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Lux and current analysis on lab-scale smart grid system using Mamdani fuzzy logic controller

Bayu Prasetyo [a, *], Faiz Syaikhoni Aziz [a], Anik Nur Handayani [a], Ari Priharta [a], Adi Izhar Bin Che Ani [b]

[a] *Electrical Engineering Department, Universitas Negeri Malang Jalan Semarang No 05, Malang, 65145, Indonesia*

[b] *Faculty of Electrical Engineering, Universiti Teknologi Mara (UiTM) Kolej Amira Uitm Puncak Alam Road, Selangor, 42300, Malaysia*

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Abstract

The increasing need for electrical energy requires suppliers to innovate in developing electric distribution systems that are better in terms of quality and affordability. In its development, it is necessary to have a control that can combine the electricity network from renewable energy and the main network through voltage back-up or synchronization automatically. The purpose of this research is to create an innovative lux and current analysis on a lab-scale smart grid system using a fuzzy logic controller to control the main network, solar panel network and generator network to supply each other with lab-scale electrical energy. In the control, Mamdani fuzzy logic controller method is used as the basis for determining the smart grid system control problem solving by adjusting the current conditions on the main network and the light intensity conditions on the LDR sensor. Current conditions are classified in three conditions namely safe, warning, and trip. Meanwhile, the light intensity conditions are classified into three conditions namely dark, cloudy and bright. From the test results, the utility grid (PLN) is at active conditions when the load current is 0.4 A (safe) and light intensity is 1,167 Lux (dark). Then the PLN + PV condition is active when the load current is 1.37 (warning) and the light intensity is 8,680 lux (bright). Finally, the generator condition is active when the load current is 1.6 (trip) and the light intensity is 8,680 (bright). Based on the test results, it is known that the system can work to determine which source is more efficient based on the parameters obtained.

Keywords: fuzzy logic; smart grid; lux and current; lab-scale.

I. Introduction

The increase in electricity used by consumers makes electricity suppliers begin to innovate in managing electricity supply so that it remains distributed to consumers with good quality. At the consumer level, many systems have been developed to save or maintain electric power stability, such as back-up voltage systems, the utilization of kWh Exim, Smart Home, building energy management system (BEMS), etc. Then at the distributor level, they have also begun to develop many systems to maintain the stability and the availability of electric power for consumers, for example installing bank capacitors and smart grid systems. The smart grid system is a modern electricity network infrastructure to increase reliability, security, and efficiency also to integrate with renewable energy sources through automatic control [1][2][3]. It is able to integrate the actions of all users, from power generation to consumers with the aim of being more efficient, sustainable, economical and safer electricity supply [4]. It is also considered as the future of electricity grid that can manage the production, transmission and distribution of electricity with modern technology [5][6][7] to solve many problems of the current electricity grid system.

Many smart grid designs have been developed to keep the supply quality maintained and some designs have also been designed to be environmentally friendly by scheduling the use of energy supplies from steam power plants and renewable energy sources such as solar panels, water generators, wind generators and so forth. This has begun to be adopted by several countries

* Corresponding Author. Tel: +62-838-3393-3230
E-mail address: bayoe.30015@gmail.com

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including countries that have large renewable energy potential. In some developing countries, the smart grid system is classified as new technology and is still being developed. The system starts with the idea of an advanced measurement infrastructure to improve demand management and energy efficiency, building reliable network protection, and assuring the network can improve itself in the event of a disruption or natural disaster [2]. In its development, the smart grid system is often integrated with fuzzy logic as a method of decision making. Fuzzy logic was introduced as a model for handling inaccurate, inconsistent, and inexact information [8][9]. A fuzzy set is an object class with a continuum of membership values. Fuzzy logic uses the rule base to change the value of input crips to the corresponding output crips [10]. By using fuzzy logic controller, we can effectively model complex non-linear systems [10]

Broadly speaking, there are three steps to model the system using a fuzzy logic controller, namely Fuzzification, Inference Engine, and Defuzzification. Fuzzification is used to change from crisp input to fuzzy variables so that it can be processed. The next step is the Inference Engine which is fuzzy input reasoning and giving rules. Then, the final step is defuzzification which converts the fuzzy output from the inference engine results to crips value based on membership function [10]. In this study, Mamdani fuzzy logic controller [11] is combined in the lab-scale smart grid system with lux and current as input parameters. Some studies use Mamdani fuzzy as a system method developer, for example, Mamdani fuzzy inference approach to assess ecological security [12] and rule-based fuzzy control methods for resetting the static pressure [13], and in this study Mamdani fuzzy logic controller is used to control smart grid.

Previously, several research projects that are related to the smart grid system had been carried out. The project such as smart grid system on a smart home by controlling the load based on the SOC battery condition where the battery input was obtained from a hybrid solar panel system with a wind generator [14]. The purpose of this project was to manage the burden so that it can reduce the use of conventional energy that is not needed. The research resulted in battery discharge off and load off when there is no grid energy if SOC $\leq$ 30 %. Then the engine load will be off when 30 % < SOC < 70 %. Finally, all loads will light up if the value of SOC $\geq$ 70 %.

In other similar studies, there have been several system design developments by giving some switching to the renewable energy system output so that it can be controlled. The study was conducted by combining distributed power supply, wind generators, and solar panels in an AC bus with the parameters used in the control system is the SOC battery [15]. From the research results, it was known that the system besides being able to produce high-quality electricity, it could also transfer electrical energy quickly to steady-state with a smooth system flow change mechanism [15].

Referring to the researches, it can be concluded that the mechanism of changing energy sources is the key to produce good electricity by utilizing conventional energy and renewable energy. This source change mechanism is adopted in the development of lux and current analysis on a lab-scale smart grid system using the Mamdani fuzzy logic controller. The difference between this research and the previous research is in the control parameters used. Previous studies referred to SOC batteries, while this research focuses more on environmental and load current conditions. Control of energy sources is regulated to maximize the potential for renewable energy and increase the efficiency of using conventional sources.

