ASIAN JOURNAL OF ELECTRICAL AND ELECTRONIC ENGINEERING
Vol. 1 No. 2 2021
E-ISSN: 2785-8189

Design and Modelling of PV-Diesel Hybrid Energy System with Fuzzy Logic Controller

Masood Alnajjar, Muhammad Mahbubur Rashid

Department of Mechatronics engineering,
International Islamic University Malaysia, Kuala Lumpur, Malaysia

*Corresponding author: mesutnajar@gmail.com

(Received: 4th August 2021; Accepted: 15th September 2021)

Abstract— Renewable energy, such as wind and photovoltaic arrays, has become the core energy in micro-grids used for supplying remote areas and areas suffering from electricity outages. Many limitations, such as weather fluctuations and low efficiency, lead to designing and developing a hybrid energy system. The integration of photovoltaic arrays and diesel gensets has become one of the most common approaches to generating electricity for remote communities. Although the integration of photovoltaic arrays and diesel gensets has the potential to reduce the cost of electricity production by harnessing free energy from the sun to reduce the power generated by diesel engines, it tends to complicate the control of the entire system due to the intermittent nature of the renewable energy sources and changing load demand. This paper proposes a fuzzy logic controller of PV-Diesel hybrid energy system, which is used as an effective tool in facilitating optimum power-sharing between the PV power source, charging, and discharging batteries and diesel generator as a backup based on the dynamics of the available PV energy at any time. Optimizing power control in the PV-Diesel hybrid energy system is key to minimizing the cost of power generation and maximizing the overall efficiency of the PV-Diesel hybrid energy system. The MATLAB-Simulink is used to design the fuzzy logic controller of the PV-Diesel hybrid energy system and to validate its performance. Five scenarios during the day have been tested to show the performance of the fuzzy logic controller. The results showed the accurate controlling of the power flow in the PV-Diesel hybrid system and the power saved about 2%.

Keywords: *Fuzzy logic controller, Hybrid Energy System, Solar Power, Diesel Engine*

1. INTRODUCTION

Energy is very important to improve the quality of economic and social life. Thus, securing stable energy sources in remote areas (off-grid) and areas that suffer from large energy shortages due to wars and poverty is essential (Garcia, 2016). These areas usually rely on a diesel generator to overcome energy problems. Still, the continued rise in petrol prices and its delivery to these areas is difficult and expensive as well, led them to use other energy sources like renewable energy sources. In recent years, these areas have begun to depend on renewable energy especially solar energy, due to the low cost of photovoltaic panels (PV) and their efficiency (Ani, 2016).

Solar energy is still insufficient because the weather is volatile, as the sun rays on rainy and cloudy days are very weak, thus reducing the efficiency of the PV solar system and could not meet the power demand. So, using Hybrid Power Systems (HPS), which combines two or more different types of renewable and low carbon generators, is the most efficient for these areas (Kumar, 2014). The main object of combining a diesel generator with any of these renewable sources is to ensure meet power demands without interruption, minimize diesel fuel consumption and pollution emissions, thus reducing the costs of saving energy and preserving the environment. PV-Diesel hybrid systems are the best optimal solution for these areas where these systems are reliable and cost-effective and can achieve lifetime fuel saving (Ani, 2016). However, improper energy flow control between the PV solar and diesel generator and incorrect battery charge/discharge algorithms causes low output power efficiency and rapid system equipment damage (Serban, 2016). The low efficiencies of traditional monitoring and control techniques have led researchers to evolve artificial intelligence-based optimizations. Suitable utilization of intelligent technologies leads to sound systems with improved performance or other characteristics that traditional technologies cannot achieve. Artificial intelligence, especially fuzzy logic controllers, has been used widely in controlling a hybrid energy system. Using the fuzzy logic controller has shown a noticeable improvement in hybrid energy efficiency.

The fuzzy controller is used to share the contribution of each source and focus on the PV solar source to exploit energy from it as can as possible. In addition, the controller is used to protect the storage battery and improve diesel performance. The inputs of the fuzzy controller are an error (e) and change of error (Δe). The error is the difference between the load power and the output power from PV. The outputs of the fuzzy controller are three control signals: battery charging, battery discharging, and diesel switch commands. The results showed the fuzzy controller could deal with three cases (morning, daylight, night) according to the load profile and three sources to decrease fuel consumption and protect the storage battery for a long time of operation. A novel fuzzy logic controller has developed of PV-diesel hybrid energy system, and compared against existed control strategy, named load following and cycle charge. This fuzzy control strategy can extend generator shutdown time, thereby reducing consumers' electricity cost (COE). System performance is evaluated using MATLAB / Simulink. Results show that COE achieved through a control strategy based on a fuzzy basis is lower than the load following and cycle charging strategy. Also, lowering COE and CO2 emissions compared to the independent generator system is 12.7% and 25%, respectively (Chok, 2019). The fuzzy logical control unit has also demonstrated the ability to eliminate the need for sophisticated and dull mathematical models as required in conventional control methods. Thus, the system was the easiest to develop. Control of energy flow in the hybrid power system is still an advanced search. Several energy control solutions have been proposed. However, many of them lack validation. Validation of a proposed design is vital to ensure the viability of a system to be implemented (Nnadozie, 2018). This work has done the validation of a fuzzy logic controller designed for PV-Wind hybrid energy systems. The control unit has been verified by adapting it to a hybrid renewable energy system and simulating test case scenarios to verify claims of control functions. The simulation results showed that the monitoring and control of supply power, load demand, and charging and discharging of the battery delivered desirable results. For each test case, the controller is confirmed to simulate expert decisions. Hence fuzzy logic controller was validated, and the authors' claims were verified (Chibuikem, 2018).

This paper will design and develop a PV-Diesel Hybrid system, in addition, to design a fuzzy logic controller which used to control between PV solar system and Diesel generator to ensure when the power from PV solar system (include batteries) will be not enough to provide the load demand, the diesel generator will cover the power lack, that ensures stable power source without interruption, reduce the fuel consumption and pollution emissions as well

2. PV-DIESEL HYBRID ENERGY SYSTEM DESIGN AND MODELLING

In this section, PV-Diesel Hybris Energy System will be designed and modelled.

