Axial Flux Motor Design for Ventilation Fans Used in The Automotive Industry

Tuba Kocaer and Yasemin Öner

***Abstract*— In this paper, it was aimed to carry out the design, electromagnetic analysis of a 3 phase and dual 3 phase, axial flux permanent magnet (AFPM) synchronous motor with power level of 240W and 3000rpm speed. The geometrical dimensions of motors were designed to be the same and the motors are intended to be used in ventilation applications in the automotive industry. The performance of 3-phase 12 slot / 10 pole AFPM motor, and a dual 3-phase 12 slot / 10 pole AFPM motor were analyzed. Finite element analysis (FEA) was used to observe the characteristics of both motors. Torque values, torque ripples, motor losses, magnetic flux density and current density were examined and the results were compared.**

Index Terms— **Axial flux permanent magnet motor (AFPM), automotive ventilation fan, performance comparison.**

I. Introduction

THE VEHICLES used in transportation, which cover an important part of human life, are shaped in line with human needs. Standards and customer acceptance tests in automotive applications, including electric vehicles, burden significant noise emission limitations for automotive applications due to the users' comfort in driving and the pollution in the environment, and as an obvious result, it is aimed to reduce the noise level in the system.

Axial fans are used in many on-road and off-road vehicles for ventilation, heating, refrigeration, and engine cooling. With the developments in the automotive sector, motors used in axial fans are desired to be long-life, low noise, high-efficiency, small-volume, low cost, and low weight. You can see a brushless direct current motor (BLDC) fan used in ventilation systems in Fig. 1. [1]

Permanent magnet synchronous motors (PMSM) and permanent magnet (PM) brushed DC motors, which are frequently used in automotive ventilation systems, are a major source of noise. As it is known, one of the most important disadvantages of brushed DC motors is that they have a torque ripple that includes acoustic noise. The torque ripple changes periodically depending on the position of the rotor and its adverse effects occur mainly at low speeds and light loads. [2]

Fig.1. BLDC fan [1]

Great exertion has been made to reduce acoustic noise and examine its causes. For this purpose, several studies have been conducted on different models to be used to reduce acoustic noise, such as in automobile applications. With these studies, many different types of the motor such as reluctance motor, IPM; motor designs, and different voltage levels were studied [3], [4],[5].

In [6], best torque density, torque quality, and acoustic noise were investigated by applying different slot/pole combinations on the performance of a fractional concentrated winding spoke type synchronous motor.

In this study, two motor designs were made for the automotive industry, which occupy a smaller volume, have high power density and efficiency, and can be used in axial flux fans. 3D analysis of the designed motors were made and the analysis results were compared. It is aimed to reduce torque ripple and losses in motors designed as 3-phase and 6-phase.

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II. Axial Flux Motor

When we examine the history of electrical machines, it is seen that the oldest electrical machines are axial flux machines (AFM) [7]. The first records of studies on axial flux motors belong to M. Faraday, and it was named as Faraday disk in 1831 [8]. In 1889, N.Tesla patented this disk-shaped electric machine. However, the use of axial flux motors has not become widespread due to the strong axial magnetic attraction force between the stator and the rotor, the challenge and cost of producing the lamination used in the stator, the difficulty of assembling the machine, and the difficulties in providing that the air gap between the stator and rotor disk is uniform and stable everywhere. [7]

Today, with the developments in magnet technology, studies on axial flux motors and their use have increased. The development of permanent magnets, the discoveries of new magnetic materials, and the global cheapness of magnets and studies on electric vehicles will contribute to the widespread use of axial flux motors.

Axial flux motors can be used instead of radial flux motors due to their higher power density and more compact structure. These motors are generally used in electric vehicles, pumps, axial fans, robots.

In axial flux motors, the magnetic flux goes directly perpendicularly through the air gap. These motors consist of a ring-shaped stator disk with windings and a rotor disk with magnets. The torque is produced at the radial distance between the stator inner diameter and the outer diameter The number of poles can be increased without changing the radial length, thus reducing the axial length and increasing the power density. Therefore, axial flux motors designed by increasing the number of poles have the ability to produce high torque at low speed. Axial flux motors are generally named according to the stator and rotor arrangement and their number, the placement of the magnets, use of the core and their slot structure.

