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DESIGN OF AXIAL FLUX BRUSHLESS DC MOTOR BASED ON 3D FINITE ELEMENT METHOD FOR UNMANNED ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

The research in order to find an optimal, efficient, and reliable design of brushless dc motor increase significantly. The compact design with high power to weight ratio will support the application of motor drive in electric vehicle. This paper presents the design and analysis of axial flux Brushless DC motor. To analyze the electrical parameters of brushless dc motor such as torque, efficiency, looses, and electric field strength which is modeled and simulated through the Finite Element Analysis Method (FEM). The proposed design is proved with the simulation software with the product of axial flux brushless dc motor with the size of 220 cm using 12 stator slots and 10 rotor poles, generates output power about 27 kW, with a speed of 2388 RPM and torque 109 Nm. This motor has a DC voltage rating of 400 V and the input current to the motor of 101 A.

Keywords: *Axial Flux BLDC Motor, Finite Element Method*

1. INTRODUCTION

Utilization of electric vehicles required for human life in the future has encouraged researcher and engineers to develop technology to improve efficiency and capability of the electric vehicle. The main technology system in vehicle are consist of batteries, electric motor, connection gears motor and supporting power electronics components. It is became a very important thing for researcher to increase the efficiency from the entire components of supporting electric vehicle. The selection of the optimal design motor is attend to be the improvement in overall efficiency of electric vehicles [1].

The research to develop of motor drive design in electric vehicle has been done to search and maximize the parameters that can improve the efficiency of electric vehicle. One of the design in motor drive that is widely used in electric vehicle research is permanent magnet brushless dc motor. In the research by Chang [2] conclude in his survey that permanent magnet brushless dc motor is better to use as electric vehicle drive because of its low cost, light weight, high efficiency, high speed and large torque. However, Chang et all do not perform 3D analysis of BLDC motor.

In this research, also presents the analysis of electrical parameters of the motor by using the finite element method based software that analyzes based on these methods. Hopefully, through the design and analysis of axial flux BLDC rotor is able to provide an overview on the motor parameters as reference in the development of electric vehicles.

Brushless dc motors consist of two type motors, axial flux (AF) and radial flux (RF). The Motor drive class for electric vehicle the usage of axial flux a quite compete with radial flux with some advantages in terms of the load withdrawal strength, heat dissipation, water gap, as well as the use of the rotor back iron [3]. Zhang et al [4] in his research conclude that axial flux able to be superior in terms of power density, efficiency and torque. However, Zhang et all also do not perform BLDC motor with 3D analysis.

This paper proposes the effectiveness of 3D finite element method to design of axial flux BLDC motor with output power rating 25 kW. The design motor is used the concept of axial flux BLDC single sided, which is used one stator and one rotor. Motor design also includes the design of the stator and rotor, stator slot number ratio and the number of poles of the rotor, design of stator winding and air gap.

2. DESIGN OF AF BLDC MOTOR

2.1. Determine parameters with DC Excitation system

Excitation system by using square-wave voltage source is the basic method in order to calculate the parameters in the BLDC system. Where, in each interval there are two phase commutations which are directly excited by the voltage. Therefore, the value of rated power and torque can be determined by the following equations:

$$P=T\omega_m=2\,E_{ph}\,I_{ph} \quad (1)$$

$$T=\frac{P}{\omega_m}=\frac{2\,E_{ph}\,I_{ph}}{\omega_m} \quad (2)$$

To find the value of a back emf voltage can be done through the flux linkage equations, the equations obtained from the torque equation as follows:

$$T=\frac{2\sqrt{2}}{\sqrt{3}}\,\pi\,B_g\,q_i\,R_o^3K_r(1\text{-}K_r^2) \quad (3)$$

T = Torque AF BLDC motor output (Nm)
B_g = flux density in the air gap (Tesla)
q_i = Loading Value (Aturn / m)
R_o = The radius of the outer circle (mm)
K_r = comparison fingers are inside and outside

2.2. Design of Axial Flux BLDC Motor

The first step in order to determine the motor parameters is by estimating the rated power, voltage, number of phase, power factor (PF) and efficiency of the motor. The following parameters of the motor to be made:

- Power = 25,000 W
- Operational Voltage = 400 V
- The number of phase = 3
- Power factor (estimation) = 0.966
- Efficiency (estimate) = 0.8

