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Open circuit V-I characteristics of a coreless ironless electric generator for low density wind power generation

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Abstract. Cogging is an attraction of magnetism between permanent magnets and soft ironcore lamination in a conventional electric ironcore generator. The presence of cog in the generator is seen somehow restricted the application of the generator in an application where low rotational torque is required. Cog torque requires an additional input power to overcome, hence became one of the power loss sources. With the increasing of power output, the cogging is also proportionally increased. This leads to the increasing of the supplied power of the driver motor to overcome the cog. Therefore, this research is embarked to study fundamentally about the possibility of removing ironcore lamination in an electric generator. This research deals with removal of ironcore lamination in electric generator to eliminate cog torque. A confinement technique is proposed to confine and focus magnetic flux by introducing opposing permanent magnets arrangement. The concept is then fabricated and experimentally validated to qualify its no-load characteristics. The rotational torque and power output are measured and efficiency is then analyzed. Results indicated that the generator produced RMS voltage of 416VAC at rotational speed of 1762 RPM. Torque required to rotate the generator was at 2Nm for various rotational speed. The generator has shown 30% lesser rotational torque compared to the conventional ironcore type generator due to the absent of cogging torque in the system. Lesser rotational torque required to rotate has made this type of generator has a potential to be used for low wind density wind turbine application.

1. Introduction

Ironcore lamination in a generator is used to confine and guide magnetic flux as to boost its efficiency to the maximum. Ironcore as what the name implies, consists of lamination of highly permeability core material which can increase the density of the magnetic flux in over several thousand. The advantage of confining and guiding the flux however giving a major drawback to the generator. When the ironcore lamination is exposed to the magnetic field, magnetic particle in the core tends to line up with the magnetic field of the permanent magnets. When the magnets rotated, its magnetic field changed in direction. This induces continuous movement of the ironcore's magnetic particle for them to align with the change of magnetic field direction and coincidently produces molecular friction. This in turn produces heat and is then transmitted/distributed to the ironcore lamination and windings. Heat causes increases in winding resistance and at the same time retains electromagnetism in the windings and ironcore laminations.

Electromagnetism in the ironcore lamination acted as a magnet and react (attract and repel) with the permanent magnets' field. The more power is generated from the generator, the more power is required to maintain its rotation as the input torque increased proportional to the power output. Therefore, the more heat is generated, the stronger the electromagnetism exists in the core causes unwanted attraction force with the permanent magnets field. Attraction force between permanent magnets and ironcore lamination in a generator or also known as 'cog' is seen as one of the major inefficiency in the generator [1-2].

Cog as the name implies, increases spinning torque where this indirectly increases the amount of work/energy used to spin the generator. Energy to overcome cog is basically proportional to the output power produced. The larger the output power is produced, the larger the amount of torque is required to spin (or maintaining the rotation speed). The presence of cog in the system however has made this conventional generator is far from being usable in low torque application [3-4]. Continuous and consistent power is required to overcome cog and the power varies when rotational speed varies.

There were many attempts made elsewhere to reduce cog to increase the application boundary of a generator [5]. Most of the efforts were focused on the ironcore optimization in design to minimize the effect of cog [6]. However, the presence of cog is still inevitable [7]. Effort made by removing iron core material from an electric motor had demonstrated great success more than a decade ago. The success story of this ironless motor has been widely shared by both among the researchers and industries. The idea behind this achievement is by removing the iron core lamination and replace it with non-ferrous material. The ironless motor works flawlessly and one of the major advantage came from it is outstanding positional accuracy and repeatability due to no cogging affecting the positioning.

Similar idea may be applied to demonstrate coreless generator design. Effort made on this subject however, is still lacking [8-10]. The idea of removing ironcore lamination material may cause non-concentrated flux and leads to deterioration in output power efficiency [3]. However, there is a method which may be used to concentrate and focus magnetic flux to create denser magnetic field. An additional permanent magnets arrangement added to the generator may be a solution to address this issue. The absence of ironcore lamination in the system also represent cog free rotation. This provides advantage in terms of very low starting torque and less counter electromotive force is produced.

2. Material and equipment

In the open circuit test for the ironless coreless electricity generator, a 2hp three-phase induction motor was used to function as the prime mover to rotate the rotor of the generator. This induction motor had a rating no-load rotational speed of 1400RPM, input voltage of 220V to 240V for delta connection, input voltage of 380V to 415V for star connection, rating current of 5.64A to 6.15A for delta connection and rating current of 3.26A to 3.56A for star connection with efficiency of 75.5% if the load usage was below half of the motor but 78.5% if the load usage was above three quarters of the motor. Table 1 shows the specification of the induction motor.

