

# Output Voltage Control of Axial Flux Permanent Magnet Generator Using Microcontroller-Based Electronic Load Controller

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## ABSTRACT

In this paper, an electronic load controller (ELC) that has a function to maintain a constant output voltage of an axial flux permanent magnet (AFPM) is proposed. It consists of three main components namely voltage sensor, microcontroller and switching driver are proposed. When the main load of the AFPM generator varies, any change in its output voltage is sensed by the voltage sensor. The output of the voltage sensor is fed into the microcontroller. The microcontroller then processes this sensor signal to give a command to the switching driver. The switching driver will generate switching pulses for an alternating current (ac) to ac power converter to control power absorbed by the dummy load in such a way that the total load power of the generator remains the same. Test results show that the ELC successfully maintain a constant generator output voltage. On the no-load condition and without using of ELC, the generator rotates at 463 rpm and produces a per-phase output voltage of 201.3 V. When the per-phase generator main load is increased up to 9 W, rotation and per-phase output voltage of the generator are dropped to 270 rpm and 126.4 V respectively. When ELC is used, rotation and per-phase output voltage of the generator are both maintained constant at 342.3 rpm and 129.0 V respectively although the per-phase load is increased up to 9 W. However, using ELC gives a negative effect of increasing generator current harmonics. Test results show that total harmonic distortion (THD) of the generator current is 5.1% and 15.3% for no-load and on-load conditions respectively when ELC is not used. It jumps to 35.7% and 70.5% for no-load and on-load conditions respectively when ELC is used.

**Keywords:** *ac to ac converter, current harmonic, dummy load, microcontroller, output voltage, permanent magnet generator*

## 1. INTRODUCTION

Nowadays, electrical energy has become one main human needs. Electrical energy is needed to carry out various activities in both the residential and industrial sectors. Consequently, demand for electrical energy continues to increase. Efforts were then taken to generate electrical energy from any primary energy resources available to balance this constantly increasing demand. Generating electrical energy involves a lot of energy conversion equipment. Among them is the generator, equipment used to convert mechanical energy put by a prime mover on the shaft of the rotor of the generator into electrical energy collected at the armature windings of the generator. Various types of the generator have been developed, among them is one named axial flux permanent magnet (AFPM) which is suitable for

small-scale power plant applications such as small wind power plant [1-3], pico and micro hydropower plants [4-7], [12-13] and even a stationary bike or motorcycle drove power plant [8]. Due to the use of a permanent magnet, no external excitation source is needed in an AFPM generator. Hence, it has a relatively simpler construction. Further, by increasing the number of permanent magnets, an AFPM generator will be able to work at relatively low rotation [9]. Having all these advantages, an AFPM generator is considered very suitable for rural or remote area electrification, an area that generally has many renewable energy resources but has not yet supplied by the existing electrical distribution grid [6-7], [10-11].

For many years, developments have been made to improve performance of an AFPM generator. One example is the development of construction of an

AFPM generator from the simplest one of single-phase single disc type into the more complex ones of single-phase and three-phase multidisc types that is aimed to increase its power capacity [9], [12-15]. Other development focused on permanent magnets and armature windings design and placement on rotor and stator discs of the AFPM generator that is aimed to improve the waveform of output voltages generated [14-15]. However, no such development has been proposed regarding the output voltage control of an AFPM generator. Because an AFPM generator uses permanent magnets as an excitation source, a variation of output voltage during variable load conditions cannot be balanced by variation of its excitation. The addition of an output voltage control unit is necessary.

In this paper, equipment generally called as an electronic load controller (ELC) that serves as an output voltage control unit for an AFPM generator is proposed. ELC controls the power flow to a dummy load connected in parallel with generator main load in such a way that the total load power supplied by the generator will always be the same regardless of variation in generator main load.

### 1.1. AFPM Generator

The type of generator examined in this paper is the three-phase double-sided internal stator AFPM generator [7]. It is a further development of the three-phase double-sided internal rotor and three-phase double-sided internal stator AFPM generators [14-15]. Figure 1 shows the construction of this three-phase double-sided internal stator AFPM generator. It can be seen that this generator has two main parts namely the rotor disc and stator disc. A stator disc is placed in the middle of two rotor discs. Each rotor disc contains 20 rectangular shaped neodymium permanent magnet poles, embedded uniformly around its inner side. Therefore, the distance between two adjacent permanent magnets is equal to 18°. To determine the nominal operating speed of the generator, the equation below is applied [15]:

$$n = \frac{120f}{p} \tag{1}$$

in which  $n$ ,  $f$  and  $p$  represent generator rotation in rpm (rotation per minute), frequency of generator output voltage in Hz and number of generator magnetic pole. If the expected frequency is 50 Hz then the nominal generator speed will be equal to 300 rpm.