2.2.1 Current flow

The estimated value of PF (cos θ) is is 0.966 based on the chart combination of numbers slot and pole with balanced concentration winding then the value of the efficiency η also be estimated with a value of 0.8. So the required current in Y connection is:

$$I=\frac{25.000}{3\times 161.31\ \times 0{,}8\ \times 0.966}=66.84\ A \quad (4)$$

For current 66.84 A using 4 pole stator winding design and are arranged in parallel so each winding will has a current about:

$$66.848\ A\ /4=16.712\ A \quad (5)$$

So it can be used wire standard American Wire Gauge laminated (AWG) that is laminated copper wire with a diameter d_i of 1.62 mm

2.2.2 Motor Loading Capacity

Calculation of loading capacity in AF BLDC motor can be determined by the following equations

$$q_i=\frac{3\,N_{ph}\ I_{rms}}{\pi\,d_i} \quad (6)$$

From the equation 6 by setting the number of windings of N_{ph} = 34, the value of the loading capacity can be calculated, as follow:

$$q_i=\frac{3\,(34)\,(16{,}712)}{\pi\,(1.62\times 10^{-3})}=334.96\ \text{kAturn/m} \quad (7)$$

2.2.3 Calculation of Motor Radius

The first step to obtain radius of motor is by determining the effective surface area of the motor that generates the torque. Effective surface area is a surface between diameter D_{se} and D_e. Based on a research by Campbell (1974) mentioned that the optimal torque for axial flux induction motor the value of ratio between D_e with D_{se} is between 0.45 to 0.65. Then, this ratio is called K_d. With the value of D_s can be obtained from:

$$K_d={}^{D_s}/_{D_{se}}=0.475 \quad (8)$$

$$D_s=0.475\times 220=104.5\ mm \quad (9)$$

Then,

- R_{in} (radius inner) $= 0.5\cdot 104.5 = 52.5$ mm
- R_{out} (radius outer) $= 0.5\cdot 220 = 104.5$ mm
- length of core (l_e) $= 110 - 52.5 = 57.75$ mm
- $R_{ave}=\sqrt{R_{out}R_{in}}=\sqrt{52.5\cdot 110}=75.81$ mm

2.2.4 Torque and Speed

From practice, maximum torque of 25 kW BLDC motor is 100 Nm. Therefore, it can be used to determine maximum speed of motor as follows:

$$\omega=\frac{Pout}{T} \quad (10)$$

$$\omega=\frac{25000}{100}=250\ rad/s=2387.4\ RPM \quad (11)$$

2.2.5 Air Gap

The proper air gap in the AF BLDC can be estimated by calculating the thickness of *stator shoe* as follows:

$$l_c=\frac{q_i}{3J\,K_{cu}} \quad (12)$$

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The selected current density is 7A / mm^2 and only on the period of acceleration of this current density. Selected conductor fill factor is 0.6 (linear distribution in conductor). From these data, the thickness of the housing of winding can be determined by:

$$lc=\frac{334.96}{3.7\times 0,8}=19.93\ mm \quad (13)$$

Electrical load also has an important role in determining the air gap. Larger air gap requires thicker magnetic element and consequently increases motor weight. Therefore, from the magnetic field strength generated between the air gap, then selected air gap distance is 1.2 mm.

2.2.6 Determine of Magnetic Field in Air Gap

From the above parameters then, it can be used to find the value of the flux density that occurs in the air gap as follows:

$$T=\frac{2\sqrt{2}}{\sqrt{3}}\pi B_g 334.96\times 10^3 (0.165)^3 0.65\left(1-0.65^2\right) \quad (14)$$

$$B_g=\frac{173.205}{5011.12}=3.4\ x\ 10^{-2}T \quad (15)$$

3. SIMULATION AND ANALYSIS

3.1. Analysis of Axial Flux BLDC Motor

In this section will perform the design of the BLDC motor stator axial flux using 3D design software. Figure 1 shows the overall design of BLDC model. Table 1 shows the specification of stator. Meanwhile, Table 2 shows details construction of slots in the stator side.