Single-sided axial flux machines are simpler than other axial flux motor structures. However, the torque production capacity of these machines is lower than other axial flux machine types. Fig. 2 shows the general structure of the single-sided axial flux machine, in which the stator core is wound and PMs are placed on the surface of the rotor disc.

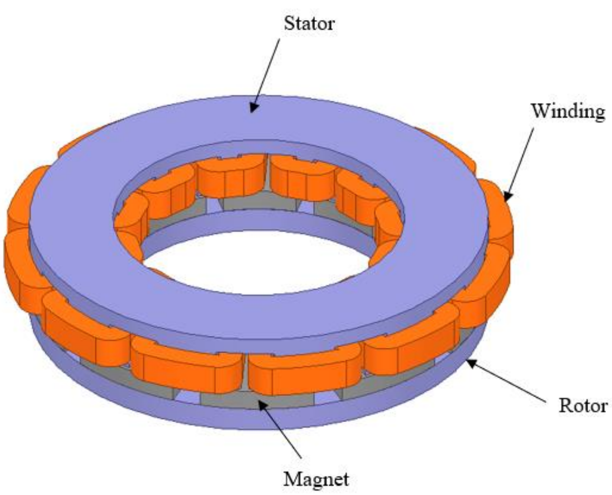


Fig.2. Construction of the single-sided AFM

Single-sided AFM provide a volume advantage at the same power when compared to radial flux motors. It is suitable for fan and pump applications where low power, less volume, less weight low cogging torque, and low noise level are required.

III. Design of Axial Flux Permanent Magnet Motor

This study, it is aimed to enable the rotor part of the AFM to be mounted directly to the impeller of the fan, thus providing a space advantage and making a thinner fan in a more compact structure. Since axial flux motors have higher power densities than radial flux motors, a smaller motor design than radial flux motors of the same power have been proposed.

In the study, the torque ripple, acoustic noise caused by the AFPM was tried to be reduced. Therefore, two AFPM designs with dual 3-phase winding set and 3-phase winding configurations with the same motor dimensions, slot/pole combination, and materials used, were designed and the results with the analysis output were compared with each other.

The 12 slot 10 poles machines are quite popular in product and technical literature [9]. By using double-layer winding in the motor structure with 12/10 slot/pole combination, the values of the fifth and seventh harmonics that significantly affect the torque ripple are reduced. In addition, it is intended to achieve low cogging torque and torque ripple from the machine. The cogging torque is proportional to the least common multiple (LCM) of the number of poles and the number of slots and the selected slot and pole combination is suitable for low cogging torque.

The winding structure of an AFPM is determined by the slot-pole combination. Also, the winding structure of PM motors is in two main forms, integrated slot winding and fractional slot winding. Fractional-slot machines with a tooth winding and PMs have certain advantages such as high power density and efficiency, short end windings, low cogging torque, high slot fill factor and no skew [10], [11].

If the value of q, which expresses that the number of slots per pole per phase, is fraction the winding is called fractional slot winding.

$$q = \frac{Q_s}{2pm} \tag{1}$$

In Equation 1, Q_s refers to the number of slots, m refers to the number of phase and 2p refers to pole pairs.

If a three-phase system is doubled by increasing the number of phases, it halves the number of slots per pole per phase. As can be seen from the Eq1, when only the number of phases is changed in a motor, q values of the three-phase motor is 0.4, meanwhile the q values of the six-phase motor is 0.2.

With the progress of the motor control techniques and power electronics equipment used to drive the motor, the FSCW multiphase motor has significant advantages due to its high power densities and short end winding lengths [12],[13]. Multiphase motors have been studied in the literature because of their effects such as improvement in EMF waveform, higher performance, lower phase current, increased efficiency due to lower rotor losses, reduced acoustic noise, reduced torque ripples and increased torque density.

