International Journal on Advanced Science Engineering Information Technology

Vol.11 (2021) No. 4
ISSN: 2088-5334

Implementation of Three Phase Axial Flux Disc Permanent Magnet Generator for Low-Speed Horizontal Axis Wind Turbine

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***Abstract*—The wind speed characteristic in Indonesia requires a low-speed generator for a wind turbine generator system. One type of generator suitable for a low-speed wind turbine is the Axial Flux Disc Permanent Magnet Synchronous Generator (AFDPMSG). This type of generator uses permanent magnets to produce axial flux in the rotor disk, making it easier to implement for wind power generation. This paper discusses the design of three-phase AFDPMSG compatible with low-speed Horizontal Axis Wind Turbine (HAWT) in the single coreless stator and single rotor configuration. The AFDPMSG stator is designed using 15 coils coated with fiberglass, while the rotor is designed using 18 poles of Neodymium N52 type permanent magnet. To drive low-speed AFDPMSG with large mechanical torque, the HAWT is designed using six blades made of fiberglass with NACA6412 type airfoils. The magnetic characteristics of AFDPMSG were analyzed using SolidWorks software based on the finite element method. Then the electrical characteristics were verified through simulations using Matlab software and experiments using horizontal axis wind turbines. Both simulation and experimental results show that AFDPMSG has produced voltage and power for a low-speed wind turbine as expected. HAWT has been able to drive the AFDPMSG with a speed of 263 rpm at a wind speed 9 m/sec so that the AFDPMSG can produce the output voltage 14 volts with the output power of 580 Watts. These results are close to the AFDPMSG rating design.**

***Keywords*—HAWT; AFPMG; neodymium N52; permanent magnet; fiberglass.**

Manuscript received 7 Jan. 2020; revised 17 Jul. 2020; accepted 13 Dec. 2020. Date of publication 31 Aug. 2021.

I. INTRODUCTION

Wind energy is one of the renewable energy sources that began to be developed for electricity generation in Indonesia. The wind energy conversion into electrical energy uses two primary energy converters, namely wind turbines and generators [1]. Several wind turbines are applied to electric power generation, but horizontal axis wind turbines (HAWT) dominate because they have many advantages over vertical axis wind turbines (VAWT). Some of HAWT's advantages include high efficiency with high power coefficient, high tip speed ratio, and the rotor speed is more easily controlled [2]-[4]. Therefore, in this paper, HAWT was chosen to drive the generator in wind power plants.

The HAWT is designed to be connected directly to a generator without a gearbox to improve power plant efficiency so that the power loss on the shaft can be minimized [5]. In this concept, the low-speed generator is needed to match the wind turbine's rotation speed rating. Several types of generators have been used for wind power generation systems, such as doubly-fed induction generator (DFIG) [6]-[7], squirrel cage induction generator (SCIG) [8] and permanent magnet synchronous generator (PMSG) [9]–[14]. PMSG many selected for a low-speed wind turbine because it can operate at low speed, so it does not need a gearbox. Also, this machine has several other advantages, as though high efficiency, good power density and smaller size for the same power than other machine types [11]–[15].

PMSG is grouped on axial flux permanent magnet synchronous generator (AFPMSG) and radial flux permanent magnet synchronous generator (RFPMSG) based on the flux direction. AFPMSG is more profitable for small power applications because it can be designed without a stator core, making it lighter and easier to implement [16]–[22]. Therefore, AFPMSG was chosen as a generator for low-speed wind turbines in this paper. AFPMSG is designed in the form of single stator using fiberglass as the core and single rotor using the aluminum disc as a permanent magnet holder, so it is also called axial flux disc permanent magnet synchronous generator (AFDPMSG). In order to operate at low speeds, the AFDPMSG rotors are made 18 poles using a Neodymium

N52 permanent magnet, while the stator uses 15 pieces of the coil in a three-phase configuration.

Low-speed AFPDMSG requires a drive with high mechanical torque. Therefore, the HAWT used as an AFDPMSG drive must produce large mechanical torque at low rotor speeds. The mechanical torque characteristics of HAWT are determined by the blades' number and shape [3], [4]. Large mechanical torque from HAWT can be obtained by widening the blade and increasing the number of blades. The HAWT was designed using six blades made of fiberglass to achieve this goal. The blade shape is designed using NACA6412 type airfoil.

II. Material and Method

Research with experimental methods is presented in this paper. The research objects discussed in this paper are AFDPMSG and HAWT. The experiment was carried out with several steps, namely the design of both HAWT and AFDPMSG, manufacturing HAWT and AFDPMSG and continued with testing to obtain the feasibility of HAWT and AFDMPSG. The design phase includes calculations to get parameters used as a reference for making HAWT and AFDPMSG. The calculation is done manually and simulations using software, such as SolidWorks software, to determine the magnetic flux density and MatLab software parameters to see the AFDPMSG output voltage in the simulation. The steps, methods and materials used in this study are described in the following sections.

