Voltage generation characteristics of an Axial Flux Permanent Magnet (AFPM) generator

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Abstract. A specially designed low-speed generator was enveloped based on low-speed turbines. The axial flux permanent magnet (AFPM) generator type is chosen to meet these needs. The generator consists of a stator and a rotor. The distance between the stator and rotor was studied to determine the characteristics of the AFPM generator. Besides, the impact of rotational speed on the output voltage also considers - the stator armatures made of copper wire with a diameter of 0.2 mm. The number of turns of a winding was 200 turns, which produced a resistance of 100 ohms. The shape of the armatures adjusted to the shape of the magnet. The rotor discs occupied by 18 magnets arranged symmetrically. The size of the magnet was 50 mm long, 30 mm wide and 13 mm thick. The laboratory test conducted by placing the rotor ranging from 23 mm to 15 mm, with changes in the distance of 2 mm each, from the stator. From the measurement, the linear equation of output voltage versus the rpm curve obtained as well as the output voltage versus the stator-rotor distance equation. The results show that the increase of rpm and the closer the rotor-stator distance, the higher the output voltage.

1. Introduction
A power generation system uses for the utilization of renewable energy. One of them is wind power system. It is shown in figure 1 [1]. The plant consists of a wind turbine that is used to convert fluid kinetic energy into shaft energy. The shaft rotation is conditioned to match the rotation of the generator using a transmission system. The transmission system is connected to the generator so that the generator rotates to produce electricity [2]. The electricity is conditioned by transformers and rectifiers to match the load.

![Figure 1. Wind power generation system with constant speed turbine.](image)

The main problem in wind energy utilization is the fluctuation and the low speed of the wind [2-5]. Thus, a specially designed low-speed generator is needed to overcome these problems. Axial flux
permanent magnet generator (AFPMG) is a suitable generator type to be applied in low-speed turbines such as vertical axis wind turbine (VAWT) [6]. AFPMG is a new class of generators which are considered having higher efficiency and more effective than radial flux generators [7,8]. It can work at low speed because it has some permanent magnets. The magnets within the rotating part of the generator called the rotor. The armature windings that placed on the stationary part of the generator called the stator [9]. There are various types of AFPMG generators, including single-sided slot less, single-sided slotted, double-sided internal rotor, double-sided inner stator, and multi-disc [2, 9-11].

The generator output voltage can be calculated using equation (1).

\[ E_{\text{per-phase}} = k \times n \times p \times N \times \Phi_{\text{max}} \]  

where \( k \) is a constant, \( n \) is the rotor rotational speed (rpm), \( p \) is the number of magnet poles, \( N \) is the number of turns per phase, and \( \Phi_{\text{max}} \) is the maximum flux of the armature winding. The sufficient value of the output voltage at the armature winding determined by parameters such as rotor rotational speed \( n \), the number of generator poles \( p \), the number of turns of the armature windings \( N \) and the maximum magnetic field strength \( \Phi_{\text{max}} \). The value of \( k \) is influenced by Air gap, air quality, copper winding material composition, and size of the armature windings, the heat of component and the position of the armature winding. The number of magnetic poles and rotations, in addition to the voltage, also influences the frequency calculated by using equation (2).

\[ f = n \times p / 120 \]  

where \( p \) is the number of magnetic poles, and \( n \) is the rotor rotational speed.

2. Methodology

Figure 2 shows the experimental setup. The voltage generated was measured using a voltmeter. The maximum rotor rotation was 1000 rpm, it was measured using a tachometer.

![Figure 2. Experimental setup.](image)

The armature windings as shown in figure 3 was made of copper wire of 0.2 mm diameter, the wire was formed to a rectangular shape with a length of about 50 mm and a width of 30 mm. The size and shape were taken to approach the size and shape of the magnets. The number of turns of a winding was 200 turns which produced a resistance of 100 ohms.

![Figure 3. The armature winding.](image)

The rotor disc occupied by 18 magnets arranged symmetrically, as shown in figure 4. The size of a magnet was 50 mm long, 30 mm wide and 13 mm thick. The type of the magnets was a sintered samarium-cobalt (SmCo) magnet.
Figure 4. Drawing of the rotor disc.