The purpose of this research is to create an intelligent control system that can determine the most efficient energy source to be used based on the parameters of the intensity of light and current at the lab-scale. This system should be able to monitor the value of light intensity in the environment around the system and the current conditions of the utility grid.

II. Materials and Methods

In general, the smart lab-scale smart grid system has a system whose working principle determines the source for the load based on current conditions and the intensity of the light on the prototype. There are three sources with utility grid (PLN) or sources from main suppliers as the main sources. Then, the second source is a 100 W_p solar panel with an AC current limit after the inverter of 2 A and the third source is a genset with a current capacity of 6 A. Figure 1 illustrates the lab-scale smart grid system flowchart to get a better understanding of how this system works.

The development of a lab-scale smart grid system is divided into two constructions namely hardware construction and fuzzy construction. The hardware construction focuses on the hardware used in the development while the fuzzy construction focuses on the formation of fuzzy rules as a basis for solving control problems based on light and current intensity parameters.

A. Hardware construction

The hardware construction lab-scale smart grid system is the development of magnetic coordination props using contactors. These visual aids are then developed by using a microcontroller and several control components to connect the energy source. In general, hardware construction can be seen in Figure 2 then the workmanship system of the lab-scale smart grid system can be seen in Figure 3, and the components used in developing the lab-scale smart grid system are available in Table 1.

The lab grid-scale design of the smart grid system has two main blocks namely the control block and the data computing block. The control block consists of a magnetic control display device in the form of a case that is developed by adding Arduino Mega and a four Channels relay as a conversion from DC control to AC control. Then, the data computation block

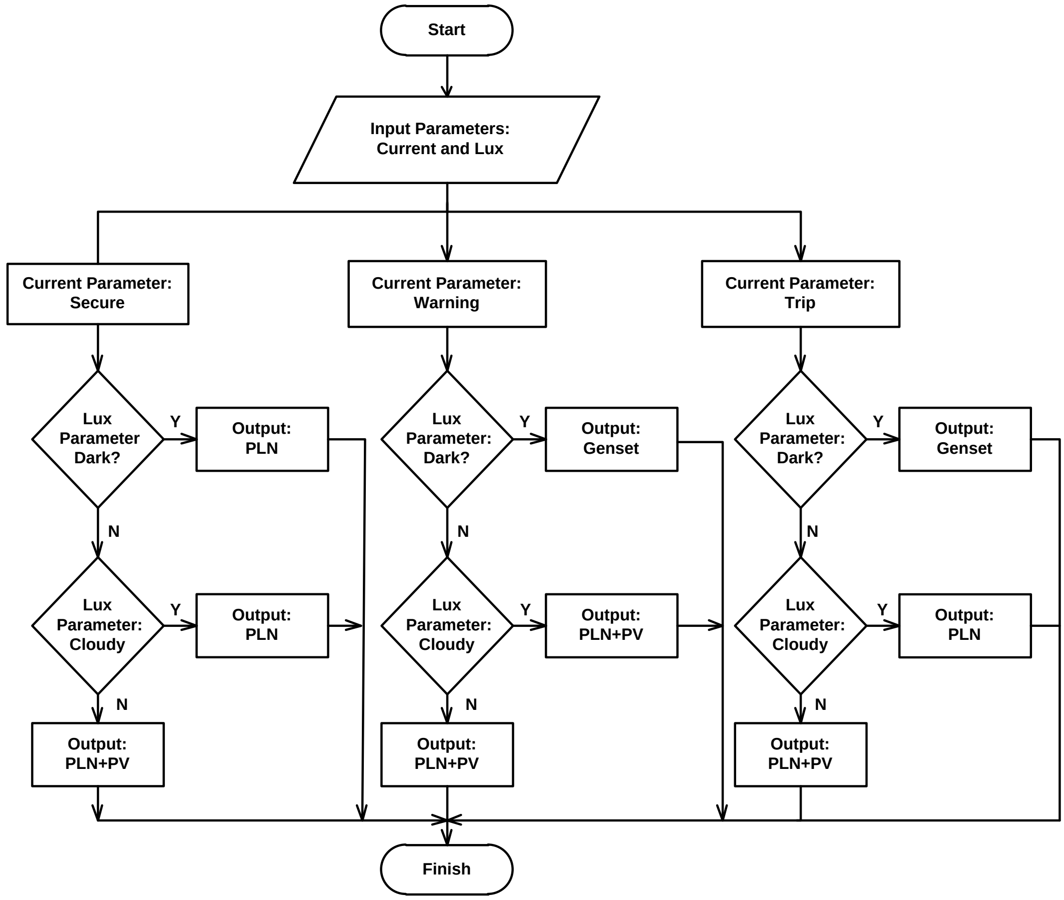

Figure 1. Lab-scale smart grid system flowchart

consists of computers that have Arduino IDE and PLQ-DAX installed as a parameter reader. The design of the lab-scale smart grid system and the control block design can be seen in Figure 4 and Figure 5.

B. Fuzzy construction

This lab-scale smart grid system is controlled by a microcontroller in the form of Arduino Mega with decision making determined by the Mamdani fuzzy logic method. Problem-solving with the fuzzy logic controller has three steps namely Fuzzification, Inference, and Defuzzification with the following explanations.

1) Fuzzification

Fuzzification is a process of changing the input from explicit forms into more linguistic forms. In fuzzification, all data is presented in the form of fuzzy sets using the membership function. In the development of the lab-scale smart grid system, there are two input parameters namely current and light intensity. Each input data will be grouped or clustered by K-Means technique. During the clustering process, turns out that in the light intensity data group, the three conditions have a wide range so system normalization is needed for analysis. The results of light intensity data groups division can be seen in Table 2 and the results of the current data groups distribution are in Table 3.

