Fuzzy Logic Energy Management Between Stand-Alone PV Systems

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Abstract- Because of its environmental benefits, PV technology is widely used in several applications. It presents an alternative solution for isolated sites that does not dispose a grid connection. However, it has drawbacks, its intermittent character, due to its dependency on meteorological parameters such as the outside temperature and solar irradiation. The energy produced by the PV systems can have an excess or deficit of electricity at the loads, which leads to unused energy or a service discontinuity. This paper presents an intelligent strategy management between photovoltaic station owners. It can be involved as follow between two customers: the photovoltaic installation production of the first customer is higher than its load requirement; however, the neighboring station has a lack of energy to cover its load. In this case, it brings energy from station 1 to cover the insufficiency and vice versa. The batteries intervene neither, if the required energy cannot be provided by the local and the neighbored stations, nor, to store the excess power. The dual standalone photovoltaic system was created using MATLAB Simulink environment. Basing on the fuzzy logic controller, the proposed management exchange algorithm is applied for a two stand-alone PV-battery stations. The Mamdani is one of the widely known fuzzy inference system. It ensures continuous energy delivery to the load while minimizing wasted power. The simulation results demonstrate the previously mentioned controller performances and effectiveness between standalone PV systems.

Keywords PV system, Renewable energy, Fuzzy logic control, Mamdani, Batteries, Energy management.

Nomenclature

PV: Photovoltaic
MPPT: Maximum-power point tracking
MPP: Maximum-power point
dP_1L_1: The difference in power generated by the first station and load 1 [W]
dP_2L_2: The difference in power generated by the second station and load 2 [W]
FLC: Fuzzy logic controller
i_{B1}: Current of the first battery [A]
i_{B1ref}: Reference current of the first battery [A]
i_{B2}: Current of the second battery [A]
i_{B2ref}: Reference current of the second battery [A]
N_s: The number of photovoltaic panels connected in series
N_P: The number of photovoltaic panels connected in parallel
PL_1: The load power 1 [W]
PL_2: The load power 2 [W]
P_{PV_1}: The first station generated power [W]
P_{PV_2}: The second station generated power [W]
P_{B1}: The amount of power provided by the battery to feed the load 1 [W]
P_{B2}: The amount of power provided by the battery to feed the load 2 [W]
P_{S1}: The provided power from the first station to feed load 1 [W]
P_{S2}: The provided power from the second station to feed load 2 [W]
P_{S21}: The provided power from PV2 to feed load 1 [W]
P_{S12}: The provide power from PV1 to feed load 2 [W]
v_{Bus}: DC bus voltage common to both stations [V]
v_{B1}: Voltage of the battery 1 [V]
v_{B1ref}: Reference voltage of the battery 1 [V]
v_{B2}: Voltage of the battery 2 [V]
v_{B2ref}: Reference voltage of the battery 2 [A]
ΔI_{pv}: Photovoltaic current variation [V]
ΔV_{pv}: Photovoltaic voltage variation [V]

ΔT_C: Cell temperature variation [°C]

1. Introduction

Due to fossil fuel depletion, renewable energies have become the effective source of energy. It is clean and does not need maintenance. It has a disadvantage, which is the intermittent character, due to the variability of the meteorological data [1].

There are two main types of the photovoltaic systems: the grid-connected and the standalone. Grid-connected PV systems are intended to meet the annual total demand of the electric energy. Indeed, Off-grid photovoltaic systems are typically intended to meet energy needs at any instant [2].

There are two types of standalone PV systems: with and without storage systems. The first type has as advantage that it can provide the required energy continuously [3]. However, it is so expensive due to the existence of the storage systems. However, the second type is cheaper and does not need maintenance. For energy consumption continuity, the first type is recommended. Instead of dealing with the issue of insufficient energy, installation owners prefer extra-dimensioned installations. In this case, The PV station will produce more electric power energy than the electric load requirement at any instant, especially on sunny days. This extra electric power energy will be wasted if it is not used or stored.

In this paper, we propose to connect neighboring off-grid electric installations in a micro-grid to share the extra-generated electric power. The proposed system was created on the MATLAB/Simulink environment. In this electric micro-grid, the electric installation with extra power energy transferring the excess energy to the other nearby electric installations that do not have enough energy to meet their loads. The excess of energy will be stored in the batteries. Accordingly, there is no loss of energy and the system continues to operate in normal cases. The proposed Simulink model encloses all the standalone PV system components, which are the PV station with the MPPT algorithm, the boost converter, the batteries and the loads.

Thus, an efficient management algorithm is recommended to maintain an equilibrium between the energy produced and the energy requirements of the loads. This algorithm will decide how the installation feeds its load energy requirements: from the local installation, from batteries or from borrowing energy from a nearby installation. Furthermore, Fig. 1 depicts the use of two PV stations in this work. If there is enough energy, every PV station can feed its load. In the event of a power lack, the batteries and both stations step in to help.

The FLC is widely applied for many complex applications. It can be used for electricity network control based on voltage, current and temperature cable parameters [4]. It has showed a good accuracy level in the control of a bidirectional full power charger that allows both charging the electrical vehicle and supplying vehicle energy to grid (V2G) [5]. The FLC resolves the cooking time of the microwave oven automatically based on the food type and quantity [6]. It is also used for hybrid systems including renewable energies with and without storage systems [7-8]. Indeed, a FLC strategy is presented and implemented in a standalone hybrid PV system , in order to decrease the battery operational life and assure the power continuity [9-10].

The Mamdani is a well-known fuzzy logic controller that has been used for energy management between stand-alone PV systems. The fuzzy logic controller requires three steps, which are the fuzzification, inference and the defuzzification [11].

This work is organized as follows; the section 2 illustrated the components of a stand-alone PV system. Section 3 presented the studied FLC steps. Section 4 illustrated the analysis of the different steps of the Mamdani controller. Section 5 presented the simulation results in terms of performances and effectiveness of the proposed fuzzy logic topology. The main conclusion was reached in section 6.

