Performance investigation of standalone wind power system equipped with sinusoidal PWM power inverter for household consumer in rural areas of Indonesia

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Research paper

Performance investigation of standalone wind power system equipped with sinusoidal PWM power inverter for household consumer in rural areas of Indonesia

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ABSTRACT

This paper proposes the performance investigation of a standalone wind power system equipped with sinusoidal pulse width modulation (SPWM) power inverter for household consumption in rural areas of Indonesia. Indonesia, which is in the tropics, has the potential for developing wind power plants. One of the potential areas is the South Coast, Bantul, Yogyakarta Special Region, the location of this research. This work has designed, assembled, and tested a 4-kW wind power plant using a permanent magnet synchronous generator (PMSG) driven by a horizontal type of turbine. The test results show that the power plant can generate electrical energy suitable for meeting the electricity needs of residents' homes. This success indicates that the generator's voltage is good enough and feasible to be stored in the battery. Although the voltage's value depends on the wind speed, it is adequate because it is close to the nominal voltage that the PMSG generator should produce. The electrical energy generated by this power plant is stored in the battery bank. Also, the performance of the SPWM power inverter has been demonstrated in the experimental tests of resistive and inductive loading. This power plant's development follows government's commitment to utilizing renewable energy sources as priority energy as a strategy to reduce dependence on fossil energy and overcome the environment.

1. Introduction

The Government of the Republic of Indonesia's current national energy policy is the use of primary and final energy (Syahputra et al., 2015). This energy utilization target meets the national power generation capacity in 2025 of 115 GW and 2050 to 430 GW. Besides, for Indonesia's people, the use of electricity per capita will be achieved in 2025 of 2500 kWh, and in 2050 it will be 7000 kWh (Syahputra and Soesanti, 2020). Utilizing energy resources to fulfill national electrical energy, the government is targeting the use of new and renewable energy by 23% by 2025 as long as its economic value is met. In that year, the use of petroleum was limited to 25%, coal to a minimum of 30%, and natural gas to 22%. In 2050 the use of petroleum is increasingly limited to only 20%, coal to a minimum of 25%, natural gas to a minimum of 24%, while using new and renewable energy by 31% (Syahputra and Soesanti, 2019). The targets set out in the National Electricity General Plan show that the government is very serious about developing and utilizing renewable energy sources that are very potential in Indonesia (Hariadi et al., 2018). The lack of conventional energy sources that rely on fossil fuels and coal and environmental problems that are increasingly worrying are the leading causes of renewable energy sources (Djalal et al., 2021).

One of the potential renewable energy sources to be developed in Indonesia is wind energy (Fauzy et al., 2021). The government will continue to strive to create and utilize renewable energy, including wind energy, as the national energy backbone to achieve the national energy mix target of 23% from renewable energy by 2025 (Suharyati et al., 2019). Local governments, private companies, universities, and the general public have been encouraged to developing wind power generation technology in various regions. The area of Indonesia, which is traversed by the equator, has an enormous wind potential. Areas with potential wind energy are the southern regions of Java, Bali, Nusa Tenggara, Maluku, Sulawesi, and Papua. One of the places on the island of Java that has a high potential to generate electricity from wind energy is the coast in the Bantul Regency, Yogyakarta Special Province. The wind speed in this area ranges from 3 to 12 m/s (Syahputra et al., 2017). These relatively good wind speeds come from the vast seas of the Indian Ocean.

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Researchers from various countries have researched wind power plants' applications and efforts to improve their performance. Several researchers have proposed using wind power plants for standalone systems to meet electrical energy needs. The literature review begins with the optimal turbine blade design for a standalone system. Svorcan et al. (2018) performed an aerodynamic performance analysis of wind turbine blades using a different numerical approach. The investigation of the flatback airfoil effect applied to a 10 MW wind turbine blade has been carried out by Jeong and Kim (2018). Furthermore, in the operation of wind power plants in a standalone microgrid, Zhou et al. (2019) have considered changes in load. They proposed a standalone microgrid system's operation taking into account the load power capacity. The power plant in the microgrid system consists of a wind and biomass hybrid system. Many independent hybrid systems have been implemented to meet the needs of electrical energy in remote rural areas. Usually, these areas do not get electricity supply from national or private electricity supply companies.

Mohammed et al. (2020) designed a standalone wind power plant for supplying electrical energy to residential loads. This power plant provides electrical energy to rural areas in Iraq that do not yet have access to the electricity grid. Diab et al. (2019) performed optimization of wind power generation size for rural areas in Egypt. Optimization is done to get the most competitive energy costs. Rehman et al. (2020) optimized a wind-powered renewable energy power generation system with other generators to supply rural electricity in India. Chen et al. (2020) made a wind power forecast model in a deterministic manner to get the wind turbine output power. This forecasting model features forecast accuracy based on statistical characterization of wind turbine output with the help of a new wind power stochastic cloud model. Li et al. (2018) proposed an improved single-engine equivalent method for improving wind power generation performance. This method is applied by calibrating the post-disruption power recovery behavior. Natural wind power plants are simulated with extensive wind scenarios. The analysis results show that wind turbines with varying wind speeds can recover initial active power at a specific ramp rate after cleaning the disturbance.

Quispe et al. (2020) studied and applied wind power plants using vertical and horizontal axis wind turbines. This generator has been applied in urban and rural areas around Lima, Peru. This study analyzes the feasibility of a turbine type by comprehensively studying the wind characteristics based on monthly and annual data to obtain the average speed. This data is used to design suitable wind power plants.

Kleftakis et al. (2014) designed a microgrid consisting of diesel and wind turbines for rural electrification. The development of a wind power plant model using a PMSG generator was designed using RSCAD RTDS software. The performance of the microgrid system is then tested in a Power Hardware environment. The operating strategies applied are frequency control, inertial system response, and field control load reduction. The designed system consists of a synchronous generator, an electrical load, and a PMSG wind turbine.

Alvarez (2017) modeled and simulated a wind power plant with a capacity of 800 W. This power plant is dedicated to rural areas of Ecuador. This wind power plant model is continued with the construction phase with performance optimization. Consumers of electrical energy that utilizes are rural houses in Ecuador. This power plant can be operated at very low wind speeds by utilizing a PMSG generator. Alarabi and Aly (2016) modeled a wind power plant in Simulink-Matlab software. The model has been validated with the original model, and the results have good performance.

Sharma et al. (2017) designed a 100 W micro-scale wind generator and studied its performance and reliability. This power plant is beneficial for supplying electric power in rural Tamilnadu, India. Wind potential with a minimum speed of 3 m/s at the height of 30 m can be used to rotate a wind turbine with a capacity of 100 W. This environmentally friendly power plant is very suitable for use with various limited facilities in these locations. The development of this power plant can serve electricity in people's homes and provide job opportunities for the local community.

The references above are one of the considerations and comparisons of what this research has done. The novelty of this research is the actual realization of wind power plants that are applied to the tropics on the southern coast of the island of Java, Indonesia. This power plant can serve the electrical load for consumers equivalent to two houses or four food stalls located in the vicinity. The characteristics of the wind at the research site are unique; that is, the wind speed and direction vary significantly according to changes in time. An essential contribution of this research is to promote the use of renewable energy and assist the Indonesian government in the program of providing renewable energy power plants, which is targeted to reach 23% of the total national power generation by 2025. Another novelty of this research is the design of a 5-kW sinusoidal pulse width modulation (SPWM) power inverter, which is implemented in a wind power plant. The SPWM power inverter was tested with resistive and inductive loading to analyze its performance.

2. Wind power systems

2.1. Wind energy potential in Indonesia

Indonesia has a wind energy potential of up to 60.647 GW, based on the National Energy General Plan (Hui et al., 2016). Areas that can develop wind power plants are the southern islands of Java, Bali, Nusa Tenggara, Papua, Maluku, and South Sulawesi. A map of wind potential throughout Indonesia is shown in Fig. 1. The government already has a renewable energy development program derived from wind power as part of the target of 23% renewable energy sources by 2025. The government's plan to build more wind power plants will bring many benefits to the broader community. The first advantage is that wind power generation does not require a fossil energy source, which is quite expensive and will run out at a particular time. This condition is very realistic that Indonesia has now become an importer of fuel oil. The second advantage is that wind power is one of the green energies that are environmentally friendly so that it is in line with environmental conservation efforts and reducing CO_2 emissions. The third advantage is that a wind power plant can be built in the middle of the sea, so there is no need for land acquisition. Land acquisition has become a thorny problem in several areas. The fourth advantage is that it can be built in remote areas to meet people's needs in remote areas of the country. This effort can increase the national electrification ratio and equal distribution of electricity supply for all Indonesian people. The fifth advantage is the cost of production, which is more competitive when compared to fossil energy. Technological developments have made the price of electricity from wind power plants cheaper and able to compete with electric energy derived from fossil energy. However, wind energy has the disadvantage that weather conditions positively influence it, making it difficult to predict (Anon, 2017). This disadvantage is at least when compared to other renewable energy power plants such as hydropower or conventional energy such as steam power plants which are less affected by the weather.

