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# Modeling and Fuzzy Logic Control of a Stand-Alone Photovoltaic System with Battery Storage

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**ABSTRACT** **This work aimed to study and control of a photovoltaic installation with batteries. The system is composed of a photovoltaic generator and a bank of batteries that are used to supply a load. The maximization of power is obtained using perturb and observes (P&O) algorithm and fuzzy logic controller (FLC). It is proposed to add a supervisor to manage the different powers, protect the batteries against overcharge and deep discharge and of course to satisfy the load. MATLAB/Simulink is used in simulations. Obtained results showed that the proposed power management control run the global systems with a good agreement under variable solar irradiance and temperature conditions.**

**Keywords:** Photovoltaic, Battery, Power Management, Fuzzy Logic Controller, Perturb & Observe, Power Maximization

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## 1. INTRODUCTION

In photovoltaic systems, it is important to use efficient maximization strategies to maximize power under all environmental conditions [1-3]. Concerning optimization, many MPPT algorithms exist including direct and indirect methods. Each of them has advantages and disadvantages and depends on the analog digital applications intended, the number of variables, the number of sensors used, the precision and of course the degree of complexity and therefore the cost. Moreover, other factors may come into play in order to choose the right method for the system under study, such as the dependence on photovoltaic generator or search speed of the maximum power point.

Traditional methods such as; perturb & observe, incremental conductance yield good results, and are very useful if the application does not require high requirements such as intelligent methods. Other more sophisticated methods such as; FLC, Fuzzy Logic Sliding Mode Controller (FLSMC) are also interesting because of their performance [4]. In recent years, metaheuristic methods such as; ant colony optimization, swarm optimization particle, and the others have been developed with very high performances.

Concerning the good management of different sources in a system, several studies were carried out on this problem and several solutions have been proposed [5-22]. All are based on the power balance and allow the load to be satisfied under different climatic conditions. Some methods are very simple, and offer flexibility for different sources of a hybrid system [23]. Others are more intelligent, and of course give more accurate and efficient results. While a general overview on the management of hybrid systems is available in the literature, it must be concluded that all the works focused on intelligent energy management and for different applications such as; electrification, water pumping, where the authors demonstrated the effectiveness of the system regardless of variations in climate conditions and load.

In this context, intelligent energy management applied to photovoltaic systems with batteries is presented in current study. Our contribution is an application with power management control (PMC) designed to manage any random variation in climatic conditions and load variations. It consists of a photovoltaic (PV) generator and a battery bank, both of which supply a load.

For maximization, we preferred to choose a classic and simple method (P&O) as well as the FLC.

Simulation results were obtained under MATLAB/Simulink for both configurations to monitor the power flow and verify the effectiveness of the proposed energy management.

## 2. MODELING

The studied system is illustrated in Figure1. It comprises of a PV generator, two DC/DC converters, a battery bank and an inverter supplying an AC load. The power management depends on the three switches state ($K_1$, $K_2$ and $K_3$), where $K_2$ for photovoltaic panels, $K_3$ for batteries and $K_1$ for the compensation.