2.1 Photovoltaic Panel System Modelling

To model the photovoltaic panel, we have to model the PV cell firstly. Figure 1 shows the equivalent circuit of the photovoltaic cell. The PV cell circuit involves a photocurrent, diode, parallel resistor, or shunt resistor R_{sh} (leakage current) and a series resistor R_s. This model is recognized as a single diode solar cell model (Roy Chowdhury, 2010).

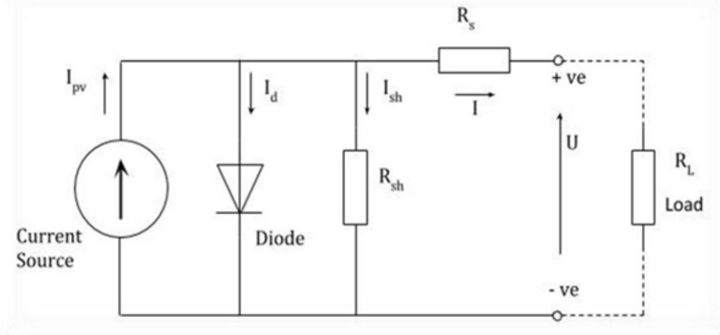

Fig.1. Equivalent Circuit of PV Cell.

Based on both Kirchhoff's circuit laws and the PV cell circuit shown in figure 1, the PV current can be stated as follows:

$$I_{pv} = I_{ph} - I_D - I_{sh} \qquad (1)$$

$$I_{pv} = I_{ph} - 10\left[exp\left(\frac{(V+I_oR_s)q}{nKTNs}\right) - 1\right] - I_{sh} \qquad (2)$$

Where:

I_{pv} shows the photovoltaic current (A)

I_{ph} shows photogenerated current (A); (this current will be calculated in the following equation)

V shows the solar cell voltage (V)

I_o shows the saturation current; (this current will be calculated in the following equation)

R_s shows series resistance (Ω)

q = Elementary charge constant $(C) = 1.60217646 \times 10^{-19}C$

n represents diode ideality factor

K = Boltzmann constant $(J/K) = 1.3806503 \times 10\text{^}(-23)\, J/K$

T is solar cell temperature (K)

N_s represents the series-connected cells

I_{sh} represents the shunt current (A) (this current will be calculated in the following equation)

Equation (1) is the general equation of solar cells. Whereby, the PV current depends on another three currents, which are photogenerated current I_{ph}, saturation current I_o and shunt current. These currents are calculated as follows:

- The photogenerated current I_{ph} primarily based on the temperature of cell and solar irradiation, which is represented as:

$$I_{ph} = \frac{[K_i(T-298) + I_{sc}]G}{1000} \qquad (3)$$

Where, K_i is the temperature coefficient of the cell's short current of the cell panel, T is the cell's reference temperature, I_{sc} is the short circuit current and G is the solar radiation (kW/$m2$).

- The PV saturation current I_o varies with the cell temperature, which is described as:

$$I_o = I_{rs}(\frac{T_c}{T_r})^3\, exp\left[\frac{qEg}{nK}\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right] \qquad (4)$$

Where I_{rs} is reverse saturation current of the cell panel, and it can be represented as:

$$I_{rs} = \frac{I_{sc}}{exp^{(\frac{qv_{OC}}{nN_sKT_C})-1}} \qquad (5)$$

Where q is the band-gap energy of the cell, and V_{oc} is the cell's open-circuit voltage.

- The shunt current is represented by the following equation.

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \tag{6}$$

Where, R_{sh} represents the shunt resistance (Ω).

2.2 Battery System Model

In this work, the batteries will be used as an energy storage system. This subsystem relies on the general battery block provided by the Simscape power system in the Simulink environment [15]. There are four types of batteries supplied to use: Lid-Acid, Lithium-Ion, Nickel-Cadmium, and Nickel-Metal-Hydride. The type of battery that will be chosen for this system is a Lid-Acid battery. The battery will be connected with the system using a bi-directional DC-DC converter, which will be controlled using the fuzzy logic controller to charge and discharge the battery. For the lead-acid battery type, the model uses these equations (Tremblay, 2009):

- Discharge Mode (i<0)

$$V_{batt} = E_0 - R \cdot i - K\frac{Q}{Q-it} \cdot (it + i^*) + Exp(t) \tag{7}$$

- Charge mode (i>0)

$$V_{batt} = E_o - R \cdot i - K\frac{Q}{it-0.1 \cdot Q} \cdot i^* - K\frac{Q}{Q-it} \cdot it + Exp(t) \tag{8}$$

Table 1: The Parameter of Lid-Acid Battery

Parameter	Values
Nominal voltage (V)	12
Rated capacity (AH)	5.4
Initial state-of-charge (%)	20
Battery response time (s)	1e-4

Figure 2 shows the battery and bidirectional converter was modelled using MATLAB-SIMULINK.

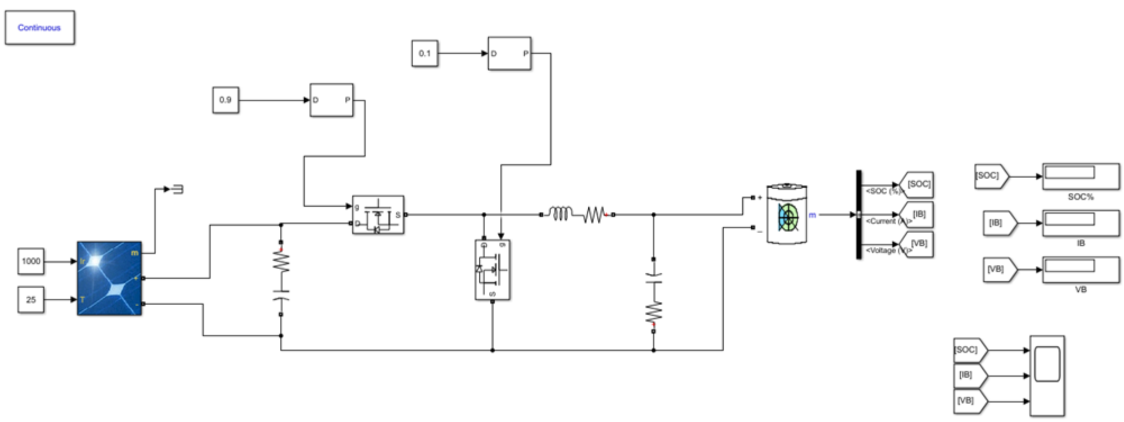

Fig. 2. Battery Connected with PV Panel using Bidirectional Converter.