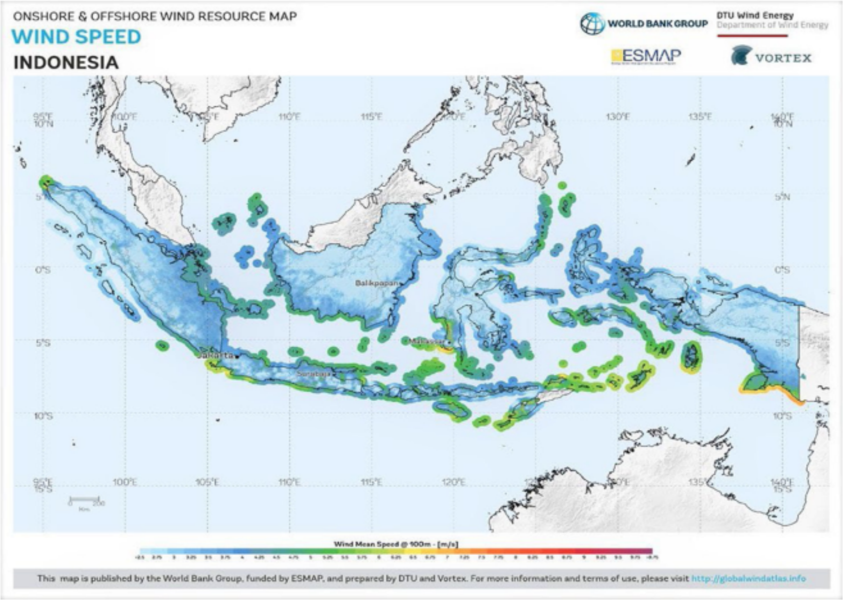

Fig. 1. A map of wind potential throughout Indonesia.

2.2. Wind turbine characteristics

The working principle of a wind power plant is that the wind turbine's kinetic energy will rotate the wind turbine at a certain speed that allows the generator to generate an electric voltage (Letcher, 2017). The wind speed variable is essential to know because it determines the operation of the plant. There are the minimum and maximum allowable wind speed limits for wind turbine operations. The wind speed that has the kinetic energy to move the wind turbine depends on the density of the air. The electric power (in watts) generated by a wind power plant can be found using the following equation (Manwell et al., 2009).

$$P = 0,5C_p\rho Du^3 \tag{1}$$

where C_p is the coefficient of electric power, ρ is the air density in kg/m^3, D is the cross-sectional area of the turbine blade in m^2, and u is the wind speed in m/s. Another essential variable to know is the wind turbine tip speed ratio. This ratio can be defined as the ratio of the linear velocity of the angular velocity and the wind turbine blade's speed, which can be expressed by the following equation.

$$\lambda = R\omega/u \tag{2}$$

where R is the turbine rotor radius in meters and ω is the angle velocity. By substituting Eq. (2) into Eq. (1), we get the new equation.

$$P = 0,5C_p(\lambda)\rho D(R/\lambda)^3(\omega)^3 \tag{3}$$

Finally, the equation for calculating the output power of the wind turbine can be obtained as follows.

$$P = 0,5\rho DC_p(u/\lambda) \tag{4}$$

Fig. 2 shows the power characteristics of a wind turbine in this study. The output power of the wind turbine depends on the speed of the wind that hits the turbine. The higher the wind speed, the greater the wind turbine output power produced.

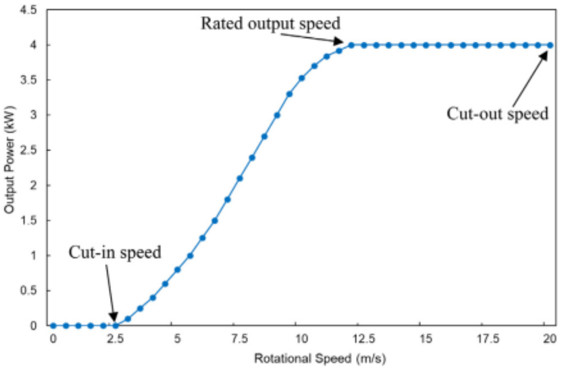

Fig. 2. Typical power characteristics of a wind turbine in this study.

However, the characteristics of the turbine output power to the wind speed are not linear. Based on Eqs. (1) to (4), it can be observed that the higher the wind speed hitting the wind turbine, the higher the wind turbine rotation. This high turbine rotation causes the PMSG generator rotor rotation to be high, resulting in high electrical power. The conclusion is that the higher the wind speed, the higher the electric power that can be generated by wind power plants.

When the wind speed exceeds the maximum allowable limit for wind turbine operations, the turbine's capacity will decrease. There is even a time for a wind turbine to be cut-off if the wind speed reaches a certain level. In this study, the maximum wind speed that allows a wind power plant's operation is 12 m/s. This speed is consistent with the wind characteristics at the research location on the south coast of Bantul district, Yogyakarta Special Region province, Indonesia.

2.3. Permanent magnet synchronous generator

Wind turbines are classified into two parts based on the turbines' rotation speed, namely fixed speed wind turbine (FSWT) and variable speed wind turbine (VSWT) (Mohammad et al., 2014). FSWT is a wind turbine where if the rotor rotates at the angular speed, it will be constant with changes in the wind, which is determined based on the gear ratio, system frequency, and the number of generator poles. FSWT has the advantages of a simple system, low maintenance costs, and the use of minimal power electronic circuits, such as power inverters and power rectifiers. However, FSWT has the disadvantage that the turbine cannot operate at varying wind speeds at a constant rate, so the energy produced is relatively small and cannot reach maximum efficiency. Another drawback is that the FSWT results in high fluctuations in the output power to the grid system, which can cause system disturbances. Furthermore, VSWT is a wind turbine where the rotor rotates at angular speed and changes based on wind speed. VSWT can achieve maximum wind energy conversion efficiency over a wide range of wind speeds. In this case, the wind turbine can adjust the rotational speed based on the wind speed, proportional to the rotor speed. Maximum efficiency can be obtained at different wind speeds by maintaining the tip speed ratio at optimal conditions. Generally, the wind turbine generator in VSWT is connected to the grid system through a power converter system. The converter system activates the generator speed control, which is mechanically coupled to the wind turbine rotor. VSWT has several advantages, namely being able to accommodate increased wind rates, improving power quality, and reducing mechanical stress. VSWT generally has an efficiency of 5% compared to FSWT, and the electric power generated can be easily controlled. However, the disadvantages of VSWT are the relatively higher investment costs due to the use of power converters and increased power losses and control complexity.

In the power analysis of PMSG, the synchronous generator model is generally based on the approach that the magnetic flux distribution in the rotor is in the form of a sinusoidal wave. Thus, the magnetic flux can be expressed by a vector, and the induced voltage in the stator winding (E_s) can be expressed as follows (Hansen and Michalke, 2008).

$$E_s = \omega_e \varphi_M \tag{5}$$

and,

$$E_s = 2\pi f_e \varphi_M \tag{6}$$

where ω_e is the electrical angular velocity, f is the power frequency of the system, and φ_M is the permanent magnetic flux of the PMSG.

The PMSG generator voltage equation in steady-state conditions can be expressed in the d-q reference frame, which refers to the rotor-oriented equation as follows.

$$v_{gd} = R_g i_{gd} - \omega_e \varphi_{gq} + \varphi_{gd} \tag{7}$$

$$v_{gq} = R_g i_{gq} - \omega_e \varphi_{gd} + \varphi_{gq} \tag{8}$$

The stator flux component of the PMSG generator is expressed as:

$$\varphi_{gd} = L_d i_{gq} + \varphi_M \tag{9}$$

$$\varphi_{gq} = L_q i_{gq} \tag{10}$$

where v_{gd} and v_{gq} are PMSG generator terminal voltages, i_{gd} and i_{gq} are PMSG generator stator currents, and L_d and L_q are PMSG generator stator inductance in the d-q reference model.

Furthermore, the electric torque equation of the PMSG generator can be stated as follows.

$$T_e = \frac{3}{2} p \varphi_M i_{gq} \tag{11}$$

Finally, the equation for the active and reactive power of the PMSG generator can be expressed as follows.

$$P_G = T_e \omega_m = \frac{3}{2}\left(v_{gd} i_{gd} + v_{gq} i_{gq}\right) \tag{12}$$

$$Q_G = \frac{3}{2}\left(v_{gd} i_{gd} - v_{gq} i_{gq}\right) \tag{13}$$

where P_G is the active power of the PMSG generator, Q_G is the reactive power of the PMSG generator, p is the generator pole, and ω_m is the mechanical angular velocity.