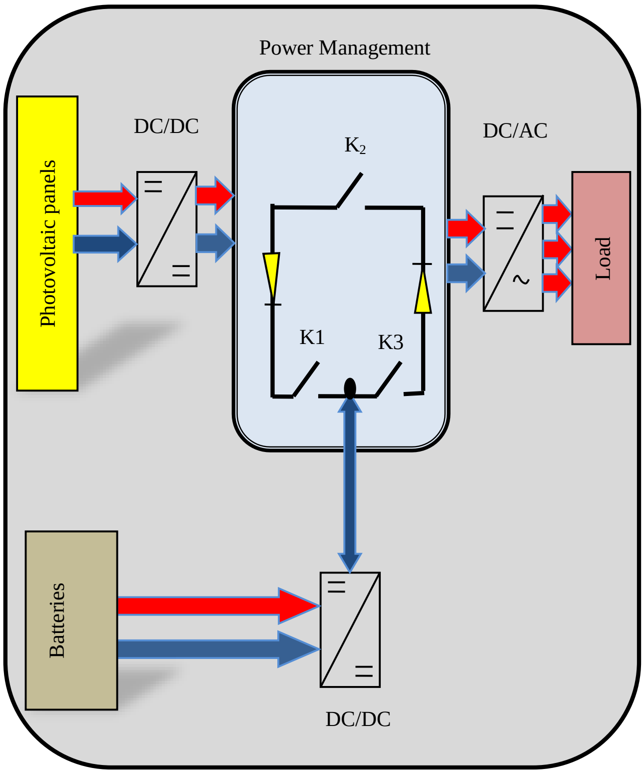



Fig.1. Studied configuration with variable load

### 2.1. Photovoltaic panel model

The model considered in current study is obtained from [6-8] and is given in Figure 2.

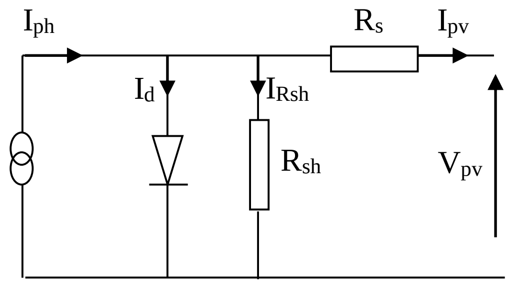



Fig. 2. Equivalent circuit of photovoltaic cell used in the study

Where: $I_{ph}$ is the photo generated current, $I_d$ is the diode-current, $I_{Rsh}$ is the shunt-leakage current, $R_{sh}$ is the shunt resistance, $I_{pv}$ is PV current, $R_s$ is the series resistance, and $G$ is the solar radiation [6, 25].
The electrical equations of photovoltaic module are:

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \quad (1)$$

$$I_{pv} = I_{ph} - I_0 \times \left[ \exp\left( \frac{q \times (V_{pv} + R_s \times I_{pv})}{A \times N_s \times K \times T_j} \right) - 1 \right] - \frac{V_{pv} + R_s \times I_{pv}}{R_{sh}} \quad (2)$$

A test bench, seen in Figure 3, has been constructed to obtain the different electrical characteristics. The utilized PV module parameters are listed in Table 1.

