Power density comparison of multi-air gap axial flux permanent magnet motor for electric vehicle

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Abstract. Electric vehicles are a necessity now, especially in the future. The efficiency of electric vehicles continues to be improved, especially in the drive system or electric motor. One type of electric motor used in an electric vehicle that has high efficiency and power density is permanent magnet axial flux motor. This paper explains the comparison of power density on two designs of axial flux motor. A single and multi-air gap axial flux motors had been compared. The finite element method (FEM) simulation is used to determine the power and volume of those motors. The results presented that the two air gaps power density axial flux motors were 195.3 W/kg while those multi air-gap motor with four air gaps had 283.6 W/kg. The results shows that four air-gap has a bigger power density than two air-gaps.

1. Introduction
Fuel oil from 2000 to 2014 total consumption increased to 315 million barrels of oil equivalent, along with the improving economic growth in Indonesia, this data is presented in Outlook Energy Indonesia 2016 by the Technology Assessment and Application Agency (BPPT). The pattern of fuel consumption in Indonesia, which is increasing every year, is one of the consequences of the Indonesian people's habit of increasing consumption levels of gasoline vehicles. Excessive use of fuel energy can be reduced by using electric vehicles because electric vehicles are one of the excellent and practical solutions and make these electric vehicles a necessity in the future.

Electric vehicles are based on an electric power system as all resources. There are no internal or external combustion engines onboard. Electric power as an energy source that can drive two-wheeled vehicles and four wheels. The main advantage is the high power efficiency conversion through the electric motor proposition system [1]. The efficiency of the motor is highly prioritized in designing an electric vehicle. One type of motor that shows excellent performance is the axial flux motor.

Axial flux motor type is also called motor with disk type. It is an attractive alternative to conventional motors because of its disk-like shapes, compact fabrication, and high power density. Axial flux motors are most comfortable for electric vehicles, fans, pumps, valve controls, flight systems, machine tools, robots, and industrial equipment. This type of motor has a larger diameter than conventional motors. Thus providing high inertia that can be driven as a flywheel [2]. Motor efficiency can be measured using several software models. One of the factors to achieve flux density efficiency can be measured using FEMM software. This software is used and focused on analysing the magnetic flux density. To analyse the magnetic field working in the motor [3].
2. Theoretical background

2.1. Axial flux motor

Nowadays, many areas need more things like power density, low weight, low material, low cost, excellent cooling, and ventilation. Axial flux motors or often abbreviated as AFPM are motors that have good criteria to be used in the future. AFPM is more compact than the RFPM engine shown in Figure 1; it is recognized as having the ability to get more power density than an RF engine [4].

![Figure 1](image)

**Figure 1.** (a) RFPM engine, (b) AFPM engine [4]

AFPM machines are recognized that can get better power density than RFPM machines. Therefore AFPM can be applied because it is efficient and effective, and its capabilities are superior to RFPM [5]

2.2. Multi-sided axial flux motor

To assess the potential of a multi-stator engine, a double stator AFPM engine is considered. This machine has two disks (stator) that support entanglement (Figure 2). On the rotor, parts are connected three magnetic disks which are connected to each other in order to act as a driving shaft in the drive motor system which will later be connected to the wheels.

![Figure 2](image)

**Figure 2.** Display (a) 3D dual stator AFPM engine, (b) 3D sketch pf a double stator AFPM machine [6]

2.2.1. Axial flux motor multi-sided design

In this paper, the axial flux motor is designed with a multi-sided model that has two winding disks, which become the stator while three interconnected magnetic disks which become the rotor Figure 2.
To develop an axial flux motor requires an initial step by determining the parameters as targets to be achieved in Table 1.

| Parameter                      | Value     | Unit |
|--------------------------------|-----------|------|
| WxTxH Magnet Specifications    | 35x8x50   | Mm   |
| Type of Magnet                 | N52       | -    |
| Modules Magnet                 | 32        | Units|
| Inter Magnet Spacing           | 10        | mm   |
| Number of Twists               | 3         | Turn |
| Diameter wire                  | .8        | mm   |
| Air gap                        | 1         | mm   |
| Power                          | 1000      | Watt |
| Operational voltage            | 60        | V    |
| Number of Phases               | 3         | Phase|

The multi-sided flux axial motor design in this paper is designed with a coreless type (figure 3), where there is no metal element on the winding disk. Still, here the windings are coated with resin material. So there is no slot winding (slot less). The coreless type will not produce cogging torque so that the efficient level is better and very useful for use in electric vehicles.

Figure 3. Display (a) three magnetic disks that function as rotors (b) two winding discs that function as stators
To assume the maximum power density with no load, the thickness of the rotor seat can be calculated by the following equation:

$$y_r = \frac{1}{B_{\text{sat}}} \int_0^\pi B_{rH}(r, \theta) r_r d\theta$$  \hspace{1cm} (1)

Copper loss is calculated using the following equation:

$$P_{Cu} = 2I^2 R$$  \hspace{1cm} (2)

On the stator stand the angle changes $\beta$ depending on the angle $\theta$ by following the following equation:

$$\beta = \theta + \theta_0 + \omega t$$  \hspace{1cm} (3)

### 2.2.2. Finite element method magnetics simulation

The simulation used in this paper is Software Finite Element Method Magnetics version 4.2 (FEMM 4.2). Figure 5. shows the topology of the axial flux motor in 2D, there are two sides of back iron with a thickness of 10 mm, on each side there are 4 magnets, the type of magnet used is NdFeb 40, with a water gap of 1 mm.

**Figure 4.** Design of multi-sided flux axial motors

**Figure 5.** 2D topology design in FEMMM 4.2 in one module
3. Results and discussion
The simulation results show the flux velocity, the magnetic field lines can be measured for strength, and the magnetic flux density distribution in an axial flux motor module can be seen in Figure 6.

![Figure 6. Distribution of flux in a simulation](image)

Figure 6. shows the flux density, the flux density of each part of the axial flux motor in the simulation has a certain colour variation, where the colour explains and identifies the flux density.

It can be seen from Figure 7 that the distribution is good at the active part of the conductor. The maximum magnitude of the magnetic flux in the region also determines the triggering winding time. The amount of flux density in the region can be seen in the following figure.

The power output can be calculated from the flux density plotted above. The total weight of the motor is taken from 3D design properties.
4. Conclusion
Power density means the amount of power per unit volume. The finite element method (FEM) simulation is used to determine the power and volume of multi-sided axial flux motors. The results showed that the two air gaps power density axial flux motors were 195.3 W/kg, while those with four air gaps motors had 283.6 W/kg. The results shoes that four air-gap has a bigger power density than two air-gaps.

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