



Smart grid photovoltaic system pilot scale using sunlight intensity and state of charge (SoC) battery based on Mamdani fuzzy logic control

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Abstract

The Utilization of renewable energy such as a photovoltaic system is the foremost alternative in transfers generated by conventional power plants, but the lack of photovoltaics is support for light intensity. The purpose of this research is to develop a pilot-scale smart grid photovoltaic system that can regulate the supply of electrical energy from either the battery or the power supply. The control system in this study uses the Mamdani fuzzy logic method in determining automatic system performance. This system monitors the intensity of light and battery which are then used as automatic safety parameters on the power supply, battery, and photovoltaic. The results of this study display the indicator results from the microcontroller in supplying electrical energy for the use of electrical loads. Power Supply has been served the load when the battery is in a low state which have a voltage <11 Volts, the battery has been served the load when the condition of the battery is in a medium and high condition which has a voltage of 11.5 < ; ...; <13 Volts. PV has been served batteries or loads when the light intensity is cloudy and bright which have a light intensity of 3585 < ; ...; <10752 Lux. This system can reduce dependence on conventional energy without reducing the quality of the energy supply at load and Photovoltaic system dependence on light intensity does not affect the supply of energy consumption to electrical loads.

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Keywords: renewable energy; photovoltaic systems; fuzzy logic.

I. Introduction

The benefits of photovoltaic panels can be relied upon especially in areas that have high sunlight intensity and high temperature. Most of the electrical energy sources for electricity generation come from fossil fuels. While fossil fuel reserves on earth are increasingly limited so the price of electricity is getting more expensive every time. Fossil fuels themselves are fuels formed from the bowels of the earth which have been used for millions of years. At this time fossil fuel reserves in nature are increasingly scarce. This is caused by the use of electricity which is too dependent on fossil-powered electricity. Solar electronic devices utilize photovoltaic cells (PV) which are used to produce small power but are

relatively expensive devices, where the costs can be easily absorbed [1]. The development of hybrid systems on smart grids that prioritize Utility Grid as the main electricity source does not provide significant changes to the creation of environmentally friendly technology.

Green technology and smart grid technology have changed the use of electricity to become more efficient. This technology enables power system operators and consumers to increase energy efficiency and reduce greenhouse gas emissions (eg carbon dioxide) by optimizing energy distribution and management [2][3]. This study uses PV as the main source of smart grid systems which hybrid with conventional energy, so that the supply of electricity is more efficient and the electrical load remains stable.

The high price of PV devices and batteries that are not comparable to the energy produced, this study uses a source of electricity and a pilot-scale electric load (lite scale) that still meets the stability

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requirements of electricity supply with energy-efficient and environmentally friendly loads. Research on the use of smart grid pilot project PV systems has been developed by Ramakrishna Kappagantu (2015) [4]. with the theme of obstacle analysis of the system implementation of a smart pilot solar PV roof project in the Puducherry area. This system utilizes PV that is hybridized with a utility grid without utilizing a battery as a backup. So that it can reduce the dependence on the utility grid during the day and when the intensity of sunlight is high. Without utilizing the battery SoC system, this research is less than optimal in suppressing the dependence on the utility grid.

The application of fuzzy logic (Fuzzy Inference System, hereinafter abbreviated as FIS) can be done using various methods, including the Tsukamoto method, the Mamdani method, and the Takagi-Sugeno method [5]. In the Mamdani method, the application of the implication function uses MIN, while the composition of the rules uses the MAX method [6]. The output of the inference results for each rule is expressed in z, which is in the form of a regular set (crisp) determined based on its μ -predicate (degree of membership). The final result is obtained using the weighted average. The Sugeno method is similar to the Mamdani method, only that the (consequent) output is not a fuzzy set, but a constant or linear equation [7]. The value generated from the light intensity and battery voltage in this study, the system is used as an automatic control for power supply.

The fuzzy logic method used as a control in a photovoltaic system was developed by Neeparaj Rai (2018) [8] with the theme of fuzzy logic-based control on a hybrid PV-Battery system independently for DC loads. This research focuses on the use of PV and batteries to serve electricity loads. This system works without relying on energy sources from the utility grid so that the stability of the load supply is less than the maximum. Similar research has been developed by (Sofia Lalouni and Djamilia Rekioua) (2009) with the theme of modeling and simulation of a photovoltaic system using fuzzy logic controller [9], the basis of this system was developed for maximum power point tracking (MPPT) control simulations aimed at maximizing supply of electricity from PV, this research is still in the form of simulation, so there is no real scale of the system. Many other studies on MPPT-based PV systems, such as those developed by C. S. Chin and K. T. K. Teo (2011) with the theme of MPPT-based fuzzy logic for PV modules that are influenced by solar radiation and cell temperature [10].

This system utilizes solar radiation and cell temperature to maximize the power supply from photovoltaics, This system does not utilize battery back up SoC and without hybrid with the utility grid. other studies based on MPPT were developed by Chia Seet Chin and Yit Kwong Chin (2012) with the theme of MPPT-based fuzzy logic for PV arrays in partially shaded conditions [11]. This system was developed to stabilize the power supply in PV when some of the PV modules shine in the sunlight, The stability of the electrical load in this study is less than the maximum

because it does not utilize batteries and hybrid with a utility grid. Another MPPT-based fuzzy logic research system developed by Ayaz Ahmad and Dr. L. Rajaji (2013) with the theme of Modeling and Design of Novel Control Algorithms for Grid-Connected Photovoltaic (PV) Inverters [12]. This system was developed to maximize the power supply from the inverter connected to the inverter, this research only maximizes inverter performance without maximizing PV and SoC batteries for load supply. Other research has been conducted by Efrain Bernal, et al (2017) [13] on fuzzy-based reactive power control for smart PV inverters in LV distribution systems. The research can reduce the reactive power injection of the PV and minimize the increase of the voltage and power loss. However, this research only stabilizes the performance at the PV inverter without considering the battery SoC.