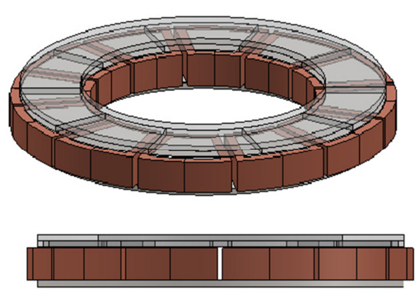


Figure 1. Design of AF BLDC assembly using 3D software

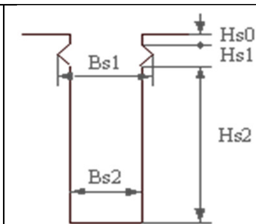
Table 1. Specification of Stator

Motor Type	*Single Sided*
Stator Type	*Slotted stator*
Stator Position	Upward
Number of Stator Slot	12
Outer Diameter of Stator (mm)	220
Inner Diameter Stator of (mm)	104.5
Core Stator Length	30
Material Stator Type	D23_50

The use of AF BLDC motors with single sided motor in terms of its simple construction and capable of generating good power to weight ratio with relatively low manufacturing costs. In order to simplify the motor circuit, the slotted stator has been selected.

This comparative figures will be recommended for the implementation of commercial motorcycles. The number of 12 slots and 10 poles is capable of producing a low cogging value and low cost. The value of the back-EMF is also relatively low.

Table 2. Specification Stator Slots

DATA SLOT STATOR	
Stator Slot Design	
Hs0 (mm):	1
Hs1 (mm):	0
Hs2 (mm):	19
Bs1 (mm):	15
Bs2 (mm):	15
Stacking Factor	0.95

Design specifications of stator slot adapted to the needs of the number of motor windings. The more precise comparison of the extent required by entanglement with the extent of slots used, mechanical losses will be reduced. It also maximizes the stator core area related to the magnitude of the field area that will be created.

Design of stator windings are selected using three phases, and connected in wye (Y). For the AF BLDC motor, this will affect the value of currents required by the motor and the back - EMF waveform. The winding type is *whole-coiled* with 34 number of windings, designed to the needs of the motor current. Type of conductor used in the design of axial flux motors BLDC are rectangular wire. The selected conductor has a width of 4.36 mm and a thickness of 1.02 mm where the magnitude adapted to currents needs. Table 3 shows the specification of the windings.

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Table 3. Specification of Stator Winding

DATA STATOR WINDINGS	
Number of phase	3
Winding connection	Y
Number of Parallel Branch	1
Number of winding layers	2
Winding type	Whole-Coiled
Coil Pitch	1
Winding Factor	0.93
Number of Coil	34
Number of Wire per Conductor	1
Wire Width (mm)	4.36
Wire Thickness (mm)	1.02
Coil Width (mm)	14.58
Coil High (mm)	9.12
Conductor Material	Copper

Table 4 Specification of Rotor

DATA ROTOR	
Rotor Type	AXIAL PM
Rotor Position	Bottom
Number of poles	10
Outer Rotor Diameter (mm):	220
Inner Rotor Diameter (mm):	104.5
Core Rotor length (mm):	10
Core Rotor Stacking Factor	0.95
Steel Type of Rotor:	D23_50
Magnet Length	57.75
Magnet Thickness	8

The rotor specification of axial flux BLDC motor with 10 poles, the outer and inner diameter are considered to the diameter of the stator. Basically, the magnetic field is less sensitive to changes in the thickness of magnet and is most sensitive to the type of material itself. Nowadays, the largest magnetic force that can be used for the application of an electric motor is Neodymium magnet. Its value can reach 1.4 Tesla. Table 4 shows specification of rotor.

3.2. Input Motor Characteristics

Characteristics of the motor input consists of the magnitude of the input current, voltage and cos α. The simulations performed for t=0 up to 6.6 ms. The simulation results show the current value of the I_{RMS} = 82.47 A, with steady state at time t = 2 ms. Voltage in RMS is obtained at 162.31 V, steady state at t = 2 ms. Figure 2 shows the waveform of input current and Figure 3 shows the input voltage.