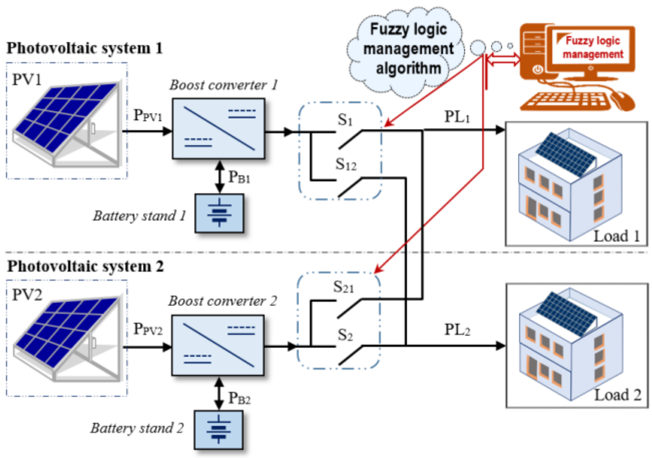

Fig. 1. Dual standalone photovoltaic system.

2. Components of the Studied PV Power System

A stand-alone photovoltaic system is much utilized in several areas where there is not an electrical power grid. Indeed, photovoltaic panels, MPPT control, a boost converter and batteries compose an off-grid photovoltaic system with discrete PID controller [12]. The Whole system was designed using the MATLAB/Simulink environment as addressed in Fig. 2.

2.1. Photovoltaic array

The photovoltaic panels convert the sunlight into electricity. An array can be formed by connecting several PV modules in series and parallels [13]. The photovoltaic array is a non-linear system. It is characterized by its equivalent cell circuit, depicted in Fig. 3, and its (I-V, P-V) curves [14-15].

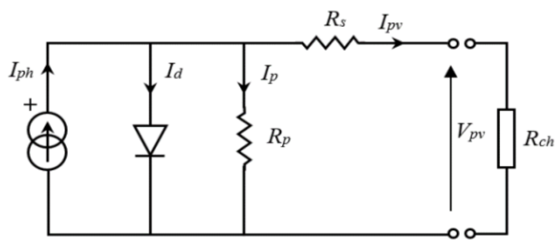

Fig. 3. The solar cell equivalent electric circuit.

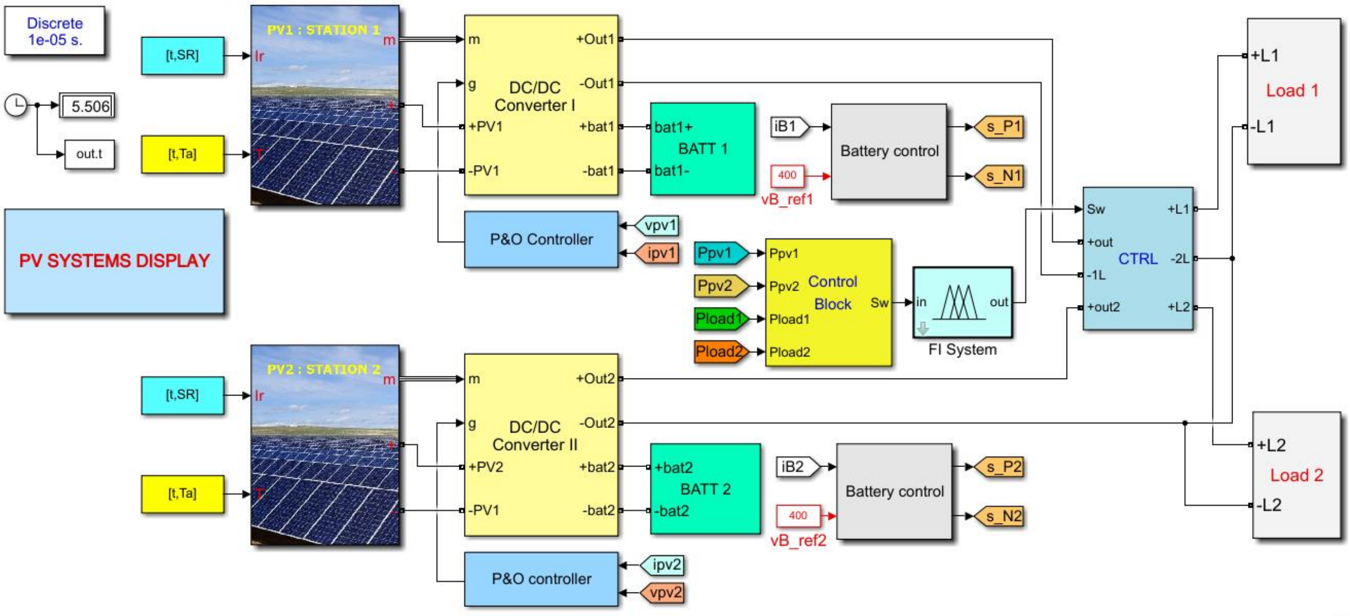

Fig. 2. Dual standalone PV systems fuzzy logic energy management.

Numerous mathematical models have been developed to define the non-linear behavior resulted from semiconductors junctions. The most known model is the 'Four Parameter Model'. The PV arrays efficiency of mono-crystalline and poly-crystalline is presented in [16-17].

The equivalent circuit current I_{pv} can be defined, using the voltage of the PV array V_{pv}, as follow [18]:

$$I_{pv} = I_{sc}\{1 - F_1[exp(F_2 V_{pv}^m) - 1]\} \quad (1)$$

Where:

$$F_1 = 0.01175 \quad (2)$$

$$F_2 = F_4/V_{oc}^m \quad (3)$$

$$F_3 = ln\left[\frac{I_{sc}(1+F_1)-I_{mpp}}{F_1 I_{sc}}\right] \quad (4)$$

$$F_4 = ln\left[\frac{1+F_1}{F_1}\right] \quad (5)$$

$$m = \frac{ln[F_3/F_4]}{ln[V_{mpp}/V_{oc}]} \quad (6)$$

Where V_{mpp}, I_{mpp} are the MPP voltage and current, respectively. The OCV (open circuit voltage) and SCC (short circuit current) are denoted by V_{oc} and I_{sc}, respectively.

In general, the PV system is affected by the climatic conditions (irradiation and temperature). The following equations can be used to process the adaptation of equation (1) with the variation of meteorological data:

$$T_c = T_a + (NOCT - T_{cr})\frac{SR}{SR_r} \quad (7)$$

$$\Delta T_C = T_C - T_{cr} \quad (8)$$

$$\Delta I_{pv} = \alpha \frac{SR}{SR_r}\Delta T_C + \left(\frac{SR}{SR_r} - 1\right) I_{sc} \quad (9)$$

$$\Delta V_{pv} = -\beta\, \Delta T_C - R_s\, \Delta I_{pv} = \frac{ln[F_3/F_4]}{ln[V_{mpp}/V_{oc}]} \quad (10)$$

Where: T_{Cr} and SR_r are the solar cell temperature and the irradiation at the standard climatic conditions (25 ºC, 1000 W/m²). T_c , SR are the solar cell temperature and irradiation, respectively. T_a denotes the cell ambient temperature. α, β are the temperature coefficients for SCC and OCV, respectively. R_s represents the serial resistance.