Previous research on photovoltaic systems with fuzzy logic control has been developed with the theme of fuzzy logic on energy management from photovoltaics for solar homes developed by Fathia Chekired (2017) [14]. This research presents a strategy in supplying electricity load from a photovoltaic network system back up, where this system utilizes a Photovoltaic network as a backup energy source, while the main energy source uses a utility grid. Fuzzy logic control in this study focuses on photovoltaic systems and the use of loads without involving the utility grid. Input data used in this study is the production of power in PV, the power stored in batteries, then the use of loads on consumers, this research is still less than optimal in reducing dependence on utility grids because the PV system and battery are not as main electrical energy but are still as back up of electrical energy.

Research developed by Ramakrishna Kappagantu has no battery system, so the renewable energy system is less than optimal in reducing dependence on conventional sources of energy. While the research by Neeparaj Rai, the system has not utilized the renewable energy sources without utilizing conventional energy sources, so that the load is only supplied by PV that works optimally when the environment is supportive. Other research developed by Fathia Chekired renewable energy systems has not been a primary source (back up). So it still depends on the utility grid as the main source.

The purpose of this study is to create a device system on a pilot-scale that can to automatically control energy supply by adjusting environmental conditions. the novelty in this study is to prioritize renewable energy as the main source and power supply as a back up of energy. With this pilot-scale system, it is expected that the electrical load can reduce dependence on conventional energy.

II. Materials and Methods

A. Hardware construction

The control circuit is designed by adjusting the shape of the solar cell monitoring trainer, where the trainer is equipped with a PV with a capacity of 100 Wp which is located separately from the trainer, an LDR sensor to measure the intensity of light placed in



Figure 1. Solar cell monitoring trainer

a location adjacent to the solar cell, a relay to control battery input and load, microcontroller to set the logic on/off of the relay. As in Figure 1, Figure 2 and Figure 3, there are two designs on the trainer namely the top design and the bottom design.

The trainer is equipped with a measuring tool to monitor the components at each point. In addition, the trainer is also equipped with a solar charge controller to regulate the incoming current and voltage in accordance with the capacity of the battery, battery type VRLA 12V with a capacity of 7.2 Ah, as many as 3 DC lights, 12 V DC to 220 V AC inverter, AC lights as much as 6 pieces.

Mikrokontroler that is used to control the energy supply is Arduino mega which is connected to the LDR sensor and the voltage sensor. Where the voltage sensor serves to detect the capacity of the battery and the LDR sensor to detect the intensity of sunlight that illuminates photovoltaics. As in Fig. 4. After Arduino gets information from the LDR sensor and the voltage

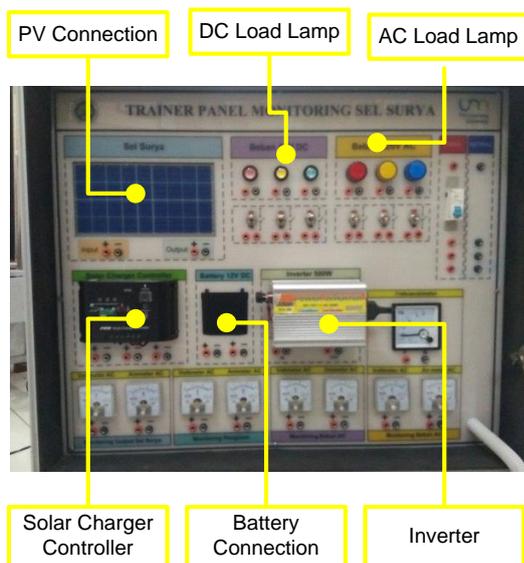


Figure 2. Top view

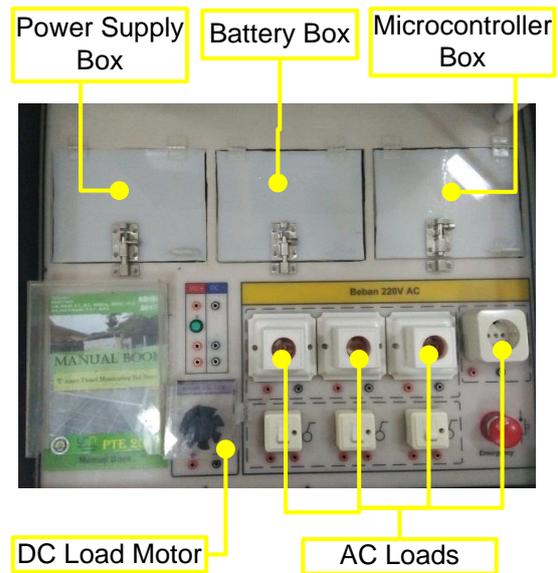


Figure 3. Bottom view

sensor Arduino will control the relay in accordance with the program.

As in the Flowchart in Figure 5, if the light intensity is low and the battery condition is low, the relay will disconnect the channel to the load and the power supply that is connected to the Utility Grid for the load. So that the load can be served even in conditions without sunlight.

Fuzzy settings are programmed to execute relay conditions from grouped variables. If this system is implemented it will be useful to minimize dependence on the utility grid. The components used for microcomputer control systems are in Table 1.

Table 1. Microcontroller components

no	Component	Type	Amount
1	Arduino	mega	1
2	Voltage Sensor	0 – 25 Vdc	1
3	Light Sensor	LDR	1
4	Project Board		1
5	Jumper Cable	Male and Female	
6	Port Cable	Micro to PC	1
7	Relay 4 Chanel	5 Vdc Control	1