Both sides of the stator disc of this generator are designed to be fully occupied by three-phase armature windings  $R$ ,  $S$  and  $T$ . Because the number of permanent magnet poles of the generator is 20 then a cycle of the three-phase sinusoidal generator output

voltage is equal to 36° of mechanical rotor movement. Therefore, the three-phase armature windings  $R$ ,  $S$  and  $T$  are placed at a distance of 12° between one and another. Next, because each side of the stator is expected to be fully occupied by three-phase armature windings  $R$ ,  $S$  and  $T$  then the total number of armature windings required is 30. Each side of the stator disc will contain 15 armature windings or 5 armature windings per-phase.

The magnitude of induced voltage ( $E_a$ ) in each phase of the armature winding of an AFPM generator is formulated by the following equation [15]:

$$E_a = k_1 \times n \times p \times N \times \Phi_m \tag{2}$$

in which  $k$  represents a constant value,  $N$  represents the number of turn of each phase of the armature winding and  $\Phi_m$  represents flux strength of magnetic pole. Because number of magnetic pole, number of turn of each phase of the armature winding and flux strength of magnetic pole of the generator are constant then equation (2) becomes:

$$E_a = k_2 \times n \tag{3}$$

Equation (3) shows that magnitude of the induced voltage in each phase of armature winding is merely a function of the speed of the AFPM generator. The magnitude of induced voltage in each phase of an armature winding of the AFPM generator varies proportionally to its speed.

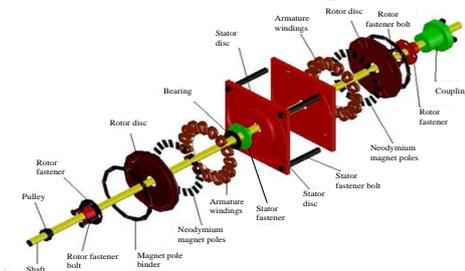


Figure 1. Three-phase double-sided internal stator AFPM generator

### 1.2. ELC

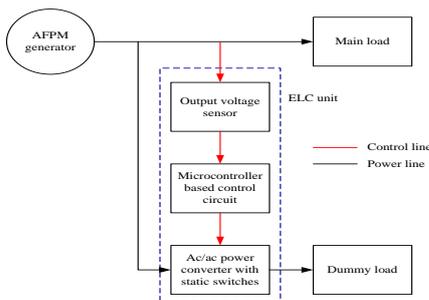
ELC is an important additional device of the AFPM generator. Its main function is to keep the frequency and magnitude of an output voltage of the generator constant during load variation. The function of ELC is quite similar to the governor of a generator of a conventional large-scale power plant unit. When the generator is loaded, the current flow in armature winding is results in a voltage drop due to its resistance ( $R_a$ ) and inductive reactance ( $X_a$ ). Higher current results in a higher voltage drop and lead to a lower generator output voltage. Equation that relates

generator output voltage ( $V_o$ ) and load current ( $I_{ag}$ ) is as follows:

$$V_o = E_a - I_{ag}(R_a + jX_a) \quad (4)$$

in which  $E_a$  is formulated by equation (2) or (3). Equation (4) shows that voltage drop caused by generator load current, armature winding resistance and inductive reactance has to be balanced by an increase of armature induced voltage in order to maintain the constant generator output voltage. Unfortunately in case of the AFPM generator, increasing armature induced voltage by increasing flux strength could not be done. Further, increasing armature induced voltage by increasing the speed of the generator is not preferred due to the change in frequency of voltage generated. Using ELC is one option to be taken to keep the output voltage of the AFPM generator constant during load variation.

Basically, ELC will control the power of a dummy load connected in parallel to the generator main load so that the total load power of the generator remains the same. When the generator main load increases, the power to the dummy load decreases, and vice versa. When generator main load is maximum, no power is delivered to the dummy load. Inversely, when no-load is connected to the AFPM generator, the power to the dummy load is maximum. Therefore, the total load power of the generator is always constant regardless of variation in generator main load. With constant total load power, output voltage and speed of the AFPM generator will also be constant. Regarding this basic operation principle, an ELC unit will consist of the following three main components: a voltage sensor circuit, a microcontroller-based control circuit and ac to ac power converter circuit. When the main generator load varies, a change in generator output voltage is sensed by the voltage sensor which is then forwarded to the microcontroller. The microcontroller processes this sensor signal to generate switching pulses with certain angles for the ac to ac power converter so that power delivered to dummy load is controlled in such a way to give constant total load power. Figure 2 below shows a block diagram of an ELC unit.



