Length of magnet | $W_{pm}$ | Weight of permanent magnet |
| $\tau_f$ | Magnet spacer | $W_{total}$ | Total weight |

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 following equation.

$$W_{total} = [k_i[\pi(R_o^2 - R_i^2) * (2\,W_{sbi} + 2\,d_s)] - N_s(\,d_s * w_{sb})\,(R_o - R_i)]\rho_i + \left[[A_{ss} * S_f * N_s(R_o - R_i)] * \rho_{cu}\right] + \left[[(2\pi(R_o^2 - R_i^2) * L_m) - ((R_o - R_i) * L_m * \tau_f * N_m * 2)] * \rho_{pm}\right] + \left[[2 * L_{cr} * \pi(R_o^2 - R_i^2)] * \rho_i\right] \quad (17)$$

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 (CAD) program is shown in Figure. 3.

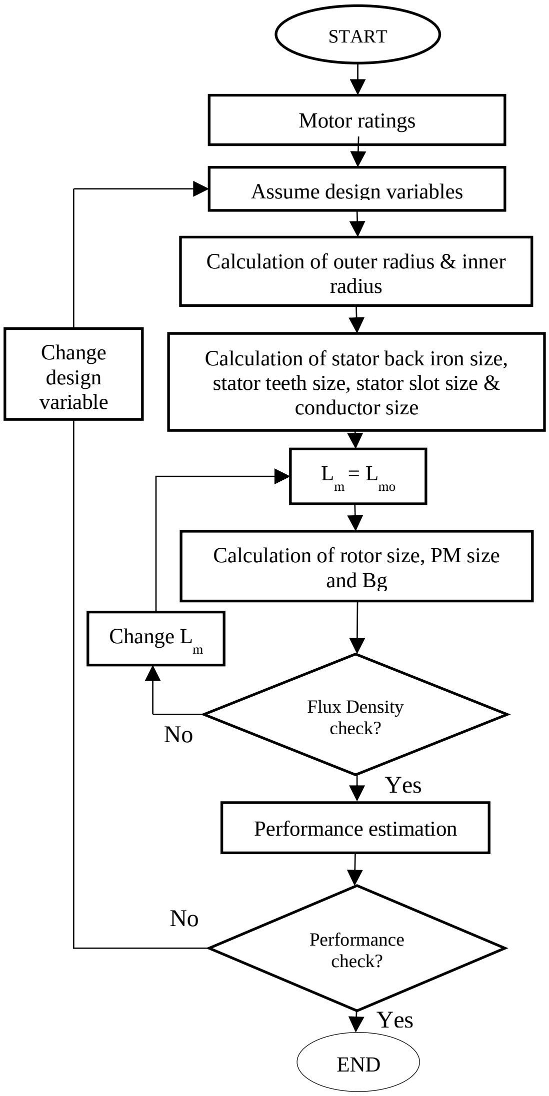



Figure 4. Flow chart of CAD program for Axial Flux PMBLDC Motor

CAD program corrects assumed design variables if predicted performance differs from expected performance of motor. Computer-aided design (CAD) program for Axial Flux surface mounted PMBLDC motor is developed incorporating decision making loops.

Performance improvement of motor is crucial design issue for energy conservation, environment protection and sustainable development. Weight 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 ensure performance parameter [9]. In this paper, investigation is focused on weight reduction of Axial Flux motor with genetic algorithm (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. Flow chart of GA based optimization technique is shown in Figure 4. 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 GA based optimization technique. Definition of an engineering problem and its volume govern size of the population [10].

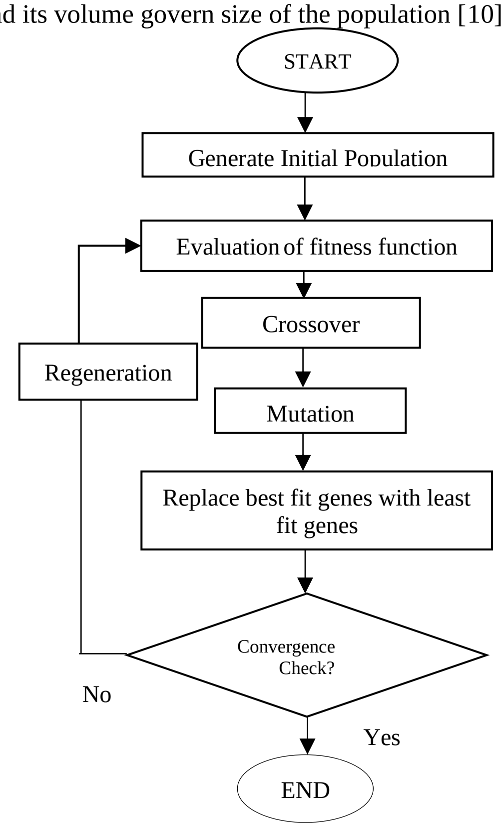



Figure 5. Flow chart of GA based Optimized CAD program

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 efficiency is given fitness of "2" others are given "1" and the chromosome with lowest efficiency is given fitness "0". The selection process aims at retaining the chromosomes with the high efficiency and discards the chromosome with lowest efficiency. This is done by first arranging the chromosomes in the descending order of their weight from lowers to highest; 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.