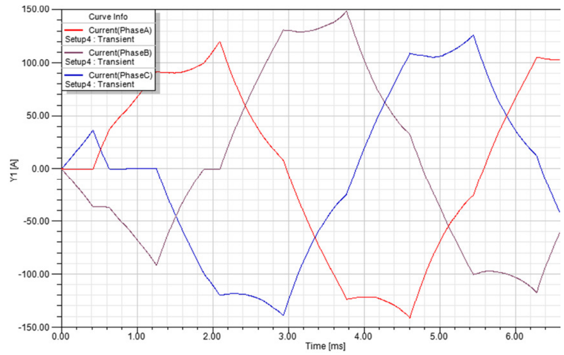

Figure 2. Current Waveform for t = 6.6 ms

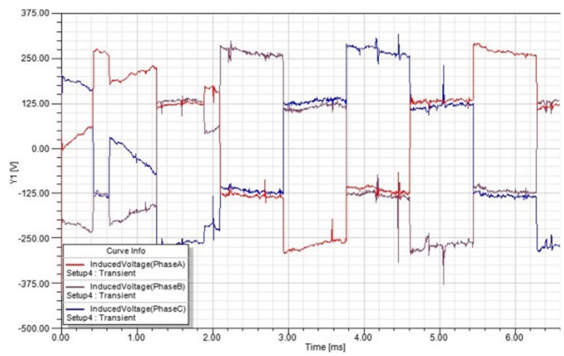

Figure 3. The Voltage Waveform for t = 6,6 ms

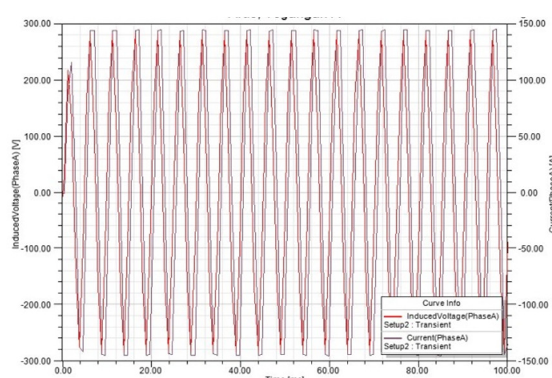

Figure 4. One-phase Voltage and Current Waveforms for BLDC Motor

By comparing the initial design calculations with a rated P_{out} = 25 kW, the simulation result is I_{RMS} = 82.47 A, while the the current in RMS is = 66.84 A. This difference is because of the output power from simulation is P_{out} = 27.307 kW. The efficiency and cos α also have changed. *Cos α* is the phase angle difference between input voltage and current waves. According to Eq. 16, *cos α* = 0.78 From Figure 4 it can be explained that due to inductive characteristic of BLDC, the current is not in a phase with the input voltage.

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$$\alpha = \frac{t_{(I=0)} - t_{(V=0)}}{T} \times 360° \quad (16)$$

3.3. Torque-Speed Characteristics

Characteristics of torque and speed is one of the main parameters for calculating the reliability of the motor. In this simulation of AF BLDC motor, according to the previous calculations, is used reference speed 2388 RPM with a torque output value of 100 Nm. With a span of time t_1 and t_2 are 10 ms and 100 ms respectively, on reference speed is 2388 RPM, so the output torque is =109 Nm. The torque value in each time are shown in Figure 5.

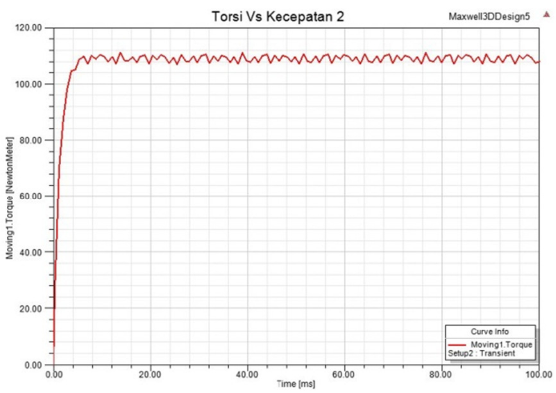

Figure 5. Torque for n= 2388 RPM and t = 100 ms

3.4. Input Power Characteristics

The required input power for axial flux BLDC motor can be calculated from eq. 17.

$$P_{in} = 3\,V\,I\,Cos\,\alpha \quad (17)$$

So that the input power is 31.22 kW.

