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Energy management of PVP/Diesel/Battery system

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***Abstract*—The present work proposes a fuzzy switching control of domicile apparatus feeding from a photovoltaic panel (PVP), a diesel generator and a battery. The principle consists in managing connections of apparatus on PVP or diesel generator according to criteria of optimization in view to extract the maximum of energy from the PVP in the day and store the not used PVP energy in the batteries for the night use. The simulation had been done by using Matlab then validated by exploiting a 1kWp PVP and apparatus of different power 50, 100, 200 and 250W. Finally, an energy balance valorised the energizing contribution of our approach.**

***Index Terms*— Photovoltaic panel, Diesel generator, Battery, Apparatus, Fuzzy command.**

I. INTRODUCTION

The energy production is a challenge of great importance for the years to come. The more time passes the more energy needs for the industrial companies increase. During these last years, the development of the countries is systematically related to the energy production. Unfortunately, most of the world production came primarily from the fossil sources. There, it is deduced that this consumption is a serious danger to humanity. One cannot avoid the consequences such as the gas emissions, pollution, the destruction of fauna and the flora. The additional danger is that an excessive consumption of the stock of natural resources reduced the reserves of this type of energy in a dangerous way for the future generations.

The photovoltaic energy is considered as an alternative for electric power generation in domestic applications.

In most recent researchers, various control strategies are proposed and used for power split for energy management [1, 4]. Different technique are used for the energy controller in the photovoltaic systems, the most usual controllers are based neural networks, fuzzy logic (FL) [1-3].

There are several approaches for the development of management of the energy in renewable energy system. Most of them emphasized on hybrid photovoltaic panel (PVP)/Wind/Battery systems [5- 7], where wind energy is another source besides a PVP. In these hybrid systems, PVP and wind energy complement each other and the role of the battery is less important than in the PVP/Battery system.

In our previous work [1], the FL controller for the management of energy of PVP system is presented. This system is connected to the grid, and then in we can't use this controller in the area far from grid. Finally, the hybrid mode is the combination of PVP with other energy sources. Published studies proposed either new design of PVP hybrid energy systems [8-10] or PVP hybrid power systems sizing [11].

Research interests are essentially related to the management of renewable energy [1], Nevertheless, the main problem in photovoltaic applications remains the battery cost [2, 12], and the protection and synchronization systems of grid connected PVP essentially when using large scale photovoltaic power station [13]. This problem was solved when we replaced the battery or the grid with diesel generator. With PVP/diesel system we can avoid the problem of battery cost and the synchronization of the grid connected. Moreover we used a fuzzy logic controller for the management of energy in our system.

In this work, a new operating mode is proposed where a diesel generator is considered as a complementary electric source to supply energy to domestic apparatus during the day and store the not used PVP energy in the battery for the night use. The installation incorporates a 1kWp PVP, a diesel generator, four apparatus of powers 50, 100, 200 and 250W and a switching unit. A fuzzy decision making algorithm gives orders to the switching unit so as to connect each device either to the PVP output or to the diesel generator. The decision of the appropriate connection mode is based on criteria that offer maximum exploitation of the energy delivered by the PVP during daylight depending on load demand without disturbing however apparatus' function. The energy management system is implemented using the Matlab software as a programming tool. After implementation, the system has been tested with a measured data base of climatic parameters of the region of Sfax-Tunisia. The results validation is illustrated over four days representing the seasons of the year. Furthermore an energy audit was established and showed that the proposed system is able to bring efficiency during daylight up to 95% of the PVP generated energy.

The various sections of this paper are organized as follows. Section 2 describes the development of the proposed approach. The fuzzy control algorithm of the proposed approach is introduced in Section 3. Section 4 shows the simulation results. Finally, Section 5 provides perspectives and conclusion.

II. DEVELOPMENT OF THE APPROACH

Our approach is to use a PVP without a storage system in an isolated environment i.e. in an isolated area without supplied power. Thus, with an adequate control (switching system) apparatus can be supplied either from the generator (diesel) or directly from the PVP. The decision of the power source, of each apparatus, is based on the principle of to favor the direct feeding from the PVP in order to maximize the power offered by the PVP. Obviously, the PVP may not be in any charge to the network. This approach should at least avoid the problems posed by the user on the network, on the one hand, and enjoy the benefits presented by the autonomous mode on the other hand.