Table 1. Specification of the three-phase induction motor used in the experiment.

	Type of connections	
	Star connection	Delta connection
Horsepower	2hp	
No-load rotational speed	1400RPM	
Efficiency (<1/2)	75.5%	
Efficiency (>3/4)	78.5%	
Input voltage	380V-415V	220V-240V
Rating current	3.26A-3.56A	5.64A-6.15A

Since the motor was using alternating current supply to power up, the inverter was used to convert the direct current supply into alternating current supply so that the motor could operate. Based on the data obtained from the manufacturer datasheet of the inverter, the inverter had an efficiency of 96% when working within the rated load. Wires were used to connect the power source to the inverter. They were also used to connect the inverter to the motor. To measure the wave frequency and the voltage output of the three-phase circuit of the ironless coreless electricity generator, the oscilloscope was used. The oscilloscope was connected to the end of the three-phase circuit by using wires. The tachometer was used to measure the rotational speed of the rotors of the generator. Figure 1 shows the block diagram for the connection of the ironless coreless electricity generator in open circuit test.

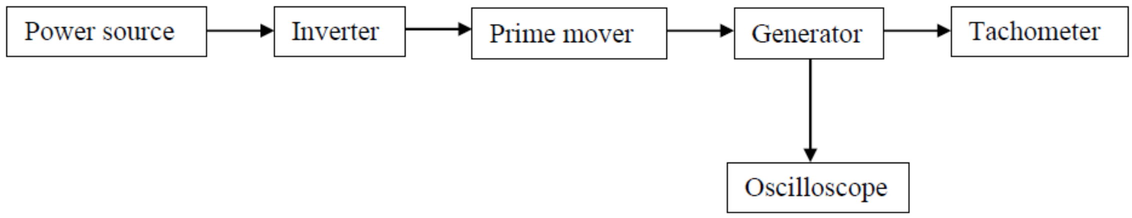

Figure 1. Block diagram for the connection of open circuit test.

3. Experimental setup and procedures

Before connecting the circuit to the induction motor, it was first aligned with the ironless coreless electricity generator. The center of motor shaft should be around 189mm from the surface of test bed to align them with the shaft of the ironless coreless electricity generator. The plate which supported the motor was then tightened using M8 bolts and nuts after the height of motor was set. The distance between the ironless coreless electricity generator and the motor was aligned horizontally by adjusting the generator. The bottom surface of the ironless coreless electricity generator was then locked on the test bed using M8 bolts and nuts. After the induction motor was well aligned with the generator, the connection between the induction motor and the generator was tightened with specifically made socket using socket cup point grub screws.

After the test bed was completely set up (Figure 2), the three-phase induction motor was connected using star connection as it could support higher voltage. The inverter was connected to power supply and the motor after the ironless coreless electricity generator and the motor were in place. The three-phase circuit of the ironless coreless electricity generator was then connected to the oscilloscope. When all the mechanical assembly and electrical assembly were done, the experiment began. After the power supply was switched on, a specified amount of power transferred to the motor was set by the inverter. The input power of the motor was controlled by the inverter using frequency input in the inverter. Once the setting was done and the rotational speed of the rotor was stabilized, the rotational speed of the rotor was observed using tachometer and recorded. To clearly obtain the graphical output wavelength from the oscilloscope, the *x*-axis was set to 10 milliseconds per column and *y*-axis was set to 50V per division, depending on the output voltage of the experiment. When the rotors were rotating, wave frequency and the output voltage were produced (see Figure 3). When everything was observed to have been completed, screenshots of the oscilloscope were taken and the data were transferred into the computer for data extraction process.

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Figure 2. Experimental test bed and setup.

4. Open circuit tests results and discussions

In the open circuit test, there were fifteen experiments carried out with various rotational speed settings Table 2. Figure 3 show the results of experiment screenshots from the oscilloscope with three colors to indicate different waveforms in the graph. Each color represented the output for U-phase voltage output, V-phase voltage output and W-phase voltage output, respectively. The x-axis represented times while the y-axis represented output voltage. The results showed the three-phase voltage output in the open circuit test was pure sinusoidal wave. Normally, the experimental results for other generators would not show such outcome without having done the augmentation on the output of the electricity generator. This was the selling point of this ironless coreless electricity generator because without adding extra equipment to produce or modify the output became pure sinusoidal wave, the losses in the system would be minimal. The statement regarding to the losses was supported by the findings of Tamura's research on calculation method of losses and efficiency of wind generators [11].

