Advances in Engineering Research, volume 207
Proceedings of the 2nd International Seminar of Science and Applied Technology (ISSAT 2021)

Modification of the Single-Phase AC Induction Motor to the Low-Speed Single-Phase AC Permanent Magnet Generator

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ABSTRACT

This paper discusses the design of the low-speed single-phase AC permanent magnet generator through the modification of a squirrel cage single-phase AC induction motor. Both rotor and stator of the single-phase AC induction motor are modified. Eight permanent magnet poles are embedded in the rotor so that generator will rotate at a relatively low speed of 750 rpm and produce an sinusoidal AC voltage with a frequency of 50 Hz. The total number of stator windings and slots remains the same: four stator windings and 36 stator slots. However, the number of turns for each stator winding is increased to 600 turns. Therefore, each stator slot is housing 150 conductor turns. The permanent magnet generator is expected to generate an sinusoidal AC output voltage with a magnitude in the range of 110 - 115 V when it rotates at 750 rpm. Laboratory tests with a constant speed of electric motor drive have been conducted. Results of the no-load test show that generator output voltage is 110 V when it rotates at 749.3 rpm. However, the output voltage generated is not sinusoidal as indicated by its total harmonic distortion (THD) value of 15.8%. Results of the on-load test show that generator voltage drops vary from 8.2% to 29.1% and 4.5% to 26.4% respectively on linear resistive and non-linear load. On the same loading condition, the generator efficiency varies from 53.5% to 66.7% and 32.6% to 67.5%.

Keywords: *ac generator, ac motor, no-load test, on load test, permanent magnet, single phase.*

1. INTRODUCTION

Indonesia, particularly for many remote areas not connected yet to the existing electrical grid, usually have a lot of small rivers with a large amount of hydro energy potential that can be converted to electrical energy. However, many obstacles met in harnessing the hydro potential energy of these small rivers. Among them is the low elevation of the river results in a low speed of water stream. Low speed of water stream requires low-speed hydro turbine as well as low-speed generator [1], [2]. Furthermore, a generator with a separate excitation source cannot be used since the existing electrical grid has not connected to these remote areas. A permanent magnet generator is more suitable for this purpose. Thus, two main components necessary to convert the hydro potential energy of small rivers to electrical energy are the low-speed hydro turbine and the low-speed permanent magnet generator. In the first stage, the low-speed hydro turbine converts the hydro potential energy of the small river into shaft rotational mechanical energy. Then, a low-speed generator converts further the shaft rotational mechanical energy into the electrical energy.

A low head hydro turbine is one kind of low-speed hydro turbine [3]. A low head hydro turbine has several blades that directly contact and move along with the water stream. All blades are supported by a wheel firmly attached to the shaft of the turbine. The wheel then delivers the motion of blades to the shaft of the turbine. The shaft of the turbine is supported by bearings placed at both sides, left and right sides of the shaft. The bearing housing is firmly attached to concrete floors constructed at both sides of the small river.

There are many kinds of permanent magnet AC generators. Among them is the axial flux permanent magnet, shortly referred to as AFPM, generator. The construction of an AFPM generator is relatively simple as compared to a conventional generator. It has a disc-shaped rotor and stator. AFPM generator is widely used in small-scale electrical power generation is with a low-speed prime mover such as wind power generation [6-8], pico and micro-hydro power generation [9-11], [14-15],

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or motorcycle and stationer bike power generation [12]. The ability of this generator to work on low-speed prime mover depends on the number of permanent magnet poles. The higher number of permanent magnet poles of the generator is, the lower speed of the generator will be [13]. The other kind of permanent magnet generator is the conventional one with a cylindrical-shaped rotor and stator. This generator may be developed through the modification of single-phase AC induction motor. A single-phase AC induction motor works on principles of electromotive force shortly referred to as emf, and magnetic field interaction [16]. A single-phase AC induction motor has two kinds of stator windings namely the primary winding and the secondary winding. Also, a single-phase AC induction motor has two different kinds of rotors namely the squirrel cage and wound rotors [16]. When modifying a single-phase AC induction motor to an single-phase AC permanent magnet generator, the squirrel cage rotor is preferable and more suitable.

