# Computer Aided Design of Axial Flux Permanent Magnet Brushless DC (PMBLDC) Motor for Direct Drive Application

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*Abstract*—**Axial Flux Permanent Magnet Brushless dc (PMBLDC) Motors are being developed for many applications due to their attractive features. The design of Axial Flux Permanent Magnet Brushless dc (PMBLDC) Motor is not straight forward but intensive. A number of inter-related factors have to be taken into account. A comprehensive computer-aided design (CAD) procedure for an axial-flux permanent magnet brushless dc (PMBLDC) motor having a stator sandwiched between two permanent magnet rotors for direct drive application is presented in this paper. The basic output equations are derived and used for the design algorithm. The design of the magnetic section is followed by permissible allowable flux density in rotor and stator. The developed CAD program gives the design data and the calculated performances of the motor.**

**Keywords**—***Brushless DC motor (BLDC), Axial Flux Permanent Magnet Brushless dc (PMBLDC) Motor, Direct Drive, Computer Aided Design (CAD), Permanent Magnet (PM).***

## I. INTRODUCTION

Development of industries has rapidly increased the demand of motors and varied the usages and applications accordingly. Conventional DC motors are not efficient and they need a commutator and brushes which are subject to wear and require maintenance. Recently, Permanent Magnet Brushless DC (BLDC) motors are increasingly used in various domestic, industrial and in traction applications.

BLDC Motor has been the most popular electric motor that is being used in electric vehicle applications. Electric motor that is being used in electric vehicle can be classified as indirect-driven or direct-driven motor. In the class of direct-driven motors, the axial-flux motors have additional advantages in terms of better heat removal configuration, more balanced motor torque and adjustable air gap. These types of motor are directly mounted inside the wheels. They transmit mechanical power directly and do not use gears mechanism for power transmission. Due to that reduction of gears overall efficiency improves and reduces the weight of the vehicle.

There are two types of permanent magnet brushless dc motor namely Radial Flux Motor (RFM) and Axial Flux Motor (AFM). RFM is having simple construction and straight forward design. AFM gives more advantages compared to RFM i.e. adjustable air gap, balanced rotor-stator attractive forces, higher efficiency and planner geometry [2].

Axial Flux Motors (AFM) can be constructed in one of the following ways:

i. Single stator and single rotor (one air-gap),
ii. Single stator sandwiched between two rotors (Double air-gap),
iii. Single rotor sandwiched between two stators(Double air-gap),
iv. A verity of multiple stators and rotors (Multiple air-gap)

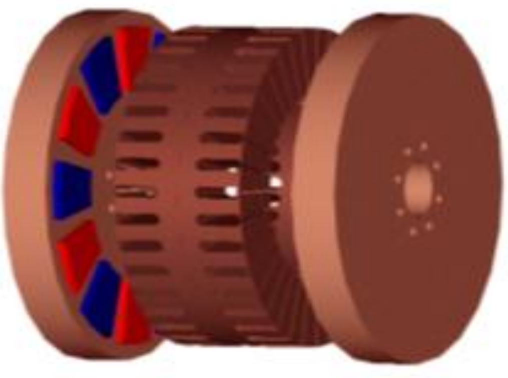

Fig.1 Single Stator Sandwiched Between Two Rotor AF PMBLDC Motor

Single stator sandwiched between two rotors topology of the AF PMBLDC Motor is given in Fig.1. In this paper complete design procedure is discussed. It is the best topology because it provides higher torque and higher power density [3].

## II. CONCEPTUAL DESIGN

The main purpose of designing an axial flux motor is to obtain the complete physical dimensions of all the parts of the motor. Axial motors can be designed in a thin axial dimension. Following are the important stages of design of Axial Flux Permanent Magnet Brushless dc motor [1].

A. Main Dimensions
B. Stator Design
C. Rotor Design
D. Performance Estimation

A. *Main Dimensions*

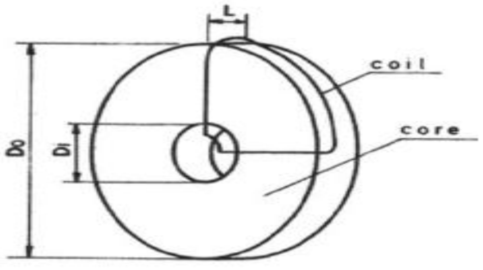


Fig.1 Main dimensions

The Output equations for the axial-flux PMBLDC motor are derived based on the expression for the torque and back emf [1], as follows:

$$P_o = T \times w_m = \eta N_c E_{ph} I_{ph}$$

$$T = \frac{P_o}{\omega_m} = \frac{\eta N_c E_{ph} I_{ph}}{\omega_m} \quad (1)$$

$$\mathrm{T} = \frac{\eta N_c \left[ \omega_m N_m N_{spp} K_w B_g n_s \left( R_o^2 - R_i^2 \right) \right] I_{ph}}{\omega_m} \quad (2)$$