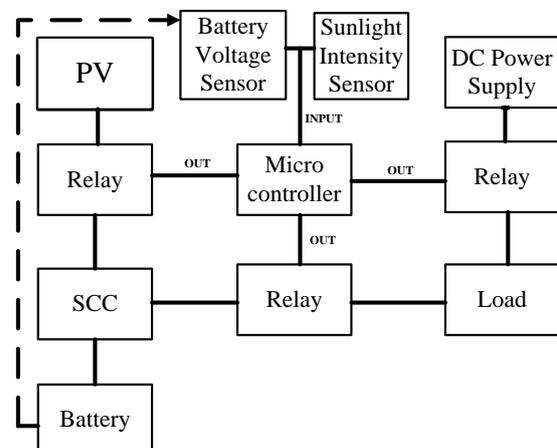


Figure 4. Control diagram

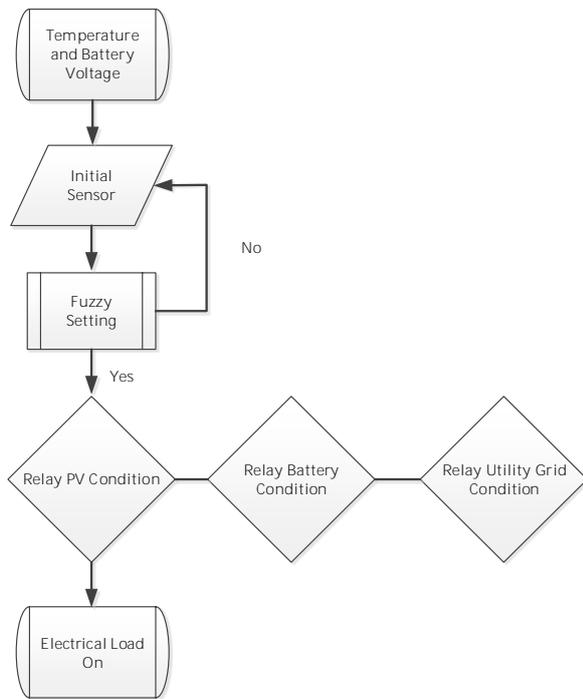


Figure 5. Flowchart control system

Before going to the testing phase, we conducted a simulation using the proteus application as shown in Figure 6. The simulation was conducted aiming to find out the working principle of the microcontroller circuit to be operated. The circuit simulation component uses Arduino Uno, four batteries with different conditions, a relay equipped with L1 and L2 and L3 for on or off indicators.

B. Fuzzy smart control

The decision-making process is carried out using the Fuzzy Mamdani Method. Several previous studies using the Mamdani fuzzy method are the Mamdani fuzzy inference approach to assess ecological security in the Pearl River Delta urban agglomeration, China [15] and the rule-based fuzzy control method for static pressure reset [16]. Fuzzy control is carried out through several stages, namely the formation of fuzzy sets; application function implications; composition of rules; defuzzification.

1) Fuzzification

Fuzzification is a process to change an input from a strict form (crisp) to fuzzy (linguistic variable)

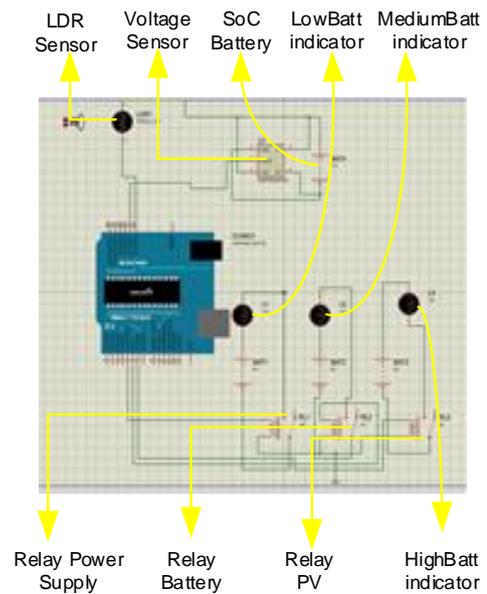


Figure 6. Microcontroller simulation

which is usually presented in the form of fuzzy sets with a function of each member. The fuzzification process on batteries is divided into three conditions. Where the condition of low battery voltage is of 10500-11000 mV, when the condition of the medium is 11000-11500 mV, and when the high condition is 11500-12000 mV. Figure 7 shows the range of battery input groups in fuzzy logic.

As with batteries, the light intensity is also divided into three conditions. Dimanagelap around 0 - 3584 Lux, cloudy around 3585 - 7168 Lux, and bright now around 7169 - 10752 Lux. Figure 8 shows the range of light intensity input groups in fuzzy logic.

If the membership function is known, the next is to determine the degree of membership or $\mu [x]$. Both inputs use 3 types of membership functions, namely linear up, trapezoidal and linear down. So in finding the value of $\mu [x]$, there are 3 ways each according to the location of the input to find the value of $\mu [x]$.

The linear up membership function has the characteristics of a straight line starting from the lowest domain value ($\mu [x] = 0$) on the left side, then moving right towards the domain with a greater degree of membership value. In linear ascending, how to determine the value of $\mu [x]$ can be using equation (1).

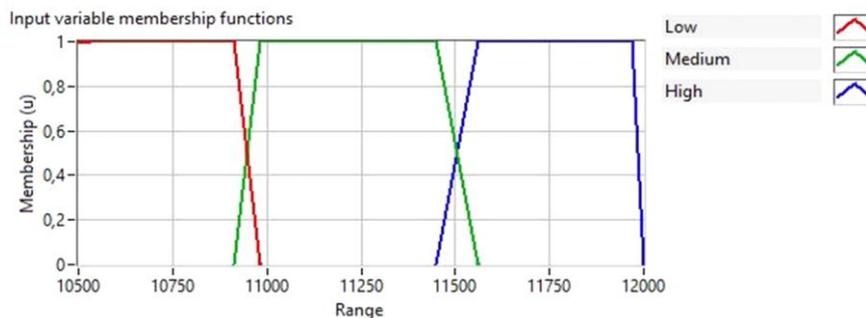


Figure 7. Battery input groups

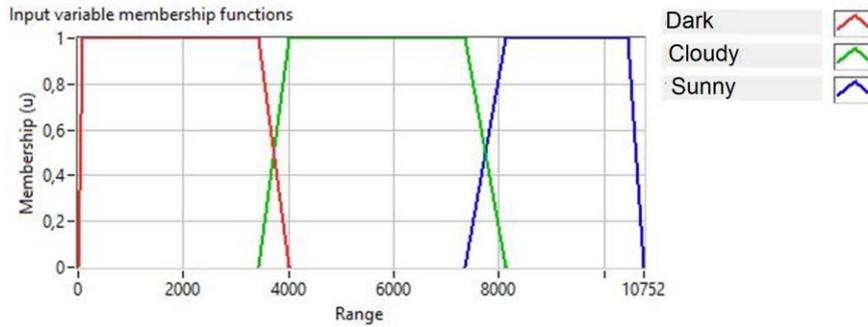


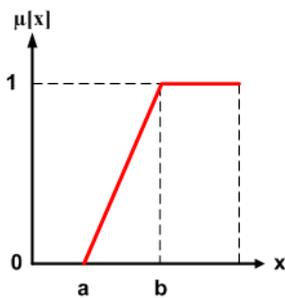
Figure 8. Light intensity input group

$$f(x) = \begin{cases} 0, & x \leq a \\ (x - a)/(b - a), & a < x < b \\ 1, & x \geq b \end{cases} \quad (1)$$