A single-phase AC induction motor can be operated as an induction generator without any modification. To operate a single-phase AC induction motor as an induction generator, the rotor speed must be higher than synchronous speed to produce negative slip [16]. An induction generator is frequently used in micro-hydropower generation and wind power generation with a relatively high speed of turbine rotation [17]. Further reference desk study shows that induction generator demands the usage of the capacitor to produce magnetization current to regulate its output voltage [18]. Therefore, modifying a squirrel cage of a single-phase AC induction motor to a single-phase AC permanent magnet generator and then using it for electrical power generation of a small river in the remote area is advantageous.

2. RESEARCH METHODS

In modifying a squirrel cage of a single-phase AC induction motor into a single-phase AC permanent magnet generator, four major steps are taken i.e. disassembling the motor, modifying the rotor, modifying the stator, and reassembling the rotor and stator followed by running series of laboratory tests.

2.1. Disassembling the motor

The purpose is to separate two main parts of the motor i.e., stator and rotor. Careful visual checking on stator and rotor cores as well as primary and secondary stator windings is undertaken to ensure that all are in good and clean condition. After separating the stator and rotor, the dimension of these two parts can be measured. Also, stator windings patterns can be recognized.

Knowing the dimension of the rotor is necessary for determining the number and dimension of permanent magnets to be embedded. The number of permanent magnets will then determine the rotation speed of the generator according to this equation below [16]:

$$n = \frac{120 \times f}{p} \quad (1)$$

where:

f (Hz) refers to the frequency of the induced or output voltage of the generator.

n (rpm) refers to the rotation speed of the generator.

p refers to the number of magnet poles.

Knowing the dimension of the stator as well as the pattern of stator windings is necessary for determining the number of windings and number of turns of each winding of the permanent magnet generator that is going to be constructed. The number of stator windings and turns per winding will determine the magnitude of generator output voltage according to this equation below [16]:

$$E_{rms} = 4{,}44 \times N_t \times N_s \times f \times \varphi_m \quad (2)$$

where:

E_{rms} (V) refers to the effective value of the output voltage of the generator.

N_t refers to the number of turns of each stator winding.

N_s refers to the number of stator windings.

φ_m (Wb) refers to the maximum value of magnetic field strength.

2.2. Modifying the rotor

In this step, the number of permanent magnet poles is embedded in the rotor of the single-phase AC induction motor. The type, size, and the number of permanent magnet poles to be embedded in the rotor depend on the size or dimension of the rotor as well as the rotation speed, frequency, and the magnitude of the induced or output voltage of the generator to be developed.

2.3. Modifying the stator

The main thing in modifying stator is to determine the number of turns of each stator winding. The number of turns of each stator winding is calculated based on the existing number and size of stator slots as well as the induced or output voltage of the generator to be developed.

2.4. Reassembling rotor and stator followed by conducting laboratory test.

After modifying the rotor and stator parts of the motor, both are reassembled to form a single-phase permanent magnet AC generator. Two different kinds of laboratory tests i.e., no-load and on-load are then conducted to get voltage generation and efficiency characteristics of this single-phase AC permanent magnet generator. The waveform of the output voltage generated is observed to determine its harmonics content.

Figure 1 and Figure 2 below show the circuit diagram of no-load and on-load tests of the single-phase AC permanent magnet generator developed. The generator is driven by a DC shunt motor. Thus, the speed of the DC shunt motor determines the rotation speed of the generator. The DC voltage supply for the DC shunt motor is obtained by rectifying the three-phase AC supply source through a set of the three-phase voltage regulator and three-phase bridge diode rectifier. The variable of DC voltage is then obtained by varying the output of the three-phase voltage regulator. The variable DC voltage is needed to vary the speed of the generator on the no-load test or to maintain the speed of the generator under variable loading conditions during the on-load test.

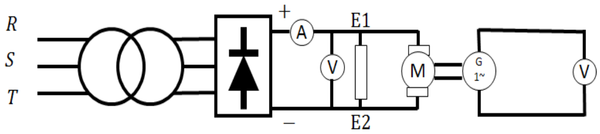


Figure 1 Circuit diagram of no-load test of the AC single-phase permanent magnet generator developed.