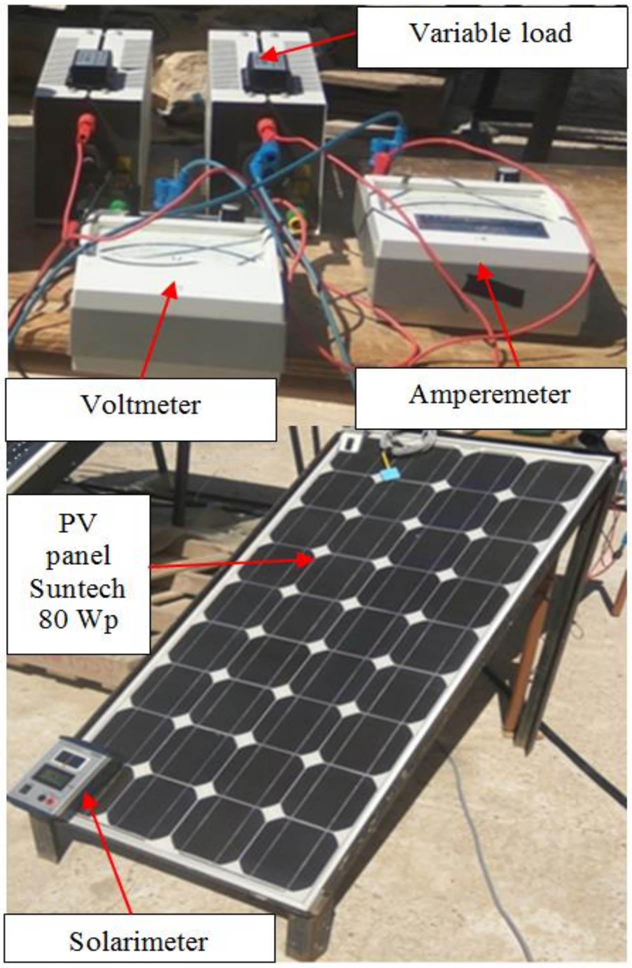



Fig.3. Experimental PV bench

Table 1. Parameters of the SuntechTPO80S-12/BB PV panel

| ***Symbols*** | ***Parameters*** | ***Values*** |
|---|---|---|
| $P_{pv}$ | Peak power | 80 Wp |
| $I_{mpp}$ | Maximum currentat MPP | 4.65 A |
| $V_{mpp}$ | Maximum voltage at MPP | 17.5 V |
| $I_{sc}$ | Short circuit current | 4.95 A |
| $V_{oc}$ | Open circuit voltage | 21.9 V |
| $\alpha_{sc}$ | Temperature coefficient of short-current | 3 mA/°C |
| $B_{oc}$ | Voltage temperature coefficient of short-current | -150 mA/°C |

Figure 4 shows the obtained results of the current-voltage characteristics under employed conditions. As it can be observed from Figure 4 that the nonlinear nature of the PV array is apparent. Thus, the MPPT algorithm was applied to increase the systems performance by keeping it always operating around a maximum power point.

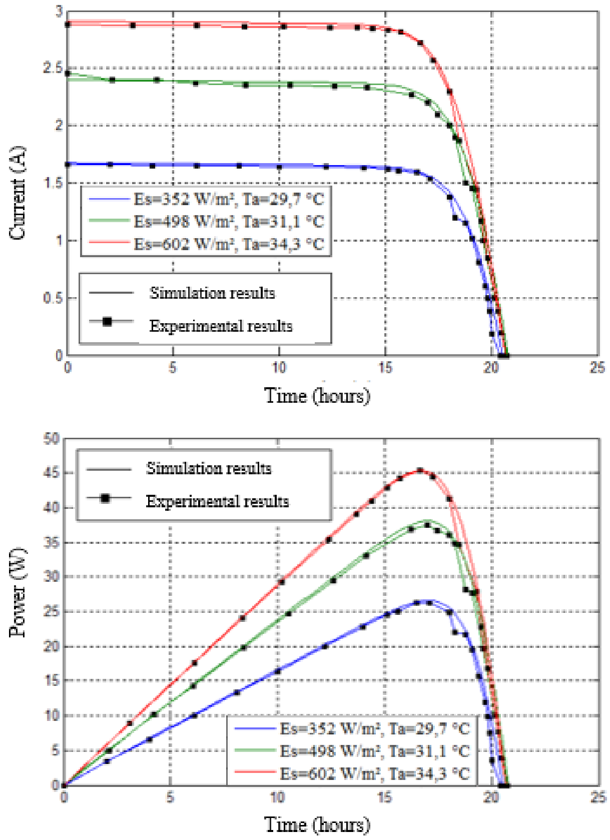



Fig. 4. Obtained I-V, P-V curve simulations and experimental results

*2.2. Battery model*

The battery used in current study with test setup based on lead acid technology is shown in Figure5.

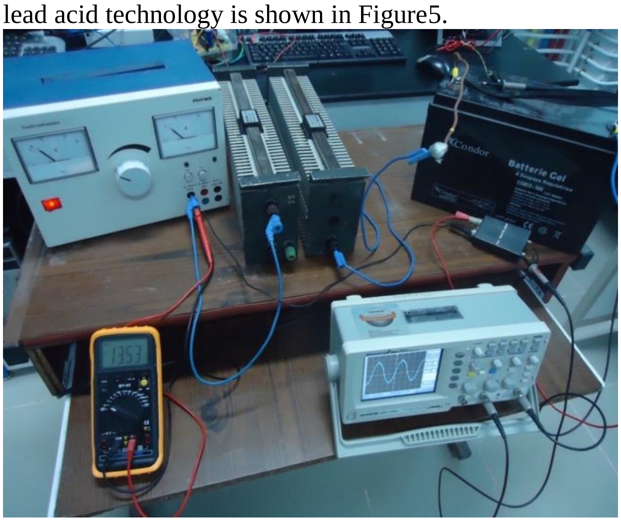


Fig.5.Used lead acid battery and test setup

The mathematical model of the battery is as follow [9-10].

