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Preliminary Studies on Number of Coil Turns per Phase and Distance between the Magnet Pairs for AFPM Ironless Electricity Generator

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Abstract. The generator that normally used in the market, which is the iron-cored electricity generator has high cogging and starting torques. By redesigning of the iron-cored electricity generator, Axial-flux Permanent Magnet (AFPM) configuration minimizes the usage of ferrite material. AFPM, one of the coreless electricity generator configuration has a less counter electromotive force (CEMF) compare to the cored electricity generator. AFPM configuration also has no cogging torque and low starting torque. Application of a coreless electricity generator is the most suitable compare to the cored electricity generator. However, it is expected that the elimination of the ferrite material within the coreless electricity generator itself increases the power generation. The configuration is the ironless electricity generator. This paper presents the design and analysis of the AFPM ironless electricity generator. There are two main parameters present in this paper, different number of turns of coil per phase and distance between a pair of the magnet. The result of the analysis shows that when the coil turns per phase increased, the voltage output and magnetic flux within the coil also increased. While increasing the distance between the magnets, the voltage output, and magnetic flux within the coil decreases.

1 Introduction

The iron cored generator is a type of the generator that widely used in the market. The usage of ferrite material on the iron-cored generator makes the generator itself become less efficient because of its high starting and cogging torques. The coreless electricity generator [1], the redesigning of the iron-cored generator by minimizing the usage of ferrite material on the generator itself, is seen as a promising solution to capture energy during in motion. Compare to the iron-cored electricity generator, coreless electricity generator had much lower cogging torque because of the elimination of the most ferrite material within the generator itself. However, compare to the ironless electricity generator, it has much lower starting torque, higher efficiency and can produce a considerable amount of electricity based on the size of the generator itself. This type of generator has no cogging effect and low CEMF resistance [2] during the operation to produce the electricity. It is because the generator itself does not have the iron core lamination that can be found in the iron-cored and coreless electricity generator. The iron-cored used in the cored system causes magnetic field between the iron-cored and the permanent magnet to resist the motion and thus, increase the starting torque and cause unnecessary loss of the electricity generated. The ironless electricity generator, the design that eliminate the usage of ferrite on the generator can further decrease the starting torque and unnecessary losses. From there, the ironless electricity generator is a promising solution to overcome issues faced by the iron-cored generator.

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2 Background Studies

It is divided into 5 sections. For section 2.1, the discussion on electricity generator is made. While in section 2.2, it discusses the magnet used in electricity generator. For section 2.3, the discussion on the coil winding, in section 2.4, it discusses the gaps between the magnets and for the section 2.5, it concludes the literature review.

2.1 Electricity Generator

Since the coreless electricity generator had no cogging torque and low starting torque, it is suitable to apply to the wind turbine. It is because there is no iron used in the stator construction and this in turns avoids direct magnetic attraction between rotor and stator [3].

For the AFPM machine, it is a type of coreless generator configuration. It has less core material than the iron-cored configuration. Moreover, AFPM machine has thin magnets, means that smaller than radial-flux counterparts [4]. The proposed generator had maximum efficiency at the rated operating conditions is 96.6% as compared to the value of 95.7% of the model of AFPM generator [5]. Compare to Radial Flux Permanent Magnet (RFPM), AFPM has a smaller volume and lower mass with the same power rating. [3].

For AFPM generator, it is made up of 2 different parts, namely rotor and stator. There are five various types of combination for coreless type generator, a double-stator slotted type, a double-rotor slotted type, a single-sided axial flux permanent magnet with stator balance, a single-sided axial flux permanent magnet with rotor balance and a slotless single-stator double-rotor type. Two-sided axial flux permanent magnet type is better than one-sided axial flux permanent magnet [6]. It is because of its high compactness, and disk-shaped profile makes the model suitable for integration with mechanical components such as wind turbine and internal combustion engine [7] and an additional generator for hybrid vehicles. This type of generator has no core and always has low inductance and thus, the increasing of current does not affect the machine performance [8]. It is cheap, easy to manufacture, and can produce up to hundreds of kilowatts of power in multi-disk operation. [9-10]. This type of generator also can operate on a wide variable range of frequency for optimal operation as well as provides an option to use the a gearless operation [11].

For the iron-core type inductors or iron-core type generator, it has high electricity conductivity due to the usage of iron in the lamination of the core. Thus, the main inductance decreases [12].