Where, $P_o$ is the rated power output,
$\omega_m$ is the rated speed,
$\eta$ is the assumed efficiency of the motor,
T is motor developed torque,
$N_m$ is the number of poles,
$N_{spp}$ is the number of slots/pole/phase,
$N_c$ is the number of coils conducting simultaneously, $K_w$ is the winding factor,
$B_g$ is specific magnetic loading,
$n_s$ is number of conductors per slot,
$R_i$ is inner radius of the stator,
$R_o$ is outer radius of the stator,
$I_{ph}$ is phase current,
$I_s$ is specific slot loading.

Outer diameter can be found out using (2). Value of the ratio of outer diameter to inner diameter ($D_o/D_i$) is taken as √3 for the optimum design [2]. So, the outer radius depends on the efficiency, torque developed by the motor, specific slot loading and specific magnetic loading.

B. *Stator Design*

For the permanent magnet motor flux is produced by the magnet. Length of the magnet highly affects flux density at air gap. Air gap flux density ($B_g$) should be as high as possible, is needed for the desired torque production. Also higher length of magnet cause to increase overall cost of the motor and lower length of magnet cause to decreases mechanical strength of the magnet. $D_o$ change linearly as $B_g$ varies between 0.45 to 0.85.

Stator back iron width $w_{bi} = \dfrac{B_g \tau_{po}}{2 B_{max} k_{st}}$ (3)

Tooth bottom width $w_{tbi} = \dfrac{B_g \tau_{pi}}{N_{sm} B_{max} k_{st}}$ (4)

Where, $k_{st}$ = staking factor = 0.5 to 0.95
$B_{max}$ = maximum flux density
$B_g$ = air gap flux density

Area of slot $A_s = \dfrac{I_s}{J_{max} k_{cp}}$ (5)

Where, packing factor ($k_{cp}$) is less than 50 percent
$I_s$ = specific slot loading

Each slot has loading within some limit it should be less than 200 A/m for optimum design. [1]. If slot loading is very much lower than main dimensions are drastically changed. Copper lose increase due to higher value of specific slot electric loading ($I_s$) but total cost reduces on account of reduction in PM requirement.

Stator axial length $L = 2d_s + 2w_{bi}$ (6)

Where, $d_s$ = depth of slot

The important requirements for the stator material are high permeability, low hysteresis, and high resistivity. A various grades of silicon steel with the silicon content of 0.5% to approximately 4.5% are available. But M-19 is the most suited material for the stator core.

C. *Rotor Design*

Out of various types of Permanent Magnet (PM) materials, Neodymium-Iron-Boron (NdFeB) is having highest energy product and also the highest residual flux density. The high remanence and coercivity of NdFeB material enables it appreciable reduction in motor. The PM length can be calculated as

Length of magnet $L_m = \dfrac{l_g B_g}{0.2\left[ \left( 0.9 \times B_{cr} \right) - B_g \right]}$ (7)

Where, $B_{cr}$ = flux density in rotor core = 1.6 to 1.8 T [4].
$l_g$ = length of air gap

Value of the air gap is taken between the range of 0.3 mm to 1.0 mm. Smaller air gap length will result in increase the phase inductance and armature reaction effect. For the PM motor recommended value of the current density ($J_{max}$) is between 4 to 10 A/mm$^2$ [2]. Smaller current density can be used for the high efficiency but with higher cost and size. Ferrite and ceramic material used for low cost motor and cost of the motor is higher when the NdFeB magnetic material is used. As the number of poles ($N_m$) increase, magnet fraction decreases, which reduce the thickness of the magnet, thereby reducing the size of the motor.

D. *Performance Estimation*

It is very essential to estimate the performance of the motor design based on design information. The different losses are estimated and subsequently the efficiency of the motor is estimated. Per phase inductance is also estimated. It is essential to revise the variables and the assumption for the more accurate and precise output of the motor [6].

