Study of permanent magnet configuration in alternate circumferential and radial flux permanent magnet flux switching machines (AlCiRaF-PMFSM)

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Abstract. Alternate circumferential and radial flux (AlCiRaF) is new design in PMSFM. AlCiRaF PMFSM offers high torque and power density. However, AlCiRaF PMFSM is a novel design that a good opportunity to be potential improved further. In this research, the nine design of permanent magnet configuration in AlCiRaF PMFSM is proposed to compare each performance possibilities. The configurations of permanent magnet are introduced to study the performance effect by changing the permanent magnet position which is PM-Bottom, PM-Middle and PM-Top for both circumferential and radial direction. Besides, the permanent magnet structure design will improve field winding area structure to provide space for future improvement. Weight of all the permanent magnets are estimated to be 0.5 kg altogether. Initially, design procedures of the all motor including parts drawing, material and condition setting, the properties setting are all explained. Then, coil arrangement test is conducted to perform 3 phase armature coil arrangement. Then, no load analysis is conducted to analyze cogging torque, flux linkage, flux distribution and back-EMF of motor followed by load analysis which analyze the torque speed characteristics and output power of the motor with different permanent magnet configuration. No load analysis and load analysis are conducted using finite element analysis of JMAG Designer 16.0. Finally, it is found that there is no significant difference that resulted and the best permanent magnet configuration compared to the Existing AlCiRaF PMFSM permanent magnet design is TRBC PM and MRBC PM due to the capability to produce high output torque and power based on the analysis conducted.

Keywords: AlCiRaF PMFSM, Permanent Magnet (PM) Configuration.

1. Introduction
Flux-switching machines are a type of brushless machines with a doubly salient structure, which has excitation sources, for example, permanent magnet (PMs) and/or field-excited windings, and armature windings on the stator, and no magnet or winding on the rotor. According to the excitation modes, there are three types of flux-switching machine, that are Permanent magnet flux-switching (PMFSM) machines, Hybrid-excited flux-switching (HEFSM) machines, and field-excited flux-switching (FEFSM) machines[1-3]. Figure 1 demonstrate the 12 Slot and 10 Poles of conventional PMFSM.

The new design of PMFSM is propose, known as the Alternate Circumferential and Radial Flux Permanent Magnet (AlCiRaF). The AlCiRaF PMFSM is first compared with the conventional
PMFSM and based on several design limitations and specifications, design improvements are then accomplished by utilizing deterministic optimization method [4-6]. This proposal takes into consideration a typical three phase structure of a permanent magnet flux-switching machine with 12 stator poles and 10 rotor poles. This project is to design the length and height of permanent magnet in AlCiRaF-PMFSM to saved space on stator. According to the PM locations, three typical topologies of HEFSM machines emerged, namely, PM-Top, PM-Bottom, and PM-Middle, respectively. Preliminary analysis shows that different configurations of magnets and field turns have a significant effect on the performance of electromagnetic HEFS machines [7-9]. The material of permanent magnet is a neodymium magnet known as NdFeB. Neoc'ymium-iron-boron magnets, in both sintered and bonded forms, offer tantalizing new design possibilities and opportunities for improved performance from electrical machines [10-12].

Figure 1. 12S-10P Conventional PMFSM.

At present, every industry in Malaysia places a high demand on innovative solutions and the use of changing technologies. The goal is to achieve not only increase productivity, reduce energy costs and machine availability, but increase optimum energy efficiency and torque as well. In addition, the PMFSM machine is a good candidate because it combines the advantages of a switched reluctance machine that are high speed and robust rotor structure and a brushless permanent magnet machine (high torque density).

As in the AlCiRaF PMFSM machines, was a design that contributes better torque, power, speed range and efficiency compared with conventional 12 Slot-10 Pole PMFSM [2]. However, AlCiRaF PMFSM design has a high instantaneous and cogging torque and good opportunity to be potential improved further. Several comparative methods have to be used to find the best way to reduce torque cogging [13-14] as well as to boost existing performance in term of torque and power.