Because of the compactness and lightness as well as their high efficiency of the axial-flux coreless machine, they are among the most suitable candidates for many automotive applications [13]. It is because of the absence of core loss that caused by the iron core itself, the coreless stator AFPM machine can operate with higher efficiency compared to the conventional iron core machines [14].

The permanent magnet configuration is gaining a reputation amongst the researchers because of their high-power density, high torque-to-inertia ratio, high efficiency [15-16] as well as their robustness [17]. A special characteristic of the axial-flux coreless permanent-magnet generator is the usage of the non-ferromagnetic holder to counteract the centrifugal forces acting on the magnet during the rotation of the rotor disks [18]. The coreless configuration of axial flux machine eliminates ferromagnetic material. Thus, it eliminates the eddy current and hysteresis losses in the generator. It can stack axially so that the mechanical construction of the coreless axial flux machine can be simplified, reduced the weight of the stator so that small size actuator can employ for winding shift [19]. However, the usage of the back iron core in the design did not totally eliminate the cogging torque since the iron somehow reacts with the electromotive force during operation.

The output differs with the different number of poles and magnet strength [20]. In the Kobayashi's research, they found out that 48 poles generate most magnetic fields compared to 12 poles and 72 poles. The increase of poles number, the size of the coreless electricity generator also increased. For the large pole number, the diameter of the magnets and coils are fixed and limit the radial length of the active area that makes the generator has large radius with small active length. While for the small pole number, low-power turbines tend to spin relatively fast, but as power increases, reduction in speed is required, the number of poles should increase. The radial length of the active area can be small compared to the radius of the stator. This kind of problem can be reduced by using trapezoidal or rectangular magnets, and active length can decouple from each other [21].

2.2 Magnets

Since the magnet carries a significant role in making the generator an efficient one, the choice of making choose of magnet need to consider well. Neodymium Iron Boron (NdFeB) magnets are well known as the best magnet to be used. The continuous progress in the new high magnetic field rare-earth permanent magnets such as NdFeB magnet has given the automotive sector excellent opportunities on novel topologies for electric machine [22]. Increased availability and decreasing cost of high-energy permanent magnet materials, which is Neodymium Iron Boron (NdFeB) magnet, has resulted in rapid, permanent magnet generator development [23]. This modern magnetic material can easily obtain in the market with different shapes and grades. Thus, the design of the usage for magnet can be done easily. There is operating temperature within the magnet itself. Below the maximum operating temperature of the magnet, the magnet works perfectly fine, which is full magnetization, can be achieved. However, when the temperature exceeds maximum operating temperature, the magnetic force depleted until it reaches the Curie temperature, the magnet totally lost its magnetic force. When talking about the operating temperature of the magnet, it is closely related to the Permeance Coefficient of the magnet. Permeance Coefficient is the method of calculation to measure the shape of magnet since the maximum operating temperature differs from the shape of the magnets. The Permeance Coefficient is higher if the magnet has long and small cross sectional area. [24].

2.3 Coil Winding

The arrangement of the copper winding should be designed well so that it is able to maximize the magnetic flux cutting and the efficiency of the generator itself. For the coreless electricity generator, coils of wire are used instead of multiple interconnected wires where the magnet rotates over them to produce the electricity. For instance, when the north pole of a magnet passing through a coil, the current flows in one direction, and when the South Pole passes over the coil, current flow through in the opposite direction.

Based on the theories, the most electricity is generated while the magnetic field is at 90 degrees to the coil winding and no electricity is generated when the magnetic field is parallel to the coil. [25]. The magnet that currently at the North Pole is pushing upward on the left radial leg of the coil. At the same time, the magnet that currently at the South Pole is pushing downward on the right radial leg. These two clockwise motions cause the electricity being generated. Notice that if both radial legs are pushing in the same direction. For example, left and right radial leg is pushing upward together at the same time, the motion cancels out each other, and thus, no electricity is generated. That is the reason that it is essential to arrange the magnet poles alternatively so that the motion will not cancels each other. The coil then connects to the three-phase power connection for maximum electricity output. To make pole pitch equal to the diameter of the coil, the thickness of the coil cannot increase more than 33% of pole pitch. It is because of geometrical relation, or simply say, the distance between coils must be equal to 133% of the pole pitch [25].

2.4 Gaps between the Magnets

The gap between magnets also a point needs to be taken care during the design of the coreless generator itself. If the gaps between them are further away, the efficiency of the generator cannot reach its full potential. If the gaps between them are too close, there is problem on placing the stator (copper coil winding) between them.

