Energy and Water Management for Drip-Irrigation of Tomatoes in a Semi-Arid District

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Abstract–In this research, an autonomous off-grid system for irrigation in semi-arid areas is presented and discussed. In these areas precise irrigation is essential: as they are characterized by availability of solar radiation, solar irrigation (supported by photovoltaic panels and batteries) is considered here. The correct operation of these installations is a necessity to ensure the correct crop irrigation and to extend the components lifetimes (batteries in particular). These objectives can be ensured by a management system that correctly handles energy and water requirements. In this research, the energy and water management for a photovoltaic water pumping installation used for irrigating tomatoes is developed by integrating fuzzy logic inside the control system. This management system first evaluates the water volume needed by tomatoes during the vegetative cycle considering a detailed model for the tomatoes evapotranspiration and irrigation frequency, following the site and crops characteristics. Based on this and the energy availability a control algorithm decides the switching of the relays which connect the main plant components (panels, batteries and water pumps). The control algorithm fulfills the objectives by considering criteria related to the water volume needed to irrigate the crops, to the safe operation of the batteries and the continuous operating of the pump. The algorithm is tested in two cases study: during normal operation and during faults related with water losses. The obtained results confirm that the irrigation demand is fulfilled, and autonomy is ensured during the vegetative season with a reduced use of the batteries.

Keywords: Water, tomatoes irrigation, photovoltaic energy, fuzzy logic, management, water losses

1. Introduction

Tomato is a drought sensitive plant, since its yield decreases considerably after short periods of water deficiency (Rodriguez et al., 2014). The regularity in watering the plants is important, especially during flowering and fruit formation (Reca et al., 2013; Rinaldi et al., 2013). Indeed, the needed water amount depends essentially on the type of the soil, the site and the weather characteristics, namely the amount of rain, the humidity and the temperature (Hillel., 2012). In semi-arid regions, generally, farmers use furrow or drip irrigation, which is a common method for irrigating tomatoes, thanks to its economic advantages in saving water and increasing the yield production (Hillel., 2012; Reca et al., 2015). Farmers adopt this technique for both greenhouses and outdoor cultivation, for which the frequency and the water volume for tomatoes irrigation depends on the growing stage of the plant, the rainfall and the irrigation installation characteristics (Raes et al., 2000; Farneselli et al., 2015; Liu et al., 2013).

In remote agriculture areas, stand-alone plants are frequently used for electricity generation for systems which provide the water volume needed for tomatoes irrigation. For agriculture applications, diesel engines are generally used for water pumping, especially in isolated and remote areas, since they are reliable, easily available and easy to use (Al-Smairan., 2012). However, experience demonstrated that there are significant limitations associated with using gensets for power generation. For instance, the high operation and maintaining costs are its main disadvantages (d'Ambrosio., 2015; Kumar., 2016) and the environmental pollution (Chen., 2016, Yahyaoui et al., 2015, a). Hence, taking advantage of the decrease in the renewable energy cost, consequently, water pumping installations based on renewable energies are increasingly deployed in remote areas (Campana et al ., 2015).

Photovoltaic Powered Electric Water Pumping Systems (PPEWPS) is the most common installation used for water pumping (Benghanem et al., 2015; Olcan., 2015; Yahyaoui., 2015, b). PPEWPS are promising solutions, especially in small scale installations in regions characterized by good amounts of solar energy over the year (Masoudinejad., 2015): it is recommended that, for installing Solar Photovoltaic (SPV) pumps, the average daily solar radiation in the least sunny month should be greater than 3.5 kW/ m^2 on a horizontal surface (Henrik., 2007). Hence, this type of installations is used in isolated agriculture area, to provide the water volume needed for irrigation, where the photovoltaic energy generated should be optimally used. In this sense, several tools have been used to optimize the use of the PV energy in agricultural applications, namely fuzzy logic (Sami et al., 2014; Paucar et al., 2015).

In fact, this tool (fuzzy logic) showed its efficiency in control issues, namely deciding the irrigation schedule and nutrient injection, depending on the climatic parameters (solar radiation, humidity, etc.) (Reca et al., 2015; Chung et al., 2015), controlling the internal climatic variables in greenhouses (Márquez-Vera et al. 2016) and for the energy management of autonomous water pumping installations, in which Fuzzy Management Algorithms (FMA) have been used to maximize the pumped water, optimize the use of renewable energy and ensure a safe operation of the battery bank (Ouada., 2013; Yahyaoui et al., 2014).