The method is to read continuously the statements of Apparatus (set by the user) on the one hand and the instantaneous power provided by the PVP on the other hand in order to decide the power source of each apparatus (PVP or diesel generator) by the transfer of control data to the switches. Decision making must ensure maximum use of power from the PVP.

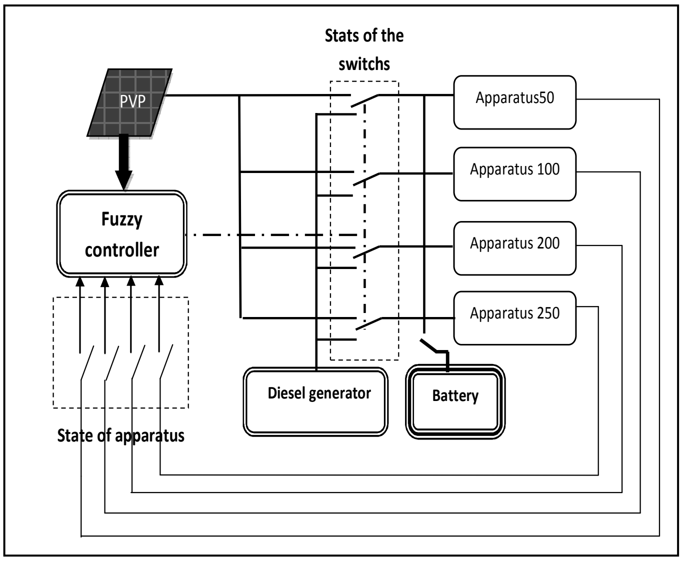

Fig. 1. Shows the block diagram of the proposed approach

The control logic examines the operating states of the apparatus (all or nothing), inquired about the value of power supplied by the PVP (acquisition of voltage and current of the panel), established a power balance (necessary and available), then decided the sound connections for optimal utilization of the panel directly.

The system treats a multivariable system. For this, we opted to the use of fuzzy logic control in our system. The choice may be considered appropriate given that the chosen tool meets the requirements of the considered control.

Our approach is to manage the control of a system which incorporates a PVP 1000WP, a diesel generator and four apparatus with 50, 100, 200 and 250W power (Figure 1). The PVP has to be fitted with a MPPT controller in order to set always the voltage at 12 volts and to maximize the power drawn from the panel. An inverter is used to transform the recovered voltage into an alternating voltage 220V/50Hz. The two power sources are used to feed the apparatus through a fuzzy control. Depending on the states of apparatus and the energy offered by the PVP, fuzzy control assumed through pre-established rules to provide in real-time, the optimal connection of each apparatus to the diesel generator or to the PVP and to maximize the power drawn by the PVP.

III. Ease of Use The fuzzy control algorithm

We propose to apply the steps of programming a fuzzy control system [3] based on what we already presented. This study, will lead us to define the apparatus state, the PVP power 1000WP and the switchs (relays) states.

The general form of a rule must verify the following condition:

A. *Knowledge base by the expert*

1) *Fuzzy partition*

a) *Apparatus states*

The fuzzy partition of the apparatus states is composed of $N_s = 2$ fuzzy subsets A_{ji}=(OFF, ON). These fuzzy subsets cover the fuzzy domain $X = [0,1]$ as shown in Figure 2.a with:

The control logic examines the operating states of the apparatus (all or nothing), inquired about the value of power supplied by the PVP (acquisition of voltage and current of the panel), established a power balance (necessary and available), then decided the sound connections for optimal utilization of the panel directly.

