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Design Optimization of Axial Flux Surface Mounted Permanent Magnet Brushless DC Motor For Electrical Vehicle Based on Genetic Algorithm

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ABSTRACT

This paper presents the design optimization of axial flux surface mounted Permanent Magnet Brushless DC motor based on genetic algorithm for an electrical vehicle application. The rating of the motor calculated form vehicle dynamics is 250 W, 150 rpm. The axial flux surface mounted Permanent Magnet Brushless DC (PMBLDC) motor was designed to fit in the rim of the wheel. There are several design variables e.g. air gap flux density, slot loading, magnet spacer width, ratio of outer to inner diameter, air gap length, current density and space factor. The main contribution in the present work is to propose the best combination of design variables obtained using genetic algorithm (GA) optimization technique and design of motor based on optimized design variables. Final validation is carried out with the help of 3-D finite element analysis (FEA) for GA based constraint and unconstraint design. The entire procedure based on GA is explained with the help of block diagram. Efficiency of the axial flux surface mounted PMBLDC motor is enhanced from 88.15 to 91.5 % using GA based design optimization. Proposed optimization technique and methodology will be useful for performance improvement of any nonlinear engineering design involving various design variables for specific application.

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1. INTRODUCTION

In order to reduce dependence on fossil fuel and air pollution produced by automobiles, one better option is to use electric vehicle powered by batteries and using electrical motor as a prime mover. Significant attention is paid to electric mobility by major automoile payers in recent years to provide environmental friendly option for transportaion. Electrical motors used in electric vehicle should possess high operational efficiency and high power density. High power density and high operational efficiency resulted in to less electric vehicle weight and more range of driving. The Permanent Magnet (PM) motors are becoming paramount machines due to many advantages over conventional machines. PM motors are inherently efficient and compact compared to conventional motors due to application of permanent magnet in place of electro-magnet [1]. They are more suitable for specific applications where enough emphasis is given on compactness and high efficiency. There are two types of PM motors; radial flux motors and axial flux motors. The axial flux motors have many advantages over a radial flux motors like high power density, high efficiency, high torque/current ratio and flat shape. Axial flux motors can be classified according to numbers and relative positions of stators and rotors. Physical construction of axial flux surface mounted PMBLDC motor revels that sandwiched stator double rotor type construction is the best suited in direct drive application in electrical vehicle [2]. Optimal design of electric motor is important hence it is point of interest for many researchers. Ilka et al. [3] presented optimization of permanent magnet DC Motor for minimum loss and maximum power density. Niaz-Azari et al. [4] presented optimal design of radial flux brushless motor considering 10 design variables. This

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paper focuses on design optimization of dual rotor single stator axial flux PM motor. The requirements of vehicle are: laden weight of 150 kg, maximum speed is 25 kmph and acceleration requirement is 25 kmph in 9 second. The rating of axial flux PMBLDC motor is calculated for this application using vehicle dynamic equations [5-7]. Motor rating of 250 W, 150 rpm calculated as per application requirements and vehicle dynamics. Sandwiched stator double rotor PM motor of 250 W and 150 rpm is designed assuming proper design variables. Computer Aided Design (CAD) algorithm is finalized. Design optimization is done using Genetic Algorithm (GA) technique. Thus, the main objective in the present work is to propose the best combination of design variables obtained using genetic algorithm (GA) optimization technique and design of motor based on optimized design variables. Finite Element Analysis (FEA) is carried out to validate CAD based design and GA based optimized design. Following sections of paper explain this work carried out and analyzed the obtained results.

2. VEHICLE DYNAMICS

Tractive force required for propelling the vehicle mainly consists three forces [5]:

(i) Frictional force (F_r)

$$F_r = m\,g\,f_r \cos\alpha + m\,g \sin\alpha \tag{1}$$

(ii) Aerodynamic drag (F_w)

$$F_w = \frac{1}{2}\rho_a\, A_f\, C_d\, v^2 \tag{2}$$

(iii) Accelerating force (F_a)

$$F_a = m\,a = m\,\frac{dv}{dt} \tag{3}$$

The above parameters are described in Table 1. Torque required is calculated by following equations.

$$T = F_t \times r \tag{4}$$

where, F_t is tractive force and r is radius of wheel. Calculated rating of motor based on the parameters of Table 1 and vehicle dynamics are represented in Table 2.

3. COMPUTER AIDED DESIGN OF AXIAL FLUX PMBLDC MOTOR

There are four main stages of electrical motor design:

(i) Calculation of main dimensions (ii) Design of stator (iii) Design of rotor (iv) Performance analysis [8]. The block diagram of computer aided design (CAD) program for Axial Flux surface mounted PMBLDC motor is shown in Figure 1.