One of the essential components of wind power generation is a generator. Several types of generators are often used in wind power plants, namely induction generators and permanent magnet synchronous generators. Induction generators are generally used in large capacity wind power plants, while permanent magnet synchronous generators are typically used in small and medium scale wind power plants (De Freitas et al., 2016). In this study, a permanent magnet synchronous generator (PMSG) is used because it has a relatively small capacity of 4 kW, which is used to meet the needs of standalone electric power at a maximum of 2 houses. PMSG is a regular synchronous type generator where the DC excitation circuit is replaced with a permanent magnet to remove the brush. The advantages of PMSG, when compared to other types of generators, are described below. PMSG components are brushless and slip ring, so that the result is that PMSG has a small physical size and a little moment of inertia. This relatively small size is very advantageous for using a standalone system because it can save the construction costs of wind power generating towers. Another advantage of PMSG is that the generator structure is simple and has high efficiency. PMSG has a rotor magnetic flux generated by permanent magnets. The PMSG construction has no rotor winding, so it can produce a high power density by minimizing the generator's size and weight. This fact is very beneficial in terms of the investment cost of power plants. PMSG does not require external excitation in its operation so that there are no copper losses in the rotor circuit. Besides that, it also has an impact on low maintenance costs. The reliability of the PMSG is very good and has high performance. Another important advantage of PMSG when used on-grid is that it does not directly affect the generator if there is a disturbance in the grid system (Wei et al., 2016). The power converter can fully control the amplitude and frequency of the generator voltage. However, PMSG also has shortcomings, which are outlined below. PMSG materials, especially permanent magnets, are relatively expensive and relatively difficult in the manufacturing process. Only large industries are capable of producing PMSG. The demagnetization process of permanent magnets requires high temperatures, making it very difficult to do in small enterprises in manufacturing. PMSG applications are very dependent on the power inverter circuit because all the power generated must be transferred through the power inverter. Meanwhile, the power losses in power electronic circuits are generally very high. However, the shortcomings of PMSG, when compared to its many advantages, make PMSG very suitable for use in standalone wind power generation systems, as used in this study. The PMSG generator circuit in a wind power plant is shown in Fig. 3.

3. Methodology

In this research, the design, assembly, and testing of a wind power plant using a permanent magnet synchronous generator

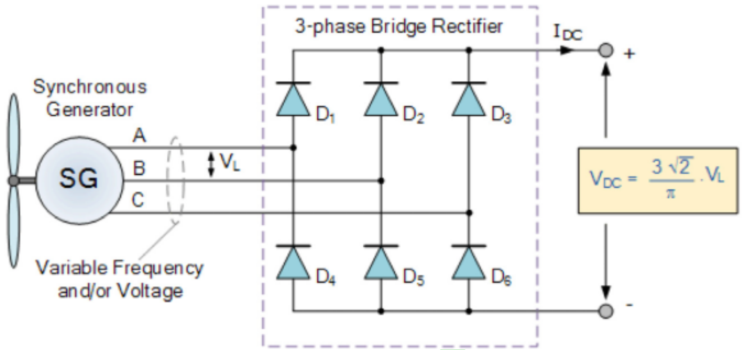

Fig. 3. The PMSG generator circuit in a wind power plant.

with a maximum power capacity of 4 kW were carried out. This power plant is expected to supply electricity to at least two houses. As an illustration, Indonesia's electrical energy customers are differentiated based on the maximum usable power capacity, namely 450 VA, 900 VA, 1300 VA, and 2200 VA. According to their daily needs, these four power levels are the types of electricity customers commonly used by the Indonesian people. They subscribe to electricity to the state electricity company. In remote areas, while the electricity network has not yet reached the place, a source of electrical energy from renewable energy such as wind power is needed. Wind power plant trials were conducted in South Coast, Bantul District, Yogyakarta Special Region Province, Indonesia. The beach is located in the southern region of the island of Java, which is directly connected to the Indian Ocean, so it has good wind energy potential, with wind speeds of up to 12 m/s.

3.1. Setting up of a 4 kW wind power plant

The complete research procedure is shown in Fig. 4, while Fig. 5 shows a circuit diagram showing the components of a 4 kW wind power plant. The initial step of the research is the design of the wind power plant. This power plant with a maximum capacity of 4 kW is designed to meet at least two residents' houses' electrical energy needs.

This 4 kW wind power plant's design consists of wind turbine components, PMSG type generators, power rectifiers, batteries, and power inverters. The wind turbine used is a horizontal type turbine with three blades. Furthermore, the generator used is a type of PMSG 3 phase generator with a capacity of 4 kW. The results of the design of the PMSG generator and the three blades of the wind turbine are clearly shown in Fig. 6. The power rectifier used is a bridge-type rectifier, because of its ability to produce the right direct voltage. The battery bank used is a deep cycle type battery because of its flexible ability to store electrical energy generated from the generator. The results of the design of a three-phase rectifier connected to a battery for electrical energy storage are shown in Fig. 7(b). The figure also shows the process of testing the power rectifier and retrieving test results data at the input and output of the power rectifier and the battery input.

The specifications of the equipment components of the power plant in this study are shown in Tables 1 to 5. Table 1 shows the technical specifications of the wind turbine. The table shows the essential parameters of the wind turbine used. Table 2 shows the characteristics of the generator used in this study, namely the PMSG type. Furthermore, Table 3 shows the parameters of the rectifier. The rectifier operated is a bridge-type rectifier, so it can produce a direct voltage as expected. Table 4 shows the parameters of the batteries used. The battery used in this study

Table 1
Characteristics of wind turbine.

Features	Quantities and units
Output power	4000 W
Base apparent power of the generator	4000/0.95 VA
Cut-in wind speed	3 m/s
Nominal wind speed	12 m/s
Cut-off wind speed	20 m/s
Maximum power at base wind speed of nominal mechanical power	0.69 p.u.
Base wind turbine rotational speed	1.2 p.u.
Pitch angle of wind turbine power characteristics	0°

Table 2
Characteristics of PMSG.

Features	Quantities and units
Electro-motive force waveform	Sinusoidal
Rotor type	Salient pole
Mechanical input	Torque (Tm)
Stator phase resistance	0.00867 Ω
Inductances (L_d)	0.00286 H
Inductances (L_q)	0.00344 H
Flux linkage	0.175 V s
Voltage constant	126.966 Ω
Torque constant	1.05 N m

Table 3
Parameters of rectifier.

Features	Quantities and units
Number of bridge arms	3
Snubber resistance (R_s)	100 Ω
Snubber capacitance (C_s)	0.1 μF
Power electronic device	Diodes
Forward voltage (V_f)	0.8 V

Table 4
Parameters of battery.

Features	Quantities and units
Number of units	4
DC line voltage system	24 V
Nominal voltage of unit	12 V (6 cell)
Nominal capacity	100 Ah
Initial state of charge	60%
Maximum discharge current	1200 A (5S)
Maximum charge current	30 A
Internal resistance	4.9 mΩ
Cycle use	14.4∼15.0 V (25 °C)
Standby use	13.5∼13.8 V (25 °C)
Unit weight	30.4 kg

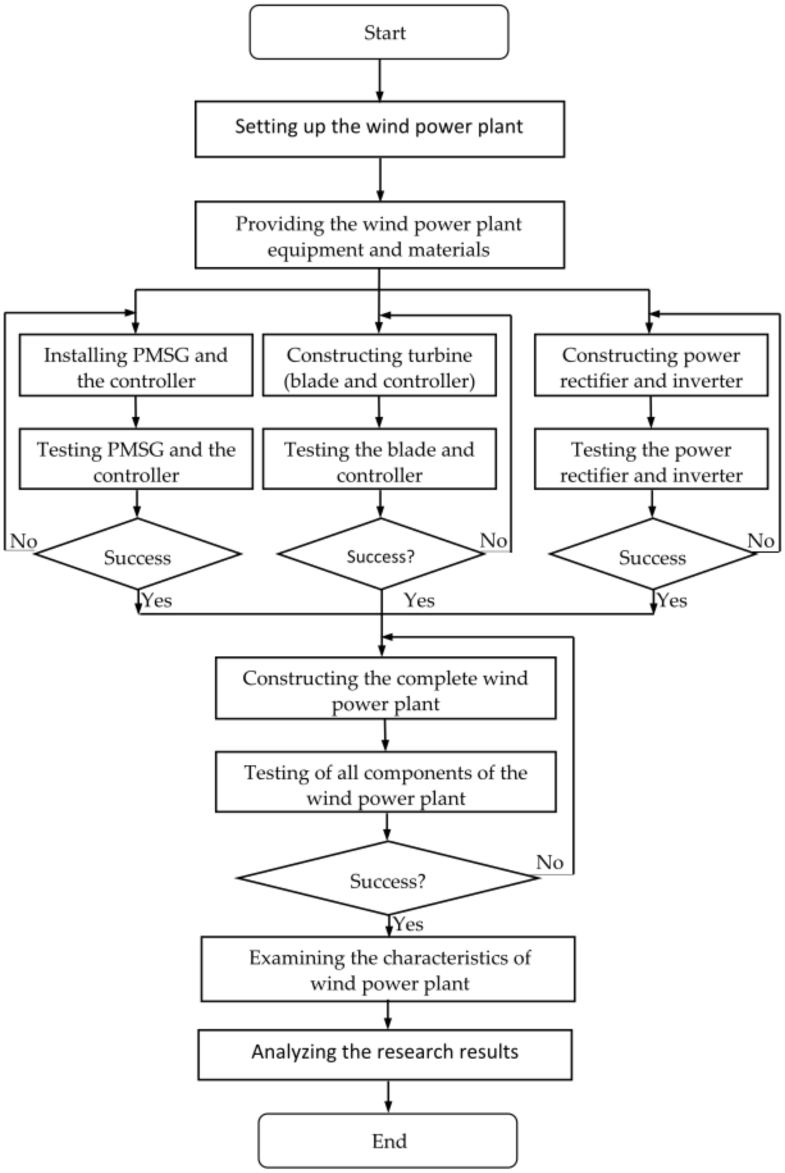

Fig. 4. The procedure in this study.

is a deep cycle type battery so that it can be used for a long time. Finally, Table 5 shows the parameters of the SPWM power inverter used.