- i= {1,2} : number of fuzzy subset
- j= {1, …, 4} : number of apparatus

These subsets verify $\forall x = ER_j \in X$ (ER_j: the j^{th} apparatus state),

$$\sum_{i=1}^{N_s} \mu_{A_{ji}}(x) = 1 \quad (1)$$

where μ_{Aji} is the membership function.

b) *The PVP (1000Wp)*

The fuzzy partition of the PVP presented in Figure 2.b is composed in $N_s = 13$ fuzzy subsets $B_l = (mf1,...,mf13)$ which cover the field of fuzzy logic Y= [0, 1000] where l is the number of fuzzy subset (l= {1, …, 13}).

These subsets verify: $\forall y = P_p \in Y$ (P_p : PVP power)

$$\sum_{l=1}^{N_s} \mu_{B_l}(y) = 1 \quad (2)$$

where μ_{B_l} is a membership function.

c) *Switch state*

The fuzzy partition of switchs states, presented in Figure 2.c is composed in $N_s = 3$ fuzzy subsets C_{jk}=(A-off,A-PVP,A-diesel) which cover the field of fuzzy logic Z= [0, 2] where k,

(k= {1, 2, 3}), is the number of fuzzy subset and j, (j= {1, 2, 3, 4}), is the switch number.

These subsets verify: $\forall z = ES_j \in Z$ (ES_j : the j^{th} receptor switch state),

$$\sum_{k=1}^{N_s} \mu_{C_{jk}}(z) = 1 \qquad (3)$$

where $\mu_{C_{jk}}$ is a membership function.

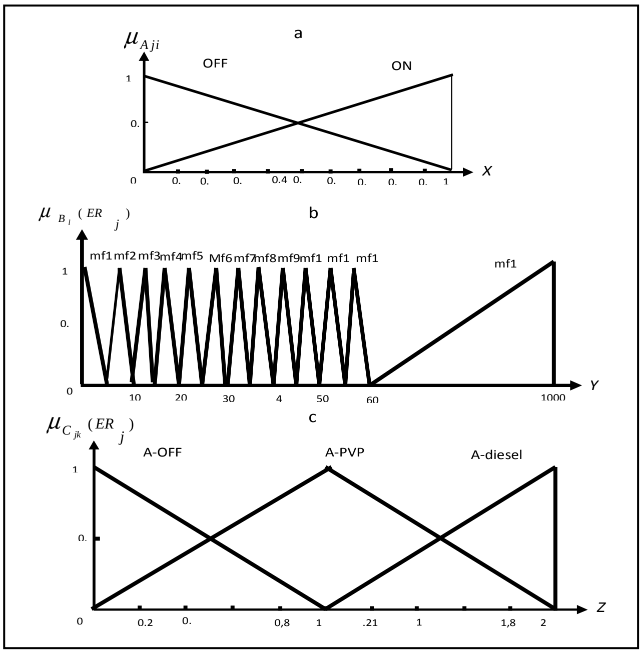

Fig. 2. Membership functions according to: (a) apparatus state, (b) PVP power and (c) relay command

2) Basic rules

The general form of a rule must verify the following condition:

If (ER_1 is A_{1i}) **and** (ER_2 is A_{2i}) **and** (ER_3 is A_{3i}) **and** (ER_4 is A_{4i}) **and** (P_p is B_l)

Then (ES_1 is C_{1k}) **and** (ES_2 is C_{2k}) **and** (ES_3 is C_{3k}) **and** (ES_4 is C_{4k})

Where i, l and k are respectively the fuzzy subsets numbers of the states apparatus, the PVP powers and states switchs.

B. Fuzzification

Fixing fuzzy partitions leading to the determination of membership functions as follows [3]:

- $\mu_{A_{ji}}$ (x) = max {0, 1-$\frac{|x_j - x_{0i}|}{\varepsilon_{x_{0i}}}$}; membership functions of apparatus.
- μ_{B_l} (y) = max {0, 1-$\frac{|y - y_{0l}|}{\varepsilon_{y_{0l}}}$}; membership functions of PVP power.
- $\mu_{C_{jk}}$ (x) = max {0, 1-$\frac{|z_j - z_{0k}|}{\varepsilon_{z_{0k}}}$}; membership functions of switchs state.

