Performance and optimum characteristics by finite element analysis of a coreless ironless electric generator for low wind density 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. There were several parameters analysed using the JMAG Designer. Transient response analysis was used in the JMAG Designer. The parameters analysed were the number of coil turns per phase, gap distance between the magnet pairs as well as the magnet grade used. These few parameters were analysed under the open circuit condition. Results showed with the increasing of gap distance, output voltage produced decreased. The increment of number of turns in the coils and higher magnet grades used, these increased the output voltage of the generator. With the help of these results, a reference point is established to get optimum design parameter for fabrication of working prototype.

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. Procedures

Electromechanical analysis could help gain the result of magnetic flux exerted by the magnet from the magnetic flux density distribution of the electricity generator design and the magnetic flux on the coil. The ironless electricity generator was designed using CAD software. The proposed design for the ironless coreless electricity generator in this research was double-rotor single-stator configuration. Within the stator, there were 12 coils which were joined using three-phase star connection. As for the rotors, 16 magnets were embedded on each rotor. The ironless coreless electricity generator model was then exported to the JMAG designer software when design was completed. The ironless coreless electricity generator model was analysed by using JMAG designer analysis software. Transient analysis was used to examine the model because it was able to simulate real life situation in which the ironless coreless electricity generator would be operating.

After choosing the type of magnets to be used in the analysis, the direction of the magnetic force was defined. Since the connection for the ironless coreless electricity generator model has to be in star three-phase connection, the circuit connection for the analysis on the model was set accordingly. The voltage probe was attached on the end of star three-phase connection so that the voltage for each phase could be shown. As for the open-loaded test, there was no load applied on the circuit. Meanwhile, for the closed-loaded test, the load was applied on the end of the star connection. After the connection for the analysis was defined, the rotation motion which needed to be applied on the rotors of the model was defined. It was set to 500 rotational per minute as the rotational speed would be the constant variable for this experiment. The U-phase, V-phase and W-phase FEM coils were defined accordingly and set to clockwise direction to avoid directional error on the circuit. These coils were then synchronised with the circuit. The method of how to set the phase for the FEM coils are readily available in the JMAG designer official website, application note section.

As for the meshing type in this analysis, the standard meshing with auto meshing method was chosen as the software is set to the appropriate meshing size by default for the ironless coreless electricity generator model. The step control for the analysis on the model for this research was set based on Equation 1 where \( t_1 \) is desired end time of the analysis and \( t_0 \) is start time of analysis. For the case on this research, the regular intervals step control was chosen. It is because by using this type of step control, the regularity of the simulated situation for the model could be shown. The number of steps used was defined as 37 steps and the number of division was set to 36 divisions. The reason for the setting to be made in such a way was because the first steps of the simulation were not so significant since the generator just started to operate. Another reason is the simulation had to run in full cycle, as 36 divisions of analysis were able to finish it with 37 steps. The reason that the simulation just ran in one full cycle is because to save the time on running the analysis on the model since the outcome of the simulation would be the same. After all the setting was done, the analysis on the ironless coreless electricity generator model was started.
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\text{Time Interval (s)} = \frac{t_1 - t_0}{\text{Division}}
\]  

Results such as the magnetic flux density contour plot, circuit voltage and magnetic flux of FEM coil were obtained in the open-loaded circuit test as there was no load applied on the analysis on the model. As for the closed-loaded circuit, the joule loss, current and electric power could be obtained since there was load applied on the analysis on the model and the current generated was flowing through the applied load. Several parameters were tested on the generator. These parameters were the magnet grade used on the model, number of coil turns per phase and gap distance between the magnets. The reason to test the parameter was to gain knowledge on how these parameters would affect the output of the model. It would also help to get the optimized parameter which could be used on the fabrication works of the ironless coreless electricity generator.

3. Results and discussions

3.1 Number of Coil Turns per Phase

There were four sets of number of coil turns per phase done in this section: 500 coil turns per phase; 1000 coil turns per phase; 1500 coil turns per phase; and, 2000 coil turns per phase. Other parameters such as magnet grade used, material used on rotor and stator and gap distance between the magnet pairs remained constant so that the best results for the number of coil turns per phase could be obtained. The magnet grade used in this analysis was N48 Neodymium magnet, while the gap distance between the magnet pairs was set to 12mm and the material used on the rotor and stator was aluminium. The only concern was how number of coil turn per phase effects the outcome, other parameters just act as the constant variables.

Figure 1 shows the magnetic flux density contour plot on the ironless electricity generator in JMAG designer software. The purple colors signify that there was no magnetic flux distribution within the area as the value of the magnetic flux density was 0T, while the lighter the blue color signifies the more magnetic flux distribution happened within the area as the magnetic flux density value fluctuated between 4.4737x10^{-2}T and 3.5789x10^{-1}T. It is good result as it shows very less magnetic flux flow outwards the rotor and stator.