TABLE I
DESIGN PARAMETER

Parameters	Values
Output Power (W)	240
Output Torque (Nm)	0.6
Phase Voltage (V)	26
Speed (rpm)	3000
Target Efficiency (%)	90

The parameters of the motor to be mounted inside the axial fan are given in Table 1. Fans used for ventilation in automotive applications are powered by 24V or 12V batteries and due to the battery output voltage, motor tests are usually performed with 26V. For this reason, the motor design was made according to the 26V supply voltage.

The design parameters and geometric dimensions of the motor, whose design and analysis have been made, are given in Table 2.

TABLE II
MOTOR DESIGN PARAMETERS AND DIMENSIONS

Parameters	3-Phase AFPM Values	Dual 3-Phase Set AFPM Values
Phase Number	3	6
Pole Pairs	5	5
Slot Number	12	12
Operation Voltage	26 V	26 V
Outer Diameter of Stator	110 mm	110 mm
Inner Diameter of Stator	70 mm	70 mm
Stator Material	M250-50A	M250-50A
Slot Opening	3 mm	3 mm
Slot Height	10 mm	10 mm
Stator Tooth Width	3.5 mm	3.5 mm
Stator Axial Length	14 mm	14 mm
Airgap	0.7 mm	0.7 mm
Magnet Thickness	6 mm	6 mm
Magnet Material	Ferrit Y30	Ferrit Y30
Rotor Axial Length	8 mm	8 mm
Rotor Material	Steel 1008	Steel 1008
Number of Turns	21	21
Wire Diameter	1 mm	1 mm
Number Of Strands	2	2
Coil Pitch	1	1

In this study, the two motors are designed to give the same outputs and the dimensions of the motors are identical. The number of turns in a coil is the same in both motors. However, the number of turns in series per phase is half of the 3-phase motor in a dual 3-phase set motor.

The phase windings of the 12-slot, 10-pole motor are divided into two sets and a appropriate phase shift is made between both phase sets, as seen in Fig. 3 (b). First set 3-phase windings expressed as A1, B1, C1 and the second set 3-phase windings as A2, B2, C2. The winding structure of the two sets 3-phase motor has a phase shift of 120 degrees between phases A1, B1, C1 and between phases A2, B2 and C2. However, there is a 90º phase shift angle between the first and second winding set. In other word, there is a phase-shifting of 90º between the A2 and A1 phases. You can see the winding arrangement of the motors in Fig. 3.

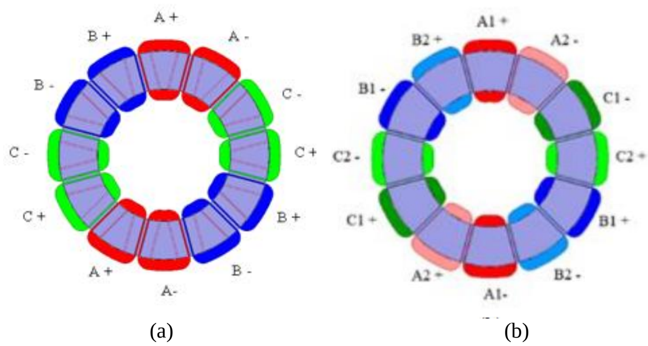


Fig.3. Winding arrangement for a 12 slot / 10 pole geometry. (a) 3-phase winding. (b) Dual 3-phase winding

A. *Electromagnetic Analyzes*

Electromagnetic analyzes were carried out in 3D with the finite element method using Ansys Maxwell software. In these analyzes made with sinusoidal current supply, moment, output power, current densities, flux densities, cogging torques, losses are examined.

B. *Torque Analysis*

The two motors were operated with the same current and voltage value. You can examine the average torque values and torque ripple of the motors from Table 3.