2.3 Diesel Generator Model

In this work, the diesel generator will be a backup system to cover the night mood. “Here, the relationship between diesel input fuel and the resulting electric power is assumed to be linear. Idle fuel consumption is around 25 to 30 per cent of the consumption at nominal rated power. Diesel stations have a separator between diesel engines and generators. To be able to handle the beginnings and engines of a diesel engine, the clutch must also be designed.” (Rebhi, 2019).

$$\frac{dw_d}{dt} = (\frac{[k_v(k_c m_f - p_o) - D_d w_d - T_{dgn})}{J_d} \quad (9)$$

$$\frac{dm_f}{dt} = \frac{w_d - w_{ref} - \frac{m_f}{\delta}}{T_d} \quad (10)$$

Where:

w_d is the speed of engine speed
w_{ref} is the speed of governor reference
δ is the gain constant of governor gain
T_d is the time constant in the governor
m_f is the fuel consumption in diesel
k_c is the combustion constant describing the efficiency
p_o is the pressure of the motor chamber when running idle
k_v is the volume of stroke
T_p is the produced torque
T_f is the friction torque
T_{den} is the load torque from generator and clutch
D_d is the constant describing the frictional losses
J_d is the total moment of inertia of the engine, clutch, and generator.

Figure 3 shows the subsystem of the diesel generator connected to the ON-OFF switch.

The diesel generator has been designed based on equations 9 and 10. A fuzzy logic controller will control the ON-OFF switch. When the solar power is too low and the battery is low, the switch will be ON.

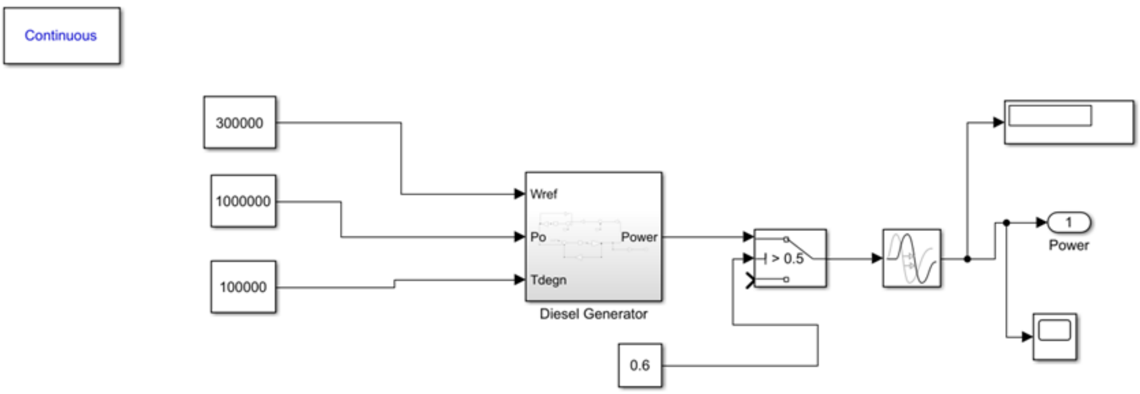

Fig. 3. The Subsystem of Diesel Generator.Fuzzy Logic Controller Model

2.4 The proposed Fuzzy Logic Controller

A fuzzy logic controller has been widely used over the last years due to its simplicity and flexibility. It is also used with nonlinear imprecise inputs [19]. Therefore, the FLC is suitable to control the PV-diesel hybrid energy system since the inputs from the PV panel and the diesel generator are not linear. In addition, the fuzzy logic controller is implemented to control the PV-diesel hybrid energy system is faster than the other traditional controllers. The intelligent power management system optimally selects the power supplies based on the availability of solar energy and battery state of charge. The proposed fuzzy logic controller has two inputs and three outputs. The two inputs of FLC are the error “e” and the state of the charge of the battery (SOC%).

$$e = P_{pv} - P_{load} \tag{11}$$

The input variable “e” is the power error in the system and the state of charge of the battery (SOC%). The outputs are three control signals. The first and second control signals are duty cycle signals “D” converted to PWM signal and sent to bidirectional charger to control charge and discharge the battery. The last signal is the duty cycle signal which will be sent to the ON-OFF switch to control start/ stop the diesel generator. Basically, fuzzy logical control has three stages: fuzzification, inference and defuzzification. These elements and the global structure of FLC are shown in Figure 4. Each input/output variable of fuzzy logic control must be stated in fuzzy set notations using linguistic forms. Therefore, fuzzification is the process of converting input/output variables to linguistic forms. The second stage of fuzzy logic is the inference in which the fuzzy processor uses linguistic rules to define the control procedure that must occur in response to a specific set of input values. The rule evaluation result is a fuzzy outcome for each type of consequence action. The last stage of fuzzy logic is defuzzification, in which the fuzzy quantity is converted into crisp quantity. In fact, there are many methods for the defuzzification process the most common one and used in this project is the centroid method or centre of gravity.

With refer to figure 4, once the inputs “e” and “SOC%” are measured, the controller converts them into linguistic variables using the membership functions. The two input membership functions are divided into five fuzzy levels which are: very positive (PP), small positive (P), middle (Z), small negative (N) and very negative (NN). The three outputs also will be converted into linguistic variables by means of the membership functions which are battery charge (BC), battery discharge (BD) and diesel generator (DG). The battery charge “BC” and battery discharge “BD” outputs are divided into five levels of membership functions the same as the inputs. The last output is “DG”, which will be divided into two levels which are start (ON) and stop (OFF).