Hence, the configurations of permanent magnet are introduced to study the performance effect by changing the permanent magnet position which is PM-Bottom, PM-Middle and PM-Top for both circumferential and radial direction. Besides, the permanent structure design will improve field winding to provide space for future improvement.
2. Design topologies and specification

2.1. Permanent magnet design
This step is too filled up the blank of machine after done designing the stator, rotor and armature coil. For nine design, the stack length value was constant 70 mm. Density of magnet was set to 7550 kg/m³ section has two types of pattern of permanent magnet which is Radial and Circumferential. In addition, the material of magnet that used is Neomax-35AH (irreversible) that contains density of 7550 kg/m³. By using density formula that shows in equation (1).

\[ \rho = \frac{\text{mass of PM}}{\text{volume of PM}} \]  

where \( \rho \) is density of magnet (7550 kg/m³), mass is 0.5 kg of permanent magnet and volume is area time stack length.

2.2. Mesh, magnetic and properties setting
The steps, end time and division are set in the step control part while the stack length is set in the full model conversion. The steps, end time, division and stack length are set to 37, 0.012s, 36 and 70 mm, respectively. The end time, \( t_e \) of the motor is acquired based totally at the equation (2).

\[ t_e = \frac{1}{f_e} \]  

where \( t_e \) corresponds to end time and \( f_e \) as electrical frequency. The formula specifies the electrical frequency at equation (3).

\[ f_e = N_r f_m \]  

where \( N_r \) is referred to as rotor machine number, while \( f_m \) is defined as motor frequency. Meanwhile, the motor frequency, \( f_m \) can be determined by equation (4).

\[ f_m = \frac{n}{60} \]  

where \( n \) is referred to as motor velocity.

2.3. Load test, torque, power and speed
The load test is simulated with the injection of the motor with specific current density \( J_A \). Torque and flux relation at various \( J_A \) locations are evaluated to determine the torque variation pattern when the different current value is injected into the motor's FEM coil. All nine models are tested and simulated to determine the characteristics of torque, power and speed. During the load test, the strength of the armature current varies between 0 to 30 A/rms/mm². The current value determined for all nine design based is shown in Table 1 by current injection of \( I_{peak} \) and \( I_{rms} \) to each current density, \( J_A \) by relation to the value of the slot area armature which is 298.7577 mm² and 42 as the number of turns from the motor specification.
Table 1. Current injection of $I_{\text{peak}}$ and $I_{\text{rms}}$ to its current density, $J_A$

| Armature coil current density, $J_A$ (A/mm$^2$) | Input current of armature coil, $I_{\text{peak}}$ (A) | Input current of armature coil, $I_{\text{rms}}$ (A) |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 0                                               | 0                                               | 0                                               |
| 5                                               | 17.7832                                         | 25.1492                                         |
| 10                                              | 35.5664                                         | 50.2985                                         |
| 15                                              | 53.3496                                         | 75.4477                                         |
| 20                                              | 71.1328                                         | 100.5970                                        |
| 25                                              | 88.9160                                         | 125.7462                                        |
| 30                                              | 106.6992                                        | 150.8954                                        |

3. Proposed PM design configuration

Initial 6S-10P AlCiRaF PMFSM model possesses twelve PMs. Six out of twelve PM is a radial pattern and another six PM is a circumferential pattern of magnetizing direction build with an alternate arrangement. It is necessary to validate the direction of magnetizing of every single of PM. The magnetizing direction of each PM is similar with initial AlCiRaF PMFSM. Figure 2, Figure 3 and Figure 4 demonstrate the proposed nine PM design of 6S-10P AlCiRaF PMFSM bottom, middle and top radial permanent magnet combine with bottom, middle and top circumferential permanent magnet. Equation (1) is used to determine the parameter of each PM design. The no-load and load analysis was carried out for all nine PM design.

![Circumferential PM](image1)
![Bottom Radial PM](image2)
![Top Radial PM](image3)

Figure 2. PM proposed design (a) BRBC, (b) BRMC and (c) BRTC PM.

![Middle Radial PM](image4)
![Middle Radial PM](image5)
![Middle Radial PM](image6)

Figure 3. PM proposed design (a) MRBC, (b) MRMC and (c) MRTC PM.
4. Electromagnetic performance analysis

4.1. Coil arrangement test
The 6S-10P AlCiRaF PMFSM of nine design PM possibilities operating principle is in order to confirm and set the location of every armature coil phase, the coil arrangement tests are examined in every armature coil separately. The flux linkage at each coil is analyzed. The flux linkage of every coil separated phase and three phase flux linkage were defined as U, V and W. By the result for three arrangement coil tests, the first combinations are group armature coil 1 and 4 together as armature coil 1 and represented as V. Then, the second combinations are group of armature coil 2 and 5 as armature coil 2 and represented as U and the other group combine armature coil 3 and 6 as armature coil 3 and represented as W. The three different flux patterns can be determined with the three-phase vector diagram. U, V, W represented as in 0°, lead 120°, and lag 120°.