A. Horizontal Axis Wind Turbine

Wind turbines in wind power plants are used to produce mechanical power that will drive the generator. Based on the direction of the blade axis, the wind turbines are categorized as HAWT and VAWT. In this paper, HAWT was chosen as the driver of the low-speed AFDPMSG because of the advantages of its features. HAWT is a type of wind turbine with lift-based propulsion. In this paper, HAWT is designed to drive low-speed AFDPMSG directly without a gearbox, so HAWT must produce high mechanical torque to drive the generator. The mechanical torque (T_m) of HAWT is written as:

$$T_m = 0.5\,\rho\,\pi\,R^3\,C_p(\lambda,\beta)\,v_w^2 \qquad (1)$$

Where R, β, C_p, λ, v_w and ρ are the blade radius, the pitch angle of the blade, power coefficient, Tip Speed Ratio (TSR), wind speed and air density, respectively. Based on (1), the mechanical torque of HAWT is influenced by TSR. The TSR value is determined by number and blade shape, while the blade shape depends on the airfoil and the blade twist angle.

The high mechanical torque for driven low-speed AFDPMS was obtained by increasing the blades' number and increasing the width of the blades. The maximum width of the blade L_{max} can be calculated as follows:

$$L \frac{2\pi R}{n_b}\frac{8}{9\,C_L}\frac{v_w}{\lambda\, v_{R_{max}}} \qquad (2)$$

CL, Vr and nb are the lift coefficient, resulting from local wind speed and blade number, respectively.

HAWT is designed to drive low-speed AFDPMSG directly without a gearbox. The AFDPMSG has a power rating of 600 watts with a rotation speed 300 rpm. Therefore, HAWT must produce mechanical power and shaft rotation speed which is equivalent to the AFDPMSG rating. HAWT is designed with many blades with radius is calculated using the following equation to achieve this goal.

$$R = \sqrt{\frac{P_m}{0.5\,\rho\,C_p\,\pi\,v_w^3}} \qquad (3)$$

Where P_m is the mechanical power of HAWT, HAWT is made with six blades with a blade radius of 120 cm, and the maximum width is 20 cm to get the HAWT following the needs of AFDPMSG. These data are obtained based on calculations using equations (2) and (3) with assuming a wind speed rating 9 m/sec and a power coefficient of 0.4. Fig. 1 shows the HAWT design in this paper.

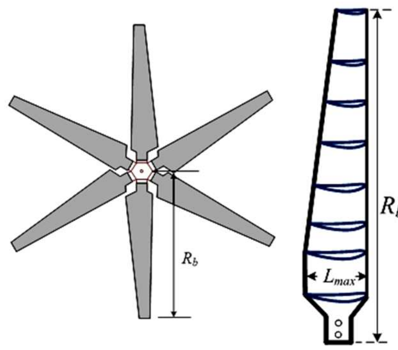


Fig. 1 Design of HAWT blade

The blade shape is designed using NACA6412 type airfoil with twist angle 10°. Fig 2 shows the NACA6412 airfoil shape for HAWT.