Based on the results of clustering, the membership function is generated. It is used to map input data points into membership values. Mapping the lab-scale smart grid system membership

Table 1.
Components in the lab-scale smart grid system

No.	Component	Total	Specification
1.	Magnetic contactor	3 pieces	14 pin model: S-N25/coil380 VAC
2.	1-phase MCB	1 piece	6 Amperes
3.	1-phase MCB	2 pieces	2 Amperes
4.	Arduino Mega	1 piece	
5.	Thermal overload relay	3 pieces	TH-N12KP
6.	Relay 4 channels	1 piece	
7.	Push button NO	4 pieces	
8.	Push button NC	2 pieces	
9.	Indicator lamp	4 pieces	5 W/220 VAC
10.	Emergency button	1 piece	
11.	LDR sensor	1 piece	LDR
12.	Current sensor	1 piece	ACS712
13.	Terminal block	14 pieces	TB2503 3 pole 25 A

Table 2.
Division of light intensity data groups before and after normalization

Condition	Division of data groups (lux)	
	Preliminary data	Data after normalization
Dark	0 – 107	0 – 3,931
Cloudy	10.8 – 5,752	3,543 – 6,997
Bright	1,075 – 10,527	6,708 – 10,527

function is done by displaying the clustering result using LabVIEW software which can be seen in Figure 6 and Figure 7. After the membership function is known, the next step is to determine the degree of membership or $\mu[x]$. The two inputs use three types of membership functions, namely linear up, trapezoidal and linear down so that in finding the value $\mu[x]$ there are three different ways according

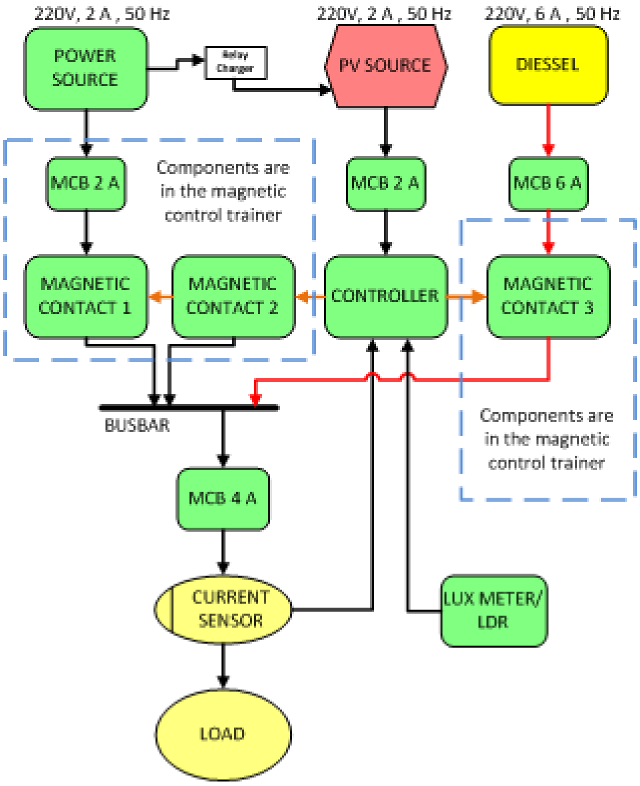

Figure 2. Smart grid lab-scale construction

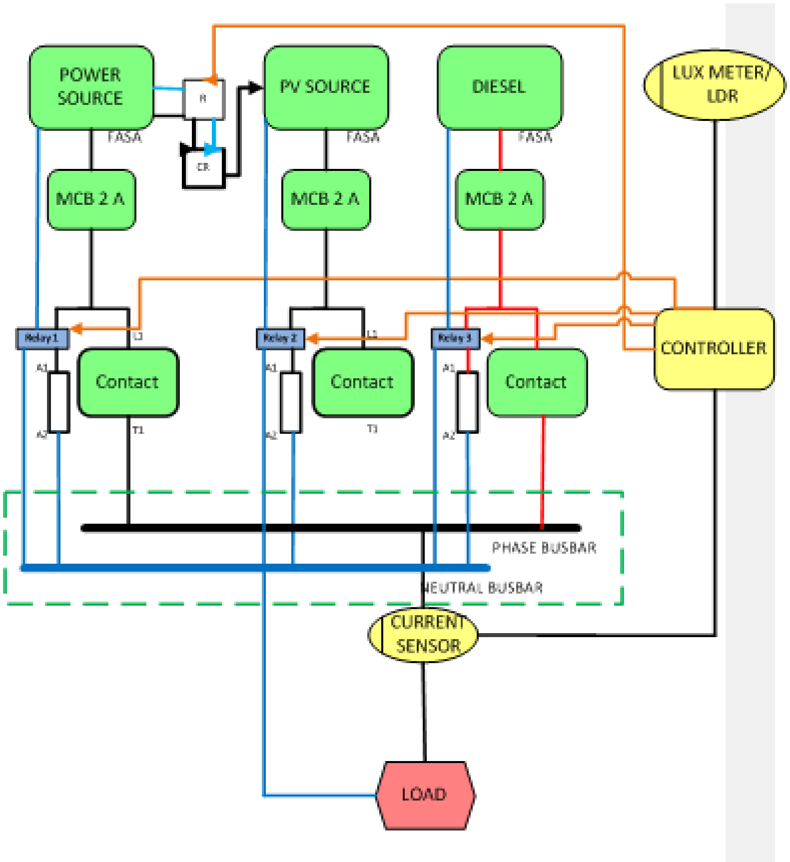

Figure 3. Smart grid lab-scale maintenance

Table 3.
Division of flow data groups

Tim	Condition	Division of data groups (A)
1	Secure	0 – 1.3
2	Warning	1 – 1.7
3	Trip	1.4 – 2

to the location of the input.

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. The membership function used in the next input is the trapezoid. Mapping inputs into degrees of membership are represented by an isosceles trapezoidal form which can be interpreted as having several main points of input having a degree of membership equal to one. Finally, the membership function used is linear down. The linear descending membership function has the characteristic of a straight line starting from the highest domain value ($\mu[x] = 1$) on the left side, then moving right towards the domain with a smaller degree of membership. The form of the three membership functions can be seen in Figure 8.

