Effect of number of permanent magnetic poles on 3D printed coreless generator rotor

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Abstract. 3D-printed coreless generator using rotors with 4 poles permanent magnet and 8 poles permanent magnet as source of external magnetic field has been presented for energy harvesting applications. The prototype of proposed coreless generator is built using 3D-printer with Black Polylactic Acid (PLA) as a filament for stator housing, rotor and other parts. The major parts of the proposed coreless generator are the stator, which has four coils of winding copper wire and two rotors with four permanent magnet and eight permanent magnets which are arranging N and S magnet poles alternately. The prototype permanent magnet generator is tested with rotational speed and load condition. The experimental results have been shown that the coreless generator can generate electric energy up to 10300 mW for rotor with eight permanent magnets and 9000 mW for rotor with four permanent magnet at 5000 rpm, respectively.

1. Introduction

Permanent magnets generators (PMGs) exhibit a prospect to build energy efficient machine [1]. The stator and rotor are the major parts of PMGs. The main function of the stator is to generate alternating current from conductor windings while the rotor consists of permanent magnets as external magnetic field to generate the magnetic interaction with the stator. Nowadays PMGs are rapidly used in numerous applications in term of powering small or large-scale electronic systems, such as wind turbine application [2], hydroelectric generation [3] and others. Even though PMGs are able to achieve high efficiency compared with other generator types, however PMGs still more costly compared to other generators [4]. Therefore, many research works focus on the design of PMGs with basic requirements such as high output power, lightweight, simple construction, and low cost [1]. Unfortunately, the design consideration of those basic requirements should be carefully conducted based on the generator configuration and materials [4].

3D printing technology has become significant importance as rapid process to develop prototypes for various type of applications such as RF/microwave components [5], aerial vehicle wing structures [6], electromagnetic shielding [7] and biomedical applications [8]. Since the 3D printing technology has capabilities to develop complex geometries from the digital drawing, this technology becomes the major advantage in the manufacturing systems. The other advantage is that the 3D printing technology can be used to develop functionalities with other manufacturing methods [9]. Additionally, 3D printing technology can improve the design and lower the weight of the structure, resulting to a very cost-effective solution and reduction of lead times [10]. Based on these results, it is a worthy probability to use 3D printing technology for developing a generator. The development of generator using 3D-printing technology have been proposed by many researches works such as 3D-printed electrostatic generator [11], 3D-printed triboelectric generator [12], and 3D-printed materials low speed PM generator [13].

In this work, the possibilities of implementing 3D printed coreless generator with two kind of rotors for energy harvesting applications is reported. Following sections will explain the fabrication of the generator and the test results of the proposed 3D-printed coreless generator for both rotors.
2. Materials and methods

2.1. Fabrication of 3D printed coreless generator

The generator is meant to convert mechanical energy into electrical energy. However, the coreless generator is a generator that use the core for coil of winding copper wire by non-ferrous materials. Most of these type of generators used Permanent Magnet (PM) in the rotor. PM in generator supplied the magnetic excitation as conversion device producing all electromagnetic energy. The advantage of coreless generator is that it can eliminate the strong interaction in magnetic field between PM and ferrous core resulting to a high resistant on rotating rotor. Therefore, the coreless generators are suitable for harnessing renewable energy such as wind, rain water, river water, and tidal energy, which produce relatively small energy. Hence, the coreless generator can capture a small amount of energy by smooth rotation without any resistant of magnetic field.

The main parts of the generator are stator and rotor. There are two types of generator: the first type has stator which is fixed at the middle and a rotor that is located at the outer stator housing, and the other type has rotor at the middle and the stator is fixed at the outer housing. The stator functioned as conductor winding to generate alternative current. While, the rotor, where the PM took place, is operating as external magnetic field to generate the magnetic interaction with the stator, thus can produce the alternative current.