$$V_{batt} = E_b \pm R_b \cdot I_{batt} \tag{3}$$

where $E_b$: voltage source and $R_b$: internal resistance. The battery capacity $C_{batt}$ can be written as [1]:

$$C_{batt} = C_{10} \times \frac{1.76 \times (1 + 0.005 \times \Delta T)}{1 + 0.67 \times \left(\frac{I_{batt}}{I_{10}}\right)} R_b \cdot I_{batt} \tag{4}$$

where $\Delta T$ is the accumulator's heat and $C_{10}$ is the rated capacity at $I_{10}$ current.

The battery state of charge is represented with Equations 5 and 6.

$$SOC(\%) = 100.(1 - \frac{Q}{C_{batt}}) \tag{5}$$

$$Q = I_{batt} \times t \tag{6}$$

where $t$ is current discharging time.

The model can be implemented in MATLAB/Simulink as shown in Figure. 6.

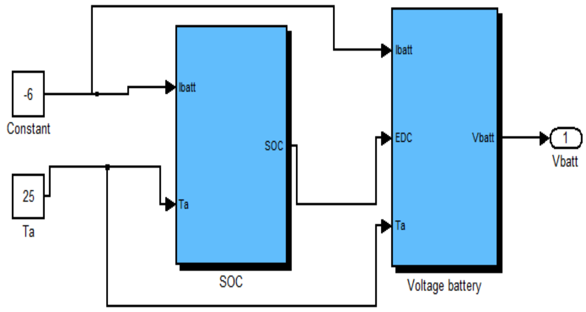



Fig. 6. Battery model used in MATLAB/Simulink

## 3. FUZZY LOGIC CONTROL

The FLC is mainly composed of three steps which are: fuzzification, inference engine and defuzzification. The MPPT fuzzy logic controller is composed of two inputs as shown in Figure 7 [24, 26-29].

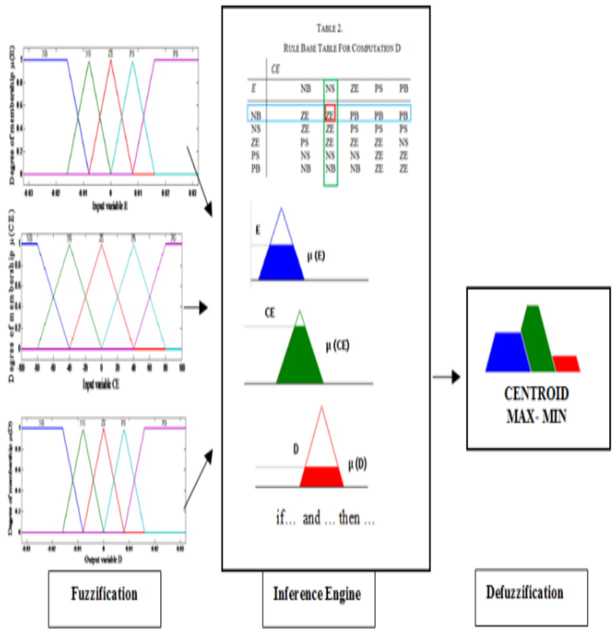



Fig.7. Fuzzy system structure

The error and the change in error are calculated as:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{10}$$