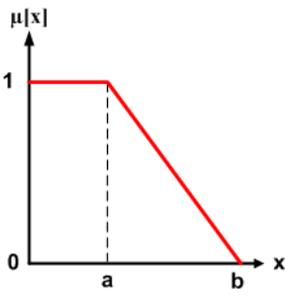
Then, the membership function used is linear down. The linear descending membership function has the characteristics of a straight line starting from the highest domain value ($\mu [x] = 1$) on the left side, then moving to the right to a domain with a lower degree of membership value. In linear descending, how to determine the value of $\mu [x]$ using equation (2).

$$f(x) = \begin{cases} 0, & x \geq b \\ (b - x)/(b - a), & a < x < b \\ 1, & x \leq a \end{cases} \quad (2)$$

The linear up and down shapes can be seen in Figure 9. The membership function used in the next input is the trapezoid. Mapping inputs into degrees of membership is illustrated by the form of the isosceles trapezoid which can be interpreted that several input points have a membership level equal to one. The



(a)



(b)

Figure 9. (a) Linear rise membership function; and (b) linear decline

shape of the trapezoid membership function can be seen in Figure 10.

In the trapezoid membership function, how to determine the value of $\mu [x]$ using equation (3)

$$f(x) = \begin{cases} 0, & x \leq a \text{ atau } x \geq d \\ (x - a)/(b - a), & a < x < b \\ (d - x)/(d - c), & c < x < d \\ 1, & b \leq x \leq c \end{cases} \quad (3)$$

After the grouping or clustering process is complete, then the fuzzification stage or the stage of changing from input data to fuzzy input forms, the next stage is the Inference stage.

2) Inference engine

Fuzzy inference engine translates fuzzy statements in rule base into mathematical calculations (fuzzy combinational). The inference phase is the stage of reasoning for fuzzy input obtained from the fuzzification process and sent to the knowledge base that contains fuzzy rules to produce fuzzy output. The Inference Engine process is carried out using the Mamdani model. The Mamdani model is often referred to as the Min-Max model. Mamdani fuzzy rules are stated in the form IF (x is A) AND (y is B) THEN (z is C) where the values of A, B, and C are fuzzy shapes, while x, y, z are crisp values. the implication function in the Mamdani Model uses the MIN function, while the composition between rules uses the MAX function to produce a new fuzzy set. In this stage, there is a process that must be carried out by beginning to make a truth table containing the rules as in Table 2.

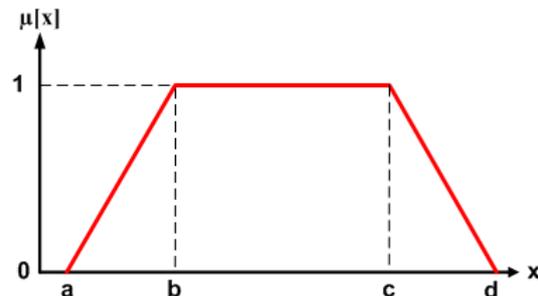


Figure 10. Trapezoid membership function

Table 2.
Principles of automatic micro control work

Light Intensity (Weather)	Battery SoC		
	Low	Medium	High
Dark	Rel PS on	Rel PS on	Rel Bat on
Cloudy	Rel PS+PV on	Rel PS+PV on	Rel PV+Bat on
Sunny	Rel PS+PV on	Rel PV+Bat on	Rel PV+Bat on

Note: Rel = Relay; PS = Power Supply; Bat = Battery; PV = Photovoltaic

Based on the truth table the following conclusions can be drawn:

- If the light is dark and the battery is low, then the PS Rel is on
- If the light is dark and the battery is medium, then the PS Rel is on
- If the light is dark and the battery is high, then the Rel Bat is on
- If the light is cloudy and the battery is low, then the PS + PV Rel is on
- If the light is cloudy and the battery is medium, then the PS + PV Rel is on
- If the light is cloudy and the battery is high, then the PV + Bat Rel is on
- If the light is bright and the battery is low, then the PV + PS Rel is on
- If the light is bright and the battery is medium, then the PV + Bat Rel is on
- If the light is bright and the battery is high, then the PV + Bat Rel is on

Fuzzy Set Operations are needed that will produce α -predicate values for each rule. In the inference process using the Mamdani Model the value of the degree of membership in each rule is applied with the minimum implication function (MIN) of the linguistic value using the conjunction rule (\cap). The formula used to determine α -predicates with a minimum implied function is

$$\alpha - \text{predicate} = \mu(x1) \cap \mu(x2) = \min \{ \mu(x1), \mu(x2) \} \tag{4}$$

Where x1 is a degree of membership of set 1 and x2 is a degree of membership of set 2.

Then after applying the MIN function, an output linguistic value is obtained which is then composed by the MAX function with the disjunction (\cup) rule. The formula used to determine the new μ value from the rule composition results is:

$$\begin{aligned} \mu_{\text{then}} &= \{ \alpha - \text{predicate } \mu(x1) \cup \alpha - \text{predicate } \mu(x2) \} \\ &= \max \{ \alpha - \text{predicate } \mu(x1), \alpha - \text{predicate } \mu(x2) \} \end{aligned} \tag{5}$$

Where α -predicate $\mu(x1)$ equals output linguistic value 1, α -predicate $\mu(x2)$ equals output linguistic value 2.

After the input parameters of the light intensity and battery are identified, the relay output parameters can be grouped as can be seen in Figure 11.

3) Defuzzification

Defuzzification can be defined as the process of changing the amount of Fuzzy that is presented in the form of sets of Fuzzy outputs with the membership function to get back its strict form (crisp). The defuzzification process in the Mamdani Model uses equation 6.

$$Z^* = \frac{\sum z \cdot \mu(z)}{\sum \mu(z)} \tag{6}$$

Where Z^* is defuzzification, Z is fuzzification, and μ represents linguistic value. The result of defuzzification determines the measuring value of the performance of microcomputer automatically on a pilot-scale smart grid PV system.