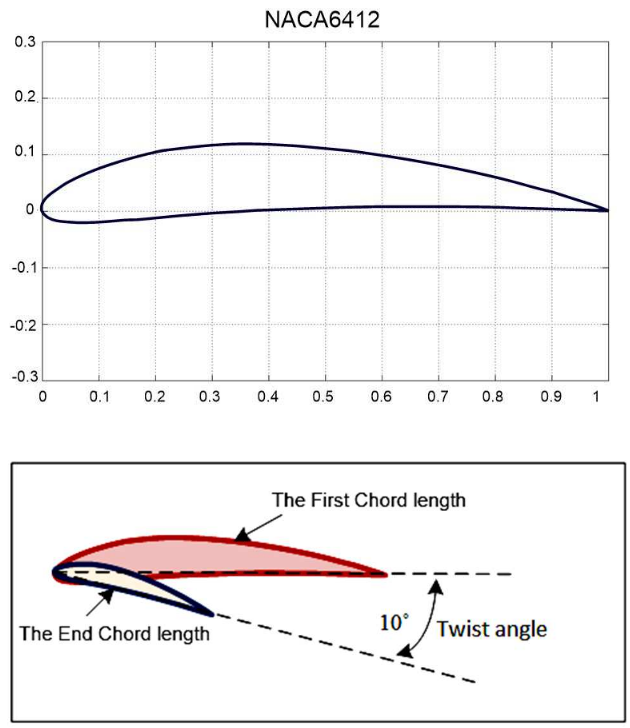


Fig. 2 The blade airfoil

The blade is designed using fiberglass material to get a sturdy blade and resistant to weather changes. This material consists of a fiberglass mat which is coated with a resin mixture. The fiberglass mat is made in five layers with three different forms to get the shape of the blade compatible with the NACA6412 airfoil and strengthen the blade structure, as shown in Fig 3(a). Fiberglass mat layers are sorted from shapes 1, 3, 2, 2, 3, and 1. Fig. 3(b) shows the process of forming a fiberglass mat for a blade. Apart from fiberglass mats for all blade layers, the airfoil formation is also carried out using molds. Fiberglass molds are made from wooden boards, as shown by Fig. 3 (c). This blade mold is coated with plastic that is smeared with oil, so that fiberglass does not stick to the mold when the blade-making process occurs.

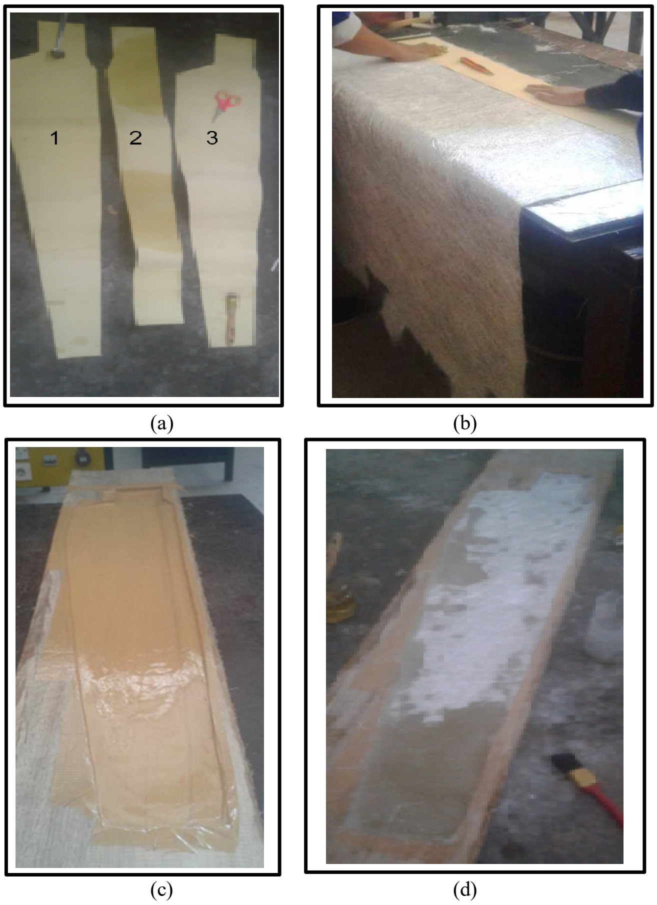


Fig. 3 The manufacturing of blade. (a) the fiberglass mat shape, (b) chopped strand fiberglass mat, (c) blade mold, (d) fiberglass molding process

The making process of fiberglass blades is carried out step by step from the first and fifth layers. Each layer is poured into a resin mixture so that each layer of fiberglass is combined with the other layers. This liquid resin is added with a catalyst to speed up the drying process of fiberglass. Fig. 3(d) shows the process of making a blade on a wooden molding board. After the mold dries' fiberglass material, then the removal of the fiberglass blade from the mold is carried out for tidying up. The fiberglass blade cleaning process includes trimming, smoothing, and leveling of the blade's uneven surface due to the resin lumps using a grinding machine. Fig. 4 shows a fiberglass blade that has been cleaned. Next, the blade is installed on the HAWT shaft. This shaft will connect with AFDPMSG. The results of mounting the blade to the shaft are shown in Fig. 4.

Fig. 4 The HAWT manufacturing results.

B. Axial Flux Disc Permanent Magnet Generator

The Axial Flux Disc Permanent Magnet Synchronous Generator (AFDPMSG) made in this paper is designed in the form of a single stator single rotor for three-phase configurations. AFDPMSG is designed to be connected directly with the HAWT without using a gearbox. AFDPMSG is designed for low rotation HAWT with the speed rating of the wind is 9 m/sec, the output power rating 600 watt, the voltage rating 12 volts, and the rotor speed rating 330 rpm for system frequency 50 Hz. The AFDPMSG is made with 18 poles of permanent magnets placed on the rotor, whereas fifteen coils are placed on the stator, where each phase has five coils. The design of AFDPMSG is shown in Fig. 5.