TABLE 1. Vehicle Parameters

Parameter	Symbol	Value
Friction co-efficient	f_r	0.011
Vehicle weight	m	150 kg
Air density at 25° C	ρ_a	1.177 kg/m^3
Grade angle	α	0 degree
Frontal area	A_f	0.9 m^2
Aero dynamic drag co-eff.	C_d	0.7
Gravitational co-efficient	g	9.81 m/s^2

TABLE 2. Motor rating

Parameter	Value
Rated power	250 W
Rated torque	15.91 N.m.
Maximum power	803.44 W
Maximum torque	58.32 N.m.

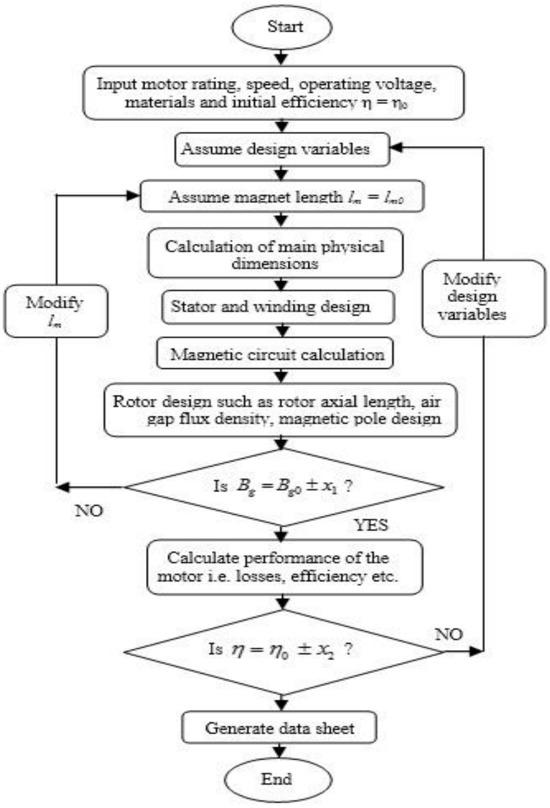

Figure 1. Block diagram for CAD

Input data for CAD includes motor power rating, speed, operating voltage, initially assumed efficiency and material availability. Based on input data design and performance estimation is done [9]. The flowchart contains two loops. If error between obtained air gap flux density and assumed air gap flux density is not within acceptable error band (±x_2 %) then inner loop will change the length of magnet (l_m) and if error between calculated efficiency and assumed efficiency is not within acceptable error band (±x_2 %) then outer loop will modify initially assumed design variables. The volume of the applied materials which depend on the motor geometry have significant impacts on the motor cost [4].

Losses in axial flux surface mounted PMBLDC motor is classified as copper loss, iron loss and friction-windage loss. Copper loss (Pcu) due to winding resistance can be obtained form following equations.

$$P_{cu} = 2 * I_{ph}^2 * R_{ph} \tag{5}$$

$$R_s = \frac{\rho * n_s^2 * \left(R_o - R_i\right)}{K_{cp} * A_s} \tag{6}$$

$$R_e = \frac{\rho * n_s^2 * \pi * \left(w_{bi} + 2d_s\right)}{4 * K_{cp} * A_s} \tag{7}$$

$$R_{ph} = \frac{N_s * \left(R_s + R_e\right)}{N_{ph}} \tag{8}$$

where, R_s slot resistance, R_e end turn resistance, I_{ph} current per phase, R_{ph} phase resistance, ns numer of conductors per slot, R_o outer diameter, R_i inner diameter, k_{cp} packing factor and A_s slot area.

Iron loss (P_i) depends on two major components called hysteresis loss and eddy current loss. Iron loss can be otained form following equation.

$$P_i = K_h B_m^{1.6} f + K_e B_m^2 f^2 \tag{9}$$

where, K_h hysteresis coefficiecnt, B_m maximum flux density in core, f frequency of flux reversal and K_e coefficiecnt of eddy current loss.

$$P_{f\&w} = \frac{1}{2} C_f \rho_r (\pi \, n^3)(D_o^5 - D_i^5) \tag{10}$$

Friction and windage loss ($P_{f\&w}$) depends on many factors like friction coefficienct, air density and speed. It is usually assumed 20% of iron loss in low speed machine. Motor efficiecny is expressed as follows:

$$Efficiency = \frac{P_{out}}{P_{out} + Losses} = \frac{P_{out}}{P_{out} + P_{cu} + P_i + P_{f\&w}} \tag{11}$$

The above equation is selected as an objective function for optimization.

