Analysis of Radial and Halbach Permanent Magnet Configurations for Ceiling fan Applications

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Abstract — Permanent magnet motor offers various advantages such as simple construction and high efficiency which are highly demand in domestic appliances. The standard single-phase ceiling fan motors that are driven by the induction motor are inherently low efficiency. This paper presents an analysis on radial and Halbach permanent magnet array configurations of permanent magnet synchronous machine for ceiling fan. The proposed design of ceiling fan machine comprises a motor and a generator in one machine that implement a concept of the single rotor double stator. An analysis was conducted via finite element analysis to compare the performance of the flux distribution, air-gap flux density and back EMF between the conventional radial and Halbach permanent magnet machine. Overall, Halbach permanent magnet machine generates a high intensity of flux lines and flux density due to the self-magnetization features. However, the generated back EMF is not significant as compared to radial permanent magnet machines. Considering the simplicity of the design, radial array machine is identified as the optimized design configurations.

Keywords - Halbach, radial, ceiling fan, permanent magnet, finite element analysis (FEA).

I. INTRODUCTION

Permanent magnet synchronous machine (PMSM) comprises of a rotor that using a permanent magnet ring to produce a constant field excitation. Thus, PMSM does not require brushes and slip rings for external supply at the rotor consequently simplify the motor construction. Moreover, PMSM has a less copper loss due to no excitation coil at the rotor part. The armature field from the stator and the constant field from the rotor are synchronised, where the armature current can be controlled by the stator voltage and frequency to control the speed and the torque of the motor. Designing a high performance and high efficiency PMSM motor applications are challenging since these machines are widely used in industry either for small voltage or high voltage application [1, 2]. However, due to demagnetization effect and the cogging torque for PMSM are high, many approaches and methods have been done to overcome these issues [3-5].

This research deals with single phase permanent magnet ceiling fan machine. Ceiling fan had become one of the cooling appliances for the hot, warm country such as Malaysia. According to a statistic reported in [6], the percentage ownership of ceiling fan in Malaysia is 93% as the electricity consumption of ceiling fan is lower than air conditioner, consuming 650 kWh per year. The efficiency of the ceiling fan is obviously related with the total energy consumption. Thus, a high efficiency designs are highly demand in order to improve the energy saving systems. The newly introduced concept in this research applied a concept of single rotor double stator that comprises two systems in one machine, the motor and the generator. These two systems are separated by an aluminum sheet functionally as a flux insulator. The generator system will harvest the energy from the permanent magnet field of rotor rotation and converted to electrical energy and supplied to other low power application such as lighting system (as been discussed in [7]). The usage of electrical power from the generated electricity can improve the total energy saving. Moreover, the improvement of the proposed design can increase the efficiency of the ceiling fan motor. Extensive literature review was conducted to obtain the best design configurations of the PMSM for the ceiling fan system such as the topologies of electrical machine, air gap configurations, rotor structure, slot/pole number combinations, stator winding and slot opening [8-13].

Recently, Halbach array has been implemented in designing numerous type of electrical machines such as in wheel applications, electromagnetic actuators and high speed spindle motor [14, 15]. Moreover, Halbach arrays are potentially exhibits a large magnetic field towards the side of the coil, while minimizing the magnetic field at the opposite side of the magnet, thus improving the air gap flux density and reducing the cogging torque effect. The features of the proposed designs for the ceiling fan machine equipped with radially magnetized magnets, have been compared in terms of air gap flux density, flux distribution and also back EMF to select the optimum design configurations as reported in [7]. However, the performance between the Halbach machine and the conventional radial machine for ceiling fan has not been reported yet for the optimizations of the ceiling fan machine design. Thus, the main focus of this paper is to investigate of the performance between the Halbach machine and the conventional radial machine for predicting the open
circuit flux distribution, air gap flux density and the back EMF validated by finite element analysis (FEA).