III. Results and Discussions

At the time of the trial, the sensors and components that have been installed are inspected first. There are obstacles to the light intensity sensor. As shown in Figure 12. The Lux meter value is not stable. Even though the microcontroller records the monitor results every second, the value of the recorded light intensity is quite far.

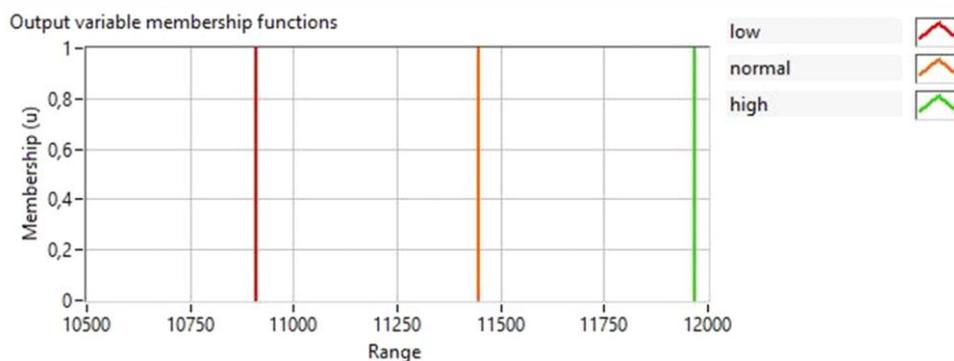


Figure 11. Relay output groups

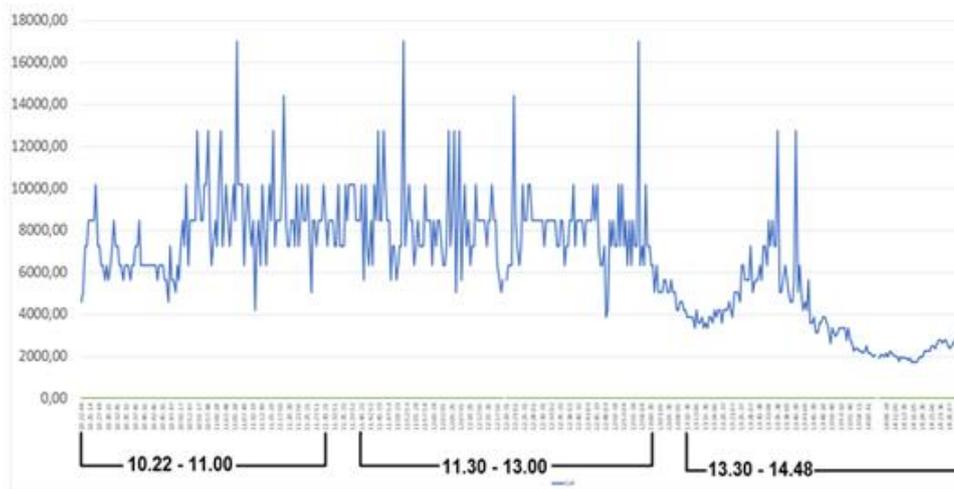


Figure 12. Monitoring light intensity

A. The condition of the power supply is on

The first condition will work when the light intensity is dark or cloudy and the battery condition is low or medium. The position of the relay will look like Figure 13. Where the first relay will connect the power supply with an electric load, while the second relay that connects the battery to the load will be disconnected, and the third relay that connects the PV with the battery will be disconnected as well. So that the load will only be served by power supplies sourced from conventional power plants.

The results of monitoring in the first condition can be seen in Figure 14. Where the light intensity is around 40 lux or below 3584 lux which indicates the light conditions in the dark. While the voltage on the battery is worth about 10.5 to 10, 7 Volts or below 11 Volts which indicates the condition of the battery in a Low state.

The power supply will work dominantly when compared to batteries and PV under these conditions. So that the electrical load will still get a good supply of electrical power even though the PV and battery are in sleep mode.

B. Battery condition is on

The second condition will work when the battery is high and the light intensity is dark or cloudy. The position of the relay will look like Figure 15. Where the first relay that connects the power supply with the electricity load will be disconnected, while the second relay will connect the battery with the load, and the third relay that connects the PV with the battery will be disconnected. So that the load will only be served by a source of electricity stored in the battery.

The results of monitoring in the second condition can be seen in Figure 16. Where the light intensity is around 38 to 42 lux or below 3584 lux which indicates the light conditions in the dark. While the voltage on the battery is worth around 11.6 to 12 Volts or above 11.5 Volts, which indicates the condition of the battery in a High state.

In this condition, the battery will work dominantly when compared to PV and Power Supply. So that the electricity load gets the power supply from the stored energy even though the PV is in a sleep state. Besides that, the power supply that comes