In linear rise, determining the value of $\mu[x]$ is by using Equation (1). In linear down, determining the value of $\mu[x]$ is by using Equation (2). In membership of the trapezoid function, determining the value of $\mu[x]$ is by using Equation (3). After the grouping process or clustering is completed, the fuzzification stages or the stage of changing from input data to fuzzy input forms, the next stage is inference.

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

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

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

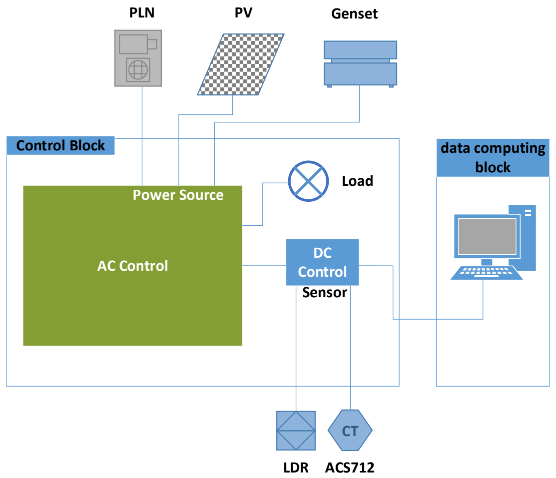

Figure 4. Design of lab-scale smart grid system

2) Inference engine using Mamdani model

The inference engine stage is the reasoning stage for the fuzzy input obtained from the fuzzification process and sent into the knowledge base that contains fuzzy rules to produce fuzzy output. The inference engine process is carried out using the Mamdani model. The model is often referred to as the Min-Max model [11]. The Mamdani fuzzy rules are stated in the form Equation (4),

IF (x is A) AND (y is B) THEN (z is C) (4)

where the values of A, B, and C are fuzzy shapes, while x, y, z are crips values. The application of the functional implication 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 create a knowledge base/truth table containing rules. The knowledge base of smart grid using LaC system can be seen in Table 4. Based on Table 4, IF-THEN rules can be determined a number of 9 conditions which can be seen in Table 5.

Seeing that the inference stage is a stage that combines two degrees of membership, it is necessary to have fuzzy set operations that will produce fire strength or α-predicate values in 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 (∩). The formula used to determine α-predicates with minimum implied functions can be seen in Equation (5).

Table 4.
Smart grid system knowledge base

Lux parameter	Current parameter		
	Secure	Warning	Trip
Dark	PLN	GENSET	GENSET
Cloudy	PLN	PLN + PV	GENSET
Bright	PLN	PLN + PV	PLN + PV

Table 5.
Fuzzy rules for the inference process

No.	Rule
1.	IF ' light intensity' IS ' dark' AND ' current' IS ' secure' THEN ' CONTACT' IS ' PLN'
2.	IF ' light intensity' IS ' dark' AND ' current' IS ' warning' THEN ' CONTACT' IS ' GENSET'
3.	IF ' light intensity' IS ' dark' AND ' current' IS ' trip' THEN ' CONTACT' IS ' GENSET'
4.	IF ' light intensity' IS ' cloudy' AND ' current' IS ' secure' THEN ' CONTACT' IS ' PLN'
5.	IF ' light intensity' IS ' cloudy' AND ' current' IS ' warning' THEN ' CONTACT' IS ' PLN+ PANEL'
6.	IF ' light intensity' IS ' cloudy' AND ' current' IS ' trip' THEN ' CONTACT' IS ' GENSET'
7.	IF ' light intensity' IS ' bright' AND ' current' IS ' secure' THEN ' CONTACT' IS ' PLN'
8.	IF ' light intensity' IS ' bright' AND ' current' IS ' warning' THEN ' CONTACT' IS ' PLN+PANEL'
9.	IF ' light intensity' IS ' bright' AND ' current' IS ' trip' THEN ' CONTACT' IS ' PLN+PANEL'

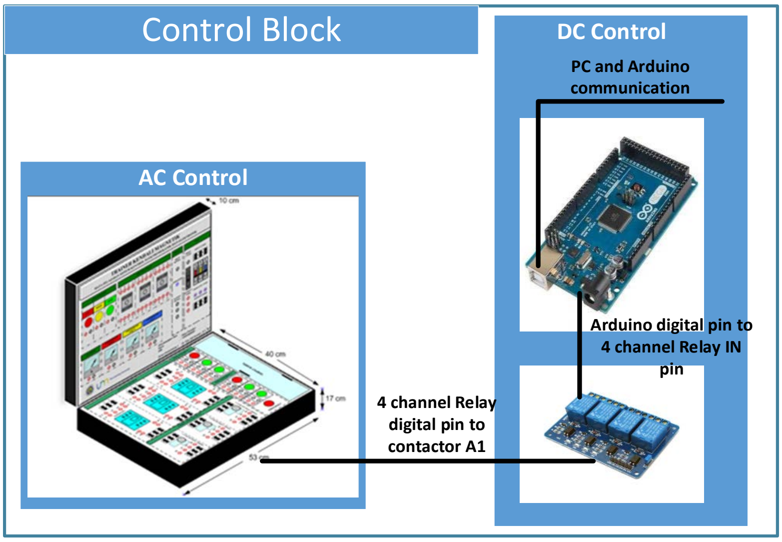

Figure 5. Lab-scale smart grid system full block design

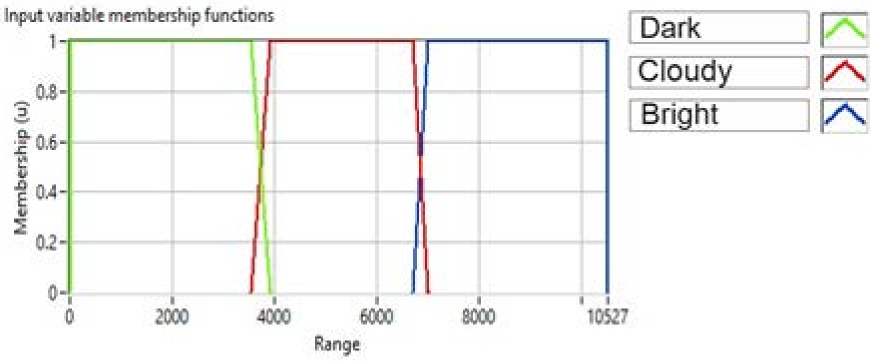

Figure 6. Membership function of lux

$$\alpha - predicate = \mu(x_1) \cap \mu(x_2) = \min\{\mu(x_1), \mu(x_2)\} \quad (5)$$