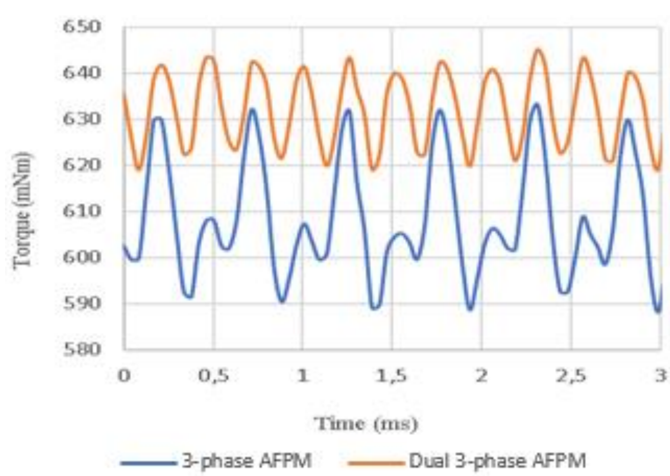


Fig. 4. The torque graph of AFPM

When the torque plots of the dual 3-phase motor and the 3-phase motor are compared, it is seen that the average torque value of the dual 3-phase motor is 2.5% higher than the 3-phase motor. In addition, It has been observed that the torque ripple value of the 3-phase motor is 3.24% higher. You can see the torque graph of both AFPM in Fig.4.

TABLE III
TORQUE VALUES

Torque Values	3-Phase AFPM	Dual 3-Phase AFPM
Average Torque (mNm)	607.98	632.41
Torque Ripple (%)	7.39	4.15

C. The EMF Waveforms

The EMF waveform of the AFPM is shown in Fig. 5 and Fig. 6. While the rms value of induced voltage in one phase of the dual 3-phase motor is 6.85V, that of the 3-phase motor is 14.12V.

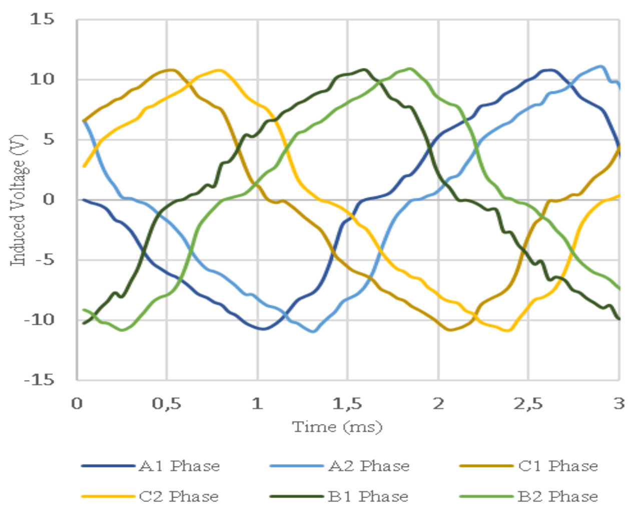


Fig.5. The induced voltage at load condition of dual 3-phase AFPM

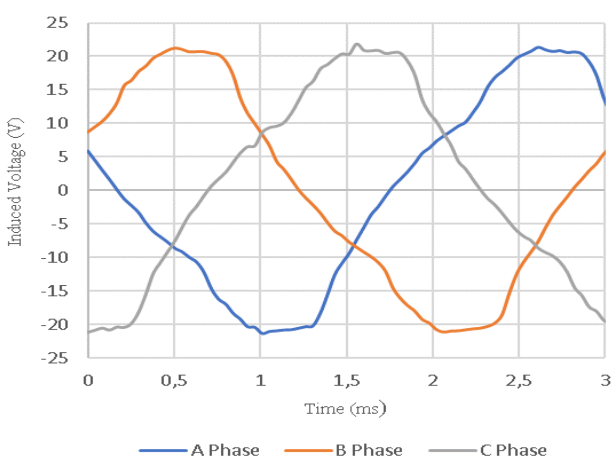
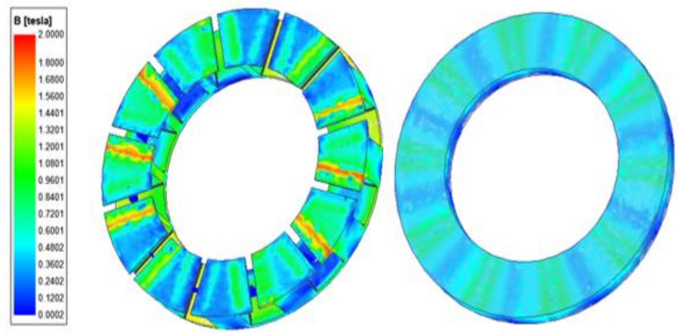