The new photovoltaic current and voltage values are expressed by equations (11) and (12).

$$V_{pv,new} = V_{pv} + \Delta V_{pv} \quad (11)$$

$$I_{pv,new} = I_{pv} + \Delta I_{pv} \quad (12)$$

The PV station is built by connecting PV cells in series (N_s) and parallel (N_p). The resulting PV power can be computed using equation (13) [19-20].

$$P_{pv} = N_S V_{pv}\, N_P\, I_{pv} \quad (13)$$

The parameters of the solar panel SOLUXTEC DAS MODUL-300 are depicted in Table1.

Table 1. Photovoltaic Panel Characteristics.

SOLUXTEC–DAS MODUL-300	
P_{max} (Maximum power)	300 W
V_{mpp} (PV module voltage at MPP)	32.15 V
I_{mpp} (PV module current at MPP)	9.35 A
V_{oc} (OCV)	39.45 V
I_{sc} (SCC)	9.90 A
α (Temperature coefficient of the SCC)	0.042%/K
β (Temperature coefficient of the OCV)	-0.30%/K
γ (Temperature approximate effect on PV power)	-0.39%/K
R_s (Serial resistance)	0.47 Ω
η_{eff} (Efficiency)	18.50 %
NOCT (Temperature of the nominal operating cell)	45 °C

2.2. MPPT technique description

To track the point of the maximum power, various topologies have been used. Perturb and observe technique (hill climbing technique), incremental conductance technique, fractional SCC technique, fractional OCV technique, neural network technique and fuzzy logic control are the most commonly used techniques [21-28].

The Perturb and observe technique is most common used in several PV application due to its practical facility in implementation. It is based on a transaction between observation and perturbation until the MPP is attenuated. The main process consists in comparing the power and the voltage at the time (t) with the data at the instant (t-1) to approximate the MPP. A small voltage perturbation is involved; consequently, the solar power is affected. If the electric power energy difference is a positive value, voltage perturbation is kept on the same track. However, if the electric power energy difference is a negative value, perturbation should be decreased until the MPP is reached [29-32]. The following flowchart summarizes the Perturb and observe MPPT technique.

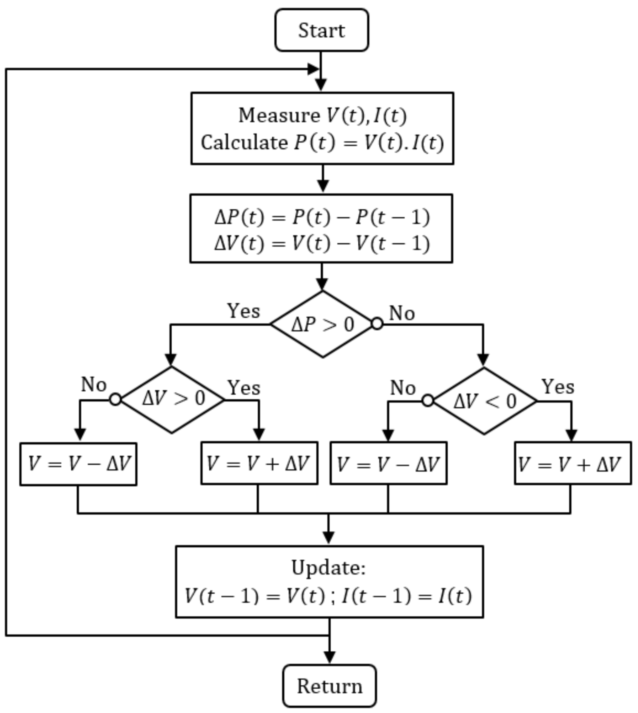

Fig. 4. The Perturb and observe MPPT technique flowchart.

2.3. Description of the boost converter

The used boost converter is a set-up DC-DC voltage converter. It can be controlled through the pulse width modulation (PWM) approach. The input of the PWM bloc is generated through the MPPT techniques [33]. The boost converter, as shown in Fig. 5, is made up of an inductor, a high frequency switch, a diode and a capacitor [34-35].

V_{out} (converter output voltage) can be presented using the input voltage based on equation (14).

$$V_{out} = \frac{V_{in}}{1-D} \tag{14}$$

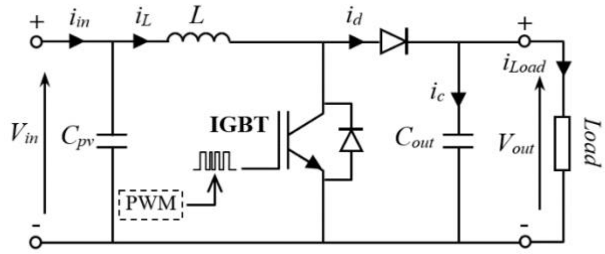

Fig. 5. The circuit model of DC/DC boost converter.

Where: D denotes the duty cycle. The converter voltage can be characterized with two operating modes: passing or blocking. They can be presented with equations (15) and (16) [31].

$$\frac{di_L}{dt} = \frac{1}{L}\left[V_{in} - V_{out}(1-D)\right] \tag{15}$$

$$\frac{dV_{out}}{dt} = \frac{1}{C_{PV}}\left[i_L(1-D) - i_{Load}\right] \tag{16}$$

Where L represents the inductance value (in Henry), i_L denotes the inductor current, C_{PV} presents the capacitor value (in Farad) and i_{Load} is the load current.

2.4. Battery Bank description

For battery modelling, the MATLAB/ Simulink is used. Indeed, Fig. 6 shows the development of a generic lithium-ion battery model basing on the Shepherd's model.