where x_1 is the degree of membership of set 1 and x_2 is the 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 (∪) rule. The formula used to determine the new μ value from the rule composition can be seen in Equation (6).

$$\mu then = \{\alpha - predicate\ \mu(x_1)\} \cup \{\alpha - predicate\ \mu(x_2)\}$$
$$= \max\{\alpha - predicate\ \mu(x_1), \alpha - predicate\ \mu(x_2)\} \quad (6)$$

where α-predicate $\mu(x_1)$ is output linguistic value 1 and α-predicate $\mu(x_2)$ is output linguistic value 2.

In the lab-scale smart grid system research, there are several rules that are analysed with the Mamdani model Inference Engine with the results are presented in Table 6. After the α-predicate value is known, it will produce a degree of fuzzy output membership. From this degree of fuzzy membership, a single fuzzy set will be produced which will be

Table 6.
Fuzzy inference results using the Mamdani model

Rule	Inference	MIN	MAX	OUTPUT
For L1 1252 dan C 0.78 obtained 2 fuzzy input data, G(1), A(1)				
1	IF LI IS DARK (1) AND C IS SECURE (1) THEN OUTPUT CONTACT IS PLN	1	1	PLN
For L1 1928 dan C 1.11 obtained 3 fuzzy input data, G(1), A(0.633), MT (0.367)				
1	IF LI IS DARK (1) AND C IS SECURE (0,633) THEN OUTPUT CONTACT IS PLN	0.633	0.633	PLN
2	IF LI IS DARK (1) AND C IS WARNING (0,367) THEN OUTPUT CONTACT IS GENSET	0.633	0.367	GENSET
4	IF LI IS CLOUDY (0,915) AND C IS SECURE(0,233) THEN OUTPUT CONTACT IS PLN	0.233	0.085	GENSET
For L1 4049 dan C 1.23 obtained 3 fuzzy input data, G(1), A(0.233), MT (0.767)				
4	IF LI IS CLOUDY (1) AND C IS SECURE (0,233) THEN OUTPUT CONTACT IS PLN	0.233	0.233	PLN
5	IF LI IS CLOUDY (1) AND C IS WARNING (0,767) THEN OUTPUT CONTACT IS PLN+PV	0.767	0.767	PLN+PV
For L1 8725 dan C 1.85 obtained 2 fuzzy input data, C (1), T (1)				
9	IF LI IS BRIGHT(1) AND C IS TRIP (1) THEN OUTPUT CONTACT IS PLN+PV	1	1	PLN+PV
For L1 9476 dan C 0.82 obtained 2 fuzzy input data, C (1), A (1)				
7	IF LI IS BRIGHT(1) AND C IS SECURE (1) THEN OUTPUT CONTACT IS PLN+PV	1	1	PLN

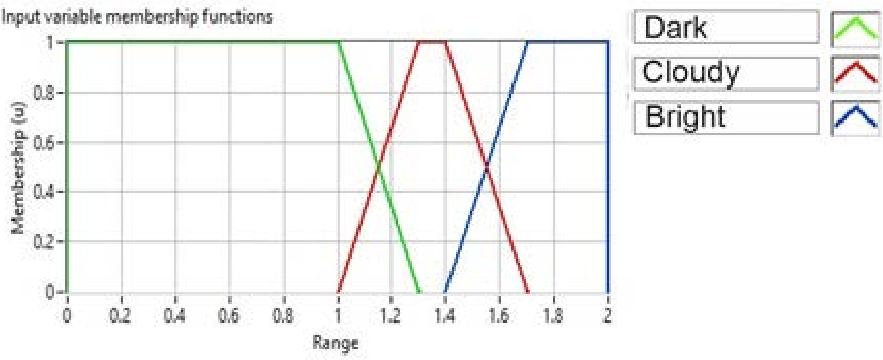

Figure 7. Membership function of current

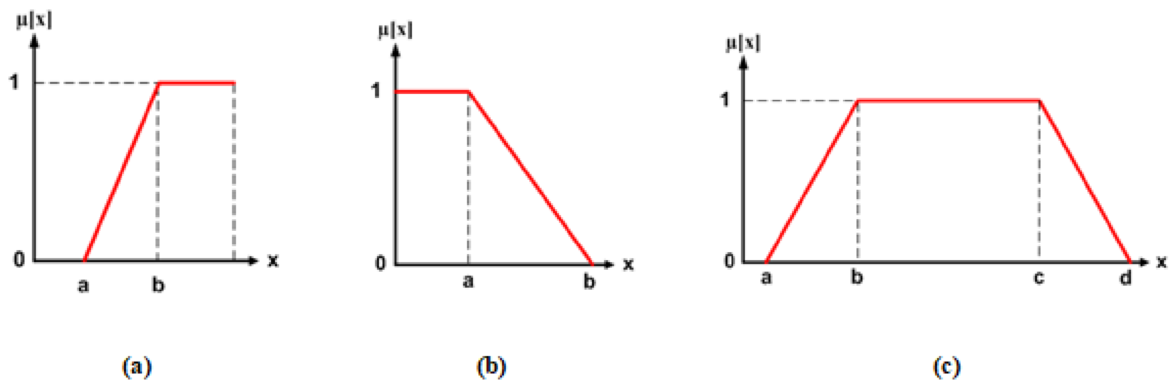

Figure 8. Membership function: (a) Linear up; (b) Linear down; and (c) Trapezoid

used at the defuzzification stage. The degree of fuzzy output membership in the lab-scale smart grid system can be seen in Figure 9.