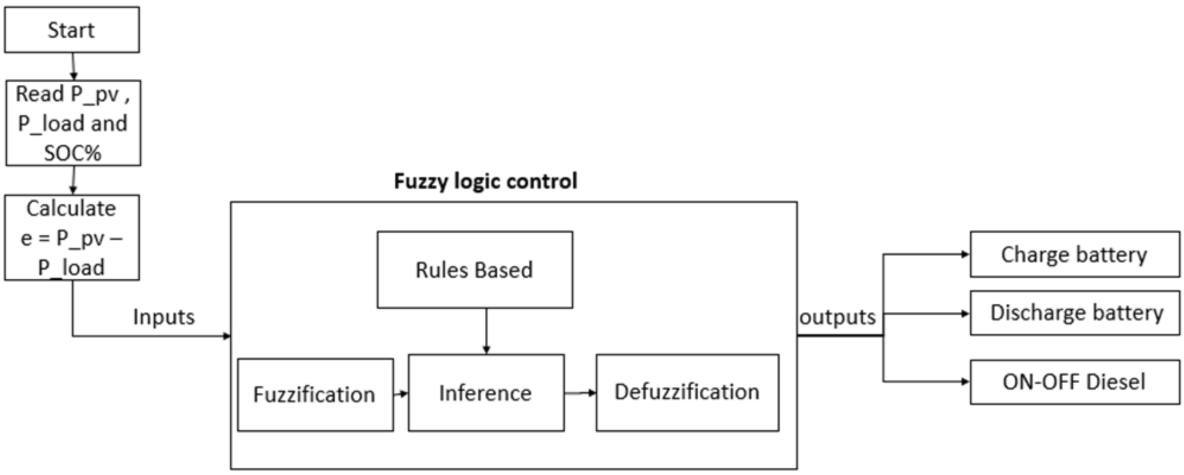

Fig. 4. The Proposed Fuzzy Logic Controller Components.

2.5 Fuzzy Logic Controller System Design

The fuzzy logic control system was designed using MATLAB software. The rule-base proposed by Mamdani was employed. The Fuzzy Logic Toolbox and its Graphics User Interface (GUI) were used to define the inputs and outputs, define the linguistic variables and values, construct the membership functions, and specify the fuzzy set operators and implication, aggregation, and defuzzification methods. In addition, surface plots for the controller were generated using MATLAB software.

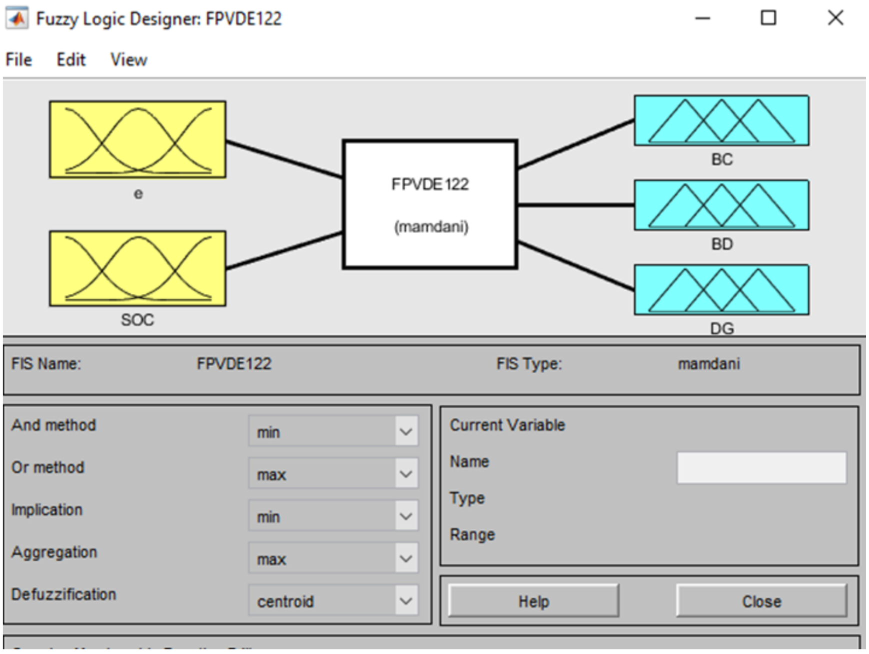

Fig. 5. Fuzzy Logic Controller Diagram.

Figures 6, 7, 8,9 and 10 show the membership function variables for both inputs and outputs.

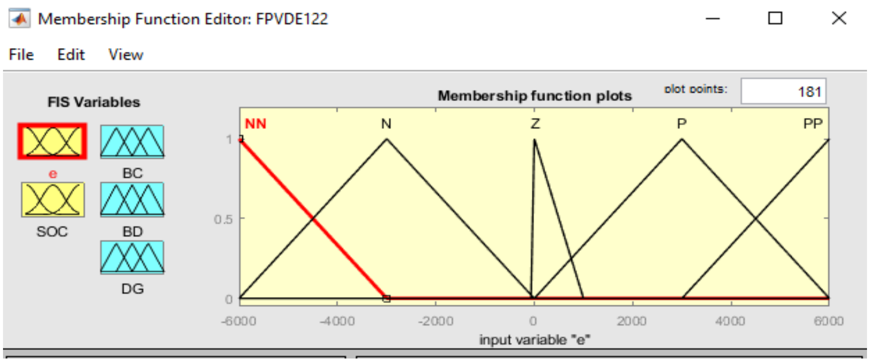

Fig.6. The Membership Function of the "e" Variable.

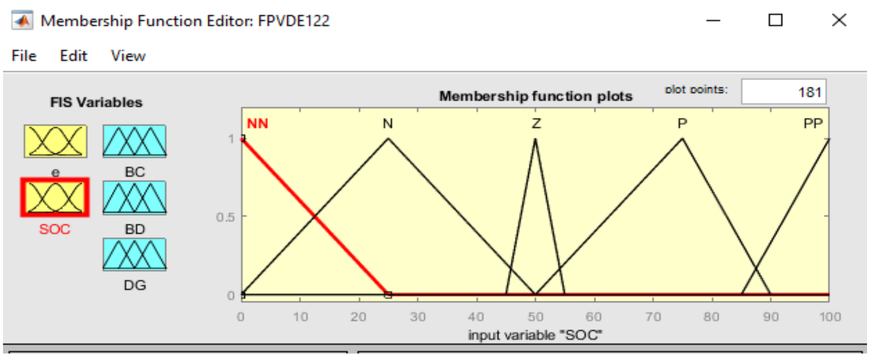

Fig. 7. The Membership Function of the "SOC" Variable.