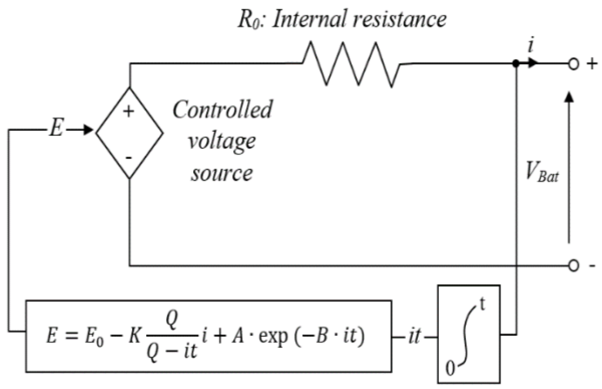

Fig. 6. Lithium-Ion battery model.

The Shepherd model presents the relationship between the battery voltage $V_{Bat}(t)$ and the battery current $i_{Bat}(t)$ for a constant discharge current. This mathematical relationship can be defined by the following equations (17) and (18) [36].

$$V_{Bat}(t) = E_0 - K\frac{Q}{(Q-i\cdot t)}\, i(t) - R_0 i(t) + Ae^{(-B\cdot i\cdot t)} \tag{17}$$

$$OCV(t) = E_0 - \frac{K\,Q}{Q-it}\, i(t) \tag{18}$$

Where:

- *E_0 represents the OCV of a fully charged battery (V).*
- *K represents the polarization resistance coefficient (Ω).*
- *Q denotes the maximum capacity (Ah).*
- *i represents the current of the used battery (A).*
- *$\int idt$ is the actual battery charge (Ah).*
- *R_0 represents the internal resistance (Ω).*
- *V_{Bat} represents the battery voltage (V).*

- *A represents the amplitude of the exponential zone (Ah^{-1}).*
- *B represents the constant of the inverse exponential zonetime (Ah^{-1}).*
- *OCV denotes the open-circuit voltage (V).*

The discharge battery curve enclose three zones, which are [37]:

- The exponential zone, it begins when the battery is full charged $(0, V_{full})$ and finishes at the end of the exponential behavior defined with (Q_{exp}, V_{exp});
- The nominal zone, it begins at the end of the exponential zone and it is characterized with a constant voltage. It is designed with (Q_{nom}, V_{nom}); and
- The full discharged zone: it begins at the end of the nominal zone and finishes when the battery is fully discharged. It is defined with $(Q_{full}, 0)$.

As The Shepherd model does not enclose the first zone, it was improved by adding some other parameters for OCV behavior at the discharge and the charge modes.

If the battery current is a positive value, the battery is discharged. The OCV for the discharge mode can be expressed using equation (19).

$$OCV_{discharge}^{(it,i^*,i)} = E_0 - \frac{K\,Q}{Q-it}\, i^* - \frac{K\,Q}{Q-it}\, it + Ae^{-B\,it} \quad (19)$$

The battery is in the charged mode if the battery current is a negative value. The OCV for the charge mode can be defined using equation (20).

$$OCV_{charge}^{(it,i^*,i)} = E_0 - \frac{K\,Q}{0.1\,Q+it}\, i^* - \frac{K\,Q}{Q-it}\, it + Ae^{-B\,it} \quad (20)$$

To keep the battery from overcharging and discharging, two limits of the state of charge were defined: SOC_{min} = 15 % and SOC_{max} = 85 %. The battery of each station (PV station 1 or 2) is controlled through a bidirectional converter (buck-boost converter) using a discrete PID controller. The PID controller Simulink model is presented in Fig. 7. According to this figure, the upper switch *sP* is used to charge the battery, while the bottom switch *sN* is used to discharge the battery.

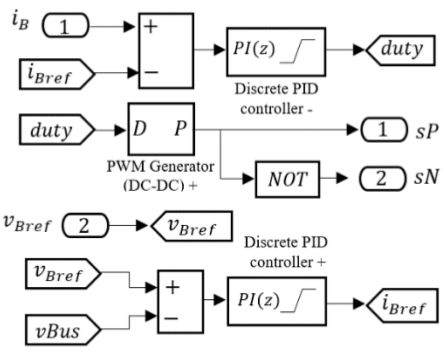

Fig. 7. Discrete PID controller Simulink model.

3. Fuzzy Control Algorithm

Fuzzy logic methodology are generally used for systems with complex relationships between its variables. In addition, it is recommended for systems where the decision-making process is necessary in real-time, which is the case of the energy management [38-39]. FLC is based on the Mamdani type [40-42]. In this work, the application of Mamdani fuzzy is sufficient for the proposed energy management.

Four steps are required for the fuzzy logic system [43-47]:

(i) The fuzzification interface where inputs data are defined in linguistic terms for rule assessment;

(ii) The expert's knowledge base and the studied system strategy are used to determine the rule matrix. The knowledge base composes of database and the rule base;

(iii) The inference involves the designed rules and determines the output data; and

(iv) The output data processor interface converts the fuzzy output data, resulted from the inference block, into crisp value. The Mamdani model utilizes the defuzzification to derive the output data.

All the steps of the FLC are summarized in the block diagram as presented in Fig. 8.

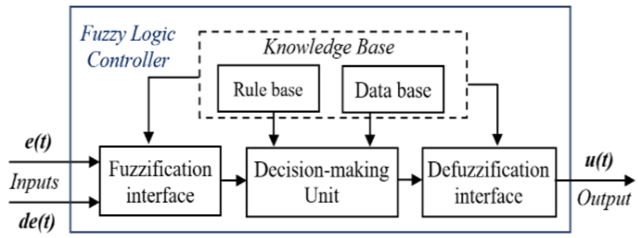

Fig. 8. Mamdani FLC block diagram.

4. Management Planning Using Fuzzy Logic

4.1. Strategy planning

In this work, in order to cover their loads, the designed system should create connection decisions between two standalone PV stations. It is to be underlined that each PV station containing a battery. Some criteria's have been followed to ensure a good management algorithm as presented in Fig. 9.

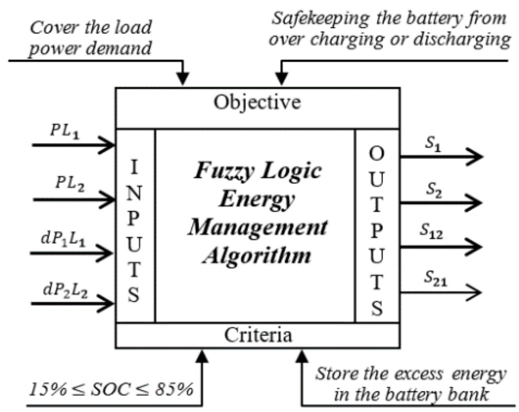

Fig. 9. The proposed approach's synoptic schema.

