Voltage Generation of Three-Phase Double Sided Internal Stator Axial Flux Permanent Magnet (AFPM) Generator

I M W Kastawan*, Rusmana

Department of Energy Conversion Engineering, Politeknik Negeri Bandung
Jalan Gegerkalong Hilir, Ciwaruga 40012, Jawa Barat, Indonesia.

*wiwit.kastawan@polban.ac.id

Abstract. This paper describes the development of a multidisc AFPM generator type namely the double sided internal stator. This generator consists of one stator disc with two surface sides placed in the middle between two rotor discs. 18 permanent magnet poles are placed in one rotor disc while 9 three-phase windings with 1450 turns per-winding are placed in one surface side of the stator disc. The laboratory test results show that three-phase sinusoidal voltage magnitude in range of 79 – 150 V (phase to neutral) is generated for 219 – 402 rpm of rotor speed. In its nominal speed i.e. 333 rpm, a 124.8 V, 50 Hz, three-phase sinusoidal voltage is generated with only 1.6% THD in average and 0°, –124°, –240° phase angles. Comparison with another type of multidisc AFPM generator namely the double sided internal rotor shows that the developed AFPM generator can produce an output voltage that is almost 2.5 times higher. Nevertheless, both generators are able to generate a relatively balance three-phase sinusoidal voltage with low THD value.

Keywords: AFPM generator, double sided internal stator, output voltage, three-phase sinusoidal

1. Introduction
Demand for electricity certainly grows year by year. To meet the demand, productions of electricity including those harnessing renewable energy resources need to be undertaken. In recent years, generating electricity from renewable energy resources such as hydro, wind and solar irradiation have been growing rapidly. Global environmental issues, in particular is the greenhouse effect caused by air pollutants released from large scale conventional fossil fuelled power plants, have strongly driven the use of renewable energy resources which are more environmentally friendly. Further, at present the renewable energy resources based power generation technologies already have higher cost efficiency because they have been developed well and have no fuel cost component. Also, they have no power transmission cost component since the renewable energy power generation units are always constructed close to load centre. Last, development of small capacity generator, power converter as well as power storage devices have facilitated the more widely use of renewable resources based power generation technology [1]-[3].

Wind and small scale hydro (micro hydro) are two popular examples of renewable power generation technology. In a wind power generation unit, power of the flowing air is converted into shaft mechanical power by wind turbine. The power is subsequently converted into electricity by generator [4]. In a micro hydro power generation unit, power of the flowing water is converted into electricity by a low head hydro turbine or hydro wheel coupled with generator [5]. Both wind and
micro hydro power generation units are facing similar problems namely the low and variable speed of air and water flow. Thus, the wind and hydro turbines as well as the generator are all of low speed type [5],[6].

The axial flux permanent magnet (AFPM) generator is considered to be suitable for wind and micro hydro applications. An AFPM generator has a number of permanent magnet poles which make it able to work on low rotor speed. Also, no external excitation source is needed. The simplest construction of AFPM generator is known to be the single sided. It consists of only one stator disc and one rotor disc for placing the armature windings and permanent magnet poles respectively [7]. However, an armature winding with a lot of number of turns and permanent magnet poles with strong magnetic field have to be used to generate higher output voltage and power. Therefore, the construction is developed further into multidisc types. A type of multidisc AFPM generator is popularly known as double sided. A double sided AFPM generator has three discs. It may consist of two stator discs and one rotor disc, named as double sided internal rotor type, or two rotor discs and one stator disc, named as double sided internal stator type [7]. Construction of the double sided internal rotor is simpler than the double sided internal stator. However, the double sided internal stator has better capability in generating higher output voltage and power. Multidisc AFPM generator with more than three discs will have more complex and heavier construction although the output voltage and power generated is much higher. In order to generate three-phase output voltage with waveform close to sinusoidal and balance in both magnitude and phase, the permanent magnet poles and armature windings of the AFPM generator have to be placed in the right mechanical angles and in such a way so that the magnetic field will be uniformly distributed and cuts all of the armature windings [8],[9].