With x_{0i}, y_{0l} and z_{0k} are respectively the real values of the variables x_j, y and z_k in their fields. $\varepsilon_{x_{0i}}$, $\varepsilon_{y_{0l}}$ and $\varepsilon_{z_{0k}}$ are respectively the routes x_{0i}, y_{0l} and z_{0k} in the fields x_j, y and z_k.

C. Inference mechanisms

Starting from the basic rules already established and from the formed membership functions during the fuzzification, the w_{jk} weights are determined by Mamdani.

If ER_1, ER_2, ER_3, ER_4 and P_p are the input values (apparatus states, panel power) in their respective fields, so their membership functions take the values $\mu_{A_{1i}}$, $\mu_{A_{2i}}$, $\mu_{A_{3i}}$, $\mu_{A_{4i}}$ and μ_{B_l}.

D. *Defuzzification*

For defuzzification we used the bisector method for fixing the states of each switch [3].

IV. The fuzzy control algorithm

We are interested in this section of the simulation of the control and operation of our system.

A. PVP model

A photovoltaic cell is basically a p-n semiconductor junction diode which converts solar light energy into electricity [3]. Its equivalent circuit is shown by Figure 3.

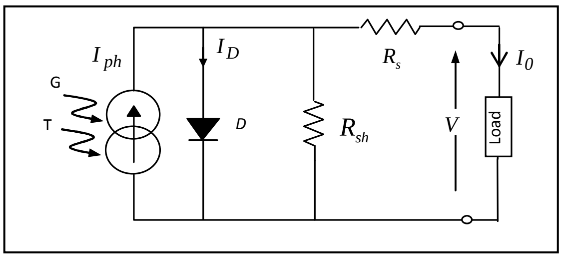

Fig. 3. Equivalent circuit of a photovoltaic cell

The fundamental equation for PVP model is given by equation (1) [28-29].

$$I_o = I_{ph} - I_{rs}\left[\exp\left(\frac{q(V + I_o R_s)}{kTA}\right) - 1\right] - \frac{V + I_o R_s}{R_{sh}} \quad (4)$$

where I_o and V are respectively the PVP output current and voltage, I_{ph} the generated photocurrent (A), R_s and R_{sh} are respectively the serial and the parallel resistances of the PV cell (Ω), q is the electron charge, k is the Boltzmann's constant. A is the p-n junction ideality factor, T is the cell temperature and I_{rs} is the cell reverse saturation current. I_{rs} is related to the temperature T by means of the following relation:

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{kqA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \quad (5)$$

where T_r is the cell reference temperature, I_{rr} is the reverse saturation current at T_r and E_G is the band-gap energy of the semiconductor. Similarly, the photocurrent I_{ph} depends on the solar radiation and the cell temperature as follows.

$$I_{ph} = [I_{sc} + k_i(T - T_r)]\frac{G}{1000} \quad (6)$$

where I_{sc} is the PVP short circuit current at reference temperature and radiation, G is the solar radiation and k_i the temperature coefficient for short-circuit current. The PVP power is then obtained as

$$P = I_o V \quad (7)$$

B. Diesel generator

For the diesel generator we used a HATZ 1B20V motor which parameters illustrated in the Table 1.

TABLE I. DIESEL GENERATOR CHARACTERISTICS

Parameters	***Caracteristiques***
Fuel	Diesel
Alternator	Synchro.
Maximum Power	2,2 kW / 220V 5 A / 12V
Frequency	50 Hz
Starting	Electrique
Noise Level	60 dBA (7 m)
Maximum Consumption	0,7 L/h
Dimensions (cm)	36 x 66 x 40
Weight	90 g

C. Battery model

A battery dynamic model is necessary for the prediction of the SOC. The considered model Figure 4 [3], is made of a volume capacity C_{bulk} to characterize the battery capacity, a capacity to model the surface capacity and the diffusion effects $C_{surface}$, a terminal resistance R_t, a surface resistance R_s, an end resistance R_e.