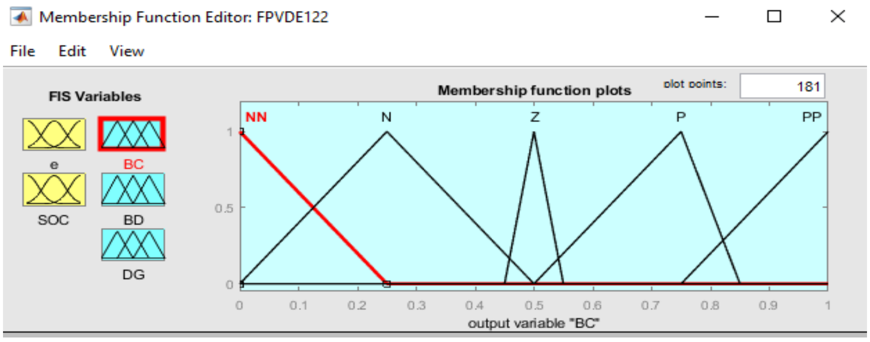

Fig. 8. The Membership Function of the "BC" Variable.

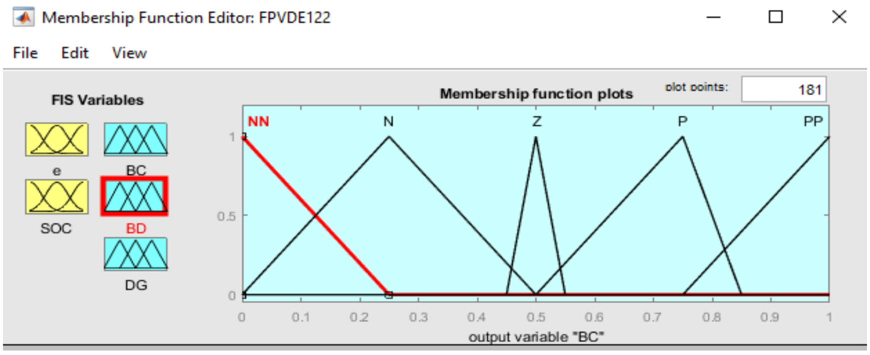

Fig. 9. The Membership Function of the "BD" Variable.

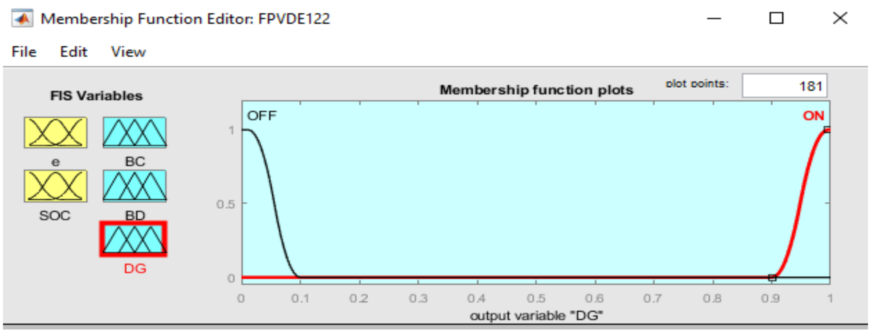

Fig. 10. The Membership Function of the "DG" Variable.

Table 2: Rules Table

SOC, e	PP	P	Z	N	NN
PP	N	Z	P	PP	PP
P	N	Z	P	PP	PP
Z	NN	NN	NN	NN	NN
N	NN	NN	NN	NN	NN
NN	NN	NN	NN	NN	NN

3. RESULTS

Applying a fuzzy logic controller in a PV-Diesel hybrid energy system is very important to manage the energy flow in the system and choose the most suitable source to supply the load based on sun availability. In this project, the fuzzy logic controller was developed and tested using MATLAB-Simulink and the online simulation results showed the performance of the fuzzy controller in the PV-diesel hybrid energy system. Four scenarios during the day have been tested to show the performance of the fuzzy logic controller.

3.1 Case 1

In this scenario, the noontime, the solar irradiance is at the highest level with 1000 W/m^2 and the battery state of charge (SOC%) is 10%. So, in this case, the P_PV = 10KW and P_LOAD = 5KW, the error will be very positive that is mean the PV solar panel can supply the load and charge the battery.

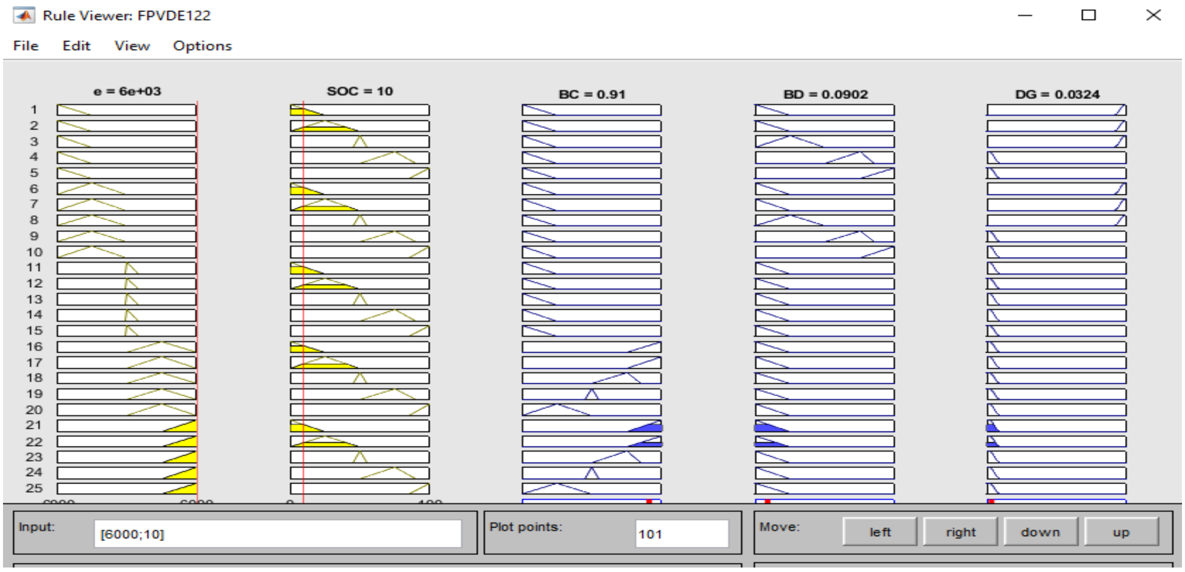

Fig. 11. Result of Rules for Case 1.