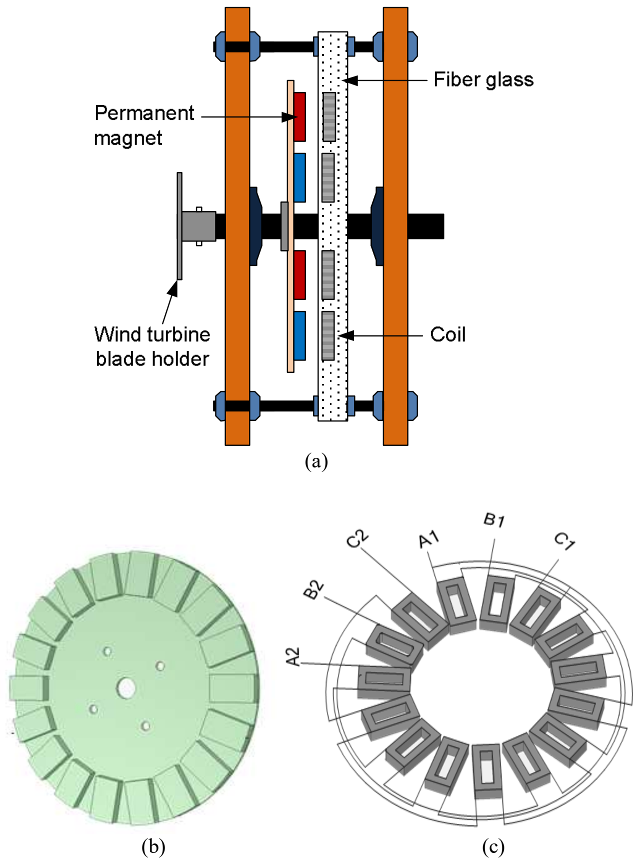


Fig. 5 The design of AFDPMG. (a) the structure of AFDPMG, (b) rotor disc, (c) stator disc

Fig. 5(a) shows the AFDPMSG structure that was designed. AFDPMSG is designed with stator disc and rotor disc facing each other. This design makes the axial flux produced by the permanent magnet on the rotor hit the stator coil. The maximum value of permanent magnetic flux on the stator coil is determined by the length of the air gap between the disc rotor and the stator disc. To get the voltage and power following the rating at the designed speed rating, the rotor's inner diameter, the rotor's outer diameter, stator diameter, number of turns per phase, and diameter of the coil wire are calculated [22]. Calculations are based on the generator rating to be achieved and the magnetic flux density that can be generated by the permanent magnets used in the rotor. Permanent magnets used in rotors are Neodymium N52 magnets with dimensions 1 cm x 3 cm x 5 cm. The magnetic flux density parameters of the permanent magnet N52 were obtained through analysis by the finite element method using SolidWorks software.

Fig. 6 shows the simulation results of testing the magnetic flux density of N52 magnets with the air gap between the permanent magnet and the stator coil is 0.5 cm. The results show that the magnetic flux on the stator coil is only in the blue range, and it shows that the magnetic flux density on the stator coil is relatively low.

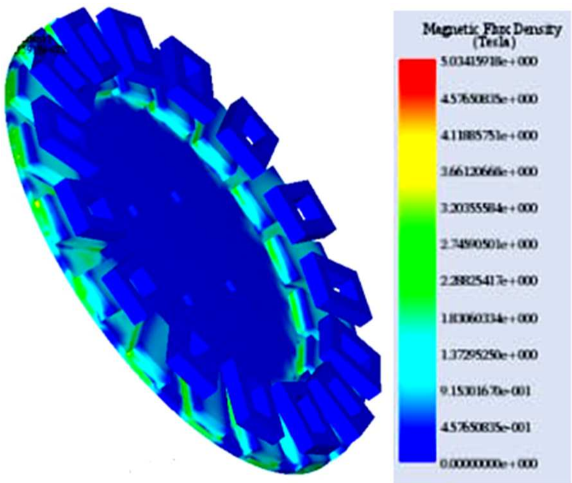


Fig. 6 The magnetic flux density of the AFDPMSG rotor

After the magnetic flux density values are obtained, then the turn number of the stator coil and the coil wire diameter is calculated based on the equation presented in [22]. Based on the calculation results, AFDPMSG parameters are obtained as described in Table 1. After all, AFDPMSG parameters are obtained from the calculation results, the next is designing and manufacturing AFDPMSG. Fig. 7 shows the manufacturing results of AFDPMSG. The stator disc is made without an iron core. For the stator coil holder, fiberglass is used without coating a fiberglass mat (Fig. 7(a)). Disc rotors are made using a 5 mm thick iron plate. Permanent magnets are placed on the disk following the design. Fig. 7(b) shows the disc rotor coated with iron glue and fiberglass to hold the permanent magnet from being detached from its holder.