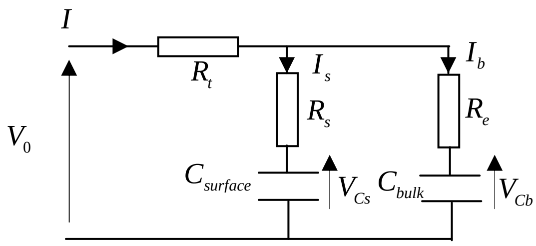

Fig. 4. Battery model diagram

The voltages in the capacities C_{bulk} and $C_{surface}$ are noted V_{Cb} and V_{Cs} respectively. The initial parameters are taken by the experimental measures [3].

The current and the voltage relation are given by Kirchhoff's voltage law application

$$\begin{cases} V_0 = I\,R_t + I_b\,R_e + V_{Cb} \\ V_0 = I\,R_t + I_s\,R_s + V_{Cs} \end{cases} \quad (8)$$

The complete state model described by [22]:

$$\begin{bmatrix} \dot{V}_{Cb} \\ \dot{V}_{Cs} \\ \dot{V}_0 \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_{bulk}(R_e+R_s)} & \frac{1}{C_{bulk}(R_e+R_s)} & 0 \\ \frac{1}{C_{surface}(R_e+R_s)} & -\frac{1}{C_{surface}(R_e+R_s)} & 0 \\ A(3,1) & 0 & A(3,3) \end{bmatrix} \begin{bmatrix} V_{Cb} \\ V_{Cs} \\ V_0 \end{bmatrix} + \quad (9)$$

$$\begin{bmatrix} \frac{R_s}{C_{bulk}(R_e+R_s)} \\ \frac{R_e}{C_{surface}(R_e+R_s)} \\ \frac{R_e}{C_{surface}(R_e+R_s)^2} - \frac{R_s R_t}{C_{bulk} R_e (R_e+R_s)} + \frac{R_t}{C_{surface}(R_e+R_s)} + \frac{R_e R_s}{C_{surface}(R_e+R_s)^2} \end{bmatrix} I$$

where

$$A(3,1) = -\frac{R_s}{C_{bulk}(R_e+R_s)^2} + \frac{R_e}{C_{surface}(R_e+R_s)^2} - \frac{R_s^2}{C_{bulk} R_e (R_e+R_s)^2} + \frac{R_s}{C_{surface}(R_e+R_s)^2}$$

$$A(3,3) = \frac{R_s}{C_{bulk} R_e (R_e + R_s)} - \frac{1}{C_{surface}(R_e + R_s)}$$

According to [33], there is a linear relation between the state of charge (SOC) of the battery and its open circuit voltage V_{Cb}, this relation is given by:

$$V_{Cb}(t) = a_1 SOC(t) + a_0 \quad (10)$$

Equivalent to:

$$SOC(t) = \frac{V_{Cb}(t) - a_0}{a_1}.100 \quad (11)$$

where a_0 is the battery out-voltage where the *SOC=0%* and a_1 is obtained if we know the a_0 value and V_{Cb} value where the SOC (t) =100%

In the case of one cell of our battery (Lead-Acid) we have [30-32]:

$$a_0 = V_{Cb}(SOC = 0) = 1.9V \quad \Rightarrow \quad a_0 = 1.9V$$
$$V_{Cb}(SOC = 1) = 2.2V$$

So according to (11):

$$1 = \frac{V_{Cb}(SOC = 1) - a_0}{a_1} \quad \Rightarrow \quad a_1 = 0.3$$

$$So \quad SOC(t) = \frac{V_{Cb}(t) - 1.9}{0.3}.100 \quad (11)$$

The battery which we used in our system is formed by six cells.

D. Simulation scheme

Figure 5 and Figure 6 show the simulation schemes of our system for January and August months. This scheme includes the following boxes:

- States apparatus are represented by switches. A switch is open (respectively closed) indicating that the apparatus is OFF relative (respectively ON).
- The photovoltaic panel is symbolized by a block delivering values between 0 and 1000. These values represent the change in power delivered by the PVP in real time.
- Each apparatus is indicated by a controlled switch in order to view if the apparatus is OFF (switch to zero), connecting the corresponding receptor on the photovoltaic panel (switch to 1) or on the diesel generator (switch to 2). Initially all Apparatus are connected to the diesel generator (switch to 2).