$$CE(k) = E(k) - E(k-1) \tag{11}$$

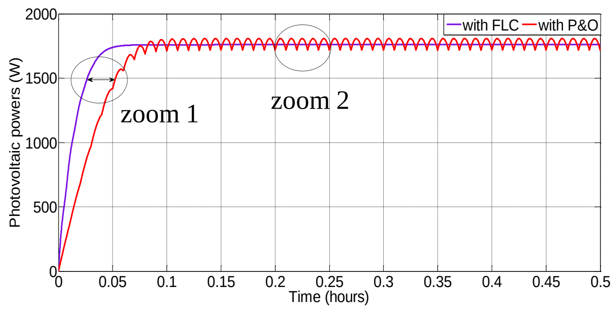
The inference matrix for the adaptation mechanism is given in Table 2.

Table 2. Inference matrix

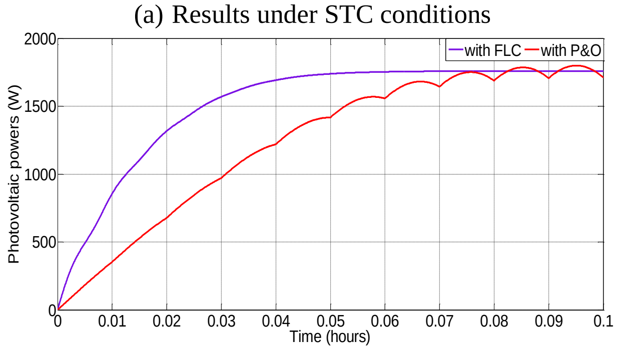
| E \ CE | NB | NS | ZE | PS | PG |
|---|---|---|---|---|---|
| NB | ZE | ZE | PB | PB | PB |
| NS | ZE | ZE | PS | PS | PS |
| ZE | PS | ZE | ZE | ZE | NS |
| PS | NS | NS | NS | ZE | ZE |
| PB | NB | NB | NB | ZE | ZE |

The fuzzification process makes possible to introduce fuzzy sets relative to the desired values to a degree of membership. According to the Figure 8, the defined classes are denoted as: *NB*: Negative Big, *NS*: Negative Small, *ZE*: Zero Environment, *PB*: Positive Big, and *PS*: Positive Small. The duty cycle (*D*) is the system's output variable that can be found with the relations of center of area (COD). Defuzzification is the last stage of the FLC [24].

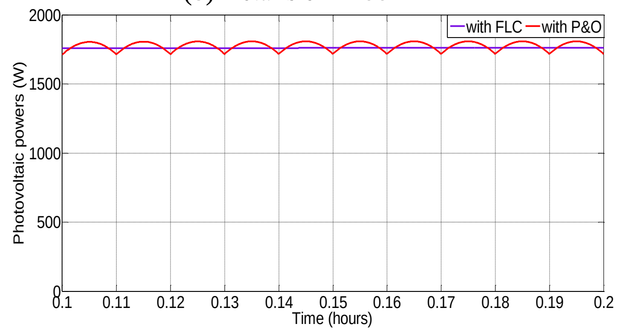
The choice of MPPT technique is important due to different parameters. In this work, two techniques (P&O and FLC) were applied. Simulation results under STC conditions are represented in Figure 8. It appears that the FLC gives a fast and precise response compared to the P&O which contains oscillations in its steady state.




(a) Results under STC conditions




(b) Details of "zoom 1"




(c) Details of "zoom 2"

Fig. 8. Photovoltaic power waveform

## 4.POWER MANAGEMENT OF THE STUDIED SYSTEM

Power management is a very important step before studying a system. It permits to manage the different sources and of course supplying the load based on the power balance. In this work, the PV power and the state of charge (SOC) of the batteries are the two important factors to control [14-24]. Under different variables climate conditions, different cases can be tested.

**Case 1 (M1):** The power available at the PV generator is sufficient to supply the load and charge the batteries.

**Case 2 (M2):** The power supplied by PV is insufficient, and in this case the compensation of batteries power is necessary to satisfy the power demand.