The optimum air gap size is calculated using Eq. 1, where B_m represent maximum flux density in the air-gap, g represent the thickness of magnet, μ_0 represent air permeability that can be calculated using Eq. 2, B_r is for remanence, H_c is for coercivity of magnet, δ represent air-gap length, H is for external magnetic field strength and lastly for m, it represent magnetic moment. [25]

$$\mu_0 = 4\pi.10^{-7}\,\frac{H}{m} \tag{1}$$

$$B_m = \frac{2g\mu_0 B_r H_c}{B_r\delta + 2g\mu_0 H_c} \tag{2}$$

In Drazikowski Łukasz and Koczara Włodzimierz's research model, their machine optimum air gap size is about 35mm. For the economic reason, they choose 33mm as their preference air-gap because increasing air-gap in between 33mm to 38mm has no significant influence on total output power.

2.5 Summary

The coreless electricity generator have different number of poles while some of them have a closer gap between rotors and different in size. To eliminate the cogging torque and the CEMF, ferrite material had to eliminate from the generator. For the coreless electricity generator, although the usage of the iron core is in minimum, still, it is not perfect to totally eleminate the cogging torque and CEMF still exist within the generator itself. To overcome such problems, ironless electricity generator configuration of the generator is a promising solution to be considered. Ironless electricity generator configuration has no core material or iron used in both rotor and stator. With the cogging torque eliminated, and CEMF is minimize and thus, less torque is require to spin.

3 Analysis on the Ironless Electricity Generator

JMAG, software that specialize in conducting electromagnetic analysis [26], is used in this study because of its specialization in the electromagnetic field. This software is capable of analyzing the electromechanical design such as Three-Phase Synchronous Generator [27]. From there, lots of parameter such as the number of turns of coil per phase and the type of magnet used can be specified. Optimization on the ironless electricity generator can be done once mastering the software.

3.1 Analysis of the Changes of Number of Coil Turns

This set of analysis is the open circuit method, which means there is no load on the circuit. The manipulated variable in this set of analysis is the number of coil turn per phase. Other variables like the material used on rotor and stator, grade of Neodymium magnet used and the rotational speed of rotor are kept constant. The effects of the coil turns per phase on the circuit voltage and magnetic flux within the coils can be clearly shown. Figure 1 shows the magnetic flux density contour plot for 500 turns per phase analysis while Figure 2 and Figure 3 displays the circuit voltage and magnetic flux within the coil respectively. In Table 1, it shows the comparison of the result gained. The voltage and magnetic flux within the circuit between the 500 coil turns, 1000 coil turns, 1500 coil turns and 2000 coil turns per phase are shown in Table 1.

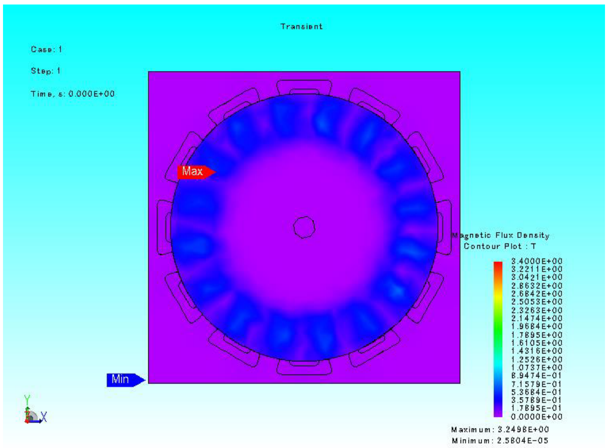

Figure 1. Magnetic flux density contour plot for 500 coil turns per phase analysis