The fuzzy controller drives the system composed by the diesel generator, the PVP and the apparatus on the basic rules and criteria which we have imposed in the lineup. The fuzzy controller examines the state of apparatus (ON: 1, or OFF: 0) and read the PVP and decides the type of connection to each apparatus in PVP or in diesel generator or apparatus is OFF, by pressing the corresponding switch. This decision is made taking into account the following criteria:

- Maximize the power of the PVP,
- Respect the priority of apparatus, that is, the highest receptor is the first priority to be supplied from the PVP,
- Accept a power margin for each apparatus up -10% to its nominal power.

When programming the rules, the power range is shared into thirteen parts, each of fifty watts, and has four Apparatus since then the Number of Rules (NR) is given by:

$$NR = 13 * \sum_{k=1}^{4} C_4^k \quad (12)$$

The programming of fuzzy controller is performed line by line. So we take each demand interval and only one applies all possible combinations of Apparatus taking into account the statements of the latter.

The simulation was performed for all months of the year and for several combinations of states of the Apparatus.

However, we chose to present as an example the simulation of November month from sunrise to sunset.

During the simulation, we developed a power audit trail in real time at each time step of 5 minutes curves of the maximum power delivered by the PVP, the used power (consumed), the lost power, the power drawn by the diesel generator during a typical day each month and the state of each switch.

The algorithm is implemented using the Matlab software as a programming tool. After implementation, the system has been tested with a measured data base of climatic parameters of the region of Sfax-Tunisia. All its input/output (T; G; ERj; ESj) have been daily recorded using a time step of 5 min. A power audit has been also established in order to determine the system performance.

The approach assessment is ensured by the establishment of a daily power audit.

Figure 5 and Figure 6 show the fuzzy commands timing of relays during daylight and plot in real time the curves of the PVP related powers (Ppv: maximum available, Pu: consumed, Pl: lost) and of the power load from diesel generator (Pd).

During function, all apparatus were switched on in order to evaluate the contribution of the PVP generation to the whole installation.

By examining the fuzzy decisions, it can be easily deduced that most commutations between diesel generator and PVP output are observed at apparatus of lower power. This is due to the above management constraints which affect the higher priority to apparatus of lower power in order to recuperate the remaining power of the ones of higher power. As well, commutations can be seen at apparatus of high power when PVP generation is available. In this case these commutations are limited to the time around midday. It is found that the consumption curve from the panel follows the variations of the power delivered by the panel which generates a low energy loss (loss = power produced - consumed power). Similarly, in the middle of the day, the measured power of the diesel generator decreases significantly especially for the warmer seasons.

It is noted that the curve of P_u follows the variations of PVP in order to minimize P_l. Similarly, P_d decreases considerably around midday especially during days of sunny seasons. These interpretations confirm the approach contribution in term of energy save and management for the whole installation.