All parts of the coreless generator are designed using Autodesk Inventor. In the stator design, there are four stacks for winding coil of copper wire that are placed perpendicular to the next coil. Two types of rotor are designed for this study. The four permanent magnets and eight permanent magnets, which both of rotors have slots for easier placement. The stator is the stationary part in the outer housing whereas rotor is the inner part which rotates. The specification of designed coreless generator are summarised in table 1.

| Parameters                  | Value                      |
|-----------------------------|----------------------------|
| Pole numbers                | 4 poles (rotor 1) and 8 poles (rotor 2) |
| Stator Slot for winding     | 4 slots                    |
| Rotor diameter              | 45 mm                      |
| Length of stator stack      | 39 mm                      |
| Stator inner diameter       | 50 mm                      |
| Stator outer diameter       | 97 mm                      |
| Air gab length              | 2.5 mm                     |
| Magnet dimension            | 60 x 10 x 10 mm³           |

Anet A8 3D printer is used for the coreless generator fabrication with 1.75 mm of diameter of Black Polylactic Acid (PLA) as a 3D printing filament. Before running the 3D printer, the design of stator and rotor should be converted to stl file, then the file is opened in Cura software for printer setting. The setting are; the heating bed temperature and nozzle temperature set to 60°C and 210°C, respectively. The printing speed is 60 mm/s with the density of 60%. The support placement was chosen as “Everywhere” type to support hanging profile and can be removed easily without effecting the whole product. Figure 1 shows the construction of stator during operation of 3D printer.

A 0.60 mm copper conductor wire is used for winding coil for four slots of the stator with 500 turns in each slot as presented in figure 1. It is essential to count the turns for winding correctly and carefully. One turn of copper wire is set next to the other with enough tense and less gaps in between the turns of copper wire [4]. This is done to produce successful coils. At the rotors, four poles and eight poles neodymium magnets are chosen due to stronger magnets as Permanent Magnet (PM) with less volume to produce the external magnetic fields as shown in figure 2(a) and figure 2(b). The arrangement of the N and S magnet poles are set alternately.
2.2. Experimental setup

In conducting this prototype, there are four types of connection wire between the coils, due to the position of poles between 4 poles PM and 8 poles RM facing to the 4 winding coil stack in the stator are different. To get better understanding of winding coil, the illustration of winding coil is being labelling into inlet wire and outlet wire as shown in figure 3. Next, each of winding coils were connected with four different connections such as inlet to inlet, inlet to outlet, outlet to outlet, and others as summarized in figure 4.
The coreless generator was tested using 4 poles PM and 8 poles PM rotor for each four types of connection winding coil as shown in figure 4. Then the output of coreless generator is connected to a bridge rectifier to convert AC to DC current, load of 12 V bulb, voltmeter, and amp meter. The schematic diagram of experimental setup can be seen in figure 5. The prototype of the coreless generator was tested with rotational speed of 3000 rpm to observe the potential power output from the different connection winding coils. From these tests, two highest power output would be selected to further experiment.

![Figure 4. Four types of connection in winding coils in stator](image1)

![Figure 5. Schematic diagram of experimental setup](image2)
The further experiments were conducted with three different conditions. First, the coreless generator was running without any load to observe an amount of voltage and frequency of output generator that could be produced, which the frequency can be determined by speed of generator multiple with total number of poles and divided with 120.

Second, the coreless generator was running with 1 load of 12 V 5 W bulb. Lastly, the coreless generator was running with 2 loads of 12 V 5 W connected parallely. For second and third experiments, the current produced from the coreless can be observed by Amp meter and Voltmeter for monitoring voltage. The coreless generator was connected to 100 W AC motor to drive the rotor during the experiments that can be controlled by speed controller from 0 rpm up to 6000 rpm.

3. Results and Discussion

Table 2 summarized the voltage and current produced from each rotors and winding coils connection of the coreless generator at speed of 3000 rpm. It can be observed that there is only one connection for each rotor that have power output, and the rest are not show any power output during these tests. The 4 poles PM rotor (rotor 1) is appropriate to the connection 2, while the 8 poles PM rotor (rotor 2) is appropriate to the connection 1. The connection 3 and connection 4 for both of rotors show no voltage and current are produced, therefore both of these connections are not suitable for rotor 1 and rotor 2.

As shown in table 2, the connection between each winding coil using inlet to outlet connection seems not properly work for 4 poles PM (rotor 1) when first stack of winding coil is facing N pole PM, while second stack of winding coil is facing S pole PM. At the same time, third stack of winding coil is facing N pole PM and fourth stack of winding is facing S pole PM. Meanwhile, if the connection between each winding coil using inlet to inlet, then outlet to outlet, the generator can generate voltage and current for rotor 1. Hence, this connection (2) is working well with rotor 1 arrangement that can generate power from coreless generator.