Zero rotor position is when the most factor of a cosine wave is at zero degree or in some other case the most is at 180° degrees. Another method to get the zero-rotor position is whilst the graph of U flux intercepts at 90° and 270° on the x-axis. If the U flux isn't at zero rotor position, the rotor is adjusted clockwise or counterclockwise by way of estimating the degree of adjustments. Figure 5 indicates that the U flux is in zero rotor position that's consist of the complete design.

4.2. Cogging torque analysis
Cogging torque is generated in the machines by the interference between the magnetic field of the permanent magnet and stator slots which causes changes in the reluctance that depends on the rotor position [6]. Cogging torque can occur when there is an air gap in the machine. The presence of cogging torque raises the flux linkage and produces a poor torque for a machine. Then, the highest cogging torque induces the machine's vibration while lowest cogging torque is the best machine condition. Fig. 6 interpreting the comparison of cogging torque graph for 6S-10P AlCiRaF PMFSM bottom, middle and top radial PM.

Data on Figure 6(a) shows that existing 6S-10P AlCiRaF PMFSM BRBC PM indicates 4.5241 Nm peak to peak in cogging torque. Furthermore, for BRMC PM shows 7.5988 Nm peak to peak in cogging torque. Then, combination of BRTC PM has a lower value than BRMC PM which is about 6.6112 Nm peak to peak in cogging torque. Figure 6(b) shows that 6S-10P AlCiRaF PMFSM MRBC PM has value 11.668 Nm peak to peak in cogging torque. Meanwhile, the value of cogging torque is almost similar to other permanent magnet topology configuration with MRMC PM and MRTC PM. Lastly, Figure 6(c) shows that 6S-10P AlCiRaF PMFSM TRBC PM indicates 11.4696 Nm peak to peak in cogging torque. From that value, there are also almost similar to another PM topology configuration which are TRMC PM and TRTC PM.
Figure 5. Flux Linkage of (a) Bottom radial, (b) Middle radial and (c) Top radial PM design that each combine with Bottom, Middle and Top circumferential PM
4.3. Back EMF

Back EMF is normally used to consult the voltage that happens in electric powered motor wherein there may be relative motion among the armature of the motor and the magnetic field from the motor's field magnets, or windings [7],[17]. Since magnetic flux is significantly increased so that induced voltages are also accelerated. Through revolving all machines at rated velocity of 500 rpm. Figure 7 show the graph of back electromotive force (EMF) is done for analysis in no load test condition for 6S-10P AlCiRaF PMFSM bottom, middle and top radial PM. Hence, there is no current being supply to the armature coil. Figure 7(a) shows that 6S-10P AlCiRaF PMFSM BRBC PM has maximum value.

Figure 6. Cogging Torques of (a) Bottom radial, (b) Middle radial and (c) Top radial PM design that each combine with Bottom, Middle and Top circumferential PM.
34.4627 V at the angle of 30° and minimum value -35.3420 V at the angle 290°. Meanwhile, for combination of BRMC PM has maximum value 36.5349 V at the angle of 30° and minimum value -38.2829 V at the angle of 280°. Then, the BRTC PM has maximum value 34.3757 V at the angle 30° and minimum value -34.2352 V at the angle of 270°. Graph for Figure 7(b) shows, 6S-10P AlCiRaF PMFSM MRBC PM has maximum value 33.4310 V at the angle of 30° and minimum value -26.748 V at the angle 290°. Followed by, combination of MRMC PM which is has maximum value which are 36.5554 V at the angle of 30° and minimum value -37.426 V at the angle of 280°. Then, for MRTC PM shows maximum value 31.7303 V at the angle 30° and minimum value -31.5247 V at the angle of 270°.

**Figure 7.** Back-EMF of (a) Bottom radial, (b) Middle radial and (c) Top radial PM design that each combine with Bottom, Middle and Top circumferential PM.
Figure 7(c) shows, $6S-10P$ AlCiRaF PMFSM TRBC PM has maximum value 44.7036 V at the angle of 30° and minimum value -44.7529 V at the angle 240°. Next, combination of TRMC PM has maximum value 39.1885 V at the angle of 30° and minimum value -39.5773 V at the angle of 280°. Lastly, the combination of TRTC PM shows maximum value 33.7853 V at the angle 30° and minimum value -33.9358 V at the angle of 270.