As we can see from figure 11, when the error is very positive and the SOC very negative, the output battery charge "BC" is 0.91 means the battery is charging speedily. On the other hand, the diesel generator "DG" is 0.0324 means OFF.

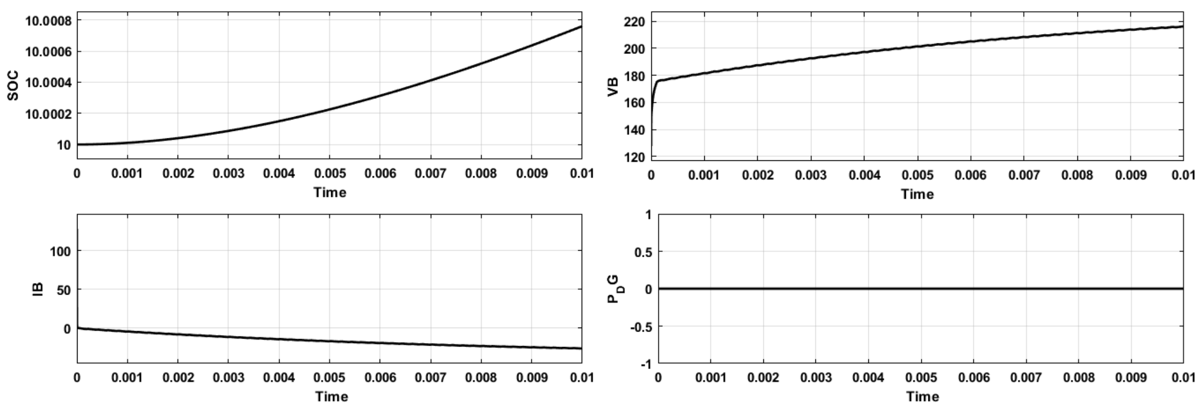

Fig.12. Results of the Implementation of Case 1.

As we can notice from figure 12, the battery is charging at the highest charging mode since the battery current charging is around 25A. The diesel generator is off since there is no power output.

3.2 Case 2

In this scenario in the late morning and early evening, the solar irradiance is at the middle level with 500 W/m^2, and the battery state of charge (SOC%) is 10%. So, in this case, the P_PV = 5KW and P_LOAD = 5KW, the error will be zero that is mean the PV solar panel can only supply the load.

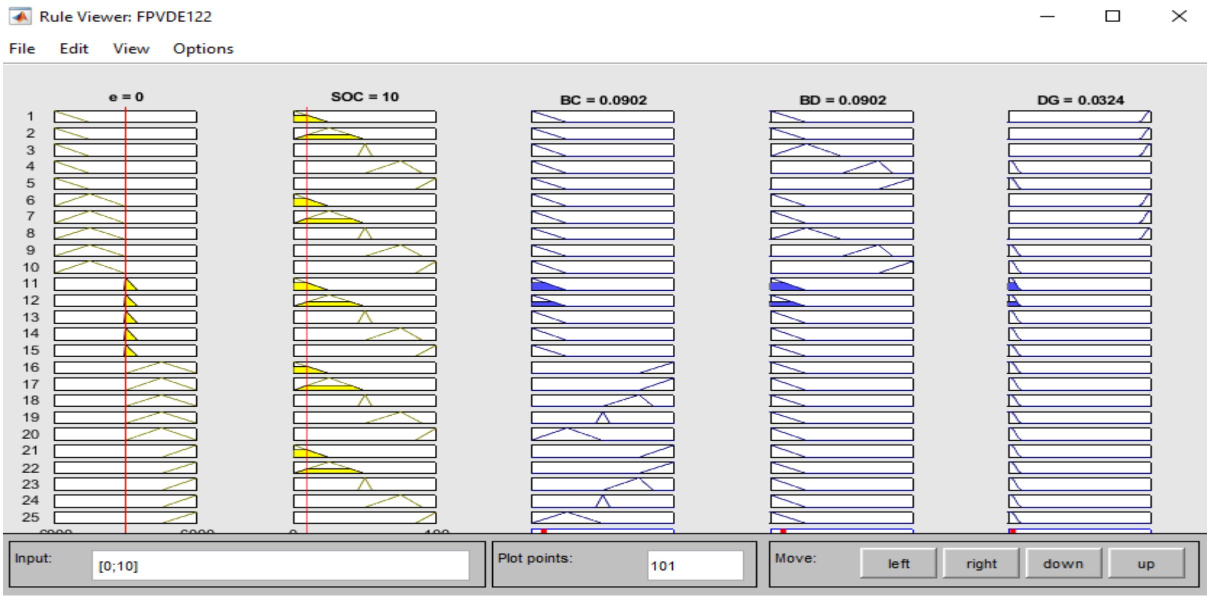

Fig. 13. Result of Rules for Case 2.

As we can see from figure 13, when the error is zero and the SOC is very negative, the output battery charge "BC" is 0.0902 means the battery is almost not charging. The diesel generator "DG" is 0.0324 means OFF.