Furthermore, the power inverter used is an inverter with an output that is pure sine-wave voltage. The second step is to prepare the equipment and materials used to assemble a complete wind power plant. In this work, the research team was assisted by PLTH Bayu Baru, Bantul Regency Government. The next step is in parallel work to install a permanent magnet synchronous generator (PMSG) and its controllers, construct a wind turbine and construct the power converter, namely the rectifier and power inverter. After the three activities have been carried out in parallel by the research team, the next step is to test each component.

Table 5
Parameters of SPWM power inverter.

Features	Quantities and units
Power	5000 W
Snubber resistance	100 kΩ
Snubber capacitance	Infinite
Power electronic device	Mosfet, diodes
Internal resistance	0.001 Ω

These tests are conducted to ensure that each part can perform as expected. If the test results still do not get the desired performance, then improvements and improvements are made. After all plant components have been constructed with good performance,

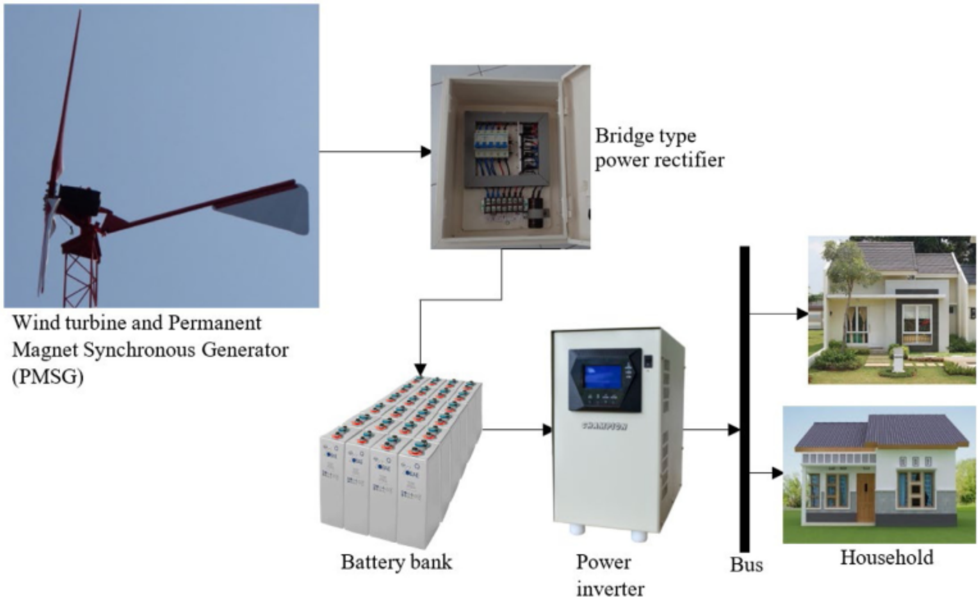

Fig. 5. The circuit diagram of a 4 kW wind power plant.

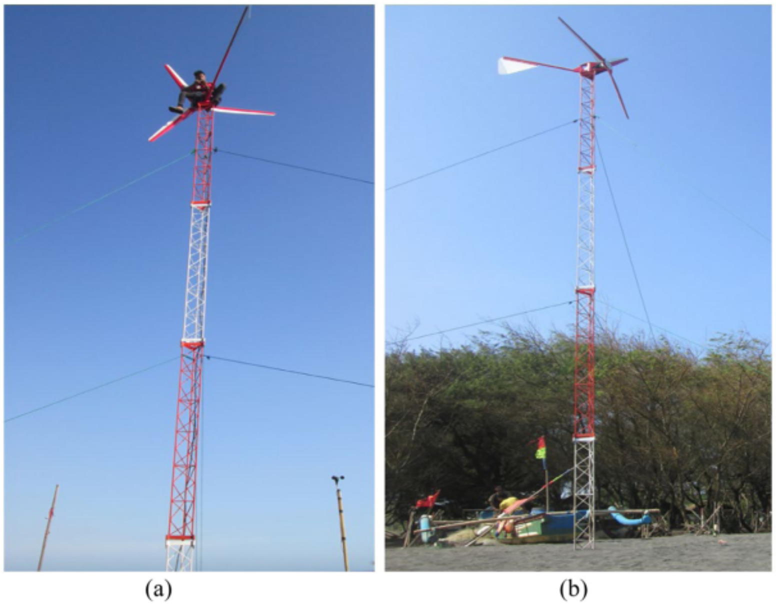

Fig. 6. The situation of testing a 4 kW wind power plant on the South Coast, Bantul Regency, Yogyakarta Special Province, Indonesia; (a) the process of installing wind turbine components and (b) testing process to observe research variables.

Table 6
Performance of SPWM power inverter with various loads.

Load (W)	Load type	Nominal voltage (V)	Output voltage (V)	Voltage deviation (%)	Output current (A)	Frequency (Hz)
400	Pure resistive	220	219.36	0.291	1.8927	50.004
950	Pure inductive	220	219.70	0.136	4.2936	50.003
1600	Resistive and inductive	220	218.79	0.550	7.1974	50.004

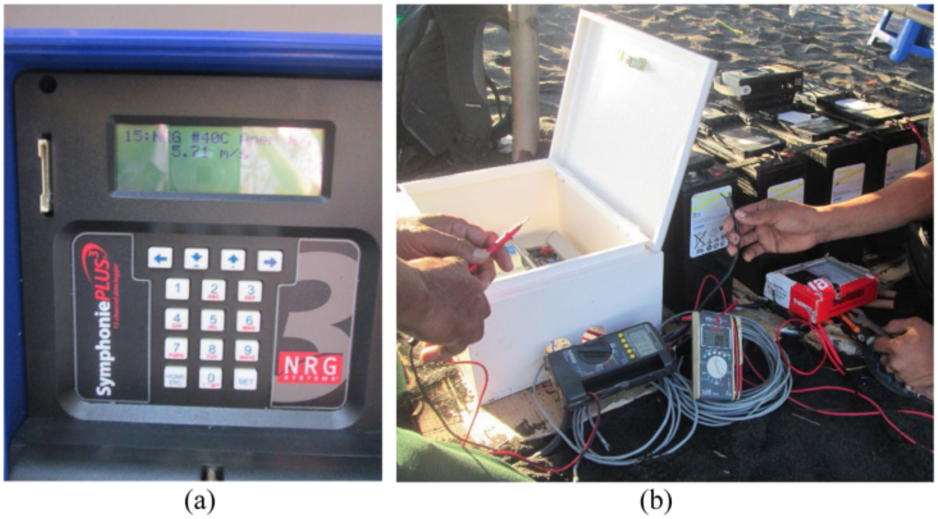

Fig. 7. The observation of research variables of a 4-kW wind power plant on the South Coast, Bantul Regency, Yogyakarta Special Province, Indonesia; (a) measuring the wind speed using digital anemometer and (b) measuring the output voltage of PMSG, output voltage of power rectifier, and charging current to the battery.

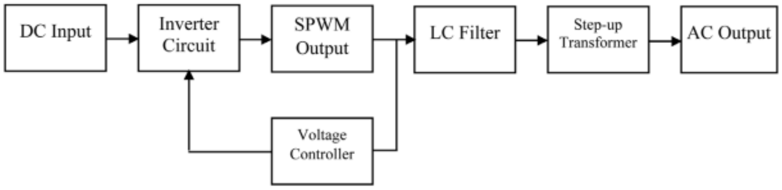

Fig. 8. Block diagram of a SPWM Power inverter.

the next step is to combine them into a complete wind power plant. The power plant is then tested at the test location, namely on the South Coast, Yogyakarta Special Region Province, Indonesia. The test was conducted for seven days, starting from 7:00 AM to 6:00 PM. This test is expected to represent the real situation if this wind power plant is used to meet the population's electricity needs. This test is conducted to determine the performance of wind power plant. Fig. 5 shows the circuit diagram of a 4 kW wind power plant, and Fig. 6 shows the situation of testing a 4 kW wind power plant on the South Coast, Bantul Regency, Yogyakarta Special Province, Indonesia; (a) the process of installing wind turbine components and (b) testing process to observe research variables.