## 5. Results and Analysis

Primary design variables used as optimization variables are scrupulously identified based on the parametric analysis. A parametric analysis has been performed to access effect of design variables on performance of axial flux motor. Availability of materials and practical design aspects decide range of primary design variables. Constraints applied in present work are of dimensional in nature and related to material characteristics. Table 3 indicates primary design variables with lower to upper band and variables assumed in initial CAD.

Table 3. Range of Design Variables

| Design Variables | Description | Range | |
|---|---|---|---|
| | | Minimum | Maximum |
| *X1* | Air gap flux density ($B_g$) | 0.4 T | 0.9 T |
| *X2* | Slot electrical loading ($I_s$) | 100 A | 400 A |
| *X3* | Stator diametric ratio ($K_r$) | 1.3 | 2.5 |
| *X4* | Max. current density ($I_{max}$) | 4 A/mm$^2$ | 10 A/mm$^2$ |
| *X5* | Packing factor ($k_{cp}$) | 0.4 | 0.7 |

Table 4 illustrates each chromosome's 1x5 array for proposed optimization.

Table 4. Representation of Chromosome

| | | | | |
|---|---|---|---|---|
| $B_g$ | $I_s$ | $K_r$ | $I_{\max}$ | $k_{cp}$ |

Weight of motor is optimized using GA technique. Effect of number of design variables on weight is shown in Table 5. It is observed that as the number of design variables are increased the fitness function (weight) is improved.

Table 5. Effect of Number of Variables on Optimal Weight

| Variables | Weight |
|---|---|
| $B_g$ , $J_{max}$ | 9.853 |
| $B_g$ , $J_{max}$ , $k_{cp}$ | 9.742 |
| $B_g$ , $K_r$ , $J_{max}$ , $k_{cp}$ | 8.519 |
| $B_g$ , $I_s$ , $K_r$ , $J_{max}$ , $k_{cp}$ | 7.56 |

Optimum weight on 7.56 kg. converged after GA based design optimization. Optimized result is obtained within 89 generations. Convergence of objective function with optimization process is shown in Figure 6.

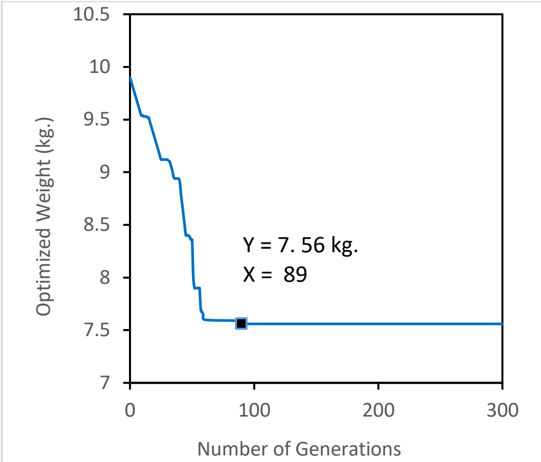



Figure 6. Optimized weight vs. no of generations

Per unit relative performance of the CAD and GA based optimized design are shown in Figure 7. In comparative analysis, CAD based design is taken as reference. It is analysed that GA based unconstraint design with 5 variables results in to minimum weight of 7.56 kg. It is evident that optimized solution is better in comparison to initial design of axial flux motor. Reduced motor weight as an outcome of optimization results into improved torque density. Cost of motor reduces as material requirement reduces due to weight optimization of axial flux motor. Efficiency of motor is slightly compromised due to weight optimization.

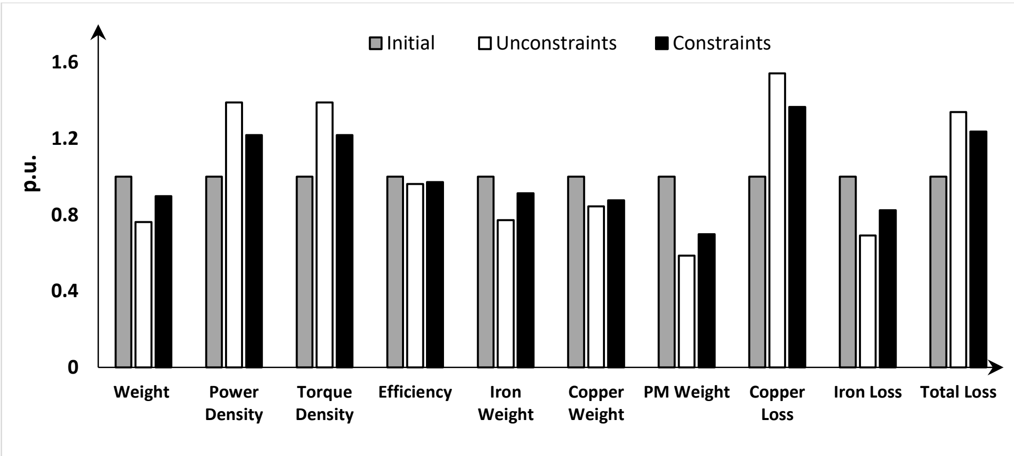



Figure 7. Relative performance of CAD and GA based optimized design R-IV

Initial CAD-based design is done considering specific ampere slot loading 140 A, specific magnetic loading 0.75 T, width of magnet spacer 7 mm, length of air gap 0.5 mm, diametric ratio 1.75. Table 6 shows that weight of motor is reduced in GA based optimized design compared to CAD based design.