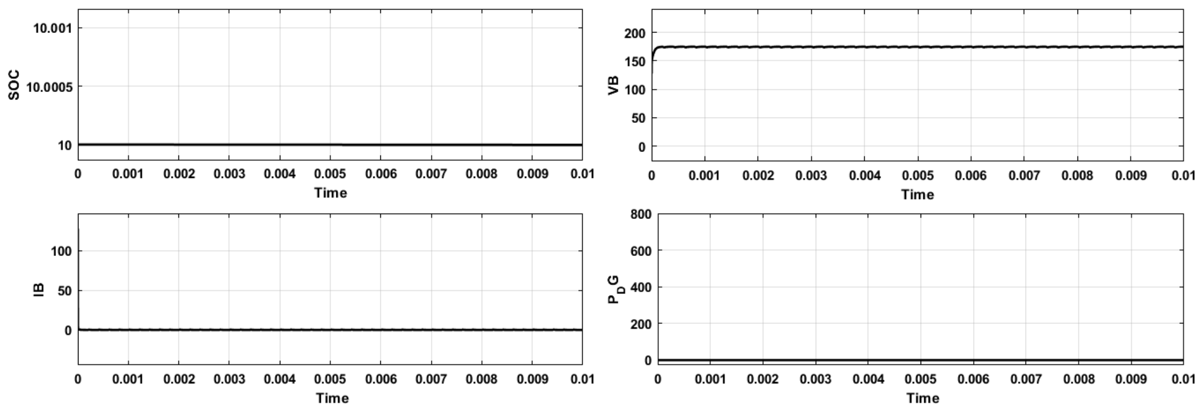

Fig. 14. Results of the Implementation of Case 2.

As we can see from figure 14, the battery is no change at the state of charge of the battery, which means the battery is not charging or discharging. The diesel generator is still off.

3.3 Case 3

In this scenario at night, the solar irradiance is at the lowest level with 0 W/m^2 and the battery state of charge (SOC%) is 95%. In this case, the P_PV = 0 W and P_LOAD = 5KW, the error will be very negative that is mean the PV solar panel can’t supply the load so, the battery will be discharged to supply the load.

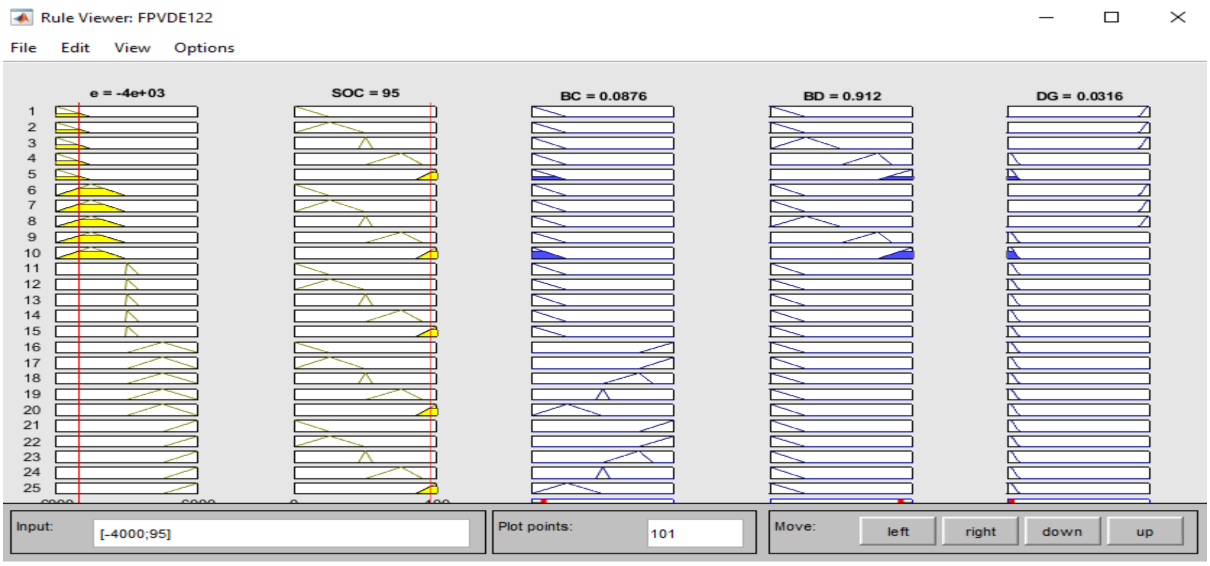

Fig. 15. Result of Rules for Case 3.

As we can see from figure 15, when the error is very negative and the SOC is very positive, the output battery discharge “BD” is 0.912 means the battery is discharging speedily to supply the load.
The diesel generator “DG” is 0.0324 means OFF.

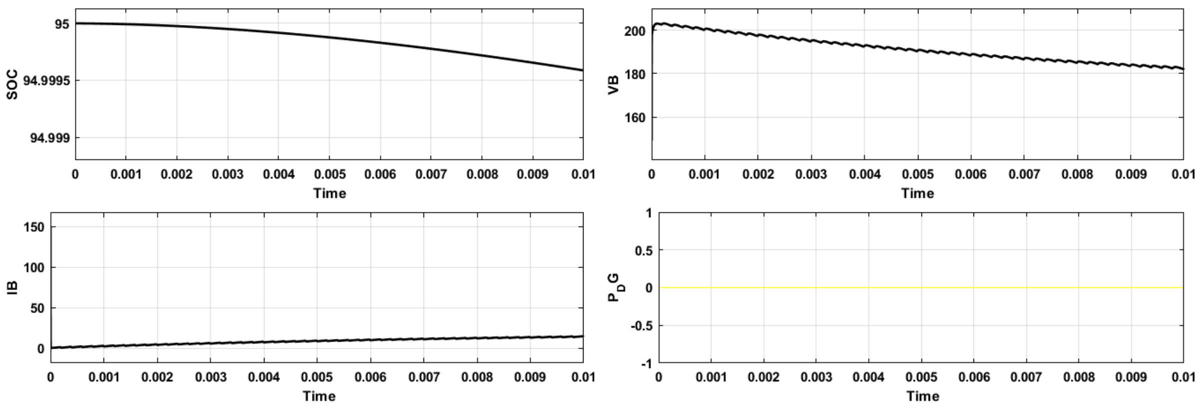

Fig. 16. Results of the Implementation of Case 3.