For rotor 2, the connection between each winding coil using inlet to outlet connection is properly working when all the stacks of winding coil are facing N pole PM. It means that the connection 1 is working when all the stacks of winding coil are facing the same pole (N or S) at the same time. Meanwhile, if the connection between each winding coil using inlet to inlet, then outlet to outlet, (connection 2) there no voltage and current are produced, since this connection can only work if the stacks of winding coil are facing N pole PM for odd number and S pole PM for even number. Hence, this connection (1) is working well with rotor 2 arrangement that can generate power from coreless generator.

The connection 2 for rotor 1 and the connection 1 for rotor 2 were chosen for further experiments. Figure 6 is summarized the voltage produced from the coreless generator for rotor 1 and rotor 2. It can be observed for both rotors that the increasing voltage is depending on the increasing of speed linearly. The generator with rotor 1 can generate voltage up to almost 25 volt at 5000 rpm with frequency of 165 Hz, while generator with rotor 2 can generated voltage up to 35 volt at 5000 rpm with frequency of 340 Hz. From this experiment, it can be concluded that this coreless generator for both rotors need higher speed to get higher voltage. Nevertheless, the generator with rotor 2 produces higher voltage and frequency than rotor 1. It means that the number of poles in rotor has a significant effect in producing voltage, where increasing poles from 4 poles to 8 poles can increase around 40% higher voltage at 5000 rpm. To implement to the renewable source of energy, the gear ratio between generator and turbine is crucial to obtain higher voltage.

By applying loads in the coreless generator with both rotors, the voltage produced reduces. Higher load is implemented, the lower voltage will be generated as shown in figure 7. However, the increasing load can increase the output current. At 4500 rpm, the voltage without load can generate almost 22 volt for generator with rotor 1, and 30 volts for generator with rotor 2. But then by giving 1 load and 2 loads, for generator with rotor 1, the voltage reduces to 16 volt and 10 volt, respectively. While the output current by giving 1 load and 2 loads, can increase from 350 mA to 500 mA at 6000 rpm.

Figure 8 shows the power out produced from the coreless generator with rotor 1 and rotor 2 for 1 load and 2 loads. It is clearly shown that both of load can produce similar results for each rotor. However, for rotor 2, power output from generator with 2 loads is slightly higher than with 1 load. Even thought, the voltage and current produced from 1 load and 2 loads are different for each rotor. This coreless
A coreless generator can produce up to 10300 mW and 9000 mW at 5000 rpm for rotor 2 and rotor 1, respectively. Therefore, it can be concluded that rotor 2 has higher power output than rotor 1 and any load applied on this coreless generator, the power will produce in similar output for each rotor.

**Table 2.** Voltage and current produced from rotor 1 and rotor 2 for each connection (1, 2, 3, 4) of coreless generator

| Rotor 1 (4 poles PM) | Rotor 2 (8 poles PM) |
|----------------------|----------------------|
| **Connection of winding coil** | **Voltage (V)** | **Current (A)** | **Connection of winding coil** | **Voltage (V)** | **Current (A)** |
| 1 | 0 | 0 | 1 | 14 | 0.32 |
| 2 | 10 | 0.25 | 2 | 0 | 0 |
| 3 | 0 | 0 | 3 | 0 | 0 |
| 4 | 0 | 0 | 4 | 0 | 0 |
Figure 6. 3D printed coreless generator voltage and frequency with increasing speed for rotor 1 and rotor 2

Figure 7. 3D printed coreless generator voltage and current with increasing speed for rotor 1 and rotor 2 at 1 load (a) and 2 loads (b)

Figure 8. 3D printed coreless generator power with increasing speed for rotor 1 and rotor 2 with 1 load and 2 loads
4. Conclusions
In this work, the experiments with prototype of coreless generator created using 3D-printed are presented with different number of poles PM. The coreless generator is aimed to be applied in energy harvesting system. It was found that 3D-printed coreless generator can generate electric energy up to 10300 mW for rotor 2 and 9000 mW for rotor 1 at 5000 rpm that can be used in low-power system. Therefore, the development of coreless generator using 3D-printed exhibits promising potential to be used for this generator. Nevertheless, further studies are required to study the process developments in variety of filaments and setting on 3D printer.

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