3) Defuzzification

In the inference engine stage, the fuzzy output is data with linguistic value types. Meanwhile, data is needed in numerical form in the control system, therefore, it is necessary to change the value of the data from fuzzy output to numeric form or called the defuzzification stage.

The defuzzification process in the Mamdani Model uses the formula according to Equation (7) as follow.

$$Z^* = \frac{\sum z.\mu(z)}{\sum \mu(z)} \tag{7}$$

where Z^* is defuzzification value, $\sum z.\mu(z)$ is moment for all region of the rule composition, and $\sum \mu(z)$ is membership value. Based on MIN and MAX values in the inference process using the Mamdani model, it can be seen the value of Z^* with the results shown in Table 7.

Table 7.
Deffuzification results

Inference	Min	Max	Defuzzification
if li is dark (1) and c is secure (1) then output contact is PLN	1	1	0.75
if li is dark (1) and c is secure (0.633) then output contact is PLN	0.633	0.633	0.97
if li is dark (1) and c is warning (0.367) then output contact is GENSET	0.633	0.367	
if li is dark (1) and c is secure (0.2) then output contact is PLN	0.2	0.2	1.38
if li is dark (1) and c is warning (0.8) then output contact is GENSET	0.8	0.8	
if li is dark (1) and c is secure (0.233) then output contact is PLN	0.233	0.233	1.34
if li is dark (1) and c is warning (0.767) then output contact is GENSET	0.767	0.767	
if li is dark (1) and c is secure (0.233) then output contact is PLN	0.233	0.233	1.34
if li is dark (1) and c is warning (0.767) then output contact is GENSET	0.767	0.767	
if li is dark (0.085) and c is secure (0.915) then output contact is PLN	0.085	0.233	1.12
if li is dark (0.085) and c is warning (0.767) then output contact is GENSET	0.085	0.767	
if li is cloudy (0.915) and c is secure(0.233) then output contact is PLN	0.233	0.085	
if li is cloudy (0.915) and c is warning (0.767) then output contact is PLN+PV	0.767		
if li is cloudy (1) and c is secure (0.233) then output contact is PLN	0.233	0.233	1.15
if li is cloudy (1) and c is warning (0.767) then output contact is PLN+PV	0.7676	0.767	
if li is bright(1) and c is trip (1) then output contact is PLN+PV	1	1	1.35
if li is bright(1) and c is secure (1) then output contact is PLN+PV	1	1	0.75

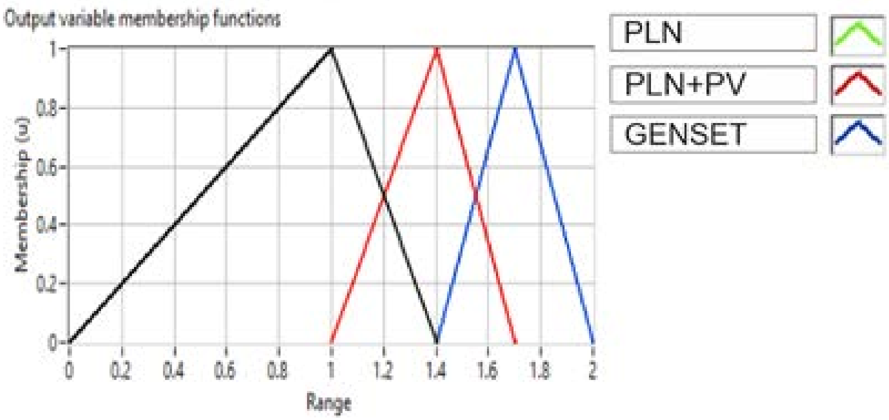

Figure 9. Membership degree in fuzzy output

III. Results and Discussions

The lab-scale smart grid system is particularly a load source control system that will be used based on the LaC or lux and current parameters by utilizing the LDR as a light intensity information finder and the ACS712 sensor as a current data finder for further processing on Arduino Nano with the Fuzzy Logic Controller method. In the development process, there are two stages of testing to know the results or performance of the developed system, namely sensor testing and overall system testing.

A. Sensor test result

Sensor testing is performed to determine the performance of the sensors used to produce accurate data. This test is carried out to ensure the accuracy of the input data which will later be processed on Arduino Nano. This test does not use the Fuzzy Logic method as a controller and only uses ordinary programming to bring up input parameter values.

1) Current sensor test

The first test is the ACS 712 sensor to measure AC current. This test is done by comparing the reading of the ACS 712 current sensor with the amperemeter. The results of the reading show the current values that have approached the measurement results of the amperemeter. The results of reading the current sensor and measuring instrument can be seen in Figure 10. It can be concluded that the ACS712 sensor can be used as a current parameter actuator because the reading value is close to the actual current. Based on the measurement, the error value of the current sensor is 3.57 %.

2) Light intensity sensor test

Light intensity was detected by LDR for 4 hours 33 minutes by taking data every 30 seconds using readings with PLQ-DAX software. The experiment started at 10:22 am until 2:55 pm. The LDR trial results can be seen in Figure 11. From the test results, it is known that the lux value that is read by the LDR is unstable or too volatile with a relatively short interval of time. Then, the repair is done at 12.00 pm. After that, it is retested and the reading of the light intensity improves even though it tends to fall due to cloudy. It can be concluded that the two sensors can be used to obtain data from the parameters of current and light intensity.