The proposed energy management focuses on maximizing the time spent in the PV stations connection. The power management algorithm is implemented using a fuzzy logic technique while adhering to the aforementioned criteria.

The fuzzy logic management algorithm consists of 4 inputs (PL_1, PL_2, dP_1L_1, dP_2L_2) and 4 outputs (S_1, S_2, S_{12}, S_{21}).

Where: P_{PV1} is the 1st station power, P_{PV2} is the 2nd station power. Furthermore, dP_1L_1 and dP_2L_2 can be formulated as follows:

$$dP_1L_1 = P_{PV1} - PL_1 \quad (21)$$

$$dP_2L_2 = P_{PV2} - PL_2 \quad (22)$$

The management algorithm consists of three operating modes:

- Mode 1: The required energy of the load is covered through its local station;
- Mode 2: The required energy of the load is covered through the local and the neighbored stations; and
- Mode 3: The required energy of the load is covered through the local station and the batteries.

4.2. *Algorithm planning*

The fuzzy logic-planning algorithm designed for energy management between standalone photovoltaic systems consists of these steps: a) expert knowledge base, b) fuzzification, c) inference diagram, and d) defuzzification [48-49].

4.3. *The expert's knowledge base*

The fuzzy algorithm model for energy management has four inputs and four outputs. In this context, five partitions are required for the Mamdani model.

For the cited inputs (PL_1, PL_2, dP_1L_1, dP_2L_2), the fuzzy partition is represented through five fuzzy sets, which are as follows: *A_i= (VL (very low), L (low), M (medium), H (high) and VH (very high))*. As shown in Fig. 10, these subsets belong to the domain x ∊ [-1 1].

Where i = {1, 2, 3, 4, 5} represents the fuzzy subsets number and μ denotes the degree of the membership function (MF).

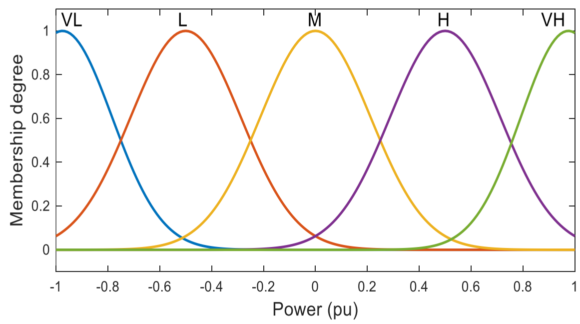

Fig. 10. Fuzzy sets of cited input data.

For the output data (S_1, S_2, S_{12}, S_{21}), the fuzzy logic partition is created by combining two fuzzy sets namely (L (Low) and H (High)). These subsets are included in the domain x ∊ [-1 1] as addressed in Fig. 11.

4.4. *The fuzzification*

The membership functions are used in the fuzzification step to convert the crisp input value to a linguistic variable.

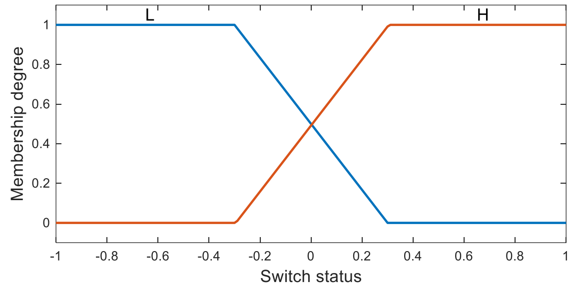

Fig. 11. Fuzzy set of the output data.

The fuzzy partitions leads to the computation of the MF's and utilizing the symmetric Gaussian type [50-51]. The Gaussian MF, depicted in Fig. 12, can be designed by the following expression:

$$\mu(x) = exp\left(-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right) \quad (23)$$

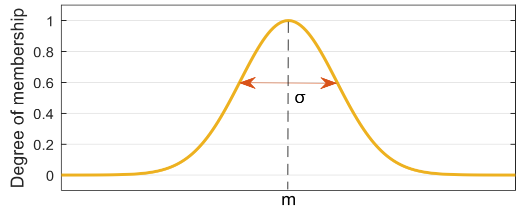

Fig. 12. Type-1 Gaussian membership function.

For the cited input variables (PL_1, PL_2, dP_1L_1, dP_2L_2)

Where x ∊ [-1 1]

$$\mu_{VL}(x) = exp\left(-\frac{1}{2}\left(\frac{x+0.975}{0.1911}\right)^2\right) \quad (24)$$

$$\mu_{L}(x) = exp\left(-\frac{1}{2}\left(\frac{x+0.5}{0.2123}\right)^2\right) \quad (25)$$

$$\mu_{M}(x) = exp\left(-\frac{1}{2}\left(\frac{x}{0.2123}\right)^2\right) \quad (26)$$

$$\mu_{H}(x) = exp\left(-\frac{1}{2}\left(\frac{x-0.5}{0.2123}\right)^2\right) \quad (27)$$

$$\mu_{VH}(x) = exp\left(-\frac{1}{2}\left(\frac{x-0.975}{0.1911}\right)^2\right) \quad (28)$$

For the output variables, which are S_1, S_2, S_{12} *and* S_{21}, respectively, the fuzzy sets are computed using a trapezoidal type membership function symbolically represented by *trapmf* in which the coefficients bi and ci are at the top while the located ai and di are at bottom of trapezoidal. Each trapezoidal function defines the shape of one side of the membership function and it can be presented in equation (29).

$$\mu(x) = max\left[min\left\{\frac{(x-ai)}{(bi-ai)}, 1, \frac{(di-x)}{(di-ci)}, 0\right\}\right] \quad (29)$$

Where ai, bi, ci, and di are equal to -0.3, 0.3, -0.3 and 0.3, respectively.

$$\mu_L(x) = \begin{cases} 0\,; & x > di \\ \frac{di-x}{di-ci}\,; & ci \le x \le di \\ 1\,; & x < ci \end{cases} \quad (30)$$

$$\mu_H(x) = \begin{cases} 0\ ; & x < ai \\ \frac{x-ai}{bi-ai}\ ; & ai \le x \le bi \\ 1\ ; & x > bi \end{cases} \quad (31)$$

4.5. The inference diagram

The inference system can be named also the decision-making unit. It presents the combination between the rules.