4.4. Torque and power performances

Figure 8(a) and Figure 9(a), the maximum output power produced by BRBC PM design is 16,133 W in under condition of speed about 4,542 Rpm. While, the maximum torque is 44.29 Nm in under condition of speed at 3,302.84 Rpm. Besides, the maximum output power produced by BRMC PM design is 15,141 W in under condition of speed at 5,598 RPM. While, the maximum torque is 41.63 Nm in under condition of speed about 3,224.72 RPM. Lastly, the maximum output power produced by BRTC PM design is 13,763 W in under condition of speed about 6,115 Rpm. While, the maximum torque is 36.06 Nm in condition of speed at 3,300.39 Rpm.

By referring on Figure 8(b) and Figure 9(b), the maximum output power produced by MRBC PM design is 17,569 W in under condition of speed about 6,189 RPM. While, the maximum torque is 44.38 Nm in under condition of speed about 3,444.59 Rpm. Besides, the maximum output power produced by MRMC PM design is 16,501 W in under condition of speed about 6,601 RPM. While, the maximum torque is 40.22 Nm in under condition of speed at 3,425.17 RPM. Lastly, the maximum output power produced by MRTC PM design is 14,593 W in under condition of speed about 7,265 Rpm. While, the maximum torque is 33.40 Nm in under condition of speed at 3,534.16 RPM.

Graph on Fig. 8(c) and Fig. 9(c) shows the maximum output power produced by TRBC PM design is 16,406 W in under condition of speed about 5,123 RPM. While, the maximum torque is 45.35 Nm in under condition of speed about 2,846.27 RPM. Besides, the maximum output power produced by TRMC PM design is 16,184 W in under condition of speed about 8,342 RPM. While, the maximum torque is 40.93 Nm in under condition of speed about 2,846.79 RPM. Lastly, the maximum output power produced by TRTC PM design is 15,835 W in under condition of speed about 9,945 RPM. While, the maximum torque is 37.30 Nm in under condition of speed about 2,879.59 RPM.

Meanwhile, based on graph in Figure 8 and Figure 9 the first and second highest of the torque performance is the TRBC PM and MRBC PM design which are 2.40% and 0.20% respectively. The lowest torque performance is MRTC PM design which is 24.59% lower than BRBC PM design.

Then, the value of output power for BRBC PM which is almost similar with existing AlCiRaF PMFSM is about 16.133 kW. The first and second highest of output power are MRBC PM and MRMC PM design that indicates 8.90% and 2.28% higher than BRBC PM design. Lastly, for the lowest output power is a design of BRTC PM is about 14.69% lower than a design of BRBC PM.

5. Conclusion

In this paper, design study of 0.5 kg PM with different configuration of AlCiRaF PMFSM has been investigated which is a Bottom Radial, Middle Radial and Top Radial PM that combine with 3 design respectively which is Bottom, Middle and Top Circumferential PM. The design procedure of all machine topologies of PMFSM has been fully explained. No load analysis has been investigated including the study of magnetic flux linkages, cogging torque, flux line distribution analysis and back-EMF. The coil arrangement test was carried out to confirm each phase of the armature coil and to indicate the machine operating principle in three phase system.

Besides, the back-EMF or induced voltage also been done in order to confirm that every design got the induced voltage below from the voltage applied source. Then, load analysis also has been investigated including the analysis of performance torque, speed and output power of each motor design guided by armature coil current density, $J_A$. From this analysis, absolutely the performance of TRBC PM design is the better performance rather than other based on torque performance and output power. Based on this study, the bottom permanent magnet in circumferential direction shows the
highest magnet utilization and the strongest flux regulation capability [18-19]. However, the cogging torque and back-EMF for the TRBC PM are about 153.52% and 29.72% respectively which is higher than a BRBC PM design. Hence, the best cogging torque remain a BRBC PM design itself. While, the lower back-EMF is MRTC PM design that indicates 7.93% which is lower than a BRBC PM design.

![Torque vs Speed Graphs](image)

**Figure 8.** Torque, Nm against speed (r/min) of (a) Bottom radial, (b) Middle radial and (c) Top radial PM design that each combine with Bottom, Middle and Top circumferential PM.
Figure 9. Power, W against speed (r/min) of (a) Bottom radial, (b) Middle radial and (c) Top radial PM design that each combine with Bottom, Middle and Top circumferential PM.

6. References

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