B. System test

In system testing, a program containing lab-scale smart grid system control with the Mamdani fuzzy logic controller method is uploaded to the Arduino board that has been connected to sensors and

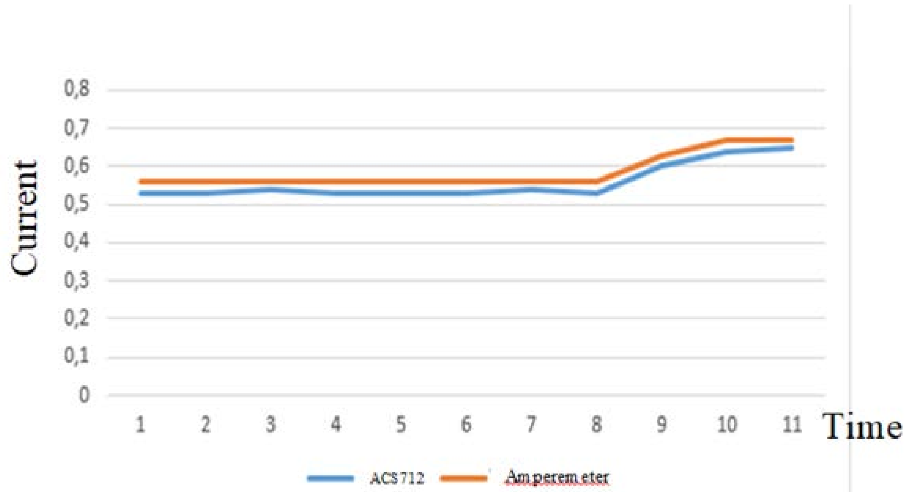

Figure 10. Comparison of ACS712 and amperemeter measurements

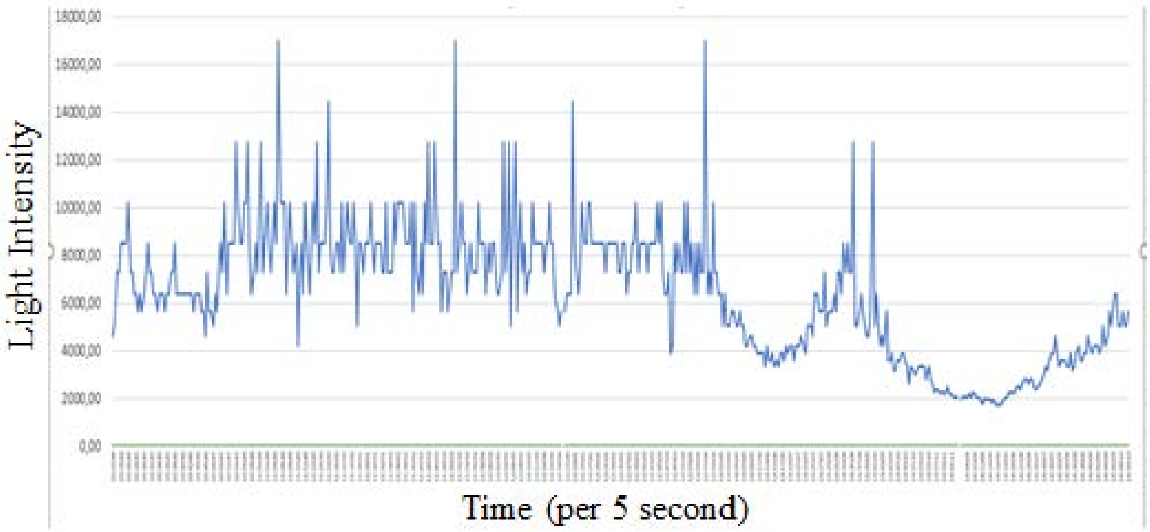

Figure 11. LDR test result data

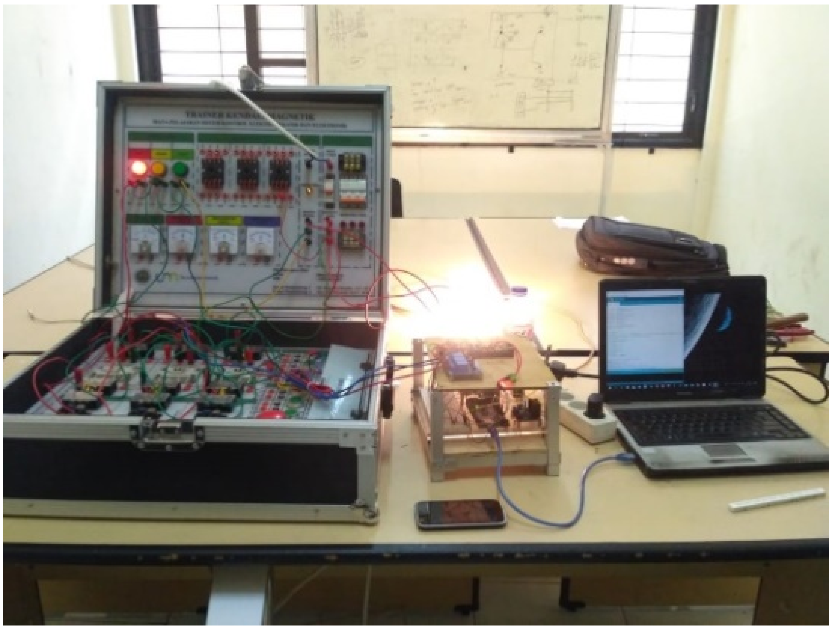

Figure 12. Smart grid system testing using LaC

control components. Then, the system is tested by changing the values of the current parameters and light intensity. Replacement of the current parameter value is done by adding or reducing the load while changing the light intensity parameter by replacing the light source with several other light sources that have different light intensities. The preparation in testing can be seen in Figure 12. The test was carried out with three conditions representing the three outputs namely PLN (utility grid), PLN + PV, and GENSET. In the experiment, the voltage source is not entered into the system and only the control of the smart grid system is tested with the result presented in Figure 13.