The performance of wind power plant can be seen by observing the observed variables, namely the wind speed, the output AC voltage from the PMSG generator, the output DC voltage from the power rectifier, and the PMSG generator's power. The power rectifier used is a bridge-type power rectifier, so the voltage rectification results are relatively perfect. The results of these seven days of study were collected and documented. The results of these studies are then analyzed to determine wind power plants' performance during the test. Fig. 7 shows the observation of research variables of a 4 kW wind power plant on the South Coast, Bantul Regency, Yogyakarta Special Province, Indonesia; (a) measuring the wind speed using digital anemometer and (b) measuring the output voltage of PMSG, output voltage of power rectifier, and charging current to the battery.

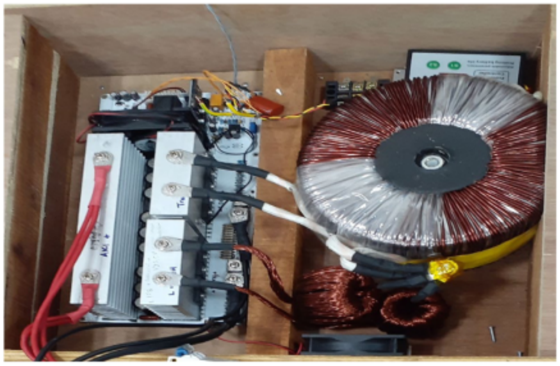

Fig. 9. Design of a SPWM Power inverter.

3.2. Setting up of an SPWM power inverter

Fig. 8 shows block diagram of a SPWM power inverter used to convert DC voltage to AC voltage. In the Figure, it can be seen that the DC input voltage is converted into an alternating voltage by the inverter circuit. The alternating voltage output of this inverter is formed into a pure sine voltage wave using a sinusoidal pulse width modulation (SPWM) device (Bahrami and Narimani, 2019). In this inverter design, the SPWM output voltage controller is used by utilizing the ATMega controller. This

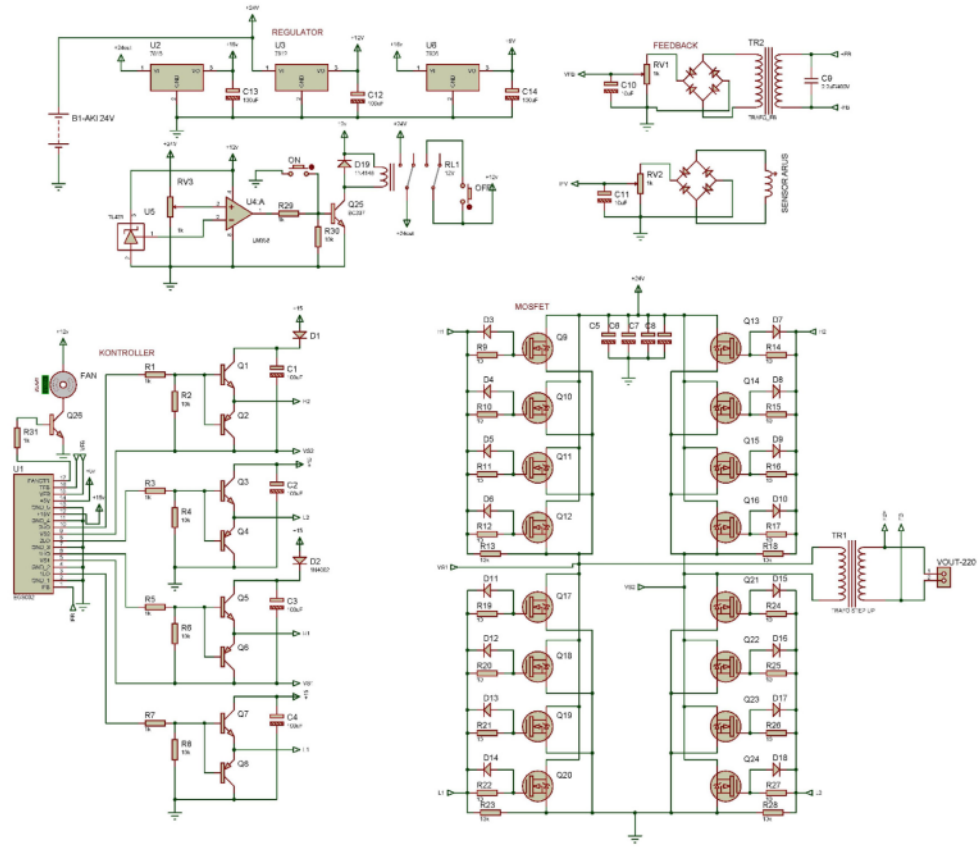

Fig. 10. Electronic circuit of a 5 kW SPWM power inverter.

voltage controller aims to ensure that the output voltage follows the nominal voltage and is in the form of a pure sine. This inverter model with voltage controller becomes an essential contribution to this research.

Fig. 9 shows design of a SPWM power inverter while the electronic circuit of this power inverter is shown in Fig. 10. The power capacity of this inverter is 5000 W. This power capacity is deliberately made more prominent than the generator capacity, which is 4000 W. This reason is that, in its application, the power inverter always experiences very high heat in its transformer components if it is fully loaded. To prevent damage due to the burning of the transformer coil on the inverter, the capacity of the power inverter is made more remarkable than the generator's capacity.

The power inverter with the SPWM method is operated with a different duty cycle in each period at a fixed amplitude pulse. In SPWM, the pulse width is modulated to obtain a controlled output voltage from the power inverter to reduce the harmonics accompanying the output voltage. The technique used in the power inverter design in this research is sinusoidal pulse width modulation. A sine wave and a triangular carrier wave with a frequency of 20 kHz are used to generate the PWM signal. A sinusoidal wave acts as a reference waveform, selected based on the inverter output frequency of 50 Hz. The triangular wave acts as a carrier with a frequency of 20 kHz. A switching signal is formed when a sinusoidal wave and a triangle wave are compared. When the sine voltage exceeds the triangle voltage, the comparator generates a pulse, which is used to activate the inverter switches.

The voltage and current outputs are filtered using a low pass filter using a 2.2 μF capacitor to get a sinusoidal output voltage, as seen in Fig. 10. The output voltage of this power inverter is in the form of a pure sine wave. This pure sine output voltage is expected to provide electrical energy with good power quality to consumers.

4. Results and discussion

The wind power plant trials were conducted in South Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Special Region Province, Indonesia. The choice of this location is because this location has outstanding wind potential. There are houses of residents around the South Coast and simple restaurants that tourists usually visit. The place of this research is also one of the tourist sites in Bantul Regency. The utilization of wind energy for electricity generation is expected to be an alternative solution for communities around the South Coast.

The potential wind energy in the South Coast, Bantul, Yogyakarta, can be seen based on the characteristic graph of the observed daily wind speed shown in Fig. 11. The highest wind speeds are around 12:00 PM to 2:00 PM. The wind speed is still relatively high in the following hours but slowly decreases until evening at midnight. Based on this daily wind speed curve, information can be obtained that the lowest wind speed occurs from 5:00 AM to 7:00 PM, around 2.5 m/s. The highest wind speed occurs at 12:00 PM, which is approximately 7.4 m/s. This data

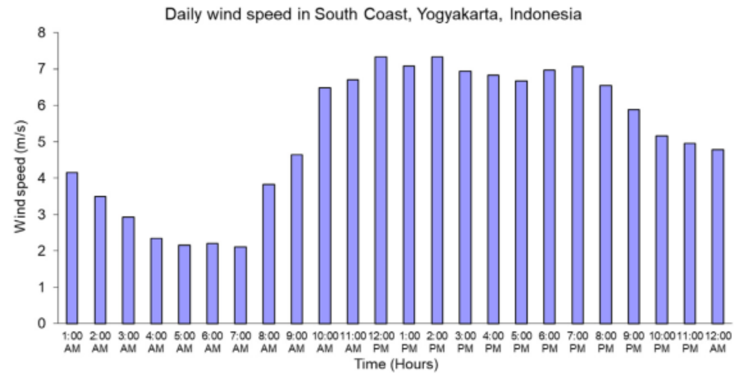

Fig. 11. The daily wind speed at the research location is on the South Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Special Region Province, Indonesia.