![Figure 1. Magnetic Flux Density Contour Plot for 500 Coil Turns per Phase Analysis in JMAG designer software.](image_url)

Table 1 shows the summary of the finite element analysis on the number of coil turns per phase. It is apparent that the torque of the rotors of the ironless coreless electricity generator remained constant when the coil turns per phase increased. The value of the rotor torque in RMS was around 2.391Nm. The
magnetic flux within U-phase coil, V-phase coil and W-phase coil as well as circuit voltage for U-phase coil, V-phase coil and W-phase coil showed an upward trend as the number of coil turns per phase increased. By comparing the results for 500 coil turns per phase and 1000 coil turns per phase, the output precisely increased one-fold as observed in the 500 coil turns per phase analysis. As can be seen in the table, the RMS value for the magnetic flux per phase in the 500 coil turns per phase was approximately 0.334Wb/phase and this increased to 0.668Wb/phase for the magnetic flux per phase in the 1000 coil turns per phase. The magnetic flux value per phase further increased to approximately 1.003Wb/phase and 1.337Wb/phase in the 1500 coil turns per phase and in the 2000 coil turns per phase, respectively. As for the value of circuit voltage, an upward trend was also observed when the coil turns per phase increased. In the 500 coil turns per phase, the RMS value was approximately 132V/phase and later increased to 264V/phase in the 1000 coil turns per phase. The value of the circuit voltage further increased to approximately 396V/phase and 528V/phase in the 1500 coil turns per phase and in the 2000 coil turns per phase, respectively.

| Table 1. Summary of the finite element analysis on the number of coil turns per phase. |
|---------------------------------------------------------------|
| Number of turns per phase (coils)                             |
| 500               | 1000               | 1500               | 2000               |
| Gap distance between the magnet                               | 12mm               |
| Magnet grade used                                            | N48 Neodymium Magnet |
| Rotational speed of rotor                                     | 500RPM             |
| Rotor Torque (Nm<sub>rm</sub>)                                | 2.391              | 2.391              | 2.391              | 2.391              |
| Magnetic flux for U-phase coil (Wb<sub>rm</sub>)              | 0.335              | 0.669              | 1.004              | 1.339              |
| Magnetic flux for V-phase coil (Wb<sub>rm</sub>)              | 0.334              | 0.668              | 1.003              | 1.337              |
| Magnetic flux for W-phase coil (Wb<sub>rm</sub>)              | 0.338              | 0.676              | 1.013              | 1.351              |
| Circuit voltage for U-phase coil (V<sub>rm</sub>)            | 131.531            | 263.061            | 394.592            | 526.123            |
| Circuit voltage for V-phase coil (V<sub>rm</sub>)            | 132.844            | 265.687            | 398.531            | 531.374            |
| Circuit voltage for W-phase coil (V<sub>rm</sub>)            | 131.233            | 262.466            | 393.700            | 524.933            |
3.2 Gap Distance between the Magnet Pairs

Table 2 shows the summary of the finite element analysis on the gap distance between the magnet pairs. What is interesting in these data is that the torque of the rotors of the ironless coreless electricity generator showed a downward trend as the gap distance between the magnet pair increased. During 14mm gap distance test, the torque RMS value of the rotors was 2.951Nm. When the gap distance increased to 16mm, the torque RMS value of the rotors decreased to 2.893Nm. The torque RMS value of the rotors was then further decreased to 2.838Nm when the gap distance increased to 18mm. In 20mm gap distance test, the torque RMS value of the rotors dropped significantly to 2.367Nm. The RMS value of torque of the rotors further dropped to 2.291Nm during the 22mm gap distance test. The torque RMS of the rotors decreased to 2.098Nm when the gap distance increased to 24mm. During the 26mm gap distance analysis, the RMS value of the torque of the rotors of the ironless coreless electricity generator decreased to 1.819Nm.

In the gap distance between magnet pair analysis, the magnetic flux and the circuit voltage of the three-phase coil of the ironless coreless electricity generator was in decreasing trend while the gap distance between the magnet pairs is increase. As shown in 14mm gap distance test, the magnetic flux RMS value per phase was 0.415Wb/phase. The magnetic flux RMS value decreased to approximately 0.366Wb/phase for 16mm gap distance test. The magnetic flux RMS value further decreased to around 0.361Wb/phase for 18mm gap distance test. When the experiment proceeded with the 20mm gap distance test, the magnetic flux RMS value per phase decreased to 0.337Wb/phase. For the 22mm gap distance test, the magnetic flux RMS value was reduced to 0.335Wb/phase. The magnetic flux RMS value per phase then further dropped to 0.294Wb/phase when the 24mm gap distance test was carried out. During the 26mm gap distance test, the lowest value of magnetic flux RMS value per phase amongst all the test results was obtained, which was approximately 0.274Wb/phase.