After the determination of the membership functions, a rule base was designed based on Mamdani [52].

The general if-then rule format is as follow: *if* $x_1 = A_1$ and x_2 is equal to A_2 *and, …, and* x_n is equal to A_n then y is equal to B. Where x_i ($i \in \{1, 2, …, n\}$) represents the input variables, y denotes the output variable and A_1, A_2, ..., A_n represent the linguistic terms of the designed MF's [53].

4.6. The output data generation

Since the presentation of the rules, the defuzzification gives real value calculation using the centroid technique based on equation (32) [54-57]:

$$Y = \frac{\sum_{r=1}^{R1} A^{ar} C^{ar}}{\sum_{r=1}^{R1} A^{ar}} \quad (32)$$

Where: A^{ar} is the output data fuzzy subset area. The rth rule of the fuzzy inference system is r. C^{ar} represents the area center and $R1$ is the number of rules involved in such circumstance.

a can be expressed using equation (33):

$$a = \text{Min}\mu_v(X_v) \quad (33)$$

Where: $\mu_v(X_v)$ is the MF's value in relation to the designed input variable X_v.

5. Simulation Results

The generated PV power can be determined through the mathematical model defined below which depends essentially on SR and T_a. The meteorological data are presented in Fig. 13.

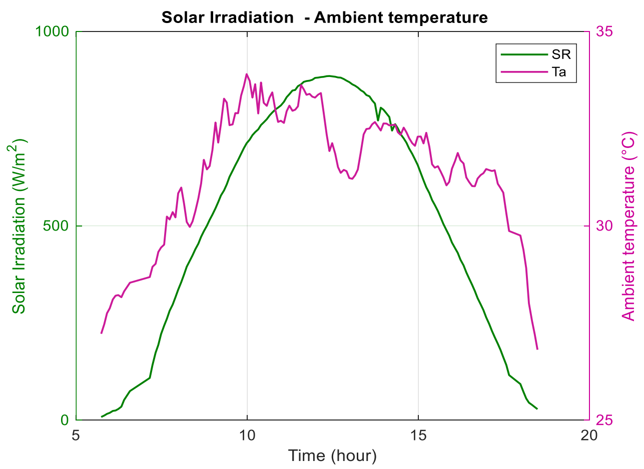

Fig. 13. The meteorological database.

The proposed system consists of two-neighboured standalone photovoltaic stations. The first system is composed of 16 photovoltaic panels SOLUXTEC–DAS MODUL-300, as shown in Fig. 14.

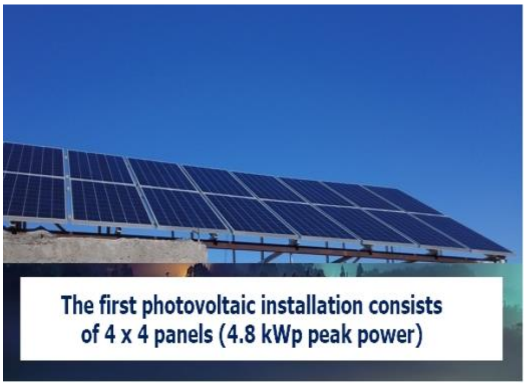

Fig. 14. The first photovoltaic station.

The second one encloses 20 panels SOLUXTEC–DAS MODUL-300, as presented in Fig. 15.

Fig. 15. The second photovoltaic station.

Each PV station has a battery-based storage system. Fuzzy logic control is used in the power management strategy. Indeed, the Mamdani controller was created in order to regulate the flow of power between the standalone PV systems. The fuzzy logic controller must be capable of detecting the generated energy and the power demand and avoiding the power losses and the disconnection of the load. Thus, the controller has been tested in a variety of load demand scenarios.

The controller's overall desired actions can be classified into two scenarios:

- **Scenario 1: The demand for electricity is greater than the produced energy**

Under this condition, the controllers must first check the available energy of the second station. If it is sufficient, the controller tracks a part of the load requirements from the local producer and share the lack from the neighbored station: S1 (S2) and S21 (S12) are switched ON. In case of insufficiency, the undersupply is covered through batteries. The worst scenario appears, when the batteries are also discharged, so the load is disconnected.

- **Scenario 2: The power demand is lower than the produced energy**

Under this condition, the controllers track the total load demand from the original producer and stocks the excess of energy in the batteries depending on their capacity.

The mentioned scenarios can be summarized in the following organogram presented in figure 16.

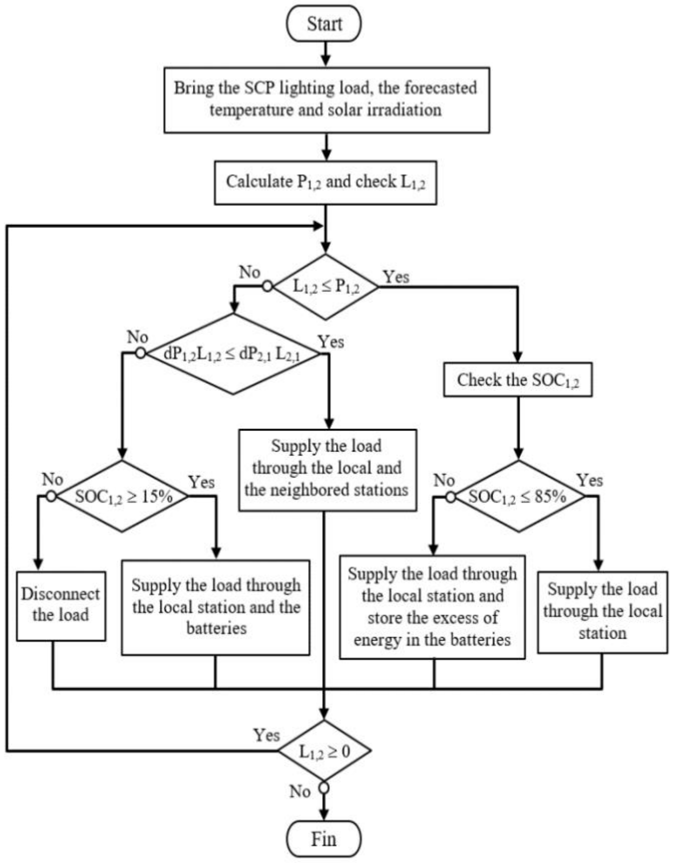

Fig. 16. The proposed management organogram.