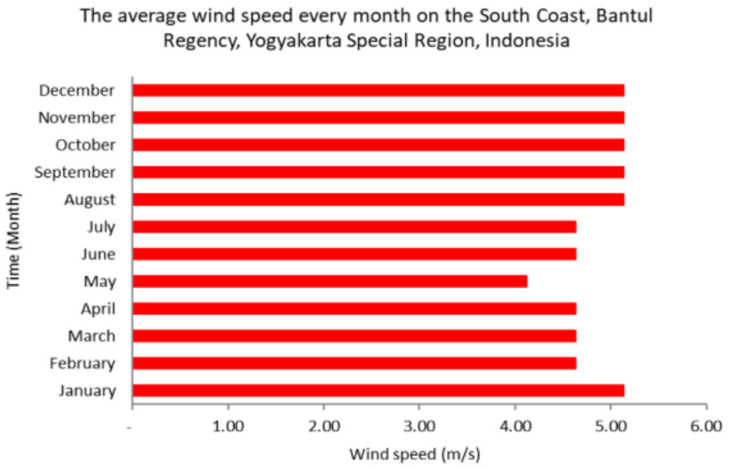

Fig. 12. The average wind speed per month at the research location is on the South Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Province, Indonesia.

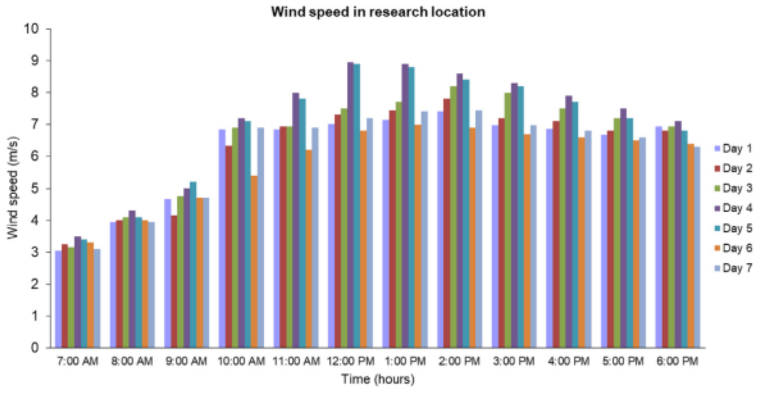

Fig. 13. The wind speed during the testing of a wind power plant with a capacity of 4 kW at the research location is on the South Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Special Province.

can be used as an initial picture to estimate the electrical energy obtained from the wind power plant applied at this location.

In order to provide a complete picture of wind conditions in this area, wind data is traced every month for a year. This data was obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). The average wind speed data every month at the research location of the South Coast, Srandakan, Bantul, Yogyakarta Special Region is shown in Fig. 12.

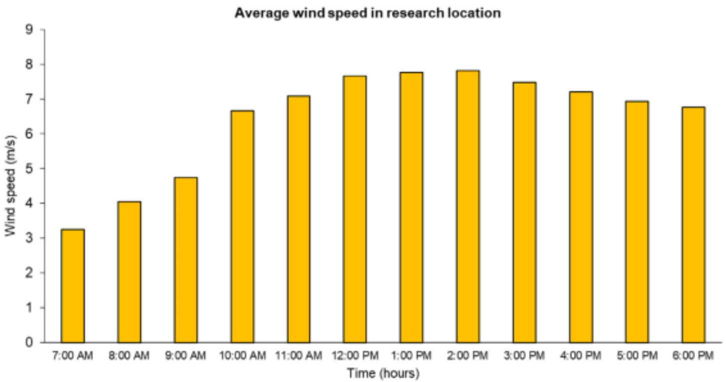

Fig. 14. The average wind speed during the testing of a wind power plant with a capacity of 4 kW at the research location is on the South Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Special Province.

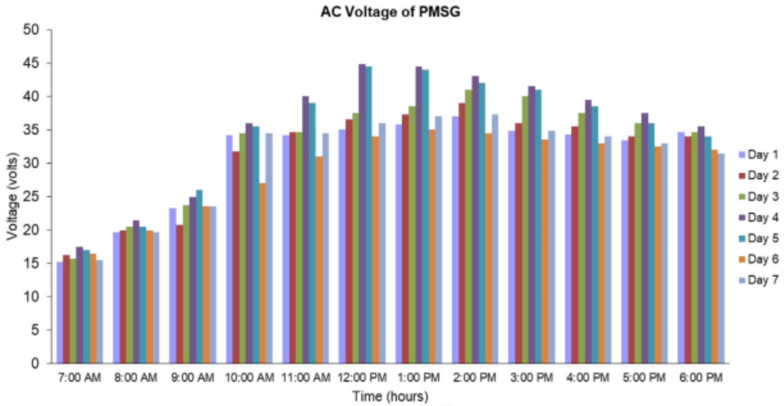

Fig. 15. AC output voltage of PMSG of the wind power plant.

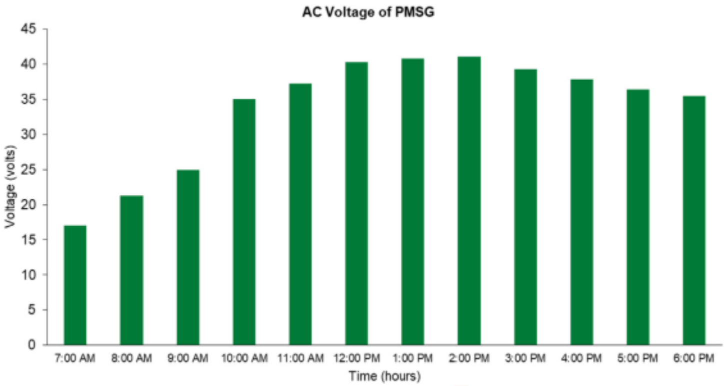

Fig. 16. The average AC output voltage of PMSG of the wind power plant.

The average wind speed during the year is 4.84 m/s. In Fig. 12, it can be seen that the lowest wind speed occurred in May, namely 4.12 m/s. The relatively low average wind speed in one month is because May is usually a transitional period, namely the transition from the rainy season to the summer. Furthermore, the highest wind speeds occur in January, August, September, October, November, and December. The wind speed during these months is 5.41 m/s.

After the wind conditions at the research location are known, research is carried out by designing and assembling a wind power plant with a capacity of 4 kW. The electric circuit diagram of a wind power plant is shown in Figs. 3 and 5. This figure shows that a power plant's main components are a wind turbine, a PMSG type generator, a bridge-type power rectifier, and a battery as storage for electrical energy. The wind turbine used is a horizontal turbine model consisting of 3 blades, each 1.5 m long. As a means

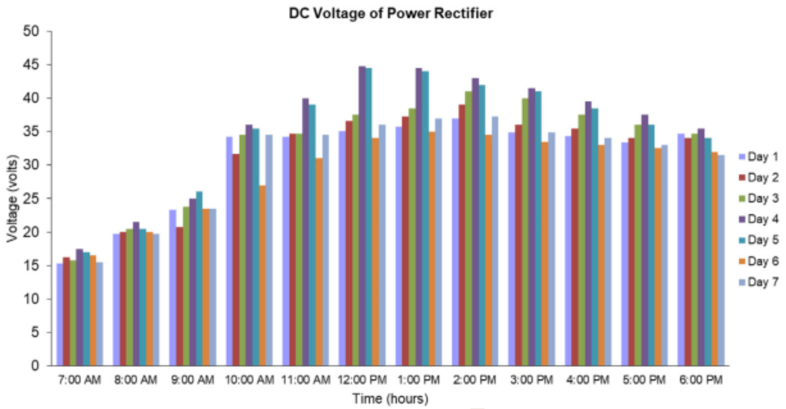

Fig. 17. DC output voltage of power rectifier of the wind power plant.

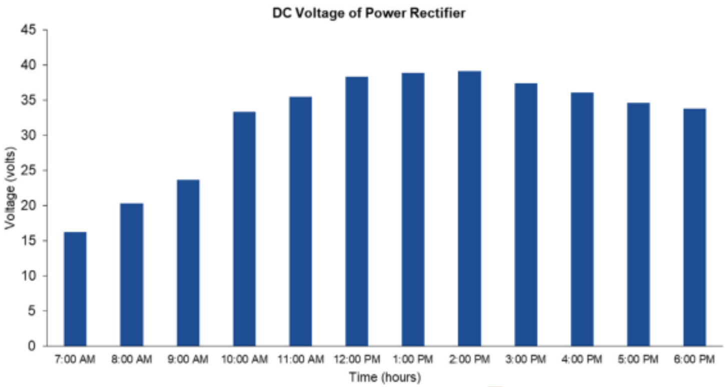

Fig. 18. The average DC output voltage of power rectifier of the wind power plant.

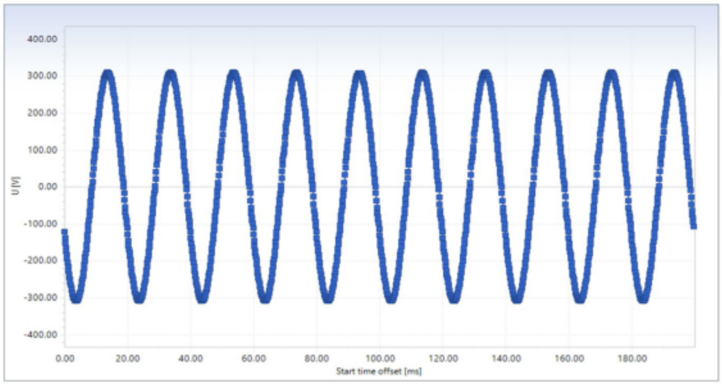

Fig. 19. The output voltage of SPWM power inverter with a resistive load of 400 W.

of supporting the power plant so that it is at a sufficient height to get wind gusts, an iron tower covered with anti-rust material is required. This triangular iron tower with 0.5 m diameter stands firmly as high as 12 m, as shown in Fig. 6. The measuring instruments used to observe research variables are digital anemometer, DC voltmeter, AC voltmeter, and ampere-meter, as shown in Fig. 7.