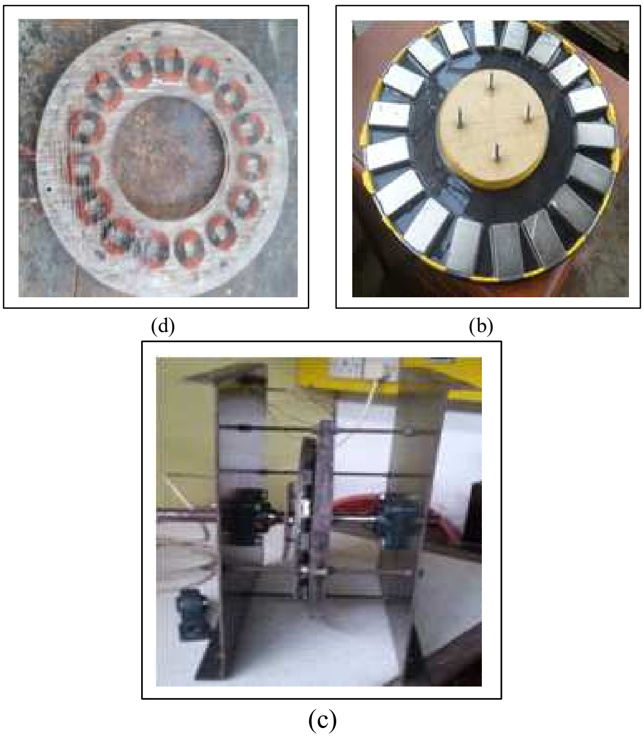


Fig. 7 The manufacturing of AFDPMG. (a) stator disc, (b) rotor disc (c) Assembled result

Fig. 7 (c) shows the AFDPMSG that has been completed. After AFDPMSG is finished, HAWT and AFDPMSG are then assembled for testing. Fig. 8 shows the HAWT and AFDPMSG configurations that are ready to be tested.

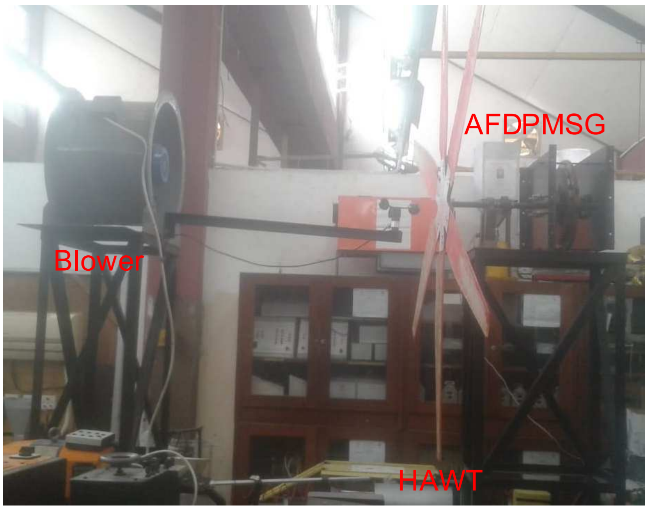


Fig. 8 Experimental setup

III. Results and Discussion

Both HAWT and AFDPMSG designed in this paper are verified through simulations and experiments. Simulations are done by using MatLab Simulink software. In this simulation, the HAWT and AFDPMSG parameters are designed according to the calculation results described in Table 1.

TABLE I
THE MAIN DATA OF EXPERIMENTS

Components	Units	Parameters
AFDPMG	Number of phase coil	5
	Total number of the stator coil	15
	Number of permanent magnets	18
	Permanent magnet size	1 x 3 x 5 cm
	Rotor outer radius	15.77 cm
	Rotor inner radius	10.77 cm
	The air gap length	0.5 mm
	The total number of phase winding turns	760 turn
HAWT	Number of blades	6
	Maximum width of the blade	20 cm
	Blade radius	120 cm

Simulations are performed to see the value of voltage, current, rotor speed, and power generated by the generator when HAWT is given a varied wind speed. In this simulation, the generator is connected to a 120 Ohm load resistor. The simulation is done by varying the wind speed from 6 m/sec to 9 m/sec, as shown in Fig. 9.