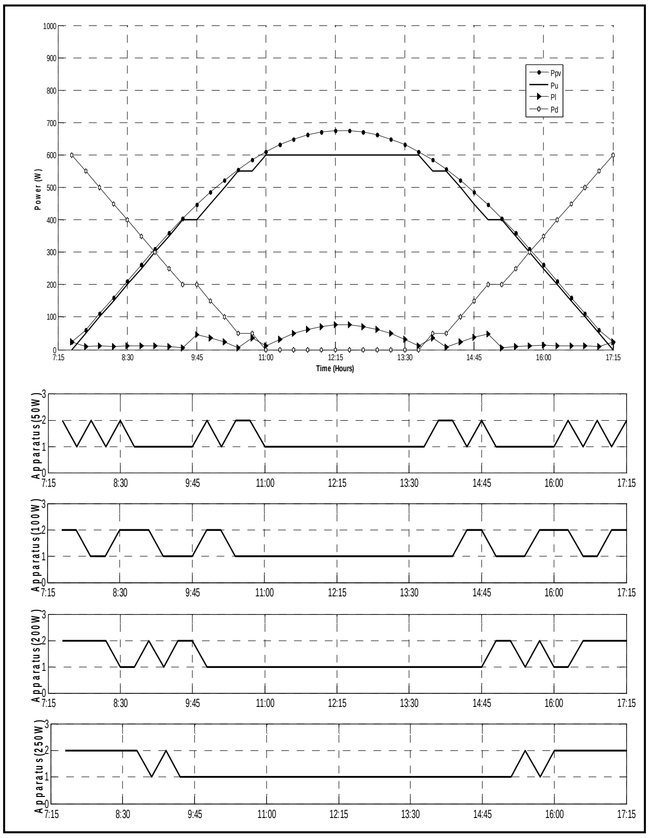

Fig. 5. Different powers and timing of relays commands of January

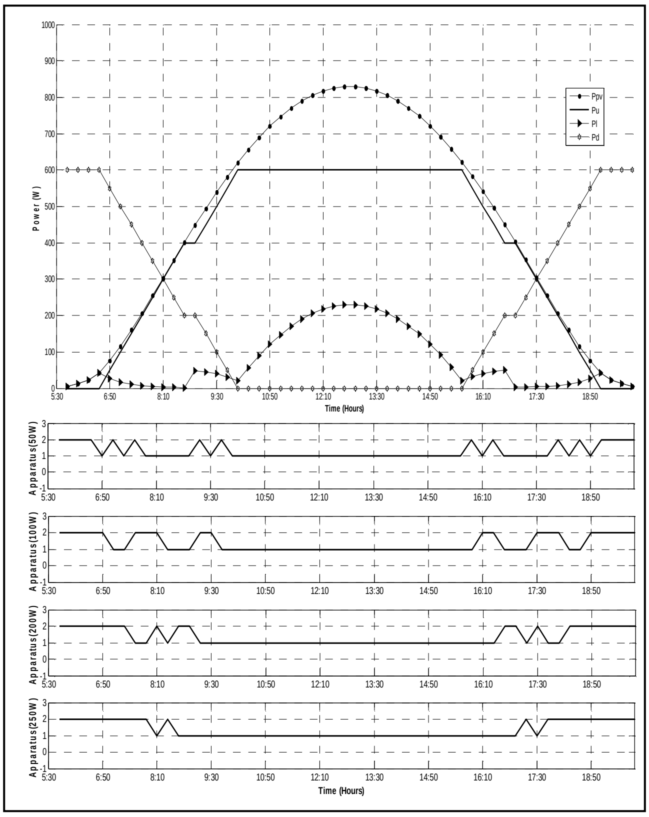

Fig. 6. Different powers and timing of relays commands of August

Figure 7 and Figure 8 show the battery SOC variations in January and August months.

These figures prove the effectiveness of this system, and shows that the system guaranteed a state of load sufficient to make function the system for some hours.

