Maximum power point tracking analysis of a coreless ironless electric generator for renewable energy application

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Abstract. The magnetism attraction between permanent magnets and soft ironcore lamination in a conventional electric ironcore generator is often known as cogging. Cogging 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 to see its performance characteristic. In the maximum power point tracking test, the fabricated ironless coreless electricity generator was tested by applying the load on the ironless coreless electricity generator optimization to maximize the power generated, voltage and the current produced by the ironless coreless electricity generator when the rotational speed of the rotor increased throughout the test. The rotational torque and power output are measured, and efficiency is then analyzed. Results indicated that the generator produced RMS voltage of 200VAC at rotational speed of 318 RPM. Torque required to rotate the generator was at 10.8Nm. The generator had working efficiency of 77.73% and the power generated was at 280W.

1. Introduction
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 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. Due to being rated as high efficiency, it
has received widest coverage of application due to its advantages compared to the conventional rotary motor. 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.

| 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.

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 adjusted 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 1), 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. 4 channels DC electronic load with maximum voltage power of 80V/channel and 300W respectively was used to give the generator load and measure the output current and power generated.

![Figure 1. Experimental test bed and setup.](image)

In the maximum power point tracking test, the fabricated ironless coreless electricity generator was tested by applying the load on the ironless coreless electricity generator optimization to maximize the power generated, voltage produced and the current produced by the ironless coreless electricity generator when the rotational speed of the rotor increased throughout the test. Nine experiments were conducted for the maximum power point tracking test on the ironless coreless electricity generator.

### 4. Maximum point tracking tests results and discussions

Table 2 shows tabulated results of power input to inverter, power input to motor, power input to generator and power output by the generator in Watts (W). Throughout the rotational speeds, it can be observed that there are losses occurred when the power is transmitted from the source to the generator. As the rotational speeds increased, the efficiency of the generator in producing electricity is increased. Since the DC electronic load used has a maximum power measuring capability at 80V and 300W, therefore the experiments have to be stopped when the power output generated was at 280W. Any increment in rotational speed and power produced beyond this threshold could damage the instrument used. Between the speed range of 167 to 318RPM, the optimum load was found to be at around 35Ω. Voltage produced was found doubled at 100VAC when the rotational speed was at 318RPM if compared to the 167RPM. The increasing of rotational speed while at the same time increases the voltage output, it also increases the output currents generated by the generator. As voltage was doubled when the rotational speed got doubled from 167RPM to 318RPM, the currents also similar trend increased from 1.44A to 2.80A. As the trends of voltage and currents are increased when the rotational speed is increased, the mechanical torque was also found increased. The increased in counter electromotive force (CEMF) existed in the copper windings has made more power is required to overcome the attraction force between the coils and magnets. The increased torque also reflects the increment of power input to the generator throughout all experiments.
Table 2. Results for power input/output, torque, voltage, currents and efficiency in maximum power point tracking test.

| Speed (RPM) | Power input to inverter (W) | Power input to motor (W) | Power input to generator (W) | Power output (Generator) (W) | Torque (Nm) | Efficiency (%) | Volt (V) | Currents (A) | Load (ohm) |
|-------------|-----------------------------|--------------------------|----------------------------|-----------------------------|-------------|----------------|---------|--------------|-----------|
| 167         | 168                         | 161.28                   | 121.77                     | 72                          | 6.96        | 59.13          | 50      | 1.44         | 34.40     |
| 189         | 190                         | 182.40                   | 137.71                     | 92                          | 6.96        | 66.81          | 56      | 1.64         | 34.96     |
| 207         | 222                         | 213.12                   | 160.91                     | 118                         | 7.40        | 73.33          | 64      | 1.84         | 35.20     |
| 223         | 263                         | 252.48                   | 190.62                     | 140                         | 8.16        | 73.44          | 70      | 2.00         | 34.40     |
| 240         | 305                         | 292.80                   | 221.06                     | 164                         | 8.77        | 74.19          | 76      | 2.16         | 34.60     |
| 258         | 344                         | 330.24                   | 249.33                     | 192                         | 9.22        | 77.01          | 82      | 2.34         | 34.96     |
| 277         | 397                         | 381.12                   | 287.75                     | 220                         | 9.92        | 76.46          | 88      | 2.50         | 34.96     |
| 305         | 445                         | 427.20                   | 322.54                     | 250                         | 10.10       | 77.51          | 94      | 2.66         | 34.72     |
| 318         | 497                         | 477.12                   | 360.23                     | 280                         | 10.82       | 77.73          | 100     | 2.80         | 35.08     |