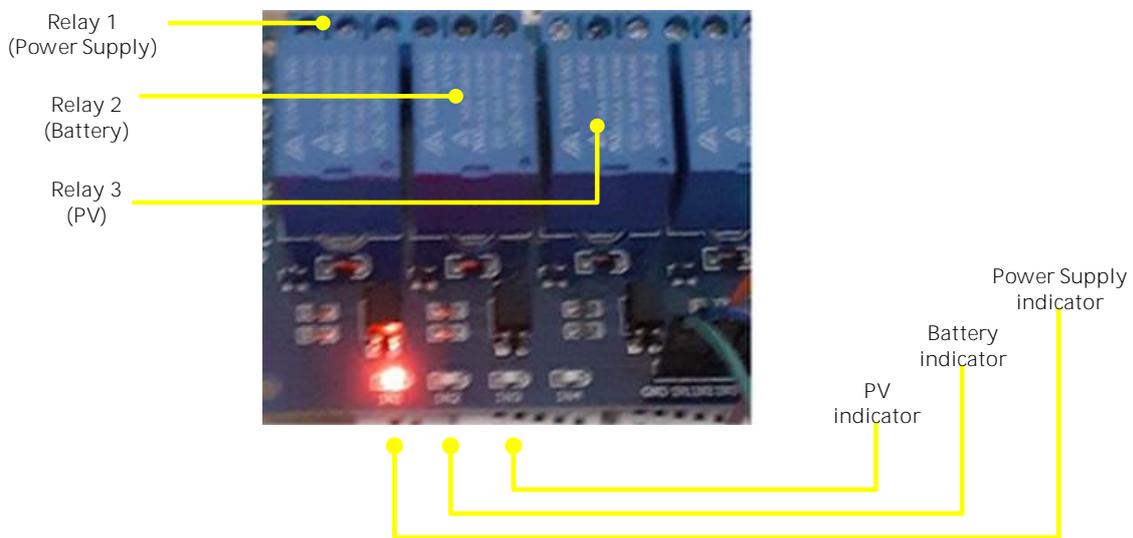


Figure 13. First condition relay

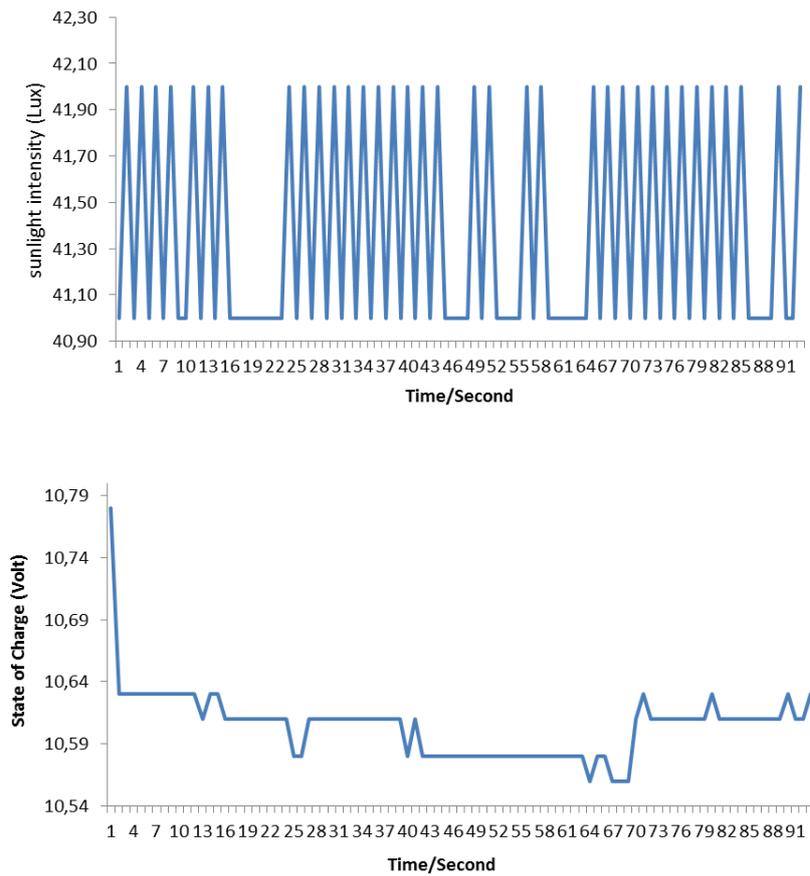


Figure 14. First condition monitoring results

from conventional energy will be deactivated, so that it can reduce the dependence on conventional electricity.

C. The condition of the power supply and PV on

The third condition will work when the light intensity is bright and the battery is low. The position of the relay will look like Figure 17. Where the first relay will connect the power supply with the load, while the second relay that connects the battery to

the load will be disconnected, and the third relay will connect the PV with the battery. So that the PV can charge electricity to the battery and the load will be served by a power supply sourced from conventional energy.

The results of monitoring in the third condition can be seen in Figure 18. Where the light intensity is valued at around 6500 Lux or above 3584 Lux and below 7169 lux, which indicates that the light conditions are cloudy. While the voltage on the