II. PROPOSED DESIGN

Halbach array has been conventionally used to produce a sinusoidal air-gap flux distribution and back EMF waveform, thus resulting in low iron loss consequently increase the efficiency of the machine [16, 17]. Moreover, Halbach also offer many attractive features such as the minimization of the cogging torque effect without the magnet skew or a distributed winding[18] and the back iron at the rotor is not essential due to the self-shielding magnetization[19]. In comparison with the conventional radial array, the maximum air-gap field produced is affected by the magnet thickness, while the amplitude of air-gap field for Halbach array is dependent on the pole numbers[20]. The Halbach permanent magnet generally fabricated in the form of discrete magnet segments or a single ring magnet.

The continuous rotating for radial vector is rotated by 180° for each magnetic pole, and for the Halbach array, the vector is rotated by 90° for each magnet for 2 segments/pole. The ideal for this Halbach array is the combinations between the radial magnet array and the Azimuthal (horizontal) magnet array [21] where the magnetic flux is vanishing at one side of the magnet and the magnetic flux at opposite side will enhanced by 2. The side cancellation depends on the Azimuthal magnet array arrangement on which will affect the direction of the radial array either in the clockwise direction or anti-clockwise direction. Figure 1 shows the cross section of conventional radial machine and 2 segments/pole orientations for Halbach machine respectively. It is verified that higher number of segments/pole will generate a better sinusoidal flux distribution and reduced the cogging torque as reported by [22], although in practice, the cost of fabrication and the complexity of the design will be higher since the Halbach machine will use more magnets compared to radial machine for the same number of pole pairs. Therefore, 2 segments/pole orientations for Halbach machine is selected for the design simplicity. The directions of Azimuthal arrays in the Halbach magnet ring are different for motor and generator as the side of flux cancellation depends on the position of stator back iron. In motor system, the stator back iron is located outside the permanent magnet rig, thus for the external field Halbach cylinder, the side of flux cancellation is at the inner of the permanent magnet ring. On the other hand, for the generator system, the stator back iron is located inside the permanent magnet ring, thus, for the internal field Halbach cylinder the side of flux cancellation is on the outside of the permanent magnet ring.

![Figure 1. Illustration of magnet orientation in PMSM. (a) Conventional radial machine. (b) Halbach machine](image)

<table>
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<tr>
<th>TABLE 1. DESIGN PARAMETERS</th>
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<tr>
<td>Magnet remanence, ( B _r )</td>
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<tr>
<td>Axial Length, ( L _a )</td>
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<tr>
<td><strong>Motor (outer part)</strong></td>
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<tr>
<td>Stator outer diameter, ( D _o )</td>
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<tr>
<td>Stator inner diameter, ( D _i )</td>
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<td>Number of pole/slot</td>
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<tr>
<td>Slot angle, ( \theta _s )</td>
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<tr>
<td>Radial air gap, ( g _r )</td>
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<tr>
<td>Permanent magnet thickness, ( t _p )</td>
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<tr>
<td>Stator tooth length, ( l _t )</td>
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<tr>
<td>Stator tooth width, ( w _t )</td>
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<td>Number of coil turns</td>
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<tr>
<td><strong>Generator (inner part)</strong></td>
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part of the rotor consists of a set of the magnet ring for motor and generator system separated by the aluminum ring as illustrated in Figure 3.

III. RESULTS AND DISCUSSION

In order to demonstrate the comparison between the radial array and the Halbach array performance, the analysis was conducted in an open circuit test using the Finite Element Analysis (FEA), Ansoft Maxwell software. The analysis was conducted to analyze the flux distribution, air gap flux density and the back EMF for motor and generator system.

A. Flux Distribution

The simulations were carried out by setting the input current 0A at the stator winding to study the flux distribution from the permanent magnet. The speed of the rotors is set as 0 rpm to analyze the direction of the vector from the permanent magnets at static conditions where the position of the radial magnet array in both machines is located at the stator tooth when the flowing of magnetic flux is at the optimum value. The flux distribution for radial and Halbach array are shown in Figure 5.