The designed Mamdani fuzzy logic controller (MFLC) consists of 4 inputs (PL_1, PL_2, dP_1L_1, dP_2L_2) and 4 outputs (S_1, S_2, S_{12}, S_{21}). The MFLC is depicted in figure 17.

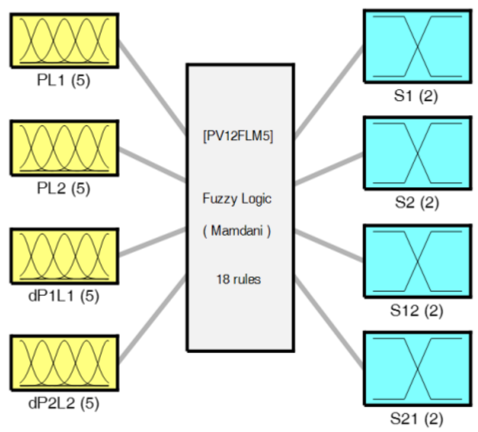

Fig. 17. The proposed Mamdani fuzzy logic controller.

The MFLC monitors the status of the load and the produced power as presented in Fig. 18-(a) and Fig. 19-(a). Besides, it generates control action founded on a set of rules. In the proposed fuzzy logic controllers, 18 rules were involved to ensure the recommended actions.

The application of the proposed MFLC for load 1 and load 2 defines the switchers' state as presented in Fig. 18-(b), Fig. 18-(c), Fig. 19-(b) and Fig. 19-(c). It is clear that the neighbored station intervenes when the photovoltaic station cannot ensure all the load requirements.

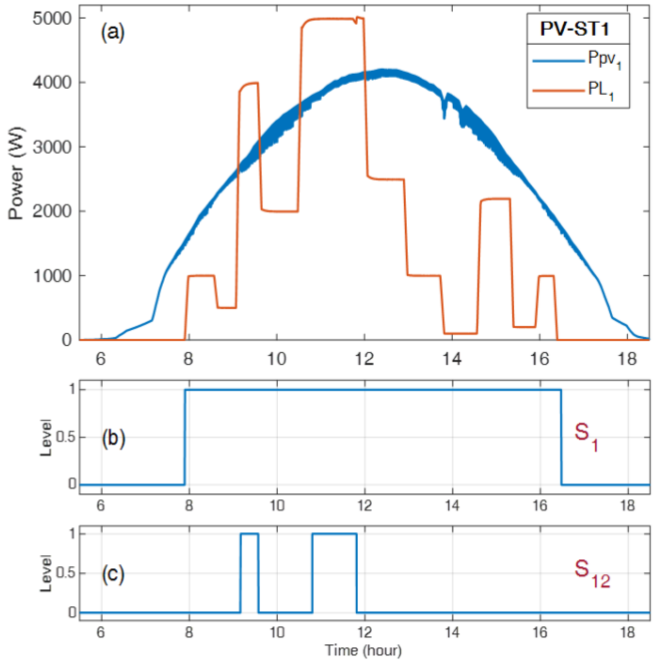

Fig. 18. The photovoltaic power and the load of the first station.

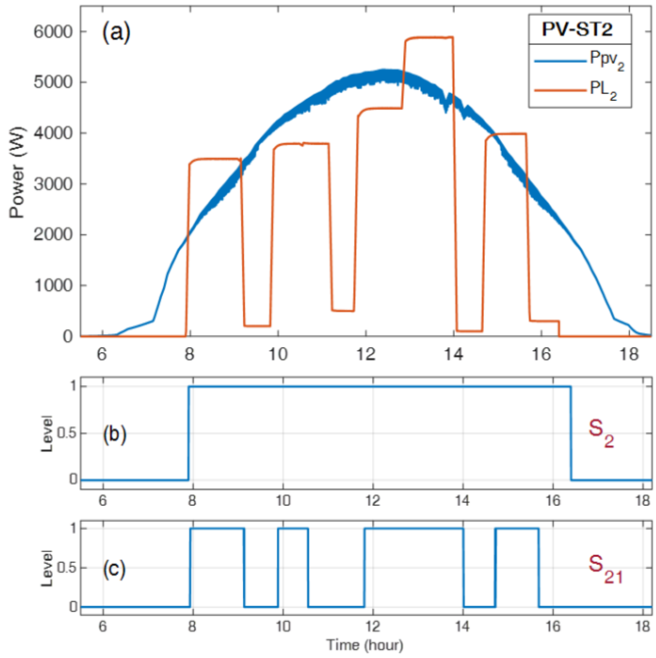

Fig. 19. The photovoltaic power and the load of the second station.

The battery is an important element for standalone systems due to the intermittent character of the photovoltaic energy. The battery can participate on feeding the load power requirements and stocking the excess of energy based on its state of charge. Indeed, Fig. 20 and Fig. 21 present the battery current, the reference current and the state of charges. As shown in these figures, the battery current and the reference current have a high degree of concordance because of the use of the PID controller.

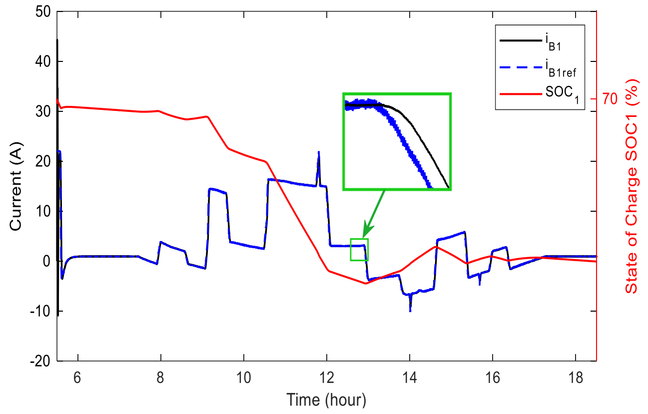

Fig. 20. The first station's battery current and reference current.