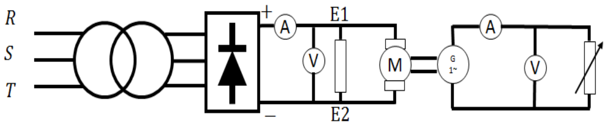


Figure 2 Circuit diagram of on-load test of the single-phase AC permanent magnet generator developed.

For the no-load test, generator output voltages for various values of rotation speed are recorded. The data is then compared to generator output voltages calculated by using Equation (2), the designed output voltages of the generator. For the on-load test, generator output voltages for various values of loads are recorded. Then, the voltage drop percentage of each loading condition is calculated as follows:

$$\Delta V = \frac{V_{NL} - V_{Lk}}{V_{NL}} \times 100\% \tag{3}$$

where:

ΔV (V) refers to the percentage of voltage drop of the generator.

V_{NL} (V) refers to the output voltage of the generator for no-load conditions.

V_{Lk} (V) refers to the output voltage of the generator for on-load condition number k.

To calculate the efficiency of the generator on each loading condition the following equation is used:

$$\eta = \frac{P_{in} - P_{losses}}{P_{in}} \times 100\% \tag{4}$$

where:

η (%) is the generator efficiency.

P_i (W) is the input power of the generator.

P_{losses} (W) is the total loss power of a generator consisted of mechanical, core, and stator winding losses.

The input power of the generator is assumed to be equal to the output power of the motor driving it. The output power of the driving motor is calculated by subtracting constant mechanical and core power losses as well as variable winding power loss from its input electrical power. The input electrical power of the driving motor is calculated as the multiplication of motor voltage and current. Meanwhile, the mechanical and core power losses are determined earlier through the no-load test of the driving motor. The winding power loss is calculated using current obtained from driving motor on-load test data.

By conducting the no-load test on the generator, both mechanical and core power losses of the generator are obtained. The stator winding loss is calculated using current obtained from generator on-load test data.

3. RESULTS AND DISCUSSIONS

3.1. Disassembling the motor

Figure 3 below shows a squirrel cage of the single-phase AC induction motor that has been disassembled. The rotor and stator parts have been separated.

Figure 3 A single-phase AC induction motor that has been disassembled.

Visual checking on these two main motor parts shows that in general, the rotor and stator cores are still in relatively good condition. The size of the rotor is measured. Figure 4 below shows the dimension of the rotor. Based on this rotor dimension, the size, and the number of permanent magnets to be embedded can be determined.

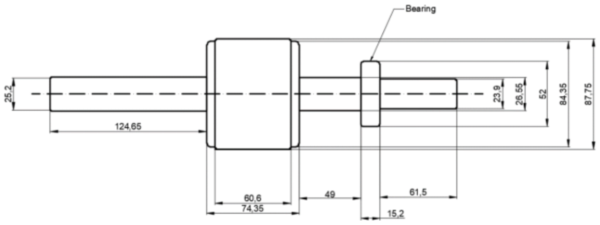
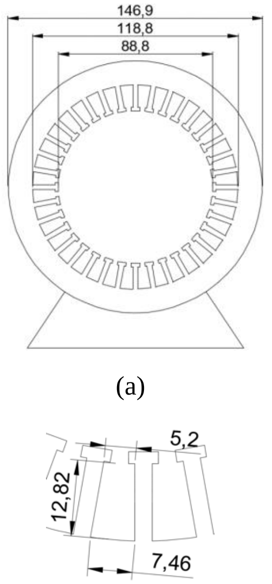


Figure 4 Rotor dimension (in mm).

The stator part has 36 slots for placing four stator windings. Dimensions of the stator and every slot are shown in Figure 5. Each of the stator winding is constructed by 162 conductor turns. The 102 conductor turns to form the stator primary winding while the remaining 60 conductor turns to form the stator secondary winding. Sizes of the conductor for primary and secondary stator windings are 1 mm and 0.9 mm respectively. Figure 6 shows the pattern of stator windings of the motor.