Table 2. Rotational speed and output voltage relation at various speed point.

Load Test	Rotational Speed (RPM)	Wave Frequency (Hz)	Output Voltage (V_{rms})	Rotational Speed Characteristic Group
1	166	22.81	39.4	Low
2	195	27.11	47.2	Low
3	262	35.16	61.3	Low
4	294	39.62	69.1	Low
5	398	53.19	92.7	Low
6	427	58.21	101.0	Low
7	465	62.81	109.0	Low
8	493	66.62	116.0	Low
9	528	69.64	121.0	Medium
10	560	75.64	131.0	Medium
11	690	92.42	159.0	Medium
12	740	100.90	163.0	Medium
13	1500	210.10	356.0	High
14	1671	228.80	403.0	High
15	1762	238.70	416.0	High

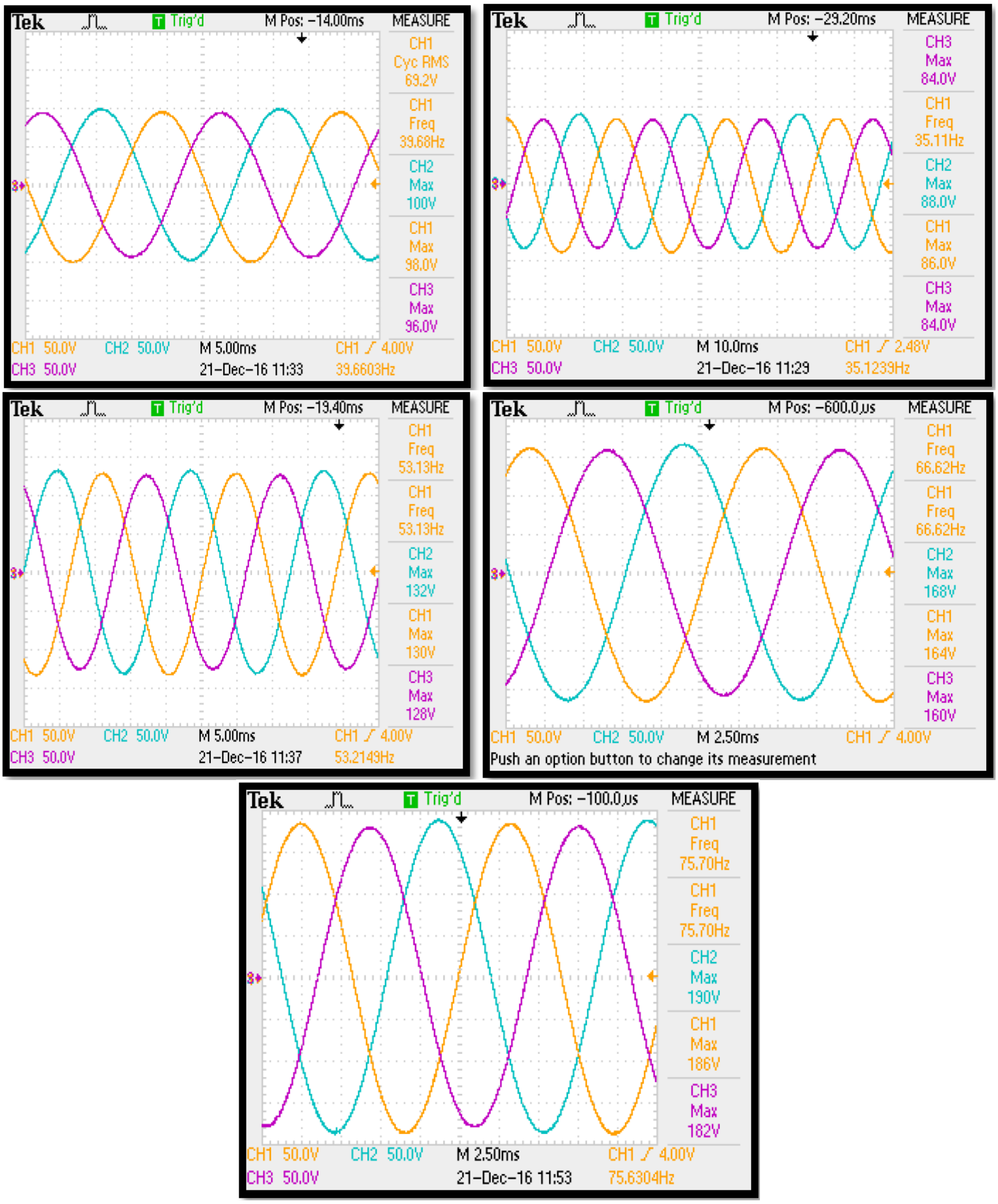

Figure 3. Phase voltages and characteristics for various rotational speed.