4. DESIGN OPTIMIZATION BASED ON GENETIC ALGORITHM

Genetic Algorithm (GA) is considered the most appropriate optimization technique for electrical motor design because it is nonlinear process involving many design variables having specified upper band and lower band [10]. Usually design variables affect each other and vary simultaneously. The nonlinear nature of the GA makes it the most suitable for motor design optimization. GA starts with number of design variables used for optimal design, the function which is to be optimized (fitness function), number of populations and generations, upper and lower limits of design variables. Figure 2 illustrates block diagram of GA based optimization technique. To optimize motor design there are mainly four operators: (i) Generate population (ii) Selection (iii) Crossover (iv) Mutation. Here motor efficiency is taken as a fitness function.

5. DETAILS OF SIMULATION

Influential design variables are identified based on parametric analysis carried out in CAD of Axial Flux surface mounted PMBLDC motor. Table 3 shows five influential design variables with appropriate range for optimization. Range of design variables is selected based on availability of materials, manufacturability and performance requirement.

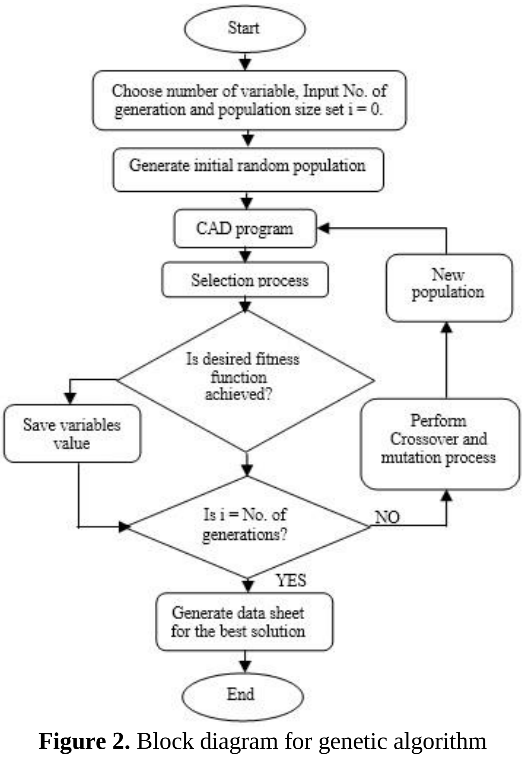

Figure 2. Block diagram for genetic algorithm

TABLE 3. Range of design variables

Variable	**Range**	
	Minimum	***Maximum***
Air gap flux density (B_g)	0.4 T	0.9 T
Slot electrical loading (I_s)	100 A	400 A
Stator diametric ratio (K_r)	1.3	2.5
Max. current density ($I_{\max}$)	4 A/mm^2	10 A/mm^2
Air gap length (l_g)	0.25 mm	1.0 mm

Application of rere earth magnets allow air gap flux density between 0.4 to 0.9 T. Current density between 4-10 mm^2, air gap length between 0.25 to 1.0 mm and slot loading between 100 to 400 A is recommended for permanent magnet motor [9].

Table 4 illustrates each chromosome's 1x5 array for proposed optimization. The population is arbitrarily produced from the given ranges of various design variables. Population is a set of different chromosomes which have different genes and different values for the objective function. Each of the chromosomes are arbitrarily generated and only one of the chromosomes from the whole population is considered.

In selection procedure, whole population is initially sorted according to the fitness value. The selection process retains the chromosome with high efficiency and discards the chromosomes with lowest efficiency.

The process of crossover ensures that sufficient diversity is maintained during the entire process of genesis. The mating pool has that population which is selected based on its fitness. Genes of the two different chromosomes are exchanged arbitrarily and it produces to two completely new and different chromosomes.

The mutation process presents abrupt and random changes in the original chromosomes. The mutation is done by either increasing or decreasing the original genes by percentage indicated by the randomly generated number.

Efficiency is optimized using GA technique and effect of number of design variables on efficiency is shown in Table 5. It is observed that as the number of design variables are increased the fitness function (efficiency) is improved.

Note that in the present study the population size selected was 100 with cross over probability as 75 and 1% mutation rate. The simulations were always carried out for 300 generations, however in few cases it is observed that the optimized result is achived within 53 generations as shown in Figure 3. The execution time for the simulation was found to be 12.34 s for 300 generations.