The first test is to make the control conditions using PLN so that the input conditions are low light intensity and low load. Then, the system is run and the results of monitoring on the acquisition of Microsoft Excel with the help of PLQ-DAX. Test results with conditions of low light intensity and low load indicate that the red indicator light and contactor 1 are on. This indicates that the source used is PLN in accordance with the desired output conditions. Then, the second experiment is carried out by changing the parameter values so that the output becomes PLN + PV by increasing current and light intensity. The test results note that contactors 1 and 2 are active than red lights and yellow lights are also on. This indicates that the sources used are PLN and Photovoltaic synchronization.

Finally, the third test is done by modifying the input thus the output that will appear is the GENSET by raising the current to near the upper limit and lowering the value of the light intensity. The results of the test turn out to be appropriate, namely contactor 3 is active and the green indicator light is on. The first, second, and third test results can be seen in Figure 14.

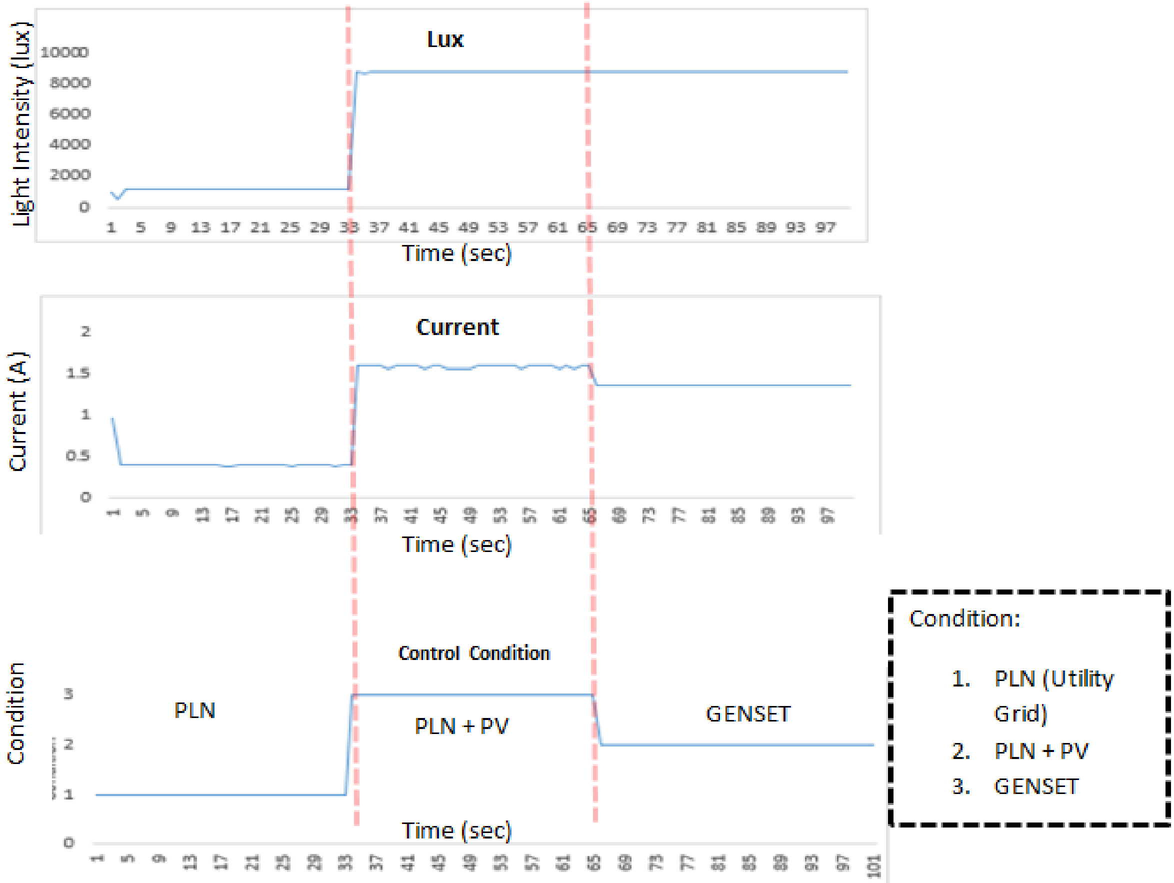

Figure 13. Testing of smart grid system using LaC

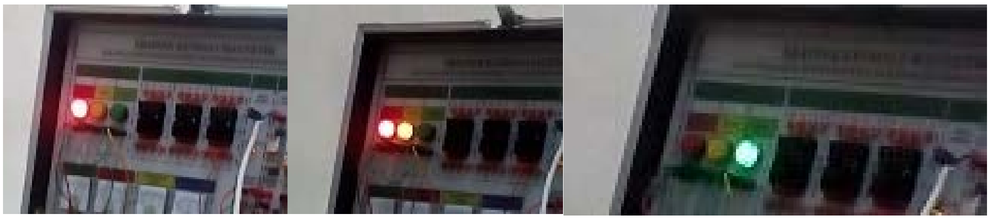

Figure 14. First testing (left), second testing (middle), third testing (right) results

IV. Conclusion

Lux and current analysis on a lab-scale smart grid system using the Mamdani fuzzy logic controller can determine the most efficient energy source by considering the conditions of light and current intensity parameters. This system utilizes renewable energy when the energy source from the sun is detected by an LDR sensor, especially when there is an increase in current demand from the installed load. This working principle increases the potential for utilizing renewable energy sources by prioritizing the supply of electrical energy from RE rather than increasing the demand for electrical energy from the utility grid. This smart grid system development can also reduce the use of electrical energy from the utility grid because there is a control system that regulates the power flow scheme when the load on the utility system approaches the highest capacity of the utility grid. LaC-based smart grid can be developed by adding several supporting components in accordance with voltage back-up and synchronization rules so synchronization can be better. With a few adjustments, this system can be implemented on a large scale electricity network system.

Declarations

Author contribution

All authors 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

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