3.5. Output Power Characteristics

The output power is given by eq. 18

$$P_{out} = T\,\omega \quad (18)$$

Therefore,

$$P_{out} = 109\ Nm \times 238 = 27.307\ Kw \quad (19)$$

3.6. Efficiency

The efficiency is given by eq. 20,

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad (20)$$

Therefore,

$$\eta = \frac{27307}{31322} \times 100\% = 88.45\ \%$$

Losses in axial flux BLDC motor mostly caused by stranded losses.

3.7. Stator Field Characteristics

Maximum flux density in stator is 2.03 T. The distribution of flux density in stator are shown in Figure 6 which shows in general that the field current and the magnetically exposed rotor surface is a linear relationship. The magnetic field stator will produce EMF on the axial flux BLDC rotor. When t = 0.05s field direction goes inward and t = 0.09 s field direction goes outward.

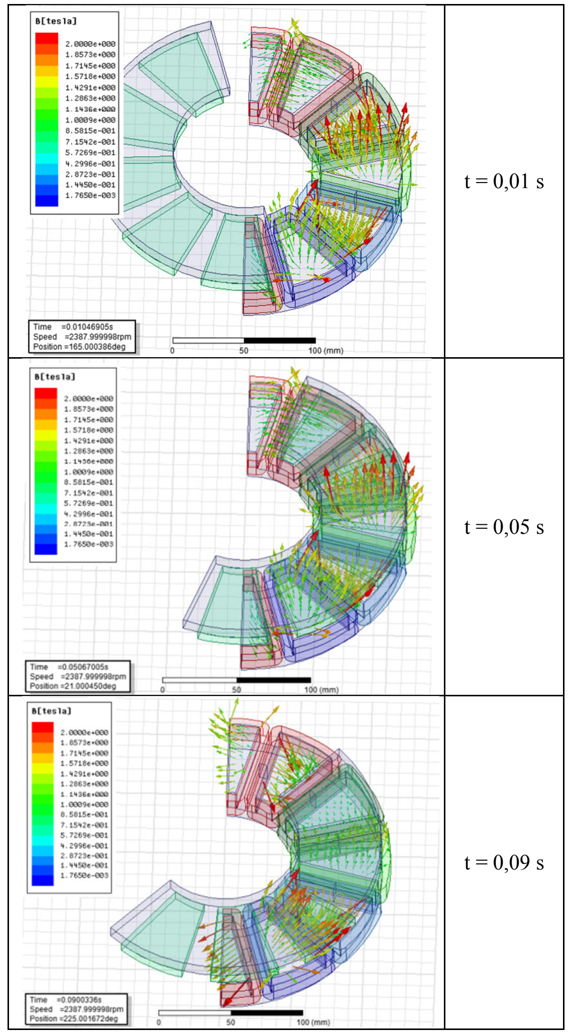

Figure 6. Stator Field Characteristics

3.8. Current Flow Characteristics in Stator

The data of current flow on the stator winding of AF BLDC motor, on various times are shown in Figure 7. Current flow direction is affected by input current from the control circuit and the mounted sensor activity which captured the permanent magnet field direction on the rotor.

3.9. Magnetic Field Characteristics in Air Gap

The simulation result of magnetic field on air gap are shown in Figure 8. From data above we can see that implication occurred by magnetic field interaction between field from rotor's permanent magnet and field from stator. Field magnitude in

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stator shifted according to rotor shifting. Besides, stator field strength mostly occurred in edge side rather than in inner side.

3.10. Losses in Axial Flux BLDC Motor

There are losses that affect AF BLDC motor. In this simulation, stranded losses effect on axial flux BLDC motor is calculated. Stranded losses is produced by windings and this cause excess heat from motor. This stranded losses decrease motor efficiency. Figure 9 shows the value of stranded loss.