(a)

(b)

Figure 5 (a) Stator dimension (in mm) and (b) stator slot dimension (in mm).

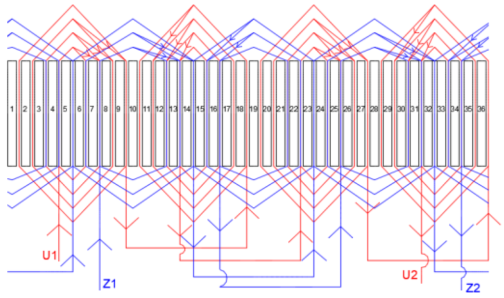
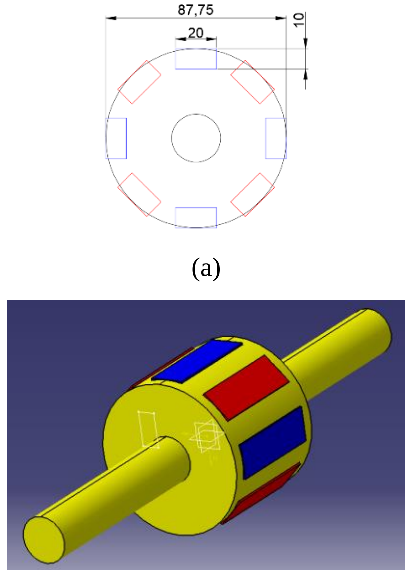


Figure 6 Stator windings of the motor.

3.2. Modifying the rotor

When modifying a squirrel cage of a single-phase AC induction motor to a single-phase permanent magnet generator, the size and condition of the existing rotor and stator as well as the design parameters such as the rotation speed of the generator, magnitude, and frequency of generator output voltage, are used as the basis. To modify the rotor, eight permanent magnet poles with each size of 60 mm × 20 mm × 10 mm and flux density of 1.46 Tesla are embedded. Thus, according to equation (1), the generator will rotate at 750 rpm to produce a single-phase AC sinusoidal voltage with a frequency of 50 Hz. Figure 7 below shows the design of the rotor with eight permanent magnet poles. The north and south poles of the permanent magnet are shown as red and blue coloured rectangular.



(a)

(b)

Figure 7 (a) Cross-sectional view and (b) 3D view of the arrangement of eight permanent magnet poles embedded in the rotor

3.3. Modifying the stator

To modify the stator, the initial number of stator windings and slots i.e., 4 windings and 36 slots are kept. However, the number of turns of each stator winding is increased to 600 turns. Therefore, each stator slot is housing 150 conductor turns. If the size of the conductor is 0.5 mm, with a cross-sectional area of 0.196 mm^2, then a stator slot with the size of 81.15 mm^2 as shown in Figure 5 (b) will be able to house 400 conductor turns. Thus, placing 150 conductor turns inside the stator slot can be done. The design of the stator winding of the permanent magnet generator is shown in Figure 8.

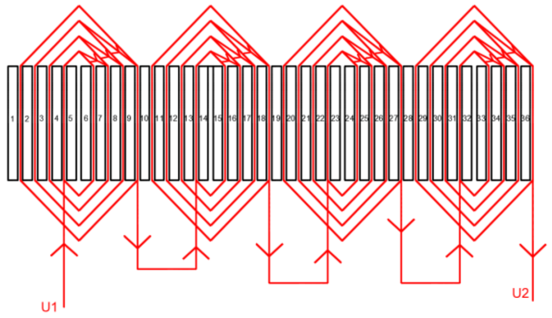


Figure 8 The design of stator windings of permanent magnet generator.

According to the equation (2), the output voltage generated will be around 113 V, 50 Hz with the number of turns, flux density, effective area, and rotation speed of 600 turns, 1.46 Tesla, 1.6081×10-^{4} m^{2,} and 750 rpm respectively. Table 1 below gives the calculated output voltage of the generator for the various value of rotation speed.

Table 1. Calculated generator output voltage for various rotation speeds.