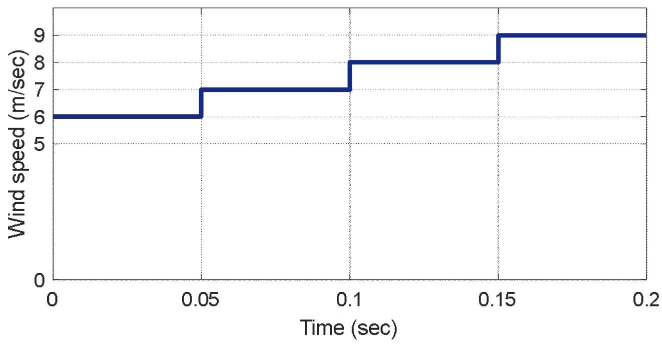


Fig. 9 Wind speed

Fig. 10 shows the results of the simulation using Simulink Matlab. Fig. 10(a) shows the rotor speed response that varies from 185 rpm at the wind speed is 6 m/sec to 280 rpm when the wind speed is 9 m/sec. This result shows that the rotor speed of the HAWT is approaching the AFDPMSG speed rating when the wind speed is at its rating value, which is 9 m/sec. This result indicates that the HAWT and AFDPMSG parameters used in the simulation have resulted in the rotor speed approaching the desired rating value, i.e., 330 rpm. The same conditions can be seen from the stator voltage response, as shown in Fig. 10(b) and 10(c). Fig. 10(b) shows the stator voltage waveform, and Fig. 10(c) shows the RMS value of the stator voltage. These results indicate that AFDPMSG can produce a voltage 10 volt at the wind speed is 6 m/sec and 14.7 volts when the wind speed is 9 m/sec. This number presented that the voltage generated by the AFDPMSG was close to the voltage rating value that was designed in this paper, which is 12 volts for a wind speed 9 m/sec. Fig. 10(d) and 10(e) show the AFDPMSG stator current response, which varies according to wind speed changes. Fig. 10(d) shows the stator current waveform, and Fig. 10(c) shows the stator current's RMS value. These results indicate that the stator current increases while the wind speed increases. This result shows that the generator output power increases according to the increase the wind speed, as shown in Fig. 11.

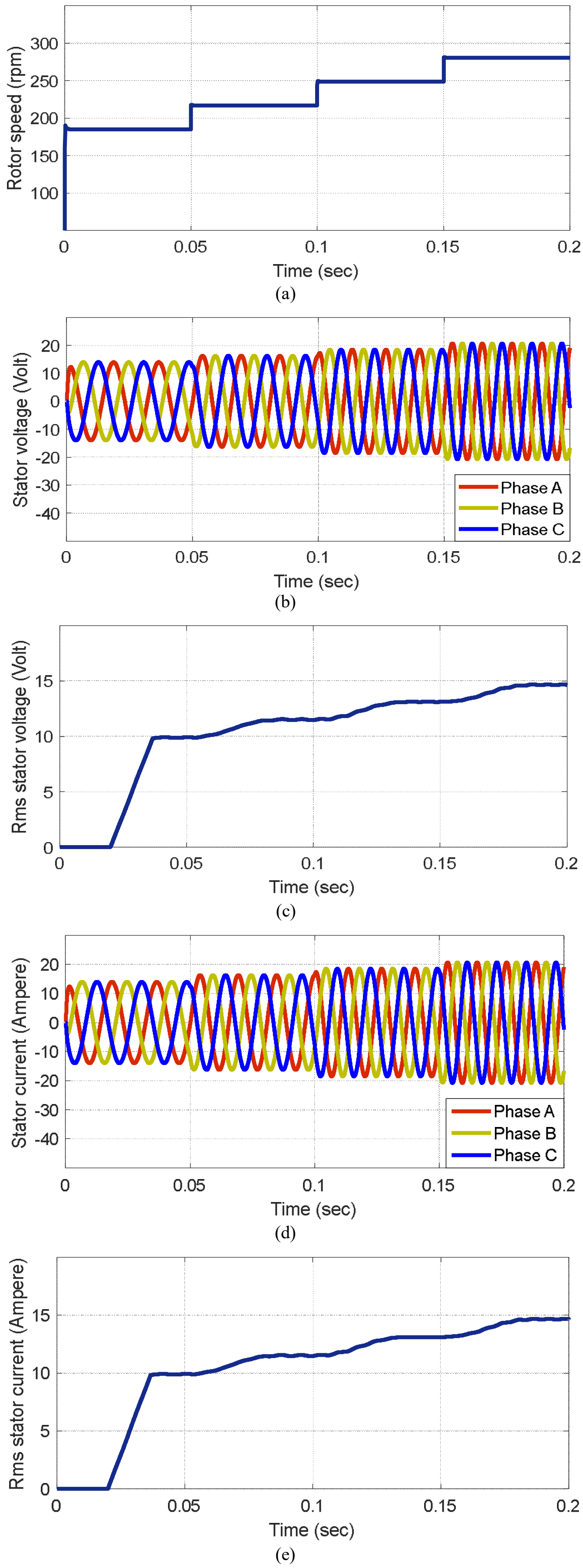


Fig. 10 The simulation results. (a) rotor speed, (b) stator voltage, (c) rms stator voltage, (d) stator current, (e) rms stator current.