It is observed that the flows of magnetic flux distribution for radial array and Halbach array are evenly distributed through the stator back iron. The interaction between the permanent magnets cause the flux evenly distributed since these permanent magnets are located side by side where half of the flux will go into the left side S-pole while the other half go into the right side S-pole in open air. With the present of laminated iron core, the flux is flowing into the stator and going back to the nearest magnet pole. However, for the Halbach array, the presence of the Azimuthal array triggering one side has a flux cancellation due to self-shielding magnetization feature. These will results the fundamental flux lines of the Halbach array magnet have more flux intensity, especially in the tooth area which is 56% higher than the radial array. The analysis proved that the Halbach array has more flux intensity and was enhanced by $\sqrt{2}$ compared to radial array for the same number of poles.
B. Air-gap flux distribution

In order to measure the air gap flux density, a non-object line was drawn at the air gap to obtain an average value of flux density. The speed of the motor system was set as 250 rpm, which indicates the average speed for the standard ceiling fan motor. Figure 6 illustrates the air gap field distribution of motor and generator for radial and Halbach machine respectively. It can be seen that the peak to peak value of Halbach array in motor system is 29% higher than with the radial array, the average value for radial is 28.9% higher than Halbach. On the other hand, for the generator system, the peak to peak value for Halbach is 24% higher than with the radial array, however, for the average value, radial is 24.1% higher than Halbach.

It is noted that the amplitude of air gap flux density in Halbach machine is not the similar as radial machine due to the relatively thick magnet ring used for both machines in this analysis. It can be seen that the air-gap field of Halbach array in the motor and the generator system is essentially sinusoidal and less ripple compared to the conventional radial array because of the Halbach magnetization. However, it is noted that the average value of flux density in Halbach machine is lower than radial machine. This can be explained that the size of radial magnet of Halbach machine is smaller than the radial machine. Thus, when the radial magnet pole in Halbach machine facing towards the slot opening of the stator, the travelling magnetic flux at the stator is at the lowest point. Therefore, the total average value of flux density is affected. Moreover, this analysis verified that the iron loss for Halbach array is much lower than radial array with a 30% reduction due to the effect of the sinusoidal flux density as shown in Figure 7. The hysteresis loss in the core loss equation is mainly depends on the flux ripple and peak-to-peak magnitude of the flux density. The sinusoidal flux density will have less ripple, thus minimize the core loss.

C. Back EMF.

Figure 8 shows the analysis of back EMF for motor and generator system respectively. The results show that the peak to peak value of back EMF for Halbach machine of motor system is increased by 5.2%, while the back EMF of generator system is increased by 0.42% which is less than 1% difference. However, the average value of back EMF for radial machine is 25% higher than Halbach machine for the motor part, whereas for the generator system, the average
value is 4.9% higher than Halbach machine. By way of comparison, the different values of back EMF are not significant, especially at the generator system.

Figure 8. Comparison of back EMF for radial machine and Halbach machine (a) motor system (b) generator system

From the analysis of the flux distribution, the peak to peak value of flux density in Halbach machine is almost 50% higher than radial, however, the generated back EMF is not significant at the generator system. This analysis proved that the radial machine have an adequate average value of flux density and back EMF compared to the Halbach machine. This is due to the flux distribution between the magnet poles is evenly distributed through the stator core and rotor back iron where there is no flux cancellation take place, therefore more flux is being captured by the winding coil and generate more back EMF.

In summary, Halbach machine has a good performance in producing a sinusoidal flux density that can minimize the cogging torque effect and core loss. However, Halbach machine used more permanent magnet for the same number of poles. Moreover, the generated back EMF in Halbach machine is not significant compared to radial machine. Thus, by considering the simplicity of the design and also the manufacturing cost, the radial machine is selected for the fabrication process. Overall, good agreements have been achieved.

IV. CONCLUSION

A comprehensive analysis was carried out to compare the performance of the conventional radial machine and Halbach machine to identify the potential candidate for the proposed design. By using the same design configurations for both proposed designs, an analysis using the FEA, has been performed for open circuit testing to predict the open circuit flux distribution, air-gap field density and the back EMF. Overall, Halbach offers a significant performance of air-gap flux density, which are more sinusoidal and less ripple for both motor and generator system, thus results in less iron loss or core loss. However, the average value of air gap flux density of Halbach array is lower because of the drop value of air gap flux density is lower than radial. Moreover, the generated back EMF between the radial and Halbach show a minor difference, especially at the generator part. Even though Halbach offers a better performance, nevertheless by considering the simplicity of the design and also manufacturing cost, the radial array machine is selected for the fabrication process.

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REFERENCES