In the 14mm gap distance test, the circuit voltage RMS value was approximately 163V/phase. The circuit voltage RMS value decreased to 152V/phase when 16mm gap distance test was carried out. The circuit voltage RMS then further dropped to 142V/phase during the 18mm gap distance test. In 20mm gap distance test, the circuit voltage RMS value was approximately 132V/phase, indicating a lower value compared to that of the 18mm gap distance test. For 22mm gap distance test, the circuit voltage RMS value was 131V/phase. The RMS value for the circuit voltage then continued to decline to 116V/phase in 24mm gap distance test. In the 26mm gap distance test, the circuit voltage RMS was 109V/phase, which was the lowest amongst all values in the gap distance tests.

3.3 Magnet Grade Used on Magnet Pairs

There were five sets of analysis on the magnet grade test. The magnet grades used were N42, N45, N48, N50 and N52 Neodymium. Other parameters such as the number of coil turns per phase, gap distance between the magnet pairs and material used on the rotor and stator remained constant so that the results for magnet grade tests could be obtained accurately. The number of coil turns per phase was set to 500 coil turns per phase and the gap distance between the magnet pairs was set to 20mm.

Table 3 shows the summary of the finite element analysis on magnet grade used on magnet pairs. From Table 3, the torque of the rotors of the ironless coreless electricity generator shows an upward trend when the magnet grade used was increased. When N42 Neodymium Magnets was used in the analysis, the RMS value of torque of the rotors was 1.958Nm. The RMS value of the torque of the rotors then increased to 2.103Nm when N45 Neodymium Magnet was used. The RMS value of the torque of the rotors further increased to 2.165Nm when the N48 Neodymium Magnet was used in the analysis. When the N50 Neodymium Magnet and the N52 Neodymium Magnet were used in the magnet grade analysis, the RMS values of torque of the rotors rose to 2.293Nm and 2.391Nm, respectively.

In the magnet grade analysis, the magnetic flux and the circuit voltage in the three-phase coil showed an increasing trend from N42 Neodymium magnet to N52 Neodymium magnet. As indicated in the magnetic flux RMS value in the N42 Neodymium magnet test, a value of around 0.303Wb/phase was obtained. The magnetic flux RMS value increased to 0.314Wb/phase in the N45 Neodymium magnet test and further increased to 0.318Wb/phase in the N48 Neodymium magnet test. The N50 Neodymium magnet test produced a value of approximately 0.328Wb/phase for the magnetic flux RMS value while the N52 Neodymium magnet test produced a value of 0.335Wb/phase, which was the highest value amongst all values in the five tests.

Meanwhile, the circuit voltage RMS value for in the N42 Neodymium magnet test was 119V/phase. This value increased to 123V/phase in the N45 Neodymium magnet test and slightly increased to 125V/phase in the N48 Neodymium magnet test. The circuit voltage RMS values in the N50 Neodymium and N52 Neodymium magnet tests continued to increase to 129V/phase and 131V/phase, respectively.
The circuit voltage RMS value in N52 Neodymium magnet test was the highest amongst all values in the five magnets grade test.

**Table 2. Summary of finite element analysis on the gap distance between magnet pairs.**

| Gap Distance (mm) | 14mm | 16mm | 18mm | 20mm | 22mm | 24mm | 26mm |
|-------------------|------|------|------|------|------|------|------|
| Number of coil turns per phase | 500  |      |      |      |      |      |      |
| Magnet grade used |      | N48 Neodymium Magnet |      |      |      |      |      |
| Rotational speed |      | 500RPM |      |      |      |      |      |
| Rotor Torque (Nm) | 2.951| 2.893| 2.838| 2.367| 2.291| 2.098| 1.819|
| Magnetic flux for U-phase coil (Wb) | 0.416| 0.386| 0.361| 0.337| 0.335| 0.294| 0.274|
| Magnetic flux for V-phase coil (Wb) | 0.415| 0.385| 0.358| 0.336| 0.334| 0.294| 0.275|
| Magnetic flux for W-phase coil (Wb) | 0.418| 0.388| 0.362| 0.340| 0.338| 0.296| 0.277|
| Circuit voltage for U-phase coil (V) | 162.989| 151.330| 141.315| 131.901| 131.531| 115.031| 107.439|
| Circuit voltage for V-phase coil (V) | 164.736| 152.881| 142.304| 133.684| 132.844| 116.692| 109.364|
| Circuit voltage for W-phase coil (V) | 162.932| 151.248| 141.110| 132.625| 131.233| 115.526| 108.128|
Table 3. Summary of the finite element analysis on magnet grade used on magnet pairs.