Rotation speed (rpm)	Frequency (Hz)	Output voltage (V)
0.0	0.0	0.0
75.0	5.0	11.3
150.0	10.0	22.6
225.0	15.0	33.9
300.0	20.0	45.3
375.0	25.0	56.6
450.0	30.0	67.9
525.0	35.0	79.2
600.0	40.0	90.6
675.0	45.0	101.9
750.0	50.0	113.2

3.4. Reassembling rotor and stator followed by conducting laboratory test.

After completing the modification, the rotor and stator are reassembled to form a single-phase AC permanent magnet generator. Then, the generator is coupled with a constant speed electric motor and is run for two different laboratory tests i.e., no-load and on-load tests.

Data of the no-load test are given in Table 2 below. One can see that at near to-rated rotation speed 750 rpm the output voltage generated is 110 V which is slightly (2,83%) lower than the calculated output voltage.

Table 2. Data of no-load laboratory test.

Rotation speed (rpm)	Frequency (Hz)	Output voltage (V)
0.0	0.0	0.0
112.6	7.5	12.0
152.2	10.1	18.0
197.7	13.2	24.0
258.0	17.2	31.5
308.4	20.6	39.0
354.0	23.6	45.0
413.5	27.6	54.0
451.6	30.1	60.0
505.3	33.7	66.0
551.8	36.8	72.0
601.9	40.1	81.0
650.2	43.3	87.0
702.5	46.8	93.0
749.3	50.0	110.0

Figure 9 shows the graphs of calculated generator output voltage according to Table 1 and generator output voltage according to no-load test data given in Table 2. Both graphs show a linear relationship between the generator output voltage and rotation speed. In general, the generator output voltage according to no-load test data is slightly lower than the calculated one. Further, as shown by Figure 10, a waveform of generator output voltage near its rated rotation speed of 750 rpm is not purely sinusoidal. It contains odd-order harmonics, particularly the third and seventh ones, with total harmonic distortion (THD) around 15.8%. A non-sinusoidal output voltage waveform is generated due to the non-uniform rotor surface. The depths of eight permanent magnets embedded in the rotor are varied. It is very hard to make each permanent magnet pole embedded exactly at the same depth when the rotor is modified manually in a public workshop.

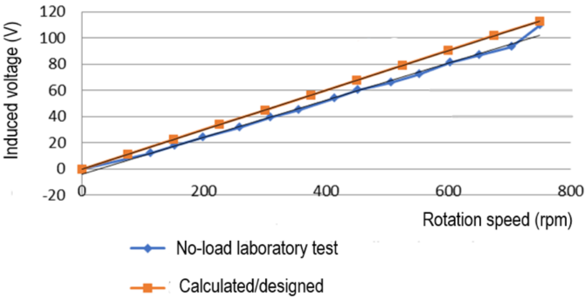


Figure 9 Output voltage of the permanent magnet generator.

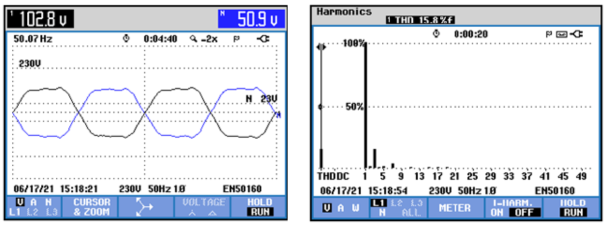


Figure 10 Output voltage waveform of the permanent magnet generator.

Data of the on-load test are given in Table 3 and Table 4. Table 3 presents data when the permanent magnet generator is connected to a resistive linear load while Table 4 presents data for non-linear loading. Voltage drops calculated from data of these two loading conditions show that generator voltage drops vary from 8.2% to 29.1% for linear resistive loading conditions. Meanwhile, generator voltage drops vary from 4.5% to 26.4% for non-linear loading conditions.

Table 3. Laboratory test data of resistive linear loading condition.