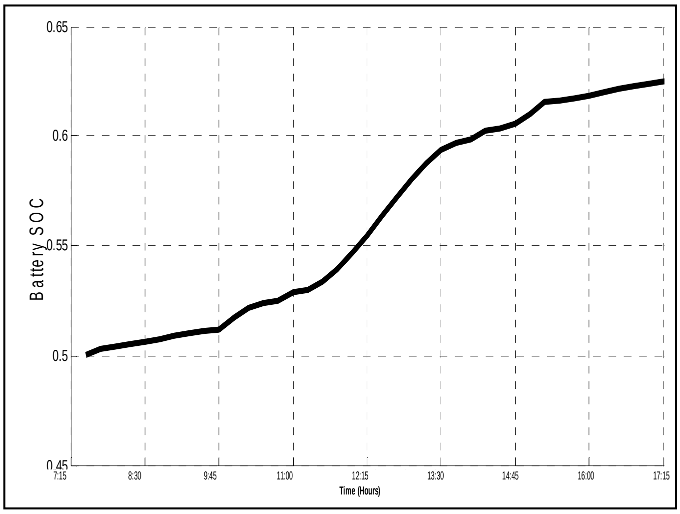

Fig. 7. Battery SOC of January

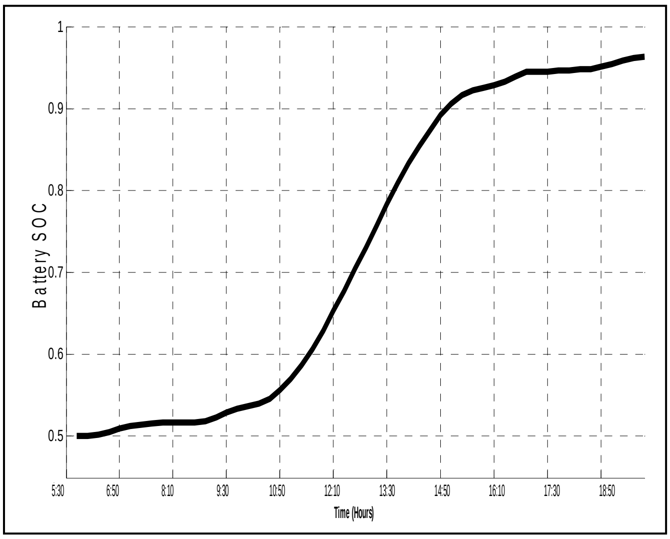

Fig. 8. Battery SOC of August

The second value of our solution was to calculate the efficiency ratio of the order made monthly. This coefficient was defined as follows:

$$\eta = \frac{E_u}{E_{pv}}.100 \qquad (13)$$

Figure 9 shows the evolution of the efficiency ratio by month. This coefficient varies between 83% and 94%, which justifies the energy contribution of our solution.

With this approach one can gain between 83 and 94% of the fuel which was replaced by free photovoltaic energy.

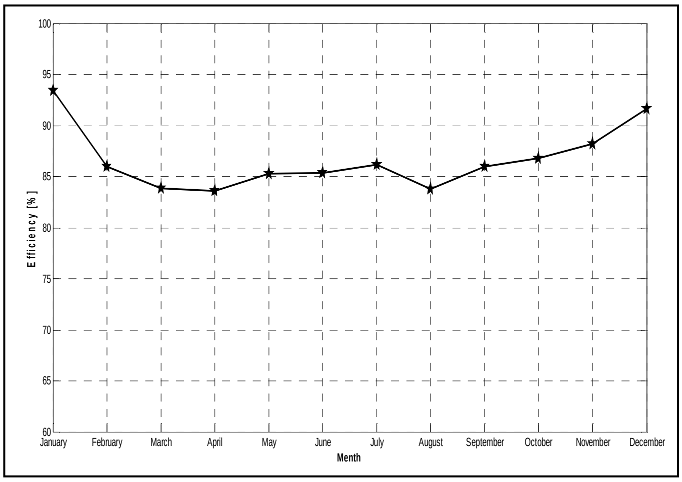

Fig. 9. Effeciency evolution.

V. Conclusion

This paper proposed an energy management strategy based on FL to control power distribution in a hybrid PVP/Diesel/Battery domestic system. Because of the complexity and non-linear aspect of the system, FL was developed to manage the energy flow. Herein the energy produced by a PVP of 1kWp is optimally managed to provide a complementary energy for household apparatus so as to offer a maximum energy saving during the day and store the not used PVP energy in the batteries for the night use. The management approach consists of a fuzzy algorithm which decides whether each domestic apparatus should be connected to PVP output or to diesel generator. Decision is made on the basis of optimum management criteria, PVP generation and apparatus states.

The developed system and its control strategy exhibit excellent performance for the simulation. This system can provided the necessary energy for the loads during the day and guaranteed a battery SOC able to feed the loads during some hours the night. The proposed system can be used for non-interconnected remote areas or isolated cogeneration power applications as a reliable and technically feasible system.

The simulation results show the effectiveness of this approach in terms of energy management through the control of switch of each apparatus and the energy used during daylight reaches more than 90% of the PVP available energy.

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