The shaft of the rotor placed on a flat table so that the shaft perpendicular and able to support the rotor disc in a horizontal position. The coil was placed on the table under the rotor with a variable distance of 15 mm, 17 mm, 19 mm, 21 mm, and 23 mm. At each of these distances, and the rotor rotated by varying rotational speed of the rotor that produced a maximum 10 volts output voltage. At 333 rpm rotation with various lengths, the voltage data was taken to determine the effect of distance or an air gap on the voltage. The value of 333 rpm chosen so that the generator could produce 50 Hz of frequency. The voltage was measured using a voltmeter, and the rotational speed of the rotor was measured using a tachometer.

3. Results and analysis

The experimental results presented in table 1.

| Output Voltage (Volt) | Rotor disc rotational speed (rpm) | Air gap (mm) |
|----------------------|----------------------------------|--------------|
|                      | 23                               | 21           | 19           | 17           | 15           |
| 1                    | 108                              | 90           | 83           | 72           | 59           |
| 2                    | 190                              | 163          | 142          | 124          | 100          |
| 3                    | 280                              | 227          | 202          | 180          | 146          |
| 4                    | 350                              | 290          | 258          | 235          | 180          |
| 5                    | 420                              | 354          | 319          | 277          | 233          |
| 6                    | 565                              | 470          | 422          | 382          | 312          |
| 7                    | 725                              | 604          | 545          | 484          | 398          |
| 8                    | 814                              | 695          | 621          | 545          | 456          |
| 9                    | 889                              | 752          | 655          | 594          | 495          |
| 10                   | 941                              | 810          | 738          | 650          | 545          |

From the table, the output voltage versus rotational speed curve obtained for each air gap, as shown in Figure 5.

Figure 5. Output voltage versus rotor rotational speed curve.
Air gap formed elevation angle that 15 mm air gap is the highest elevation angle and 23 mm air gap is lowest elevation angle. By using equation (1), $\phi_{\text{max}}$ becomes

$$\phi_{\text{max}} = \frac{V}{k \times n \times p \times N}$$

(3)

Here, the E symbol is replaced with V. Then, to find out the change in voltage at each rotational speed the equation (1) becomes

$$V/n = k \times p \times N \times \phi_{\text{max}}$$

(4)

The graph of $V/n$ versus rotational speed is presented on Figure 6.

![Figure 6. V/n versus rotor disc rotational speed curve.](image)

From Figure 6, the 15 mm air gap refers to the highest $V/n$ value of all air gaps. The index of $V/n$ will decrease as the increase in the air gap. To find the highest output voltage over each rotor versus rotational speed ($V/n$), and the output voltage for each air gap, figure 7 is presented. Figure 7 shows that the most substantial $V/n$ value is at a voltage of about 5 volts for all air gaps except for the 15 mm air gap.

![Figure 7. V/n versus output voltage curve.](image)

For the effect of an air gap analysis on rotor disc rotational speed of 333 rpm, the experimental data are presented in table 2 and in figure 8.

| Air gap (mm) | 23 | 21 | 19 | 17 | 15 | 13 |
|--------------|----|----|----|----|----|----|
| Output voltage (volt) | 3.3 | 4.8 | 5.2 | 5.6 | 6.2 | 6.7 |

Using the curve fitting method, the linear equation of the data in figure 8 is

$$V = -0.33a + 11.29$$

(5)

with a coefficient of determination ($R^2$) equals 0.9, where V is the output voltage, and a is the air gap. The curve shows that as the air gap decreases, the output voltage increases. The prediction of output
voltage value for smaller air gaps can be made using this equation. So, for the air gap value of 2 mm, the output voltage value is 10.63 volt. If the generator works at a voltage of 5 Volts, the current generated is 56.3 milliamps, and the power resulted at 281.5 milliWatts.

Figure 8. Output voltage versus air gap curve on 333 rpm rotor speed.

4. Conclusion
From the test results show that the rotor rotation is higher and the narrower the air will produce a high voltage. The highest V/n value was at 5 volts for all air gaps. The linear equation can be used to predict the output voltage value for other air gap values.

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