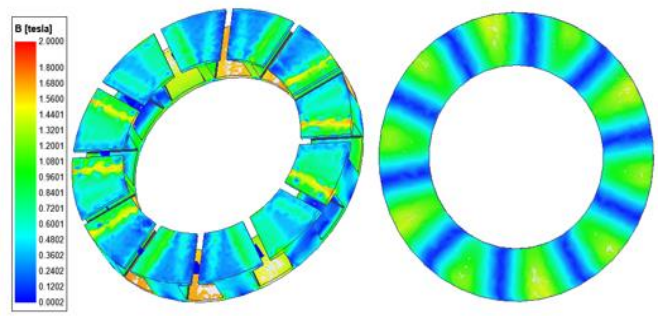
Fig.6. The induced voltage at load condition of 3-phase AFPM

D. Flux Density Analysis

Fig.7 shows the flux density of both motors. No magnetic saturation was observed in the stators and rotors of both motors. According to the results of the analysis, the maximum magnetic flux density observed in the motors is 1.7T and it was observed in the stator teeth.



(a)

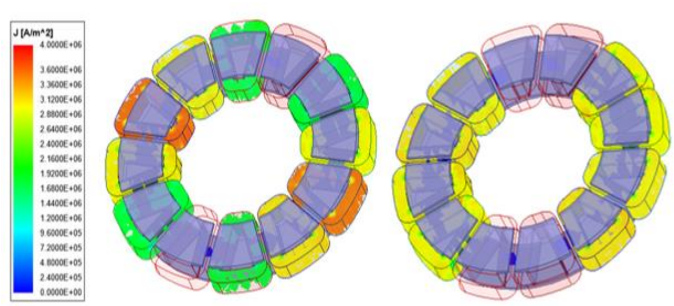


(b)

Fig.7. The flux density of AFPM (a) Dual 3-phase motor. (b) 3-phase motor

E. Current Density Analysis

You can see the current density values in the coils of both motors in Fig. 8. The maximum current density value in the coils is 3.75A. The current density values in Fig. 8 show that the motors can operate in S1 mode without any cooling requirement under nominal load conditions.



(a) **(b)**

Fig.8. The current density of AFPM (a) Dual 3-phase motor, (b) 3-phase motor

F. Loses

According to the analysis results, it was seen that the efficiency of the dual 3-phase motor was higher. You can see the losses of both AFPM from Table 4.

TABLE IV
MOTOR LOSES

Loses	3-phase AFPM	Dual 3-phase AFPM
Core Loss	4.69 W	4.38 W
Eddy Current Loss	2.42 W	2.26 W
Hysteresis Loss	1.91 W	1.77 W

As seen in Fig. 6, Tables 3 and 4, the windings of a multiphase machine produce an EMF waveform closer to the sinusoidal so the winding factor for the main harmonic is high. This results in an increase in torque per ampere for the machine. Furthermore, higher phase number winding improved armature EMF waveform as it will contain lower harmonic contents and reduced amplitude-frequency of the toque ripple thus reducing acoustic noise and reducing rotor loss by this means increased efficiency of the motor

IV. CONCLUSION

This paper presented two AFPM motor has 12/10 slot-pole combination with FSCW configurations that can be used for an automotive ventilation fan application. It is designed in such a way that the geometric dimensions of the two motors are the same, but the number of phases is different. The losses, current density, magnetic flux density, EMF waveform and torque data of the two motors designed and analyzed in 3D were compared. According to the analysis results, when compared to the three-phase AFPM motor, the dual 3-phase AFPM motor has higher torque density, lower torque ripple, and motor losses. Based on the results presented, it can be said that dual 3-phase AFPM is more suitable for the application in terms of torque ripple, acoustic noise, and efficiency.

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BIOGRAPHIES

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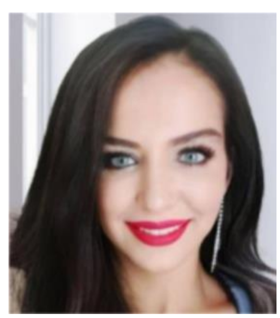

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