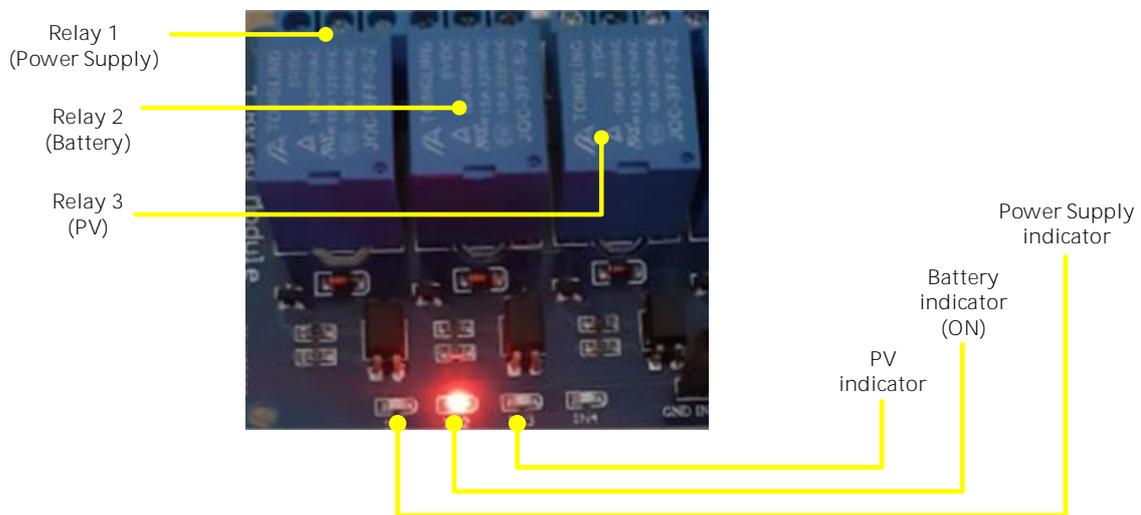


Figure 15. Second condition relay

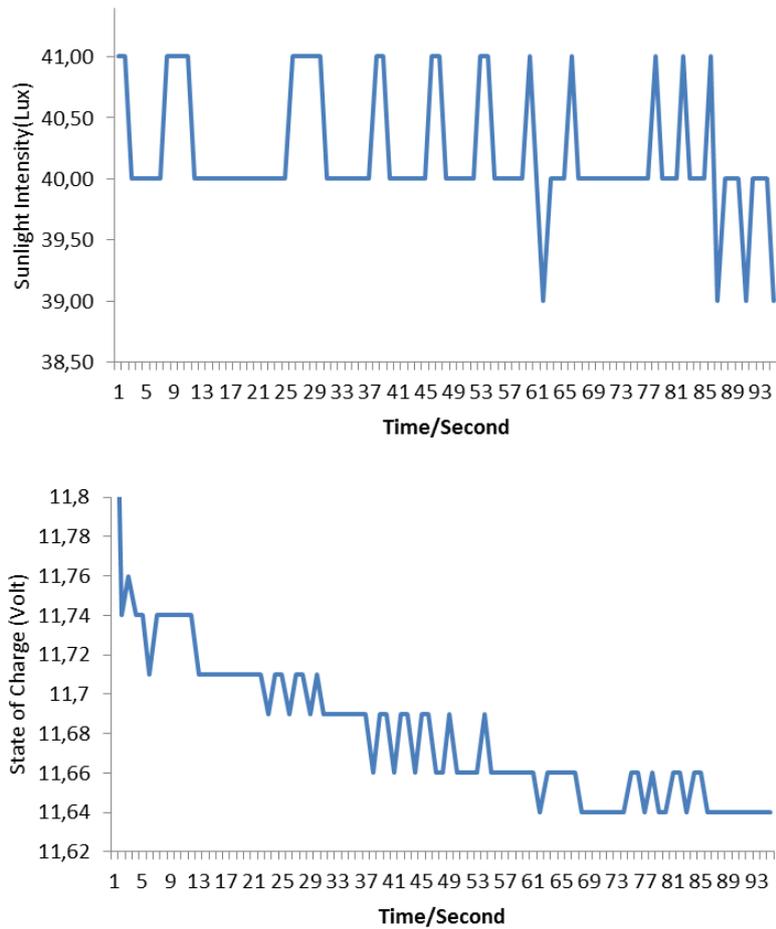


Figure 16. Second condition monitoring results

battery is worth about 10.2 to 10.6 volts or below 11 volts which indicates the condition of the battery in a low state.

In this condition, the PV and the power supply will be on working state while the battery will be charged. So that the battery will focus on charging using electricity from the PV, and the load is still supplied by the power supply while the charging process continues.

D. Battery and PV on condition

The fourth condition will work when the battery is in a medium or high state and the light intensity is in a bright state. The position of the relay will look like Figure 19. Where the first relay that connects the power supply to the load will be disconnected, while the second relay will connect the battery to the load, and the third relay will connect the PV to the battery. So that the PV can charge electricity to the battery,

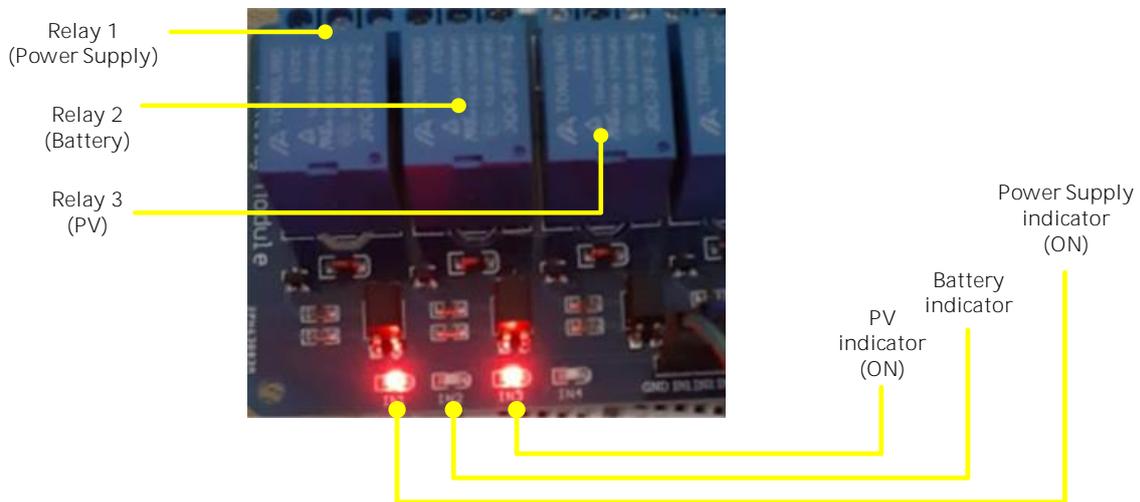


Figure 17. Third condition relay

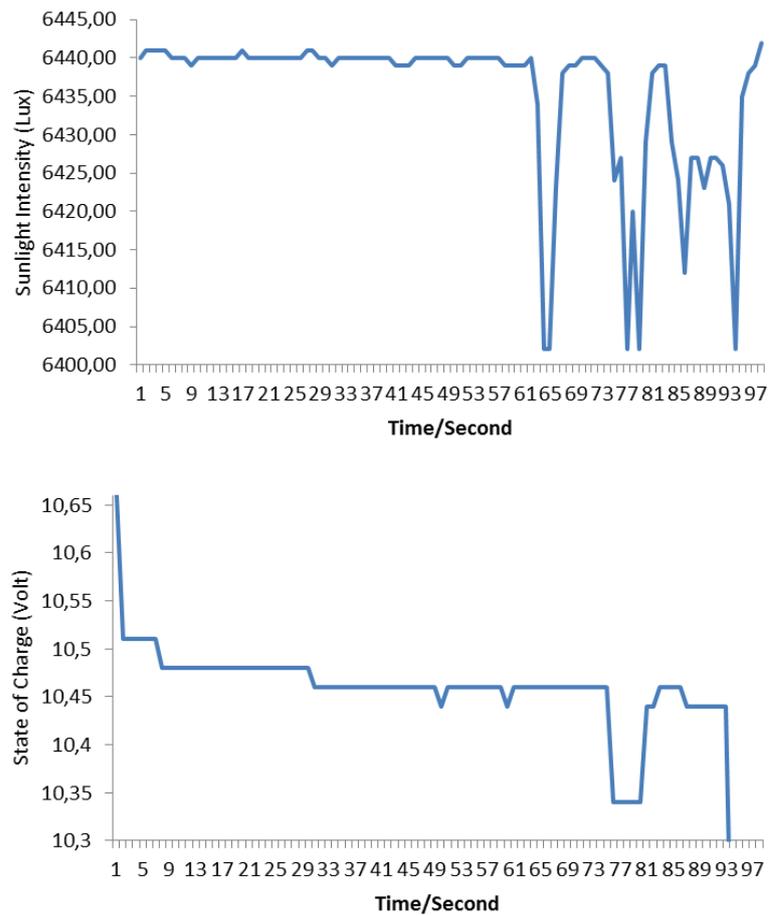


Figure 18. Results of third condition monitoring

besides that the battery will supply electrical power to the load.