Table 2 summarizes the results of open circuit test from experiment 1 to 15. The experiments were categorized into three main groups denoted as low, medium and high speed. Low speed denotes speed between 0-499rpm while medium and high speeds are ranged between 500-999rpm and above 1000rpm respectively. At low speed 493rpm, the output voltage produced is at 116Vrms while medium speed at 740rpm produces 163Vrms. The maximum speed rotated by the induction motor is at 1700rpm where at this point, the output voltage was recorded at 416Vrms.

As shown in the Table 2, it was noted that the frequency of wave increased and the output voltage produced by the three-phase circuit of the ironless coreless electricity generator increased within the time frame when the rotational speed of the rotors of the ironless coreless electricity generator increased. This is because when the rotors of the generator were spinning faster, the frequency of magnetic flux cutting in the three-phase circuit on the stator of the ironless coreless electricity generator increased proportionally. When there was more magnetic flux cut by the three-phase circuit in the stator, the voltage per phase and wave frequency of each phase produced by the ironless coreless electricity generator also increased. This explanation for the open circuit test is similar and agrees with that of Chalmers and Spooner's research findings on an axial flux permanent magnet generator for a gearless wind energy system [12].

Figure 4 shows mechanical torque plot at various speed parameter. The RMS torque is rated at nearly 2Nm as recorded. This amount of torque is due to the force required to get the generator spun at constant speed without the presence of cogging torque. It is about 30% reduction of torque compared to the ironcore type AFPM generator [13].

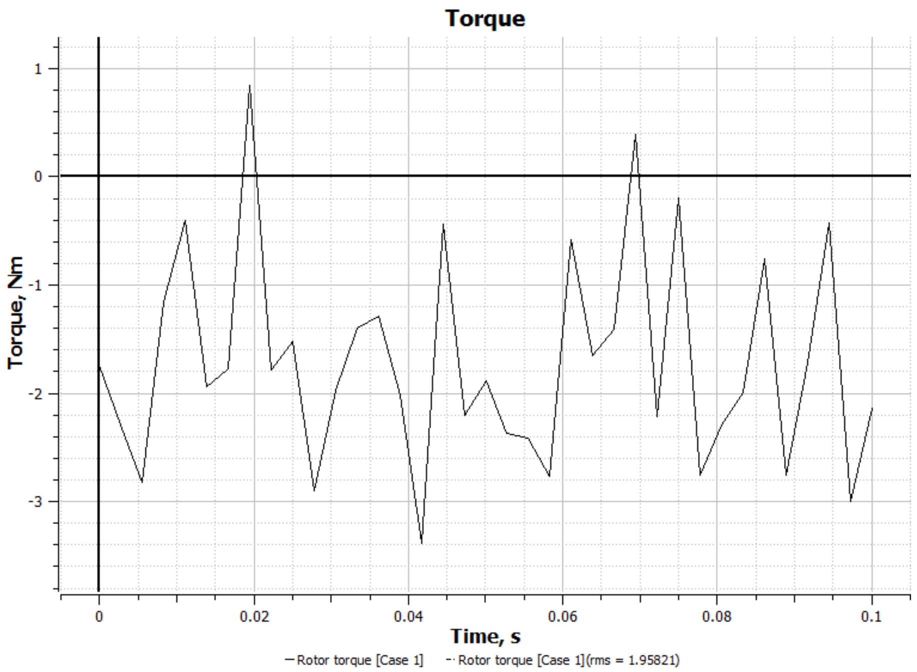

Figure 4. Mechanical torque plot rated at nearly $2Nm_{rms}$.

5. Conclusions

It can be concluded that the maximum voltage generated at maximum motor driver speed of 1762rpm was found to be at $416V_{rms}$. Pure sinusoidal voltage characteristics were observed throughout the tested low, medium and high rotational speed. The rated torque at various rotational speed was found at nearly 2Nm which is around 30% lesser than what conventional AFPM generator has to offer.

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