Table 6. Comparison of CAD and GA Based Design

| Parameters | CAD based design | GA based optimized design | |
|---|---|---|---|
| | | Unconstraint | Constraint |
| Weight (kg) | 9.90 | 7.56 | 8.8 |
| 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 |

## 5. Finite Element Analysis

Motor design and its optimization is analytical work hence its validation is necessary to establish correctness of it. Application of finite element requires less time for modeling and analysis [11]. FE modeling and analysis provides precise results. Finite element modeling and analysis has become well established and universally accepted for a tool for performance analysis of electric machines [12]. Finite element (FE) model of motor is prepared according to design information obtained from initial CAD based design 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 of CAD based initially designed motor is shown in Figure. 7 and GA based (constraint) optimized motor design is shown in Figure 8.

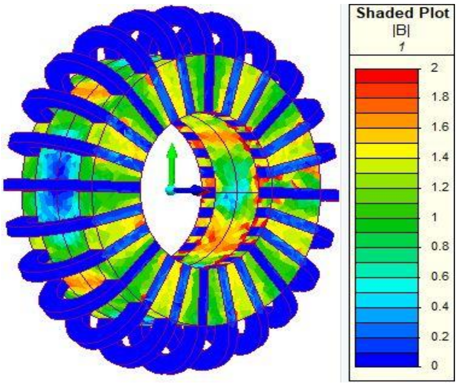



Figure 8. 3-D flux density distribution of the CAD based AFPMBLDC motor

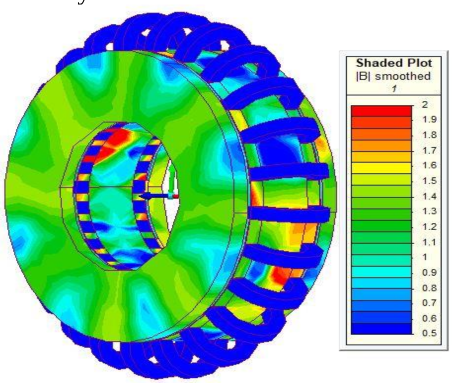



Figure 9. 3-D flux density distribution of the GA based optimized AFPMBLDC motor

It is analysed 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 respective sections. Electromagnetic torque developed at different rotor positions is determined and based on that torque profile of motor is obtained. Torque profile of CAD based initially designed motor and GA based optimized (constraint) motor design are shown in Figure 10 and Figure 11 respectively.

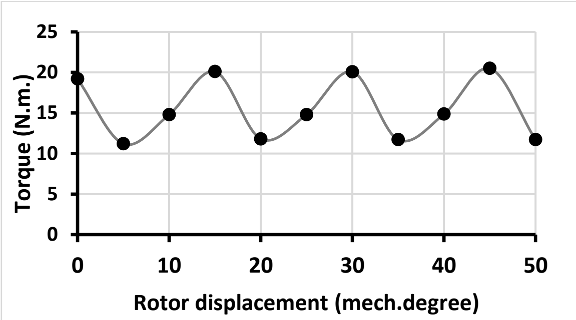



Figure 10. Torque profile for CAD based motor design

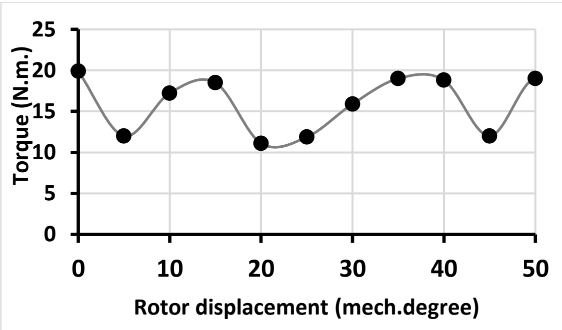



Figure 11. Torque profile for GA based optimized (constraint) motor design

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 optimization respectively. This marginal difference is attributed due to pragmatic formulas and nonlinear characteristic of core materials. Comparative analysis between CAD and GA based results are shown in Table 7.

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 (Nm) | 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 |

## 6. Conclusion

This paper presents design optimization of axial flux sandwiched stator double rotor surface mounted PMBLDC motor. Dual rotor sandwiched stator topology of axial flux motor is the best suited for electric vehicle application. Design optimization is performed with an objective of weight reduction to enhance drive range. Unconstraint as well as constraint design optimization of axial flux PMBLDC motor using GA technique is proposed. With this proposed technique, weight of 250 W, 150 rpm axial flux PMBLDC motor is effectively reduced. Weight of motor is reduced from 9.9 kg. to 7.56 kg. using unconstraint design optimization and to 8.8 kg. using constraint design optimization. At the end, finite element analysis (FEA) is performed to validate design optimization. It is analysed 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.

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