**Case 3 (M3):** There is no power from the PV generator, so the batteries supply the load.

**Case 4 (M4):** The PV power is sufficient and batteries are completely charging. In this case, the batteries are disconnected to protect them.

**Case 5 (M5):** There is no production from the PV generator and the batteries are discharged. In this case, the load is disconnected.

The management flow chart is presented in Figure 9.

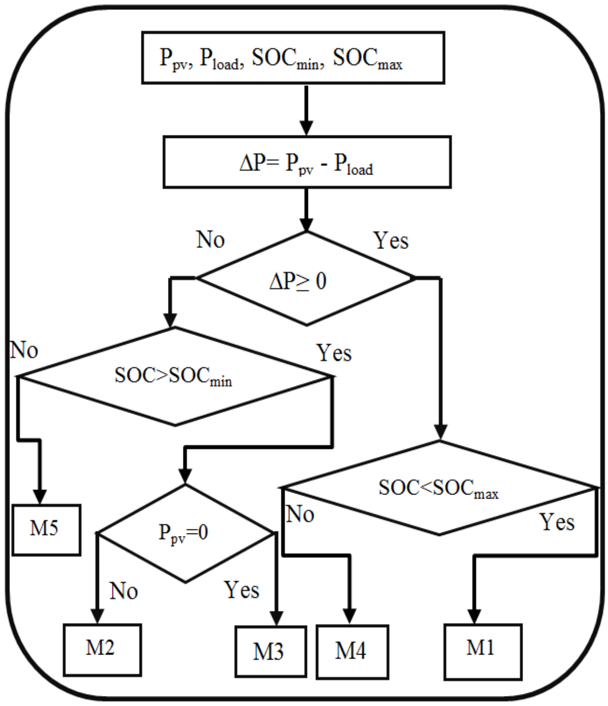


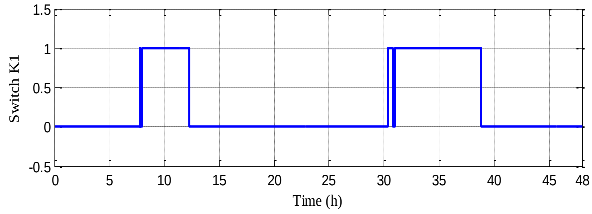

Fig. 9. Power management algorithm

The different cases based on three switches can be summarized in Table 3.

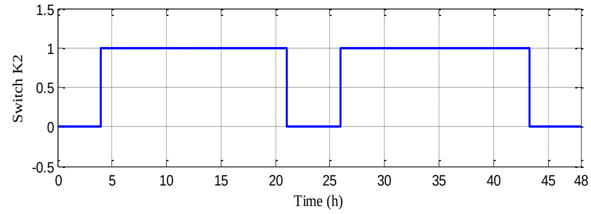
Table 3. Different cases based on three switches

| *Modes* | *Switch States* | | |
|---|---|---|---|
| | $K_1$ | $K_2$ | $K_3$ |
| **M1** | 1 | 1 | 0 |
| **M2** | 0 | 1 | 1 |
| **M3** | 0 | 0 | 1 |
| **M4** | 0 | 1 | 0 |
| **M5** | 0 | 0 | 0 |

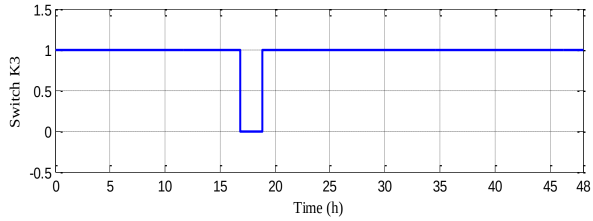
The obtained switching signals, on the other hand, are shown in Figure 10.




a




b




c

Fig.10. Switch signals $K_1$, $K_2$, and $K_3$

A load profile has been chosen as in Figure 11.