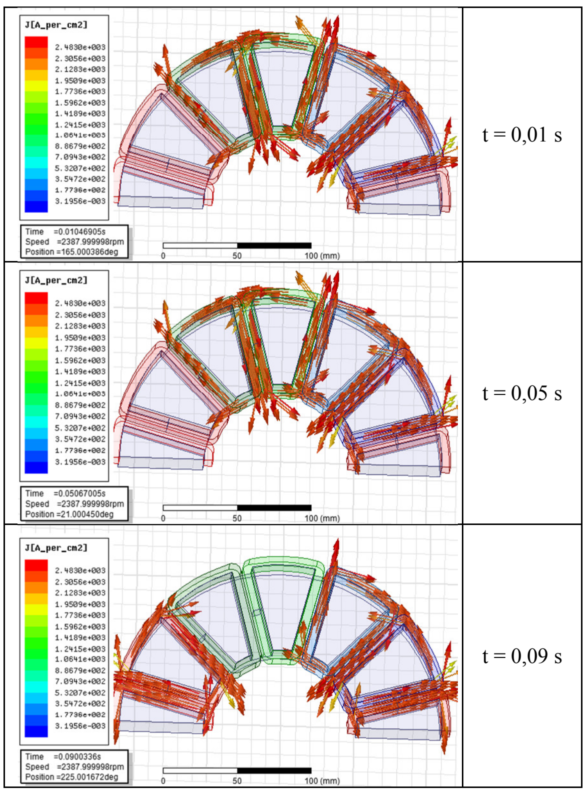
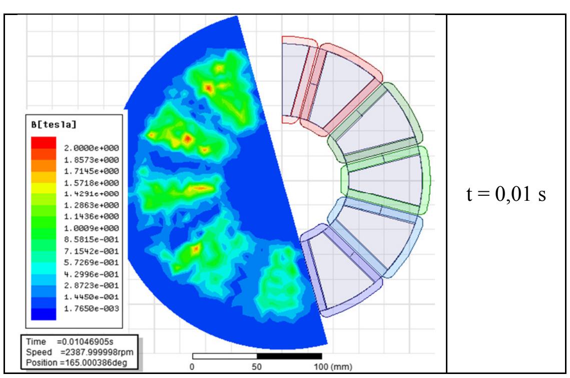


Figure 7. Current Flow Characteristics in Stator



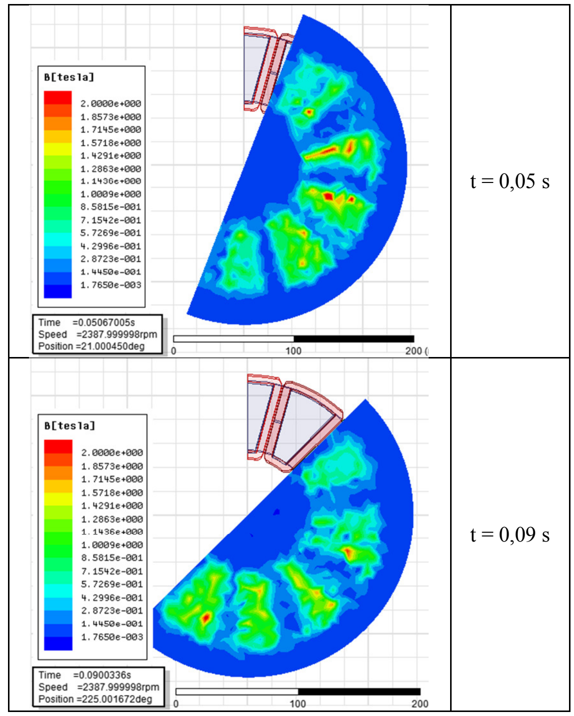


Figure 8. Magnetic Field Characteristics in Air Gap

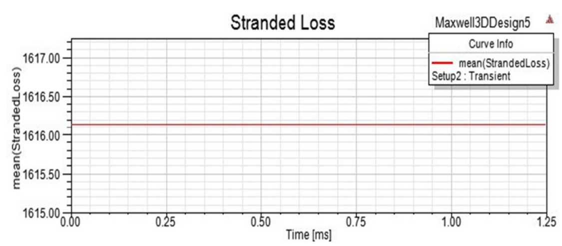


Figure 9. Stranded Losses on Axial Flux BLDC Motor

4. CONCLUSION

The 3D finite element method can be implemented successfully to model Axial Flux BLDC motor with the specification as follows:

a. Nominal RPM rating is 2388 RPM with the motor torque is 109 Nm and output power 27.307 kW. With this rated, input current is 82.47 A and motor input voltage is 162.31 V.
b. The efficiency of Axial flux BLDC motor is 88.45 % because not operates in maximum speed and torque.

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