The results of monitoring on the fourth condition can be seen in Figure 20. Where the light intensity is around 7900 lux or above 7160 lux, which indicates the light conditions in bright conditions. While the voltage on the battery is worth about 12 volts to 12.3 volts or above 11.5 volts which indicates the condition of the battery in a state of high. Battery voltage can exceed capacity (above 12 volts) because

when the battery is in high condition and the intensity of bright light, the battery and PV are both supplying power to the electrical load, causing an excess of electric charge on the circuit to the electrical load.

In this condition, the PV and battery will work, while the power supply will be deactivated. So that the load will be served by batteries and PV simultaneously without relying on power supplies that are sourced from conventional energy.

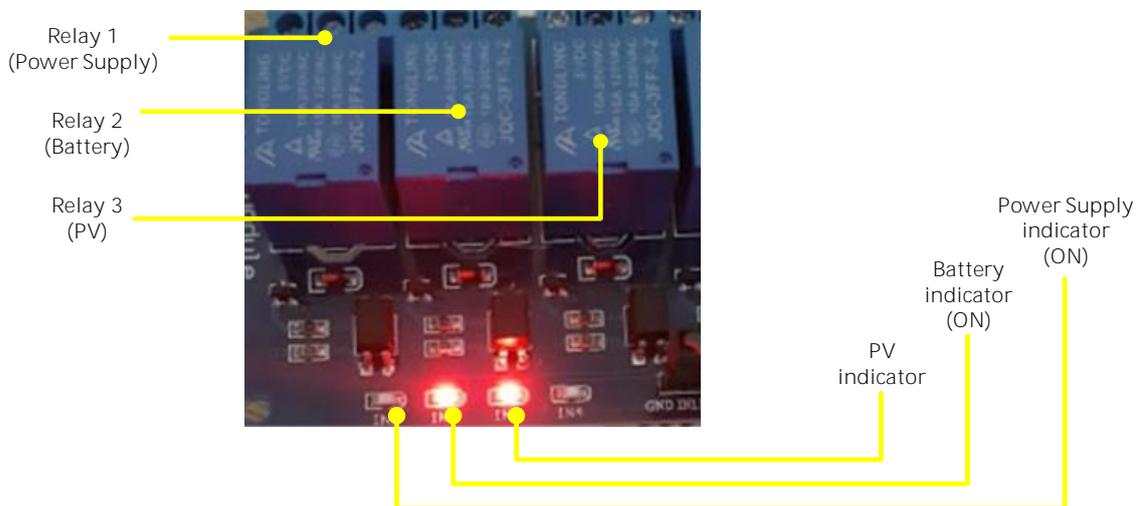


Figure 19. Fourth condition relay

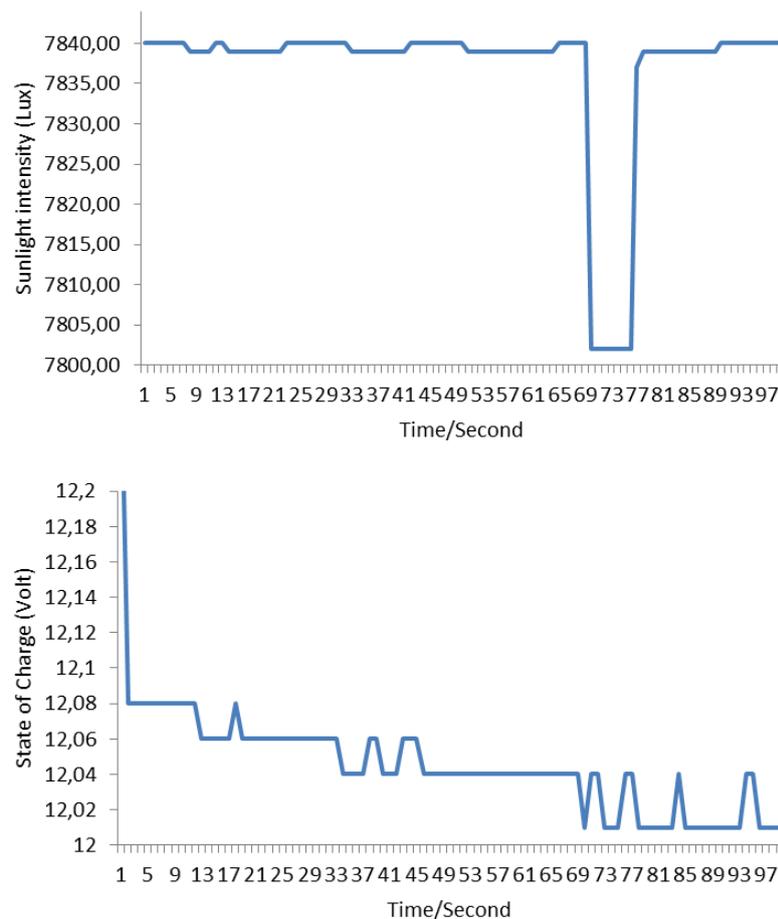


Figure 20. Results of the fourth condition monitoring

IV. Conclusion

Smart control of the photovoltaic power grid system can provide new innovations in utilizing renewable energy and can reduce dependency on conventional energy. The microcontroller switches the power line from renewable energy sources (PV and batteries) to conventional energy (power supply) automatically. In this system, the power supply which is sourced from conventional electricity works when the PV system and battery are in sleep mode. With an automatic control system between renewable energy and conventional energy, the dependence of the photovoltaic system on light intensity no longer affects the supply of energy consumption to electrical loads. This system can reduce dependence on conventional energy without reducing the quality of the energy supply at load. If this system is implemented on a large scale or scale of power plants, it can have enormous potential in the development of Renewable energy power plants.

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Declarations

Author contribution

K. Faqih, W. Primadi, and A.N. Handayani contributed equally as the main contributor of this paper. All authors read and approved the final paper.

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Conflict of interest

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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