4.1. Performance of a 4 kW wind power plant

The wind power plant's test results with a capacity of 4 kW are shown in Figs. 13 to 18. The power plant testing is carried out for seven days, each starting from 7:00 AM to 6:00 PM. The recording of research data was carried out once in one hour. Fig. 13 shows the wind speed during the testing of a wind power plant with a capacity of 4 kW at the research location is on the South

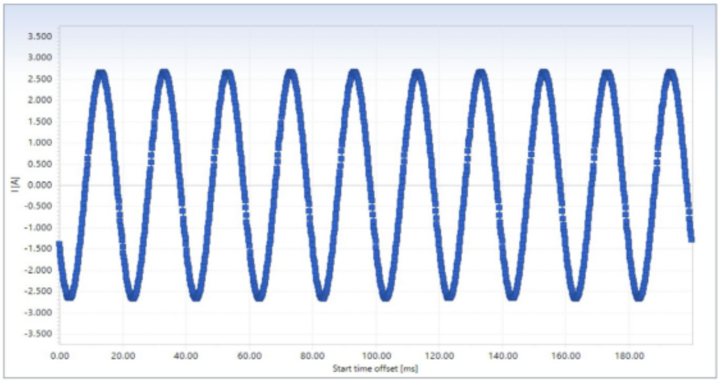

Fig. 20. The output current of SPWM power inverter with a resistive load of 400 W.

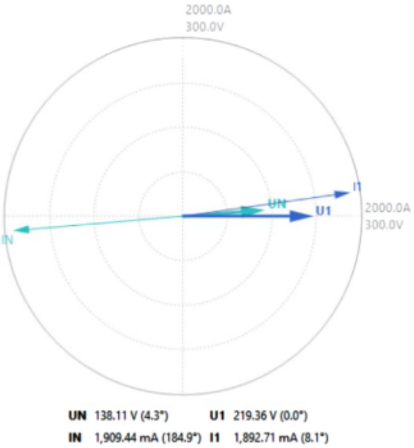

Fig. 21. Phase diagram of SPWM power inverter output voltage and current with a resistive load of 400 W.

Coast, Poncosari Village, Srandakan District, Bantul Regency, Yogyakarta Special Province. The figure shows the results of wind speed measurements for seven days, where every hour, seven wind speed measurements are shown. During the seven days, the highest wind speed was 8.96 m/s, which occurred at 12:00 PM for the 4th-day measure. The lowest wind speed is 3.05 m/s, which occurs at 7:00 AM for the 1st measurement. Based on the overall wind speed data in Fig. 13, it can be observed that the hourly wind speed during the seven days of observation has the same trend. This trend indicates that the wind characteristics of the study site are representative. This daily wind speed trend can also be seen based on the average hourly wind speed during the seven days of testing, as seen in Fig. 14. Fig. 14 shows that the highest average wind speed is at 2:00 PM, namely 7, 82 m/s, and the lowest is at 7:00 AM, which is 3.25 m/s.

The next discussion is observing the AC output voltage from the PMSG generator, as shown in the graph in Fig. 15. The PMSG type generator with a power capacity of 4 kW used in this study can produce the highest AC voltage, namely 47.04 V at 12:00 PM at the time of 4th-day testing. At that time, the wind speed was 8.96 m/s. The lowest generator output voltage was 16.01 V, which occurred at 7:00 AM on the first day of testing, at which time the wind speed was 3.05 m/s. The output voltage of this three-phase PMSG type generator measured is the phase-to-phase voltage, where the measurement results of all phases produce the same value.

The average output voltage of the PMSG generator every hour for seven days of testing is shown in Fig. 16. Fig. 16 shows that the highest average output voltage of the generator is 41.06 V, which occurs at 2:00 PM. At that time, the average wind speed was 7.82 m/s. The lowest average generator output voltage is 17.06 V, which appears at 7:00 AM, where the wind speed at that time is 3.25 m/s. Based on the observed data from the PMSG generator output voltage observations in Figs. 15 and 16, it can be observed that the generator output voltage is highly dependent on wind speed. The higher the wind speed, the higher the generator rotor rotation, so that the resulting voltage is also higher.

The AC output voltage of the PMSG generator is then rectified using a bridge type power rectifier. This voltage rectification is for storage purposes because the electrical energy will be in the battery. The results of the power rectifier output voltage observations are shown in the graph in Fig. 17. The power rectifier's highest DC output voltage is 44.80 V at 12:00 PM on the 4th day of testing. At that time, the wind speed was 8.96 m/s. The lowest power rectifier output voltage is 15.25 V, which occurs at 7:00 AM on the first day of testing, at which time the wind speed is 3.05 m/s. The power rectifier's measured output voltage is the phase-to-neutral voltage, where this voltage will be used to charge the battery-electric charge. The battery-operated is a 2-volt deep-cycle type battery with as many as 20 units connected in series.

The average hourly output voltage of the power rectifier for seven days of testing is shown in Fig. 18. Fig. 18 shows that the power rectifier's highest average output voltage is 39.11 V, which occurs at 2:00 PM. At that time, the average wind speed was 7.82 m/s. The lowest average generator output voltage is 16.25 V, which appears at 7:00 AM, where the wind speed at that time is 3.25 m/s. Based on the observed data from the power rectifier's output voltage in Figs. 17 and 18, the output voltage of the power rectifier is highly dependent on the wind speed. The higher the wind speed, the higher the generator rotor rotation, causing the resulting voltage to be higher. The output voltage of the power rectifier is also proportional to the output voltage of the PMSG generator.

Based on the research results, it can be seen that the power plant has been proven to be able to generate electrical energy that is suitable for meeting the electrical energy needs of residents' homes. It is primarily the observation data from the PMSG generator output voltage and power rectifier. The indicator of this success is that the generator's voltage is good enough and feasible to be stored in the battery. The resulting voltage is adequate

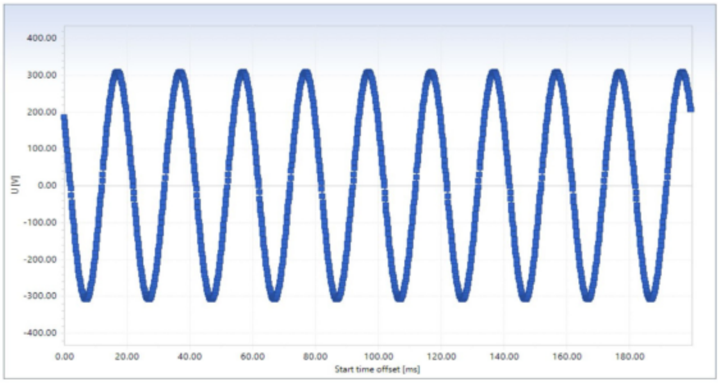

Fig. 22. The output voltage of SPWM power inverter with combination of an inductive load of 950 W.

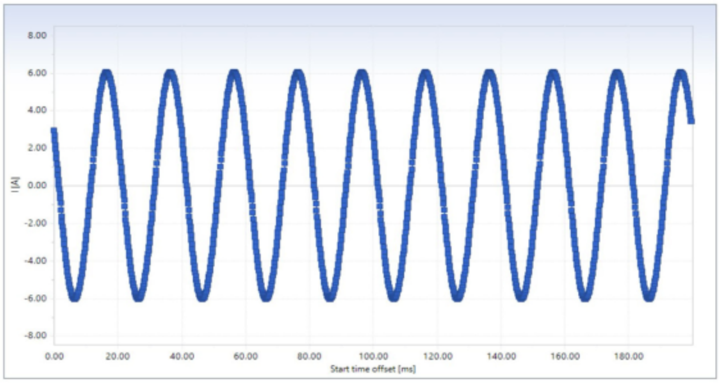

Fig. 23. The output current of SPWM power inverter with combination of an inductive load of 950 W.

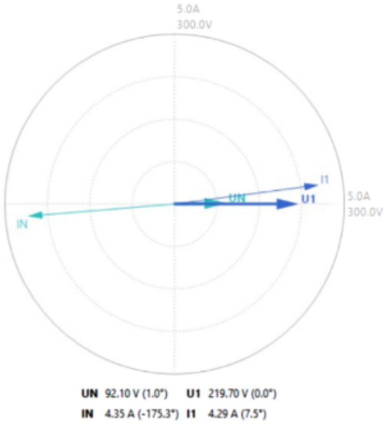

Fig. 24. Phase diagram of SPWM power inverter output voltage and current with combination of an inductive load of 950 W.

because it is close to the nominal voltage generated by the 4 kW capacity PMSG generator used in this study. This sufficient PMSG voltage directed by the power rectifier can then be connected to the battery. The provision of good batteries is a critical issue to store the valuable electrical energy that has been generated by wind power plants.