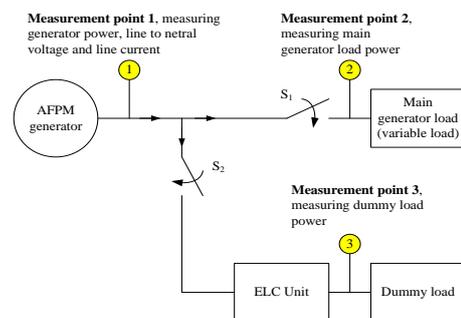
**Figure 2.** Block diagram of an ELC unit installed in an AFPM generator.

## 2. METHODOLOGY

According to the description in Section 1.2, two main steps undertaken in this research are developing the ELC unit and running a test to analyze its performance. In developing this ELC unit, the hardware design process will include the following:

1. Output voltage sensor circuit. This circuit reads the output voltage of the AFPM generator. It changes the ac output voltage of the AFPM generator into a form of dc voltage that is suitable for the input of the microcontroller unit.
2. Control circuit. This is the main circuit of an ELC unit. It controls the power flow to a dummy load by generating pulses with certain switching angles for ac to ac power converter circuit. The control process is run under a program developed using an Arduino UNO microcontroller.
3. Power converter circuit. This is an ac to ac converter circuit that converts a constant ac power input into a variable ac power output by controlling the operation of its static switches. The static switches used are Triac. Switching pulses delivered by the control circuit will drive the Triac to conduct at certain angles to control the amount of ac power goes to the dummy load.

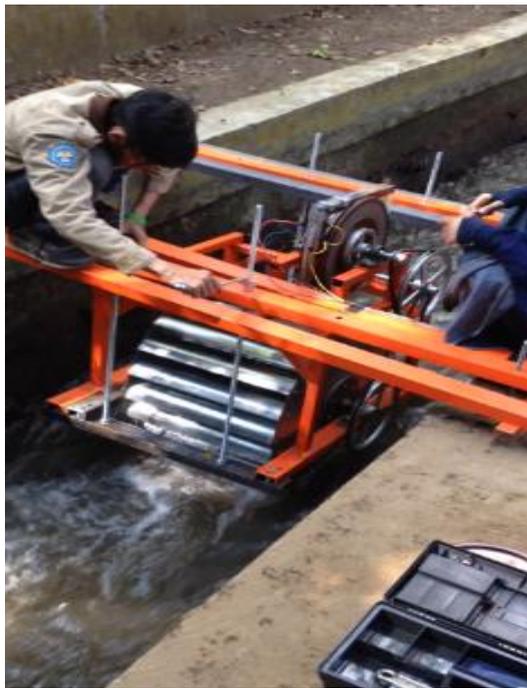
The ELC unit is then set in a power generation system diagram shown in Figure 3 below. In order to analyze the performance of the ELC unit, two different kinds of tests are conducted. The first one is a test on an AFPM generator without ELC (switch  $S_2$  is open). The second one is a test on AFPM with ELC (switch  $S_2$  is close). On both of the tests, the AFPM generator is operated under no-load (switch  $S_1$  is open) and loaded (switch  $S_1$  is close) conditions. The load power of the AFPM generator hence becomes a variable parameter of the test while its output voltage and current harmonic become the observed performance parameters. Thus measurements are taken for generator power, voltage and current, generator current harmonics, main generator load power and dummy load power. All measurements are taken by PQ Analyzer.



**Figure 3.** Block diagram of test conducted to analyze the performance of ELC unit.

### 3. RESULT AND DISCUSSION

Figure 4 below shows a picture of the test conducted to investigate the ability of the ELC unit in maintaining the constant output voltage of an AFPM generator. Results of the test are shown in Table 1 and Table 2. Using data in Table 1 and Table 2, Figure 5 is then constructed. One can see that the ELC unit has the ability to maintain a constant generator output voltage. As shown by Figure 5 (a), on no-load condition (0 W of load) and without ELC, the generator generates a per-phase output voltage of 201.3 V at 463 rpm and. The output voltages then decrease as the generator main load increases. The per-phase output voltage and speed of the generator drop to 126.4 V and 270 rpm as the per-phase generator main load reach 9 W. Next, Figure 5 (b) shows that after ELC is used, both per-phase output voltage and speed of the AFPM generator are successfully maintained constant at 129.0 V and 342.3 rpm respectively when per-phase generator main load varies from 0 to 9 W.



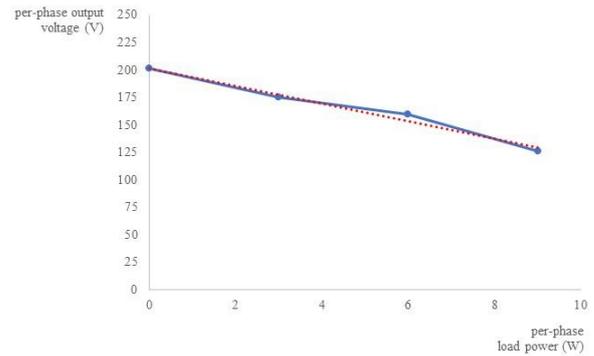
**Figure 4.** Field test conducted to analyze the performance of the ELC unit.