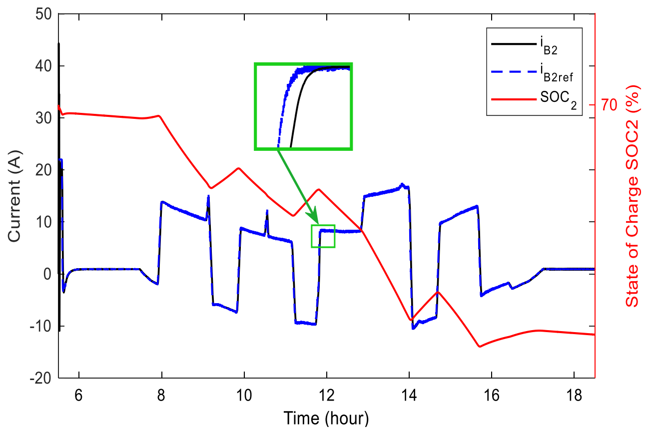

Fig. 21. The second station's battery current and reference current.

The battery voltage and reference voltage of each battery bank for the first and the second installation are displayed in Fig. 22 and Fig. 23.

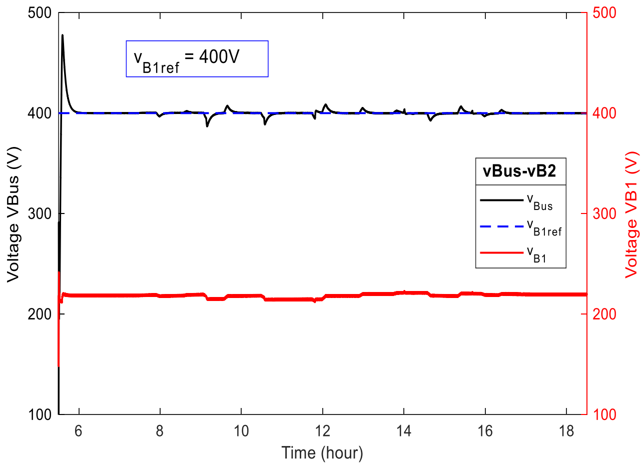

Fig. 22. The battery voltage and reference voltage of the first station.

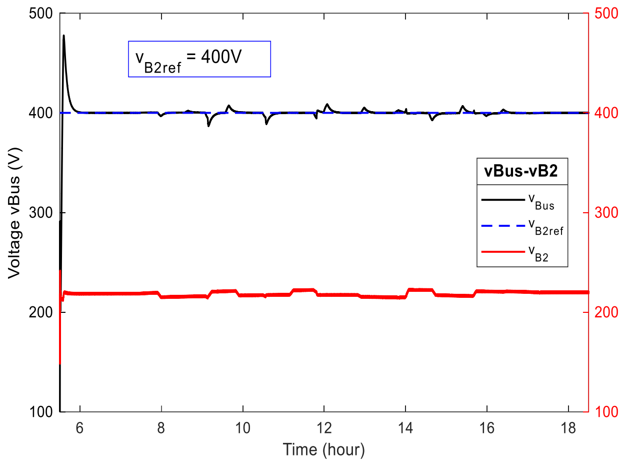

Fig. 23. The battery voltage and reference voltage of the first station.

Based on the findings of the simulation, it is clearly that the suggested MFLC ensures an efficient management of the produced energy. It can keep the load powered continuously without power losses. The neighbored station intervenes when the load is lower than the generated energy.

In order to capture specialist knowledge, the technique of Mamdani is widely used. It defines expertise in a more intuitive, humane manner. It ensures attractive results in control problems, particularly for energy management.

The percentages values of the energy given from PV1 station to load 1 (P_{S1}), the provided energy from PV2 station to load 1 (P_{S21}) and the battery energy percentages are depicted in Fig. 24. A 60 % of the load are taken from the local installation (P_{S1}), 4 % are taken from the neighbored photovoltaic station (P_{S21}) and 36 % from the battery bank (P_{B1}).

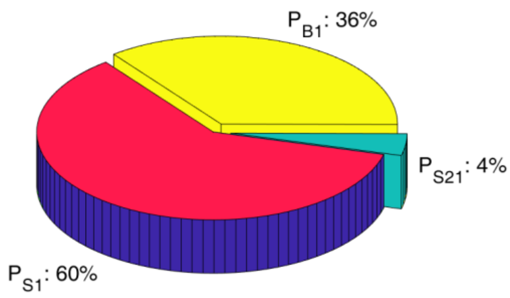

Fig. 24. The exchanged powers to feed load 1.

The percentages values of the energy given from PV2 station to load 2 (P_{S2}), the provided energy from PV1 station to load 2 (P_{S12}) and the battery energy percentages are presented in Fig. 25. A 77 % of the load are kept from the local installation (P_{S2}), 10 % are kept from the neighbored photovoltaic station (P_{S12}) and 13 % from the battery bank (P_{B2}).

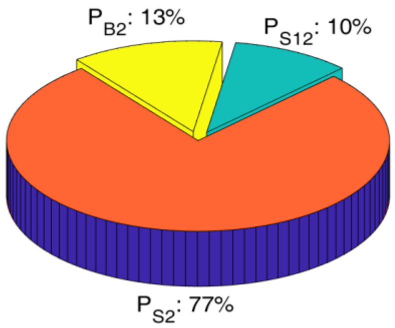

Fig. 25. The exchanged powers to feed load 2.

Referring to these simulation results, one can confirm the suggested energy management method's excellent performance and efficiency in terms of providing power exchange between PV-battery stations and service continuity without power losses.

6. Conclusion

The standalone photovoltaic system is generally used in remote area where the electrical grid is unavailable. If there is not the required energy to feed the load, it disconnects. Thus, in this paper, a new strategy was developed. It consists on sharing energy between standalone photovoltaic systems with storage system contribution. In this paper, two standalone photovoltaic stations was designed using the MATLAB/Simulink. The Simulink model encloses all the PV station elements: the PV panels with the perturb and observe technique, the boost converter, the batteries and the loads.

As the standalone system is powered from renewable source, the power management became more complex. Effective power management algorithm between two standalone photovoltaic systems have been presented. Indeed, to determine how to feed the load requirements, the proposed controller employed the fuzzy logic controller of Mamdani model. The simulation outcomes of the developed fuzzy logic controller demonstrate its efficacy in energy management in terms of ensuring service continuity and avoiding power losses.

According to the simulation results, it can be seen the high performance of the energy exchange between the two PV stations. It should be noted that the station 1 participates in supplying load 2 with a rate of 4 % and the station 2 for its part participates in supplying load 1 with a rate of 10 %. It is to be highlighted that the proposed fuzzy logic controllers can be extended to more than two standalone photovoltaic systems.

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