2. The three-phase double sided internal stator AFPM generator

The basic construction of a double sided internal stator AFPM generator is shown in Figure 1. It consists of one stator disc with two surface sides placed in the middle of two rotor discs. The permanent magnet poles may be placed in the rotor disc in two different ways i.e. surface mounted or embedded. The armature windings may also be placed in the stator disc in two different ways i.e. slot less or slotted [7].

![Figure 1. Basic construction of double sided internal stator AFPM generator [7].](image)

When the rotor disc rotates, the magnetic field (Φ) will cut the armature winding and generating induction voltage on it. Magnitude of the induction or output voltage generated depends on number of turns of the armature winding (Nw), generator/rotor rotation speed (n) and magnetic field strength (Φm) according to the following equation:

\[ E_a = k n N_w \Phi_m \] (1)
where $k$ is a constant value. From equation (1), higher output voltage will be generated if the number of turns of armature windings, generator rotation speed, or strength of the magnetic field is increased. The most common practices are to increase number of turns of the armature winding and strength of the magnetic field. Increasing the number of turns of armature windings of a double sided AFPM generator is easier than a single sided AFPM generator because the armature winding can be placed in two stator discs or two surface sides of a stator disc. Thus, size of the armature winding will remain relatively smaller. Two methods to increase the strength of magnetic field are changing the permanent magnet poles type into the stronger one or making narrower air gap in between rotor and stator discs by placing the permanent magnet poles and armature windings in embedded and slotted ways respectively. Number of the permanent magnet poles ($p$) will determine the frequency ($f$) of the output voltage generated according to the following equation:

$$f = \frac{np}{120}$$

From equation (2), an AFPM generator will work on lower rotation speed if the number of permanent magnet poles is higher. Also, higher number of permanent magnet poles with shape closer to pie circle will result in more uniform magnetic field distribution and waveform of the output voltage generated will be closer to sinusoidal.

The double sided internal stator AFPM generator that has been constructed has 18 permanent magnet poles in one rotor disc. The generator is expected to generate three-phase sinusoidal output voltage with magnitude of approximately 120 V and frequency of 50 Hz. Referring to equation (2), the rotation speed of this generator will be about 333 rpm (rotation per minute). Each of the permanent magnet poles is a bar ceramic one with dimension of $50 \text{ mm} \times 30 \text{ mm} \times 14 \text{ mm}$. All of these permanent magnet poles are embedded in around the rotor disc. Hence, the angle distance between two adjacent permanent magnet poles will be equal to $20^\circ$. Diameter of the rotor disc is $300 \text{ mm}$ with thickness of $14 \text{ mm}$. Drawing of a rotor disc and placement of permanent magnet poles in it is shown in Figure 2, while the appearance is shown in Figure 3.

![Figure 2](image-url)

**Figure 2.** Drawing of the rotor disc and permanent magnet poles of the double sided internal stator AFPM generator.
Figure 3. The rotor disc and permanent magnet poles of the double sided internal stator AFPM generator.

Figure 4 and 5 show the drawing and appearance of the stator disc and armature windings of the double sided internal stator AFPM generator that has been constructed. There is one stator disc which has two surface sides for placing the armature windings. Diameter of the stator disc is 340 mm with thickness of 20 mm. 9 three-phase armature windings are placed in each surface side of the stator disc so the total number of armature windings per-phase will be equal to 6. If each armature winding consists of 1450 turns, then the total number of turns per-phase will be equal to 8700. It has been mentioned previously that number of the permanent magnet poles of the generator is 18 and consequently the distance between two adjacent permanent magnet poles is 20°. Therefore to generate three-phase sinusoidal output voltage, each of the three-phase armature windings has to be placed in one surface side of stator disc in slotted way with an angle distance of 13.3°. Suppose that armature winding for phase-R is placed in 13.3° then armature windings for phase-S and phase-T have to be placed in 13.3° or 53.3° or 93.3°, … and 26.6° or 66.6° or 106.6°, … respectively. The two rotor discs and stator disc of the generator are then assembled by a rotor shaft for laboratory experimental purpose.