**Table 1.** Generator output voltage and speed without ELC

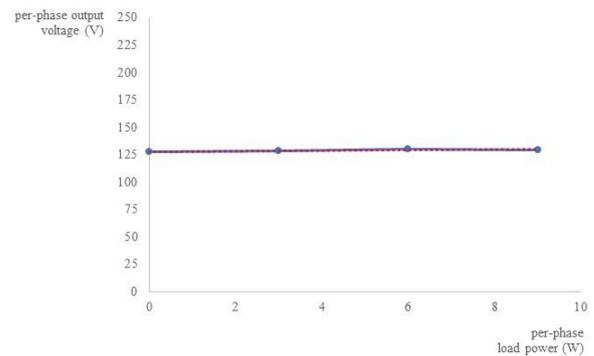
Speed (rpm)	Per-phase output voltage (V)	Per-phase generator main load (W)
463	201.3	0
381	174.9	3
323	159.7	6
270	126.4	9

**Table 2.** Generator output voltage and speed with ELC

Speed (rpm)	Per-phase output voltage (V)	Per-phase generator main load (W)
339	127.7	0
341	128.3	3
347	130.3	6
342	129.7	9



(a)



(b)

**Figure 5.** (a). AFPM generator output voltage without ELC (b). AFPM generator output voltage with ELC.

Switching of Triacs of the ac to ac converter unit to control the power of the dummy load may potentially distort the current waveform of the AFPM generator. An ideal ac current should have a sinusoidal waveform. Any other ac current waveform differs from sinusoidal is said to be a distorted current. A distorted ac current waveform contains harmonics. The more distorted the ac current, the higher its harmonics content. A measure commonly used to indicate the harmonics content of a distorted ac current waveform is total harmonics distortion (THD), expressed in percent [16]. In order to investigate the effect of using ELC on a distortion of generator current, measurement of generator current is taken by the PQ Analyzer. This measurement tool can directly

display %THD of the current being measured. Table 3 and Table 4 below show the measured current harmonic content of the AFPM generator on two different conditions: without and with the ELC unit. One can read that when the ELC unit is not used, the THD of the generator current reaches 5.1% and 15.3% for no-load and on-load conditions respectively. Then, when the ELC unit is used, the THD of the generator current jumps to 35.7% and 70.5% for no-load and on-load conditions respectively. Thus, using of ELC unit gives a significant increase in a current harmonic of the AFPM generator. Using ELC distorts the current waveform of the AFPM generator. Current harmonic introduces negative impacts such as reducing the efficiency of an electrical power system and electrical power equipment, overload on the power transformer, abnormal operation of motor and generator, neutral current flows and maloperation of a power circuit breaker [17 - 18]. Thus, efforts to minimize generator current harmonics due to using of ELC units are required.

**Table 3.** Generator current harmonics without ELC

Condition	THD (per-phase)
No-load	5.1%
On-load	15.3%

**Table 4.** Generator current harmonics with ELC

Condition	THD (per-phase)
No-load	35.7%
On-load	70.5%

Methods for handling current harmonics have been developed. Among them are the use of the passive filter, active filter, reactor (ac line or dc link) and phase-shifting transformer. A passive filter is the simplest method and less costly. However, it requires computer-based software to analyze and to determine harmonics to be eliminated, not comply with the standard of IEEE 519-1992 guidelines, may cause leading power factor and needs many passive filters for eliminating many harmonics. Using active filter give advantages such as free from resonance problems, complies with the standard of IEEE 519-1992, and has a wide range of harmonic elimination and ability to provide reactive power compensation. The disadvantages are expensive and demand hard maintenance. The phase-shifting transformer method is specially developed for solving the harmonic

problems due to the use of a three-phase rectifier. Moreover, a phase-shifting transformer may also serve as a voltage changer and provide isolation between the rectifier unit and power supply [19]. Further study is needed to select which method is most appropriate for reducing current harmonics generated by the ELC unit of an AFPM generator.

#### 4. CONCLUSION

An ELC unit for maintaining the constant output voltage of the AFPM generator has been proposed. Test results show that the ELC unit has been successfully maintaining constant generator output voltage and speed at 129.0 V and 342.3 rpm respectively. However, using of ELC unit gives a negative effect on the generator current. The harmonics content of the generator current increases significantly as compared to the condition when the ELC unit is not being used. The generator current is severely distorted due to using of the ELC unit. Thus, subsequent research on how to minimize current harmonics due to using of the ELC unit is required.

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