4.2. Performance of SPWM power inverter

This section describes the performance of the sinusoidal pulse width modulation (SPWM) power inverter, which is used to convert the DC voltage from the battery into AC voltage (Zhang and Wang, 2019). The battery output DC voltage is converted into AC voltage. The SPWM power inverter is designed to produce an output voltage with a pure sine voltage waveform. In the wind power plant designed in this research, the SPWM power inverter gets a DC power supply from the battery bank, as shown in Fig. 5. The DC input voltage for the inverter is 24 V with an AC output voltage of 220 V. The maximum power capacity of the inverter is 5 kW.

In order to test the performance of the power inverter SPWM in this research, the inverter loading test was carried out. The load test is applied to a purely resistive load, a purely inductive load, and a combined resistive and inductive load. This type of load test is intended to analyze the performance of the power inverter in serving electrical loads that electricity consumers widely use. The inverter load testing is a purely resistive load of 400 W, a purely inductive load of 950 W, and a combined resistive and inductive load of 1600 W. The load test results of the power inverter SPWM are shown in Table 6 and Figs. 19 to 27.

The first load test was a purely resistive load. The load used in the test is an incandescent lamp with a total power of 400 W. The test results show that the inverter output voltage is pure sine with a practical value of 219.36 V, as shown in Fig. 19 and Table 6. This voltage only drops 0.291% of the nominal voltage

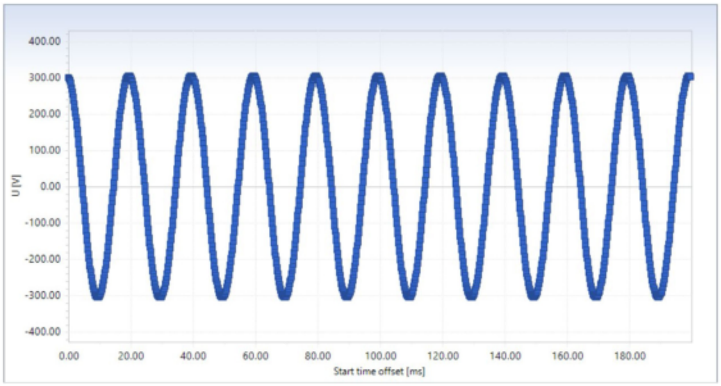

Fig. 25. The output voltage of SPWM power inverter with combination of resistive and inductive load of 1600 W.

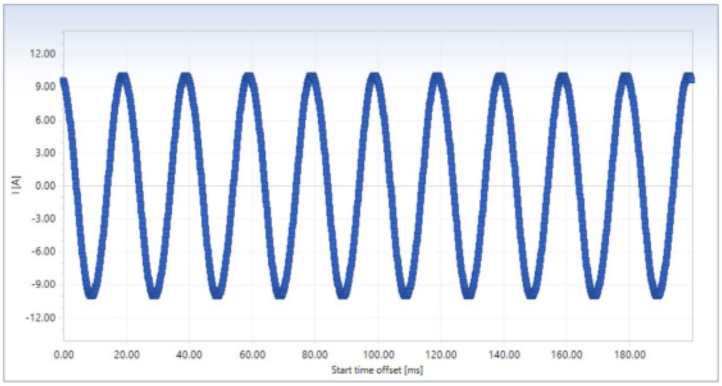

Fig. 26. The output current of SPWM power inverter with combination of resistive and inductive load of 1600 W.

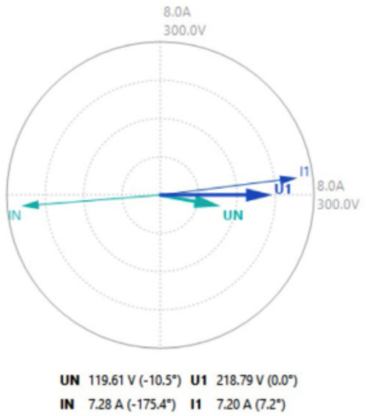

Fig. 27. Phase diagram of SPWM power inverter output voltage and current with combination of resistive and inductive load of 1600 W.

of 220 V. The pure sine-shaped voltage wave shown in Fig. 19 is obtained through measurements by a power quality analyzer. Measurements with the same tool are also carried out for current measurements and phase diagrams of voltages and currents. The measured load current is 1.8927 amperes, as shown in Fig. 20 and Table 6. The measured current in Fig. 20 is also pure sine as the inverter output voltage. The frequency of the inverter output voltage is 50.004 Hz, which follows the power frequency system used in Indonesia, which is 50 Hz. The results of observations of voltage, current, and frequency show that the SPWM power inverter, as a result of this research with pure resistive loading, has been able to produce pure sine-shaped AC voltage and current waves at the appropriate frequency of 50 Hz. Another parameter observed is the phase diagram of the voltage and current, as shown in Fig. 21. The figure shows that the load current lags 8.1° from the voltage. This result also proves that the inverter output voltage with a phase angle of 0.0° follows the reference voltage standard.

The second load test is a purely inductive load. The load used in the test is an electric motor with a total power of 950 W. The test results show that the inverter output voltage is also pure sine with a practical value of 219.70 V for a purely inductive load, as shown in Fig. 22 and Table 6. This voltage only drops 0.136% from the nominal voltage of 220 V. The pure sine-shaped voltage wave shown in Fig. 22 is obtained by measurement by a power quality analyzer. Measurements with the same tool are also carried out for current and voltage and current phase diagrams. The rated load current is 4.2936 amperes, as shown in Fig. 23 and Table 6. The load current in Fig. 23 is also pure sine as the inverter output voltage. The inverter output voltage frequency is 50.003 Hz, which follows the power frequency system used in Indonesia, 50 Hz. The results of observations of voltage, current, and frequency show that the SPWM power inverter, as a result of the study with pure inductive loading, has also been able to produce pure sine-shaped AC voltage and current waves at the appropriate frequency, namely 50 Hz. Another parameter observed is the phase diagram of the voltage and current, as shown in Fig. 24. The figure shows that the load current lags 7.5° from the voltage. This result also proves that the inverter output voltage with a phase angle of 0.0° follows the reference voltage standard.

The third load test is a combined resistive and inductive load. The load used in the test combines incandescent lamps and electric motors with a total power of 1600 W. The test results show that the inverter output voltage is also pure sine with a practical value of 218.79 V for combined resistive and inductive loads, as shown in Fig. 25 and Table 6. This voltage is only 0.550% lower than the nominal voltage of 220 V. The pure sine-shaped voltage wave shown in Fig. 25 was obtained by measurement with a power quality analyzer. Measurements with the same tool are also carried out for the current and voltage phase diagrams and currents.

The rated load current is 7.1974 amperes, as shown in Fig. 26 and Table 6. The load current in Fig. 26 is also pure sine as the inverter output voltage. The inverter output voltage frequency is 50.004 Hz, which follows the power frequency system used in Indonesia, 50 Hz. The results of observations of voltage, current, and frequency show that the SPWM power inverter, as a result of the research with resistive and inductive combination loading, has also been able to produce pure sine-shaped AC voltage and current waves at the appropriate frequency, namely 50 Hz. Another parameter observed is the phase diagram of the voltage and current, as shown in Fig. 27. The figure shows that the load current lags 7.2° from the voltage. This result also proves that the inverter output voltage with a phase angle of 0.0° follows the reference voltage standard.

5. Conclusions

This study describes the performance of standalone power plants that can be utilized by rural communities in Indonesia. Based on the research results, the power plant has been proven to generate electrical energy that is suitable for use as meeting the electricity needs of residents' homes. The indicator of this success is that the generator's voltage is good enough and is feasible to be stored in the battery. Although the voltage's value depends on the speed of the wind hitting the wind turbine, the resulting voltage is adequate because it is close to the nominal voltage that should be produced by the 4 kW capacity PMSG generator used in this study. This sufficient PMSG voltage rectified by the power rectifier can then be connected to the battery. The provision of good batteries is a critical issue to store the valuable electrical energy that has been generated by wind power plants. This renewable energy power plant application will contribute to promoting the use of environmentally friendly renewable energy. This effort also simultaneously supports the Indonesian government's program to realize 23% of the national power generation capacity from renewable energy sources. This research can be continued by measuring the power quality of the generator's output voltage, rectifier, battery, and inverter. The representation of the voltage can be observed in the form of a voltage wave. It is essential to investigate the quality of this power to evaluate whether the quality of the electric power produced by wind power plants is equivalent to the national electricity system. Besides, the recommended further research is about the parameter of CO_2 emission savings by considering households' average energy consumption.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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