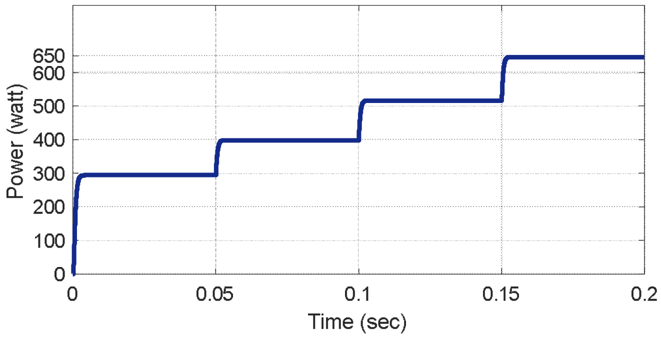
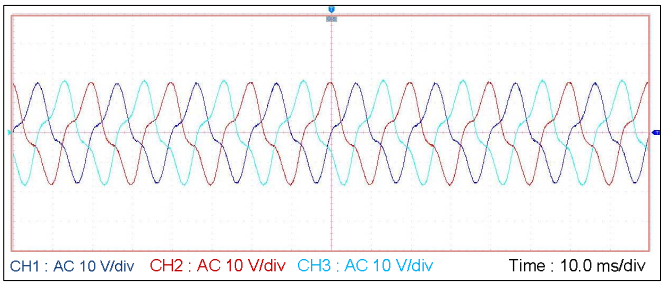


Fig. 11 The generator output power

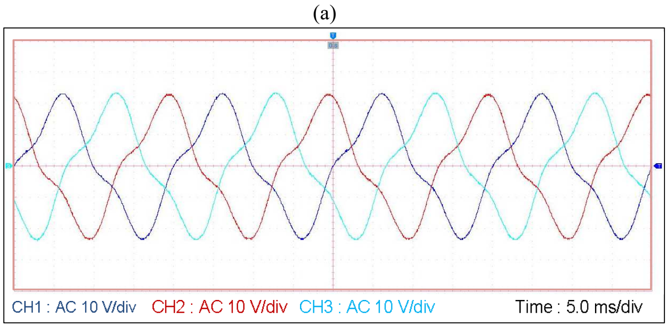
Fig. 11 shows that the AFDPMSG output power can reach 294 watts while the wind speed is 6 m/sec and 645 watts while the wind speed is 9 m/sec. These results show that the AFDPMSG power at wind speed 9 m/sec has approached the generator's designed power rating.

The next steps performed experiments to test the HAWT and AFDPMSG. Experiments were carried out to see the performance of both HAWT and AFDPMSG, which included voltage, current, rotor speed and generator output power. AFDPMSG is connected to the load resistor and tested with varying wind speeds to get the required data. In this experiment, several measuring devices are used to obtain the required data, such as wattmeter, amperemeter, anemometer and digital oscilloscope.

In this experiment, both HAWT and AFDPMSG were tested with varying wind speeds from 6 m/sec to 9 m/sec. The wind speed that will drive the HAWT is obtained from the blower, as shown in Fig 8. The variation of wind speed is done by regulating the blower motor's input voltage using an autotransformer. Fig. 12 shows the performance of the AFDPMSG output voltage measured using a four-channel digital oscilloscope.



(a)



(b)

Fig. 12 The experimental results. (a) stator voltage at wind speed 6 m/sec, (b) stator voltage at wind speed 9 m/sec

Fig. 12(a) shows the waveform of AFDPMSG output voltage when the wind speed is 6 m/sec with oscilloscope voltage parameters 10 Volt/div and time 10 msec/div. The results show that the AFDPMSG can generate voltage 9 Volt with a sinusoidal waveform. In this condition, the rotor rotates with a speed of 170 rpm, as described in Table 2. These results are close to the same as the simulation results. The voltage waveform that approaches sinusoidal shows that the permanent magnet's layout on the rotor and coil on the stator is correct according to the design.

Fig. 12(b) shows the voltage waveform at the wind speed 9 m/sec. The oscilloscope voltage parameter is set to 10 Volt/div with time 5 msec/div in this measurement. The RMS output voltage at this condition is 14 Volts, as described in Table 2. These results indicate that the output voltage produced by AFDPMSG at the wind speed rating is close to the voltage value set on the design, which is 12 volts. So, it can be concluded that the AFDPMSG made in this paper follows the rating on the design. This finding can be seen from other experimental results, such as current measurements, rotor speed, and generator output power, as shown in Table 2.