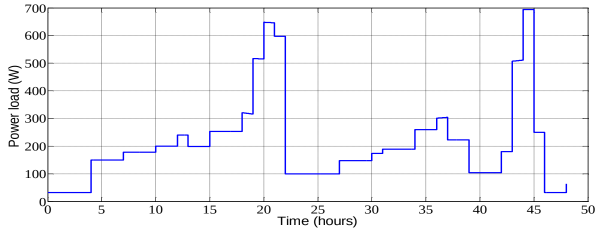
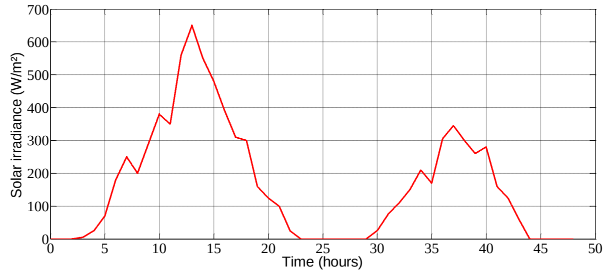
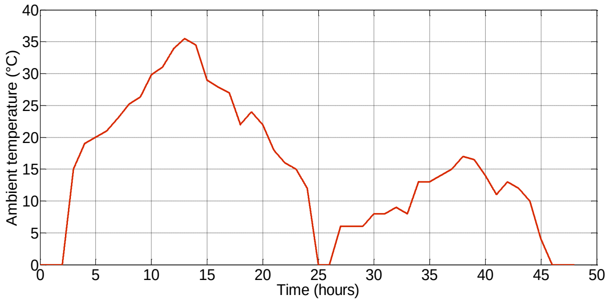



Fig.11. Profile load

The application is made under two different days as shown in Figure 12.




a)




b)

Fig.12. a) Solar irradiation and, b) temperature profiles

The sizing of the studied system has been performed. It uses a PV system of 11 panels of 80 W and 12 lead acid batteries of 12 V-100 Ah. The different powers are as follows as shown Figure 13.

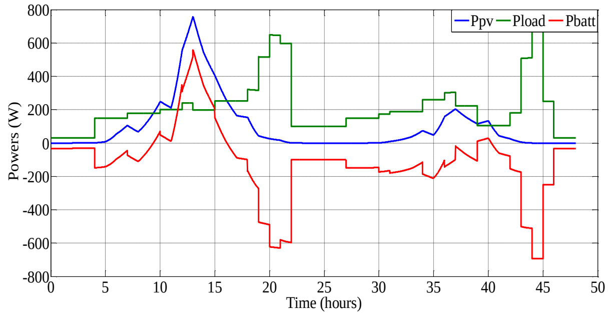



Fig.13. Photovoltaic, battery, and load power

Battery state of charge is represented to show its variations between its minimum and maximum value in Figure 14. It is noticed that the use of the management allows protecting the batteries against overcharge and deep discharge.

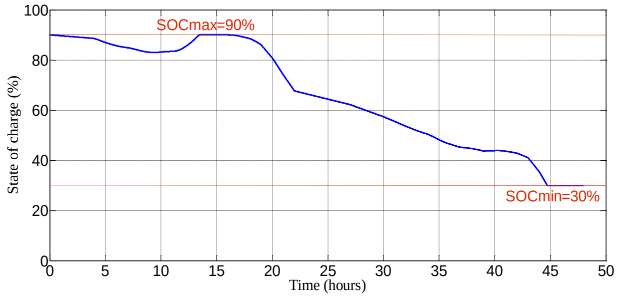



Fig.14. Batteries state of charge

It is noticed that the system operates continuously supplying the load and protects the batteries (between 30 and 90%) which show the effectiveness of the proposed management system under the various climate conditions.

## 6. CONCLUSION

A modeling and fuzzy logic control of a stand-alone photovoltaic system with battery storage has been presented. A power management of PV/battery system has been proposed. An application to supply power for a residential house has been tested both experimentally and numerically. The obtained results under MATLAB/Simulink, show the effectiveness of proposed method. Implementation of proposed method in real time and for applications such as pumping water systems would be beneficial.

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