## III. Computer Aided Design of Axial Flux Permanent Magnet Brushless DC Motor

The flowchart of the developed CAD program for the Axial Flux Permanent Magnet Brushless DC (AF PMBLDC) motor is given in Fig.2. Initially motor specifications, type of configuration, material for stator and rotor and other assumed data are the input. Main dimension of rotor and stator back iron, slot dimension, and magnet area as well as length of magnet are calculated based on the assumed efficiency. Also calculate flux density at air gap. There is one check point for the checking of air gap flux density. If air gap flux density is same as assumed ones that is 0.75T than program goes further. If not than it change the length of magnet and calculate all dimensions again. The purpose of loop for the length of magnet is for using optimum dimensions of magnet. Because the cost of magnet is highly affect the initial cost of motor. So magnet dimensions should be as less as much for the desired air gap flux density. If the efficiency is equal to same as assumed efficiency than the program ends otherwise it changes the assumed efficiency and calculates the dimensions again.

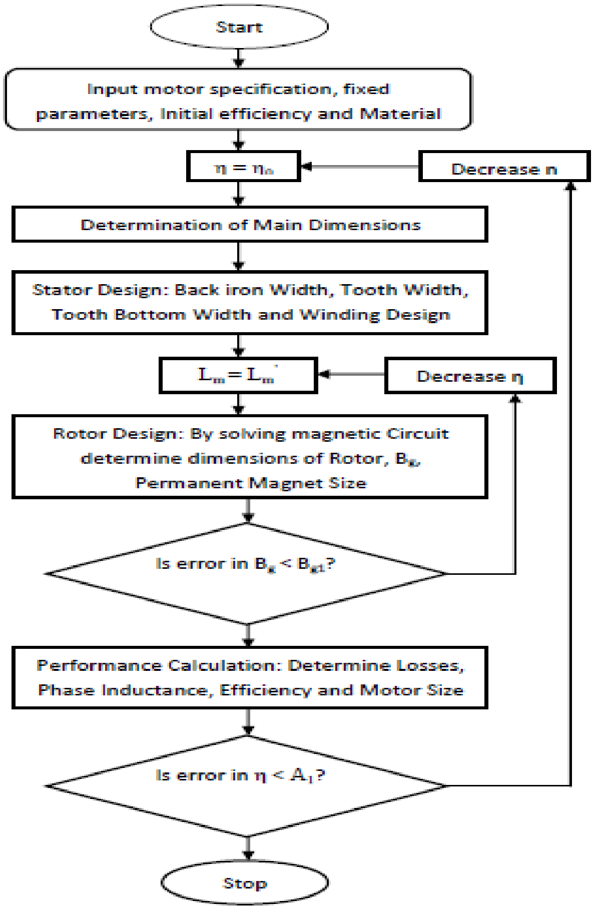


Fig.2 flowchart for CAD of AF PMBLDC motor

## IV. Result of Computer Aided Design

Three motors with the following ratings are design using the developed CAD program: 70 W, 48 V, 150 rpm; 1 kW, 230 V, 1400 rpm; 10 kW, 230 V, 1400 rpm. Important parameters of the motors are in given Table I.

It is observed that: 1) The efficiency increases with the rating: 2) The phase-inductance is more when the voltage is more; and 3) For the same voltage, the phase-inductance decreases with increase in the power rating [2].

TABLE I
DESIGN OUTPUTS OF THE AF PMBLDC MOTORS OBTAINED USING THE DEVELOPED CAD PROGRAM

| **Parameter** | **250 W** | **1 kW** | **10 kW** |
|---|---|---|---|
| Full load efficiency (%) | 92.84 | 97.11 | 97.74 |
| Stator outer diameter (mm) | 177 | 164 | 519 |
| Stator inner diameter (mm) | 102 | 94.8 | 300 |
| Length of stator (mm) | 19.6 | 31.5 | 86.3 |
| Length of rotor (mm) | 10.6 | 11.9 | 12.7 |
| Length of magnet (mm) | 2.7 | 2.7 | 2.7 |
| Magnet fraction | 0.52 | 0.74 | 0.91 |
| Inductance per phase (mH) | 14.1 | 32.8 | 28 |

## V. Conclusions

The designs of the Axial Flux Permanent Magnet Brushless dc (PMBLDC) Motor have been presented in this paper. The design of this motor has achieved the required motor specification and this design is suitable to the direct drive application. In order to optimize the machine, the power density, the diameter ratio and the air gap flux density have been chosen carefully. A comprehensive CAD procedure involves the derivation of the output equation and two self-corrective loops. Outer loop is for the Efficiency and the inner loop is for the air gap flux density for the stator sandwiched between two rotor type axial-flux PM BLDC motor is discussed. CAD programming output shows that the efficiency increase as rating increase. Three designs, one each in fractional, low, and medium hp categories, arrived at using the developed CAD program are giving the targeted torque within an acceptable tolerance band, but with high efficiencies.

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