Figure 2 illustrates the power generated by the ironless coreless electricity generator versus the rotational speed of the rotor graph. As shown in the Figure 2, the graph is increase linearly as the output power generated by the ironless coreless electricity generator increased from 75W to 380W when the rotational speed of the rotors of the generator increased from 170RPM to 318RPM. Figure 3 and Figure 4 show the current produced by the ironless coreless electricity generator versus rotational speed of the rotor graph and the voltage produced by the ironless coreless electricity generator versus rotational speed of rotor graph, respectively. As illustrated in the Figure 3, the output current produced by the generator increased from 1.5A to 2.8A when the rotational speed of the rotors of the generator increased from 170RPM to 318RPM. Figure 4 provides an explanation to justify when the rotational speed of rotors of the generator rose from 170RPM to 318RPM, the output voltage generated by the ironless coreless electricity generator increased from 52V to 100V.

Figure 5 shows the graph for the optimum resistive load used by the ironless coreless electricity generator versus rotational speed graph. From the Figure 5, it is clear that when the resistive load was around 35 ohms, the ironless coreless electricity generator produced highest output power, output voltage and output current when the rotational speed of the rotors of the generator was 170RPM to 318RPM. Figure 6 illustrates the torque of the ironless coreless electricity generator versus rotational speed graph. The torque of the ironless coreless electricity generator was increase linearly from around 6.8Nm to around 10.5Nm when the rotational speed of the ironless coreless electricity generator increased from 170RPM to 318RPM. Figure 7 shows the efficiency of the ironless coreless electricity generator versus the rotational speed graph. The efficiency of the ironless coreless electricity generator increased gradually from around 59% until around 78% and after achieving 78% efficiency, the generator became less efficient as the rotational speed of the rotors increased from 170RPM to 318RPM.
Figure 2. Power generated by the ironless coreless electricity generator versus rotational speed graph for maximum power point tracking test.

Figure 3. Current versus rotational speed graph for maximum power point tracking test.
Figure 4. Voltage produced by the ironless coreless electricity generator versus rotational speed graph for maximum power point tracking test.

Figure 5. Optimum resistive load versus rotational speed graph for maximum power point tracking test.
The reason to conduct the maximum power point tracking test was because the maximum power point could be achieved by the permanent magnet synchronous generator by varying the generator’s load [11]. The results of the maximum power point tracking test were similar with the results of the various rotational speed constant load tests. This is because the after several times and some efforts to obtain the optimum resistive load which was most suitable for the fabricated ironless coreless electricity generator, the difference of the resistive load used by the ironless coreless electricity generator was small throughout the maximum power point tracking test. Since the resistive load used by the ironless coreless electricity generator was almost constant, the only thing that would affect the output of the ironless coreless electricity generator would be the rotational speed of the rotor. For the fabricated ironless coreless electricity generator in this research, the optimum range of the resistive load was between \(34\Omega\) and \(35\Omega\).

![Figure 6. Torque versus rotational speed graph for maximum power point tracking test.](image)

![Figure 7. Efficiency versus rotational speed graph for maximum power point tracking test.](image)
In the maximum power point tracking test, the torque of the ironless electricity generator increased when the rotational speed increased. When the rotational speed of the ironless coreless electricity generator increased, the power output of the generator also increased. As the power output of the generator became higher, the counter electromotive force between the rotors and stator of the generator would likely be higher. With this, the resistance of rotors and stator would increase, thus, more force would be required to operate the generator and thus, producing a higher torque. According to [12], in their research, when the power was higher, the torque density would increase and the power density would decrease.

It was noted that in the constant load various rotational speed tests and the maximum power point tracking test, the efficiency of the ironless coreless electricity generator only increased to around 78% as the rotational speed of the rotors of the generator kept increasing. This is because the ironless coreless electricity generator itself had reached its maximum efficiency when its efficiency was around 78%. It had been anticipated that the efficiency of the ironless coreless electricity generator would still be around 78% although there would be increment on the rotational speed of the rotor of the ironless coreless electricity generator itself. The trend of the efficiency of fabricated ironless coreless electricity generator was in good agreement with that in [13] research as the efficiency of DFIG3G, DDSG and DDPMG in their research would stay constant when these generators reached their maximum capabilities. Due to the limitation on instrumentation, the fabricated generator cannot reach rotational speed to as high as the [14]. But it is believed that there is still more potential and performance that can be harnessed from the generator.

5. Conclusions

The ironless coreless electricity generator showed evidence that it could achieve up to 78% efficiency. In the maximum power point tracking test, after several attempts and efforts, the results obtained from this test were that the optimum resistive load was around 34 ohms to 35 ohms as the ironless coreless electricity generator would be able to produce maximum amount of output power, output voltage, output current, torque and efficiency throughout the rotational speed.

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