3.4 Case 4

In this scenario at night, the solar irradiance is at the lowest level with 0 W/m^2 and the battery state of charge (SOC%) is 10%. So, in this case, the P_PV = 0 W and P_LOAD = 5KW, the error will be very negative that means the PV solar panel can’t supply, but the battery can’t, so the backup diesel engine will be ON to supply the load.

Fig. 17. Result of Rules for Case 4.

As we can see from figure 17, when the error is very negative and the SOC very negative, the output battery charge and discharge "BC&BD" are 0.0902 means the battery is almost not changed. The diesel generator "DG" is 0.969 means ON to supply the load.

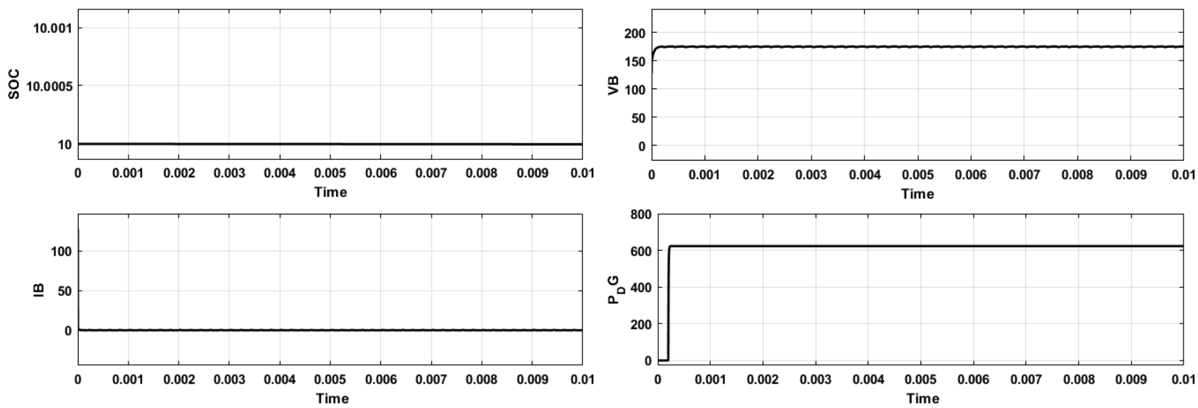

Fig. 18. Results of the Implementation of Case 4.

As we can see from figure 18, the state of the battery charge is stable. The diesel generator is working.

4. CONCLUSION

In conclusion, this paper has studied the PV-diesel hybrid energy system as a standalone energy system to solve the energy problems in areas far from electricity nets. The PV-diesel hybrid energy system is the best solution for these areas but still needs an efficient control method to control the energy flow inside the system and increase overall system efficiency. In this research, the fuzzy logic controller was proposed to control the energy flow in the PV-diesel hybrid energy system. Fuzzy logic controllers have taken place in high-performance power monitoring and control. One of the advantages of the fuzzy logic controller is saved the stress of tedious mathematical modelling of the system to be developed, thus making the controller easier to develop. The fuzzy logic controller is used to control the power flow in the PV-diesel hybrid energy system to incase the depending on the solar energy to supply the load as it is renewable energy. The fuzzy logic controller is also used to control charge and discharge the battery system and control the diesel generator as a backup source when the solar energy is not available, and the battery is empty. The fuzzy logic controller and the PV-diesel hybrid energy system have been designed using MATLAB-Simulink. The simulation of the fuzzy controller performance in the hybrid system showed the accurate controlling of the power flow in the PV-diesel hybrid energy system and the saved power about 2%.

REFERENCES

[1] Garcia, Y., O. Diaz, and R. Guzman. 2016. "Design and Optimization of PV/Diesel Hybrid Power System in a Hotel." International Journal of Energy Production and Management 2(1):52–59.
[2] Ani, Vincent Anayochukwu. 2016. "Design of a Reliable Hybrid (PV/Diesel) Power System with Energy Storage in Batteries for Remote Residential Home." Journal of Energy 2016:1–16.
[3] Kumar, U. S., & Manoharan, P. S. (2014). Economic analysis of hybrid power systems (PV/diesel) in different climatic zones of Tamil Nadu. Energy Conversion and Management, 80, 469-476.
[4] Serban, E., Ordonez, M., Pondiche, C., Feng, K., Anun, M., & Servati, P. (2016, June). Power management control strategy in photovoltaic and energy storage for off-grid power systems. In 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG) (pp. 1-8). IEEE.
[5] Rebhi, Mhamed, Ali Benatiallah, and Mabrouk Sellam. 2019. "Fuzzy Logic Control for Photovoltaic- Diesel Hybrid System Fuzzy Logic Control for Photovoltaic- Diesel Hybrid System." (February).
[6] Chok, E. T., Lim, Y. S., & Chua, K. H. (2019). Novel fuzzy-based control strategy for standalone power systems for minimum cost of electricity in rural areas. Sustainable Energy Technologies and Assessments, 31, 199-211.
[7] Chibuikem, N. E., & Ukachukwu, O. O. (2018). Fuzzy logic-based controller with dedicated safety function for hybrid renewable energy system. Journal of Energy Research and Reviews, 1-13.
[8] Nnadozie, E. C., & Oparaku, O. U. (2018). Adaptation of a novel fuzzy logic controller to a hybrid renewable energy system. Journal of Energy Research and Reviews, 1-10.
[9] Althubaiti, M., Bernard, M., & Musilek, P. (2017, April). Fuzzy logic controller for hybrid renewable energy system with multiple types of storage. In 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE) (pp. 1-6). IEEE.
[10] Roumila, Z., Rekioua, D., & Rekioua, T. (2017). Energy management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery. International Journal of Hydrogen Energy, 42(30), 19525-19535.
[11] Roy Chowdhury, S., & Saha, H. (2010). Maximum power point tracking of partially shaded solar photovoltaic arrays. Solar Energy Materials and Solar Cells, 94(9), 1441–1447.
[12] Tremblay, O., & Dessaint, L. A. (2009). Experimental validation of a battery dynamic model for EV applications. World electric vehicle journal, 3(2), 289-298.