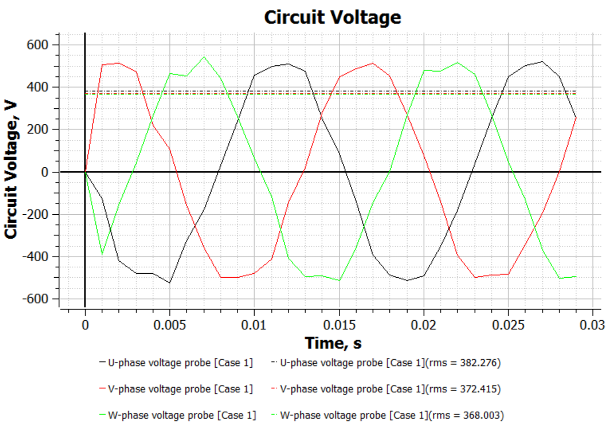

Figure 2. Circuit voltage for 500 coil turns per phase analysis

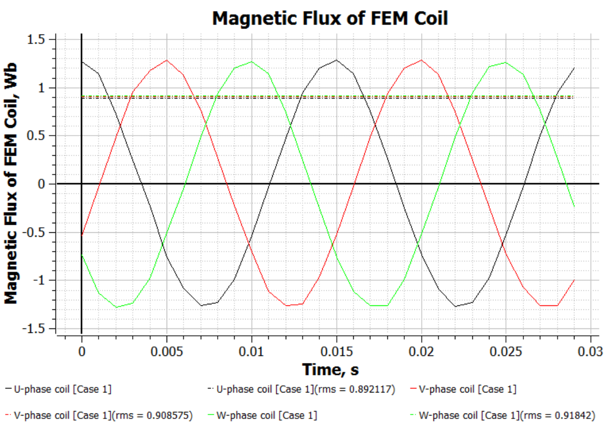

Figure 3. Magnetic flux within the coil for 500 coil turns per phase analysis

Table 1. Comparison between the number of coils turns per phase analysis

	500 coil turns	1000 coil turns	1500 coil turns	2000 coil turns
Magnet grade used	Grade N48 Neodymium Magnet			
U-phase circuit voltage (V_{rms})	382.28	764.55	1146.83	1529.10
V-phase circuit voltage (V_{rms})	372.42	744.83	1117.24	1489.66
W-phase circuit voltage (V_{rms})	368.00	736.01	1104.01	1472.01
Magnetic flux in U-phase coil (Wb_{rms})	0.89	1.78	2.68	3.57
Magnetic flux in V-phase coil (Wb_{rms})	0.91	1.82	2.73	3.63
Magnetic flux in W-phase coil (Wb_{rms})	0.92	1.84	2.76	3.67

3.2 Analysis of the Magnetic Distance

For the analysis of the gap distance between the magnetic pairs, the distance between the magnet pair is manipulated. In this analysis, it is using the open circuit configuration. Others parameter such as the material used on rotor and stator, magnet grade used and the number of coil turns per phase remain constant. There are total 5 different value of gap distance is analyzed with the distance between the magnet pairs of 12mm, 14mm, 16mm, 18mm, and 20mm respectively.

For Figure 4, it shows the magnetic flux density contour plot for 20mm magnet pairs distance simulation. Figure 5 shows the voltage within the circuit with the distance between the magnet pair of 20mm while Figure 6 shows the magnetic flux within the circuit for the 20mm distance between magnet pair analysis. Table 2 is the result comparison of different magnet pair distance.