Rotation speed (rpm)	Motor voltage (V)	Motor current (A)	Generator voltage (V)	Generator current (A)	Voltage drop (%)
749.3	26.0	1.5	110.0	0.00	0.0
752.1	29.0	2.2	101.0	0.18	8.2
751.0	30.5	2.2	99.0	0.20	10.0
750.7	35.0	3.0	88.5	0.45	19.5
749.8	38.0	3.5	78.0	0.66	29.1

Table 4. Laboratory test data of non-linear loading conditions.

Rotation speed (rpm)	Motor voltage (V)	Motor current (A)	Generator voltage (V)	Generator current (A)	Drop voltage (%)
749.3	26.0	1.5	110.0	0.00	0.0
752.6	27.0	1.8	105.0	0.08	4.5
750.1	28.5	2.0	103.0	0.10	6.4
749.0	33.0	2.8	91.5	0.37	16.8
752.1	37.0	3.4	81.0	0.60	26.4

To calculate efficiency, equation (4) is applied. Using both on-load test data given in Table 3 and Table 4, calculated efficiencies of the generator are presented in Table 5 and Table 6 below.

Table 5. Power and efficiency of the generator on linear loading conditions.

Power input (W)	Power losses		Efficiency (%)
	Mechanical and core (W)	Winding (W)	
43.8	19.0	1.4	53.5
47.1	19.0	1.7	56.0
85.0	19.0	8.5	67.7
113.0	19.0	18.6	66.7

Table 6. Power and efficiency of the generator on non-linear loading conditions.

Power input (W)	Power losses		Efficiency (%)
	Mechanical and core (W)	Winding (W)	
28.6	19.0	0.3	32.6
37.0	19.0	0.4	47.5
72.4	19.0	5.7	65.7
105.8	19.0	15.4	67.5

Figure 11 shows plots of calculated generator efficiency listed in Table 5 and Table 6. One can see that generator efficiency is relatively the same for linear and non-linear loading conditions. The generator efficiency is expected to differ when load with a higher power is applied.

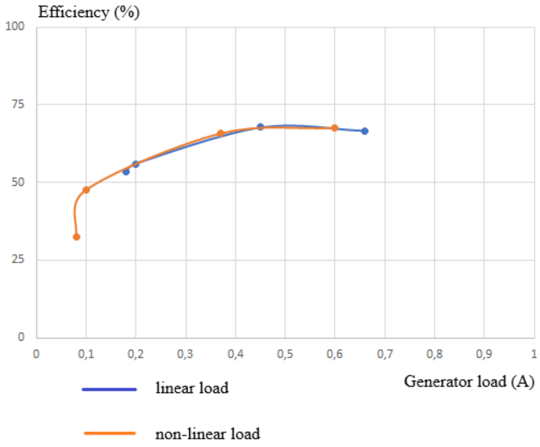


Figure 11 Efficiency of the permanent magnet generator.

4. CONCLUSIONS

A squirrel cage of a single-phase AC induction motor has been successfully modified into a low-speed single-phase AC permanent magnet generator. The generator has eight permanent magnet poles and four stator windings. Each winding has 150 turns. The generator is designed to be able to generate a single-phase AC sinusoidal waveform with a magnitude of around 113 V and frequency of 50 Hz when rotates at 750 rpm.

Laboratory test data show that under the no-load condition, the generator can produce an output voltage of 110 V when rotates at 749.3 rpm. However, the output voltage generated is not purely sinusoidal, as indicated by its total harmonic distortion (THD) value of 15.8%. Further, on-load laboratory test data show the range of generator voltage drop from 8.2% to 29.1% and 4.5% to 26.4% respectively on linear resistive and non-linear loading conditions. On the same loading condition, generator efficiency varies from 53.5% to 66.7% and 32.6% to 67.5%.

AUTHORS’ CONTRIBUTIONS

Thank you to M. Afif Dzulfiqar N. K. S. for his work on modifying a squirrel cage of a single-phase AC induction motor to a single-phase AC permanent magnet generator. Also, thank you to Harry Setiadi and Mr. Erwin Yusuf for conducting and supervising laboratory tests and providing the necessary analysis data.

ACKNOWLEDGMENTS

This research was funded and supported by Pusat Penelitian dan Pengabdian Kepada Masyarakat (P3M), Politeknik Negeri Bandung.

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