Figure 4. Drawing of the stator disc and armature windings of the double sided internal stator AFPM generator.

Figure 5. The two surface sides of stator disc of double sided internal stator AFPM generator and placement of armature windings in it.
3. Experimental results and analysis
A laboratory scale experiment, shown by Figure 6, has been set-up to investigate the voltage generation characteristics of the double sided internal stator AFPM generator that has been constructed. The AFPM generator is driven by a variable speed motor and tested under no-load condition. The generator rotation speed is then measured by a Tachometer while profile of the output voltage generated is measured by a PQ (Power Quality) Analyser unit. Figure 7 shows the block diagram of the laboratory experiment.

![Laboratory experiment set-up](image1)

**Figure 6.** Laboratory experiment set-up for investigating the voltage generation characteristics of double sided internal stator AFPM generator.

![Block diagram](image2)

**Figure 7.** Block diagram of the laboratory experiment.

Magnitudes of the output voltage generated are listed in Table 1. It can be seen the three-phase output voltage generated is balance in magnitude. The magnitude variation among three output voltages is only 2.3% in average. For generator speed in range of 219 – 402 rpm, the average of magnitude and frequency of per-phase output voltage generated vary linearly from 79.3 V to 150.1 V and 40 Hz to 60 Hz respectively.

| Generator speed (rpm) | Output voltage (V) |
|---------------------|-------------------|
|                     | Phase-R | Phase-S | Phase-T |
| 219                 | 79.9    | 78.9    | 79      |
| 282                 | 103.3   | 105.4   | 106.1   |
| 339                 | 125.1   | 127.4   | 128.6   |
| 402                 | 148.1   | 150.7   | 151.6   |

**Table 1.** Per-phase output voltage of the double sided internal stator AFPM generator.
Figure 8 shows the linear relationship of per-phase output voltage and rotation speed of the AFPM generator. Graphs in this figure conform the equation (1) as for a certain number of turns of armature winding ($N_w$) and constant magnetic field strength ($\Phi_m$), the magnitude of output voltage generated will vary linearly to generator rotation speed ($n$). In its nominal speed (about 333 rpm), the per-phase output voltage generated is about 124.8 V in average with frequency of approximately 50 Hz (shown by the red dashed line in the figure).

Figure 8. Linear relationship between per-phase output voltage and rotation speed of the double sided internal stator AFPM generator.

Further analysis shows that for the same number of armature winding turns and magnetic field strength, the double sided internal rotor (the other type of double sided AFPM generator) generates an average per-phase output voltage of 51.7 V on nominal generator speed of approximately 333 rpm [10]. This figure is almost 2.5 times lower than the average per-phase output voltage of the double sided internal stator AFPM generator that has been constructed.

Quality of the output voltage of the double sided internal stator AFPM generator is shown in Figure 9 below. One can see that waveform of the three-phase output voltage is very close to sinusoidal. Its average total harmonics distortion (THD) value is only 1.6%. Also, the phase angles of the three-phase output voltage generated are $0^\circ$, $-124^\circ$, $-240^\circ$, almost equal to the ideal phase angles of a three-phase voltage system i.e. $0^\circ$, $-120^\circ$, $-240^\circ$. The output voltage quality of this double sided internal stator AFPM generator is relatively the same with that of the double sided internal rotor AFPM generator [10].
Three-phase output voltage waveform

Phasor diagram of the three-phase output voltage

Harmonics spectrum of the three-phase output voltage

Harmonics of the three-phase output voltage

Figure 9. Profile of the three-phase output voltage generated by the double sided internal stator AFPM generator.

4. Conclusions
A double sided internal stator AFPM generator has been constructed. The generator is capable to generate three-phase output voltage that is balance in magnitude and phase angle with a waveform that is very close to sinusoidal. The double sided internal stator AFPM generator has a better output voltage generation capability than the double sided internal rotor AFPM generator.

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