TABLE 4. Chromosome representation

B_g	I_s	K_r	$I_{\max}$	l_g

TABLE 5. Effect of number of variables on optimal efficiency

Variables	**Efficiency (%)**
B_g, K_r	90.72
$B_g, K_r, J_{\max}$	90.83
$B_g, K_r, J_{\max}, I_s$	91.30
$B_g, K_r, J_{\max}, I_s, l_g$	91.50

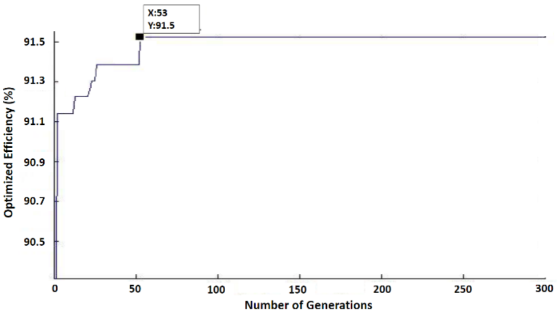

Figure 3. Variation of fitness function with number of generations in unconstraint design

The simulations were carried out on Intel CPU core 3, I3-4150 @ 3.50 GHz with 4 G RAM. Figure 3 illustrates that as number of generations are increased the fitness function (efficiency) is improved. Optimum efficiency of 91.5 % converged after 53 generations. Figure 4 shows per unit relative performance of the motor with CAD based design, GA based unconstraint and constraint design by taking CAD based design as a base. Design constraint represents limitation imposed of machine design. Constraints restrict the range of design variables due to space, manufacturability and economic considerations. Axial length of motor is considered as dimensional constraint in constraint based optimization in this work. Initial efficiency of 88.15% obtained with CAD ased design. It is observed that GA based unconstraint design with 5 variables gives the highest efficiency of 91.5% but with higher penalty of more weight of the motor 12.57 kg and hence more cost.

CAD based design is carried out assuming slot loading 140 A, air gap flux density 0.75 T, magnet spacer width 7 mm, air gap length 0.5 mm, ratio of outer diameter to inner diameter 1.75. Table 6 shows that efficiency is enhanced in GA based optimized design compared to CAD based design.

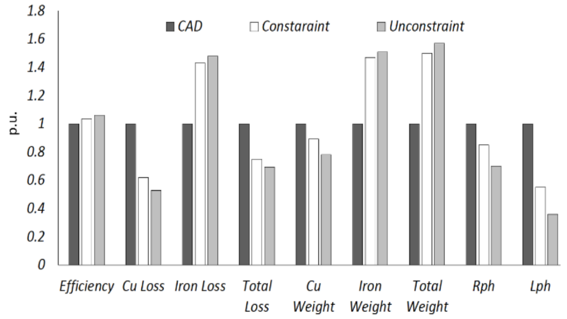

Figure 4. Relative performance of CAD and GA based optimized design

TABLE 6. Comparison of CAD and GA based design

Parameters	CAD based design	GA based optimized design	
		Unconstraint	*Constraint*
Efficiency (%)	88.15	91.50	90.85
Outer diameter (mm)	178	206.8	196.8
Inner diameter (mm)	102.8	114.8	89.8
Number of turns/slot	26	18	20
Axial length (mm)	71.2	80.9	74
Weight (kg)	7.81	12.57	12.01

6. FINITE ELEMENT ANALYSIS (FEA)

Three dimensional finite element analysis (FEA) is carried out to validate CAD and GA based constraint design. Data obtained from CAD and GA based design is used as input for FEA. FEA is used to obtain torque profile and magnetic circuit analysis of motor. Results obtained from the FEA validate CAD and GA based designs and comparative analysis is shown in Table 7. Flux density distribution of CAD based designed motor and GA based constraint designed motor is obtained from FEA and shown in Figures 5 and 7. Flux densities obtained in various sections of magnetic circuit are in line with the assumed flux densities, respectively. Torque profile of CAD based designed motor and GA based optimized (constraint) motor design are shown in Figures 6 and 8, respectively. Average torque obtained from FEA is fairly matching with CAD based designed motor and GA based optimized motor. Torque developed in FEA is marginally less by 2.45 and 3.64 % with reference to CAD and GA based optimization, respectively. This marginal difference is ascribed due to empirical formulas and nonlinear characteristic of magnetic materials.