TABLE II
THE EXPERIMENT RESULTS

Parameter		Wind Speed (m/sec)			
		6	7	8	9
Simulation	Rotor speed (rpm)	185	217	249	280
	Rms stator voltages (Volt)	10	11.5	13.1	14.7
	Power (Watt)	294	398	516	645
Experiments	Rotor speed (rpm)	170	205	230	263
	Rms stator voltages (Volt)	9	11	12.5	14
	Power (Watt)	243	360	470	580

Based on the experimental results, AFDPSMG can produce power 580 watts with a rotor speed 263 rpm when the wind speed is 9 m/sec. This output power value is close to the AFDPMSG power rating planned in this paper, 600 watts. These results also approach the results obtained through simulations with Simulink Matlab. Fig. 13 shows the comparison of simulation results with the results of the experiments conducted in this study. Fig. 13(a) compares the rotor speed of the simulation results with the experimental results. The simulation rotor speed is greater than the experimental results with a relatively small error, which is only 17 rpm when the wind speed is 9 m / sec. The same condition can also be seen from the AFDPMSG output voltage response in Fig. 13(b) and the AFDPSMG output power response in Fig. 13(c), where the value of the voltage and AFDPMSG output power of the simulation results is greater than the experimental results with relatively small differences. Nevertheless, the value of the rotor speed, the output voltage, and the output power obtained from the of simulations and experiments are close to the planned rating in this study. So, it can be concluded that the HAWT and AFDPMSG made in this study have given results as expected

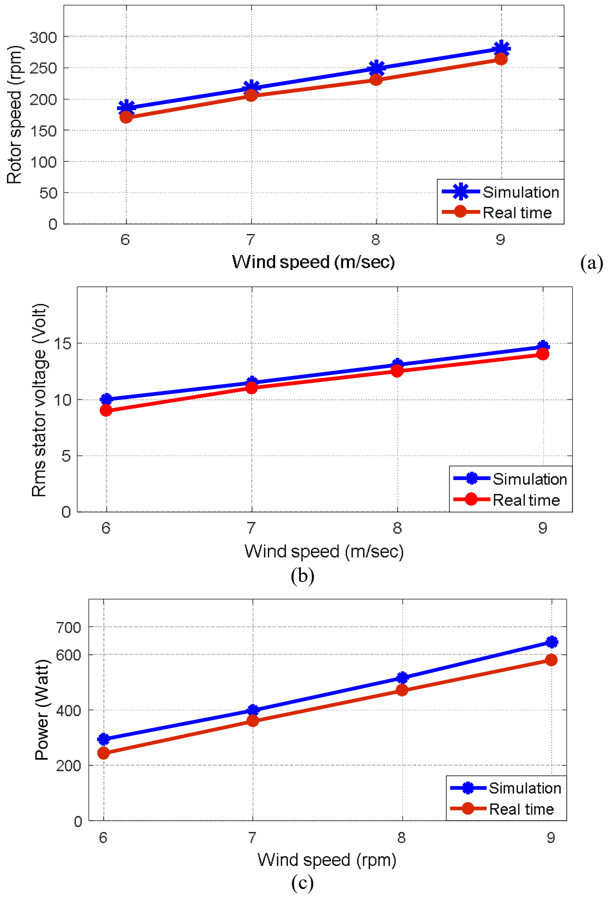


Fig. 13 Comparison of simulation results with experiments (a) rotor speed, (b) RMS value of stator voltage, (c) output power.

IV. CONCLUSION

Manufacture and testing of AFDPMSG for low-speed HAWT are discussed in this paper. AFDPMSG is designed with output power rating is 600 watts, the output voltage is 12 volt, and rotor speed rating is 330 rpm for HAWT with a wind speed rating of 9 m/sec. AFDPMSG is designed in the form of a single stator single rotor using eighteen Neodymium N52 permanent magnets on the rotor and fifteen coils on the stator. Both HAWT and AFDPMSG designed in this study were verified through simulations and experiments. AFDPMSG has been able to produce an output power of 580 watts with a voltage of 14 volts and a rotational speed of 263 rpm when the wind speed is 9 m/sec. These results are close to the AFDPMSG rating designed in this study.

ACKNOWLEDGMENT

The authors are grateful to the Ministry of Education and Culture Republic of Indonesia (Kemendikbud) for providing financial support under the research grant No :455/UN35.13/LT/2019.

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