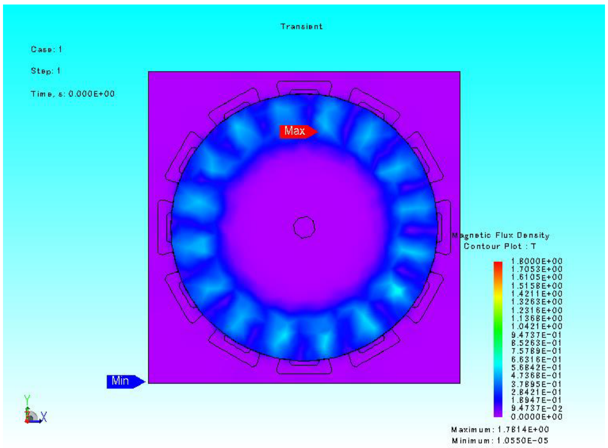

Figure 4. Magnetic flux density contour plot for magnet gap of 20mm analysis

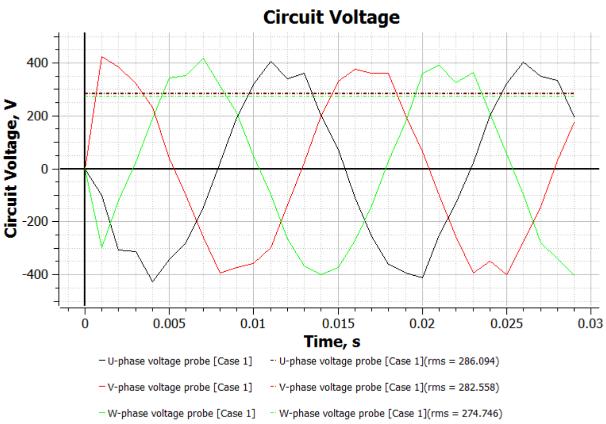

Figure 5. Circuit voltage for magnet gap of 20mm analysis

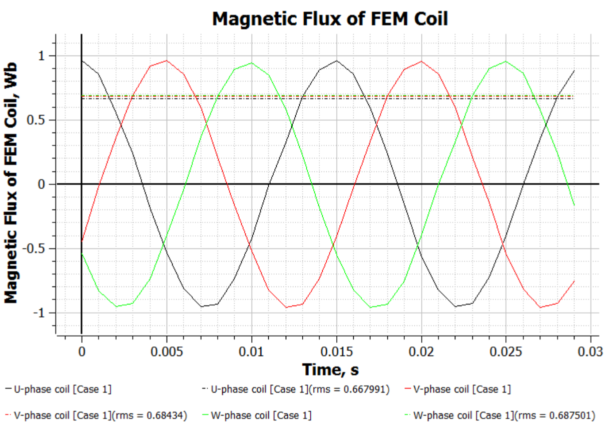

Figure 6. Magnetic Flux within the coil for magnet gap of 20mm analysis

Table 2. Comparison between the various gap distances between the magnets analyzes

	12mm	14mm	16mm	18mm	20mm
Magnet grade used	Grade N48 Neodymium Magnet				
Coil turns per phase	500				
U-phase circuit voltage (V_{rms})	382.28	353.21	329.98	307.22	286.09
V-phase circuit voltage (V_{rms})	372.42	345.63	323.00	301.67	282.56
W-phase circuit voltage (V_{rms})	368.00	338.47	317.82	295.22	274.75
Magnetic flux in U-phase coil (Wb_{rms})	0.89	0.83	0.77	0.72	0.67
Magnetic flux in V-phase coil (Wb_{rms})	0.91	0.84	0.79	0.74	0.68
Magnetic flux in W-phase coil (Wb_{rms})	0.92	0.85	0.79	0.74	0.69

4 Discussion

4.1 Discussion on Different Number of Coil Turns per Phase

When increasing the number of coil turns per phase, the result shows an increasing trend on voltage and magnetic flux within the coil. When increasing the number of coil turns per phase, it also increases the magnetic flux cutting rate, which cause the increasing of the voltage produced by the coil and magnetic flux in the coil as well. It is happening because with more turns of wire in the coil, the greater the strength of the static magnetic field around it. [28]

Refer to the Figure 7, the magnetic flux density within the design is concentrated. It is because the material used on rotor and stator is plastic, which means there is no reaction with the magnetic field. Thus, the magnetic flux is concentrated in the coil area.

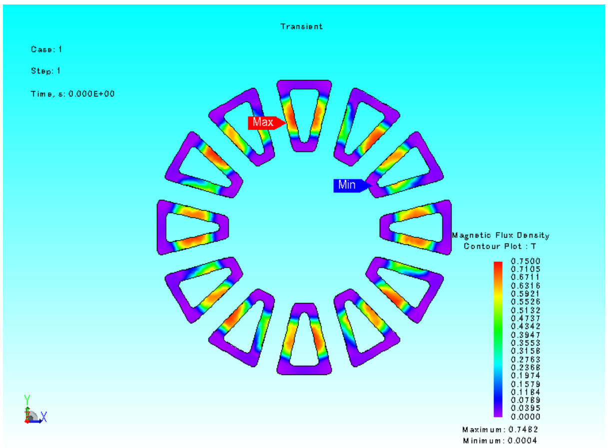

Figure 7. Magnetic flux concentrates on coil area

4.2 Discussion on Distance between the Magnet Pairs

When increasing the distance between the magnets pairs, the result shows a decreasing trend of voltage and magnetic flux within the coil. When increasing the distance between the magnets pair, the magnetic flux between the magnet decreases. With this, the magnetic flux cutting rate is decrease and thus, the voltage produced within the coil and the magnetic flux within the coil decrease. It is because the force acting between two magnetic poles is directly proportional to the product of their magnetic strength and inversely proportional to the square of the distance between the poles. [29]

5 Conclusion

Throughout the analysis, it can be concluded that the higher number of coil turns per phase, the higher voltage output and higher magnetic flux within the coil. For the gap between the magnet, it can be concluded that when the gap distance increase, the voltage produced by the coil and the magnetic flux within the coil decrease.

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