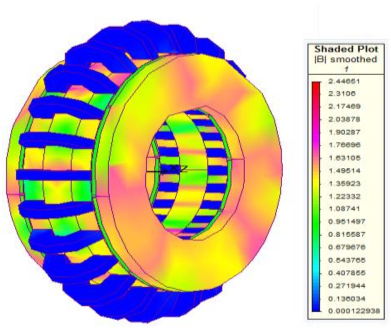

Figure 5. 3-D flux density distribution of the CAD based AFPMBLDC motor

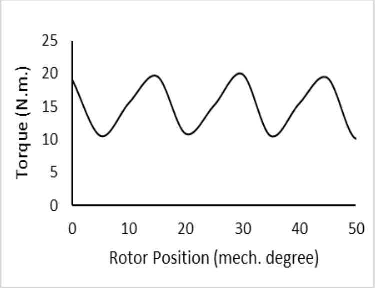

Figure 6. Torque profile for CAD based motor design

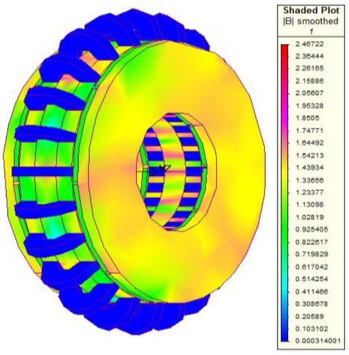

Figure 7. 3-D flux density distribution of the GA based optimized AFPMBLDC motor

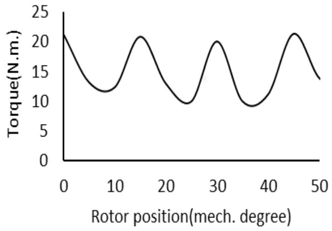

Figure 8. Torque profile for GA based optimized (constraint) motor design

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 (Nm)	15.91	15.52	15.91	15.33
Air gap flux density (T)	0.75	0.76	0.652	0.67
Stator core flux density (T)	1.5	1.66	1.5	1.60
Stator teeth flux density (T)	1.7	1.75	1.7	1.77
Rotor core flux density (T)	1.5	1.60	1.5	1.56
Phase inductance (mH)	17.4	17.9	9.4	9.8

7. CONCLUSION

Axial flux surface mounted PMBLDC motor with sandwiched stator topology offers many advantages in direct drive application. Unconstraint as well as constraint design optimization using GA technique enhances the performance of axial flux PMBLDC motor. Design optimization is carried out for 250 W, 150 rpm motor. Efficiency of same motor is increased from 88.15 to 91.50 % using unconstraint design optimization and to 90.85 % using constraint design optimization. Increment in efficiency and reduction in phase resistance is significant enhancement in performance of motor with the use of GA based optimization technique. Finite element analysis (FEA) is carried out to validate the design. Results obtained from GA based constraint as well as unconstraint design are fairly matching with the results obtained from FEA. Correctness of GA based design optimization is established.

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چکیده

در این مقاله بهینه سازی طراحی سطح شار محوری موتور جریان مستقیم بدون جاروبک مغناطیس دائم بر اساس ژنتیک الگوریتم برای کاربرد یک خودروی الکتریکی ارائه شده است. سرعت موتور محاسبه شده از طریق دینامیک خودرو 250 وات، 150 دور در دقیقه است. سطح شار محوری موتور جریان مستقیم بدون جاروبک مغناطیس دائم (PMBLDC) طراحی شد تا با لبه چرخ مطابقت کند. متغیرهای طراحی مختلفی مانند دانسیته شار شکاف هوایی، بارگذاری شکاف، عرض فاصله مغناطیس، نسبت قطر بیرونی به درونی، طول شکاف هوا، دانسیته جریان و فاکتور فضا وجود دارند. سهم علمی اصلی در کار حاضر پیشنهاد بهترین ترکیب متغیرهای طراحی بدست آمده با استفاده از روش بهینه‌سازی ژنتیک الگوریتم (GA) و طراحی موتور بر اساس متغیرهای طراحی بهینه شده است. اعتبارسنجی نهایی با کمک آنالیز عنصر محدود 3-D (FEA) برای طراحی با محدودیت GA و بدون محدودیت انجام شده است. کل روش بر اساس GA با کمک بلاک دیاگرام توضیح داده شده است. کارایی سطح شار محوری موتور PMBLDC با استفاده از بهینه سازی طراحی بر مبنای GA از 88.15 تا 91.5٪ افزایش یافته است. کارایی سطح شار محوری روش پیشنهادی بهینه سازی و اصول آن برای بهبود عملکرد هر طرح مهندسی غیرخطی شامل متغیرهای مختلف طراحی برای کاربرد خاص مفید خواهد بود.

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