|                        | N42  | N45  | N48  | N50  | N52  |
|------------------------|------|------|------|------|------|
| Number of coil turns   |      |      |      |      |      |
| per phase              |      |      |      |      |      |
| Gap distance           |      |      |      |      |      |
| between magnet pairs   |      |      |      |      |      |
| Rotational speed of    |      |      |      |      |      |
| rotor                  |      |      |      |      |      |
| Rotational speed of    |      |      |      |      |      |
| rotor                  |      |      |      |      |      |
| Rotor torque (Nm<sub>ms</sub>) | 1.958| 2.103| 2.165| 2.293| 2.391|
| Magnetic flux for U-phase coil (Wb<sub>ms</sub>) | 0.303| 0.314| 0.318| 0.328| 0.335|
| Magnetic flux for V-phase coil (Wb<sub>ms</sub>) | 0.302| 0.313| 0.318| 0.327| 0.334|
| Magnetic flux for W-phase coil (Wb<sub>ms</sub>) | 0.306| 0.316| 0.321| 0.331| 0.338|
| Circuit voltage for U-phase coil (V<sub>ms</sub>) | 119.031| 123.338| 125.159| 128.800| 131.531|
| Circuit voltage for V-phase coil (V<sub>ms</sub>) | 120.217| 124.570| 126.408| 130.086| 132.844|
| Circuit voltage for W-phase coil (V<sub>ms</sub>) | 118.760| 123.060| 124.876| 128.509| 131.233|

3.4 Discussion on the Simulation Results

During the test on coil turns per phase, the torque on the rotors of the ironless coreless electricity generator was remained constant when the coil turns per phase increase. It was because there was no adjustment made on the rotors, for example, to make the rotors heavier, and thus, the torque of the rotors remained constant. Both magnetic flux within the circuit and circuit voltage showed an upward trend with the increase in the coil turns per phase. This is because as the number of coil turns per phase increased, there would be increasing number of magnetic flux cutting process by the coil and thus, magnetic flux and circuit voltage within the three-phase coil would also increase. An increase in coil turns would cause the output of the generator, the cost as well as the size to increase. Since in this research was concerned with developing a table size ironless coreless electricity generator, 500 coil turns per phase was chosen because it required less space and minimal cost.

The circuit voltage RMS value declined while the gap distance between the magnets pairs increased in the gap distance analysis. The reason behind this is because when the distance between magnet pairs increased, the magnetic strength between the magnet pairs decreased, which caused the quality of the magnetic flux cut to drop and thus, magnetic flux and circuit voltage generated in three phase coils would decrease. If the gap distance was too close, there could be a chance that rubbing might occur between the rotor and stator, which would reduce the efficiency of the ironless coreless electricity generator. By considering this error, the gap distance between the magnet pairs of 26mm was chosen to prevent such problem from happening.

The magnetic flux RMS value and circuit voltage RMS value showed increasing trends with the increase in the grade of the magnet used in the magnet grade analysis. The reason behind it is because amongst these five grades of magnet, N52 had the strongest magnetic field and it did produce better quality magnetic flux during the three-phase coil cutting through the magnetic field. In the market, N50
Neodymium magnet and N52 Neodymium magnets can be easily obtained. N52 Neodymium magnet was the choice for making the electricity generator because it could produce better quality of the magnetic flux compared to that of the other grades. Although using N52 Neodymium magnet on ironless coreless electricity generator did increase the torque of the generator, the output of the generator did compensate on such weakness.

During the gap distance analysis, the torque of the rotors of the ironless coreless electricity generator showed downward trend as the gap distance increased. The reason behind it is because when the magnet pairs moved further away, the magnetic force between it became weakened and made the pulling force between the rotors weaker. In the magnet grade analysis, the torque of the rotors of the ironless coreless electricity generator increased when the magnet grade used on the analysis was stronger. Such phenomena occurred because when the stronger magnet was used on the rotors, it made the pulling force between the rotors became stronger. When the pulling force between the rotors was stronger, more energy would be required to spin. Thus, this would increase the torque of the rotors.

4. Conclusions
The results in this finite element analysis showed that the optimum parameters to be used were: 1000 coil turns per phase; 14mm gap distance between the magnet pairs; N52 Neodymium magnet grade; and, plastic as the material used on rotor and stator. However, due to the consideration of the manufacturing process tolerance such as deformation after machining, 500 coil turns per phase, 26mm gap distance between the magnet pairs, N52 Neodymium magnet grade used on rotor and stator was chosen. Another finite element analysis would also be conducted on the optimum parameter design so that the results could be used as the datum to fabricate the ironless coreless electricity generator.

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