The efficiency of this tool in various applications is given by its ease of use. For instance, in energy management works, fuzzy logic is a good decision tool, since it gives the possibility to describe system behaviors, and decide control decisions using linguistic rules (Casillas et al., 2013; García et al., 2013). In addition, based on the expert knowledge, the fuzzy rules are written using a simple linguistic manner, which describes the adopted approach in taking control decision (Yager et al., 2012; Bezdek et al., 2012).

Hence, this paper presents a continuation of previous published works, in which an energy management algorithm for water pumping system destined to tomatoes irrigating has been studied (Yahyaoui et al., 2015, c; Yahyaoui et al., 2015, d). The present research work focuses on the energy and water management of an autonomous photovoltaic irrigation plant in case of faults related with water losses in the reservoir and discharged battery bank (Fig. 1). Hence, in this research, the correction of the water losses that can occur is studied. In this research work, an autonomous water pumping pump plant composed of photovoltaic panels coupled to a lead-acid battery bank is considered and used to ensure the energy availability between the system components, even while low or intermittent solar radiation, and to supply a centrifuge pump, which pump water into a reservoir. These components are linked via controllable relays, which are used to decide the energy flow between the energy sources. These objectives are performed using an Energy Water Management Algorithm (EWMA) that ensures pumping the sufficient water volume needed for tomatoes irrigation. The EWMA is performed using fuzzy logic, which is used to generate the relays control signals, depending on the measured Photovoltaic Panel Generation, the depth of discharge of the battery bank, the water level in the reservoir and the water flow. In this research, Mamdani-type fuzzy logic is used within the management algorithm, since it is simple to use with little technical training and can be implemented using standard components, namely Programmable Industrial Controllers (Yager et al., 2012; Bezdek et al., 2012).

Using meteorological measurements, namely the solar radiation and the ambient temperature, and the water volume needed for the crops irrigation, the EWMA decides the switching of the relays, which link the installation's elements. Hence, the water volume needed for the crops irrigation can be pumped, the continuous pump supply and the safe battery bank operation can be guaranteed (Fig.1).

The paper is organized as follows: Section 2 details the tomatoes irrigation characteristics. The system components models are described in Section 3. The Energy Water Management algorithm principle is explained in Section 4, in which the management strategy and the algorithm's execution are detailed in depth. Obtained results of the EWMA are presented and discussed in Section 5. Finally, Section 6 gives the conclusion.

Fig. 1. Scheme of the off-grid photovoltaic irrigation plant

Nomenclature

2. Tomatoes irrigation

Generally, drip and furrow irrigation are the most used methods for tomatoes irrigation (Biswas et al., 2015; Lamm., 2015). Although mulching irrigation contributes to crop production by way of influencing soil productivity and weed control (Biswas et al., 2015), drip irrigation, which is characterized by its suitability for small and frequent irrigation applications, is selected here. Indeed, drip irrigation allows the fruit production to be increased and the fruit quality to be enhanced, since the exact water volume needed by the crops is used for irrigation (Ding et al., 2015). Hence, small but frequent water applications enable the plant to grow well, without any effect from water-stress, thanks to the frequent water applications between consecutive irrigation periods (Ding et al., 2015).

Several researchers have focused on various crops yield improvement using drip irrigation, especially tomato. Indeed, it has been reported that drip irrigation allows 30-50% higher tomato yields (Biswas et al., 2015; Chukalla et al., 2015) and its use, either alone or in combination with mulching methods, increases the tomato yield over the normal method of irrigation, which represents 44% savings in irrigation water (Chukalla et al., 2015). Therefore, the irrigation method mainly affects the crops yield production.

Moreover, an efficient irrigation must fulfill the water volume needed by the crops. Therefore, irrigation requires a good knowledge of the meteorological parameters of the target region. Among them, the reference crop evapotranspiration (ET_0) and the rainfall r_m, which can be planed for a given 10-days period (Olsen et al., 2015; Linquist et al., 2015).

In fact, in the literature, several models have been used to describe the crops evapotranspiration. For instance, some researchers used the Penman-Monteith method, which depends essentially on the net radiation at the crop surface, the mean air temperature, the soil heat flux, the saturation and mean actual vapor pressure, the water density and the wind speed (Fleischer., 2015). Other works presented the evapotranspiration as a function of the sunlight duration and the air temperature (Obid et al., 2013). For instance, the Blaney-Criddle method includes the seasonal crop coefficient k_c, in addition to the sunlight duration and the air temperature, which provides better patterns of the needed water volume (Pereira et al., 2015). Hence, in this research study, the Blaney-Criddle method is used to model the evapotranspiration of tomatoes, since it is simple to evaluate (few parameters are needed), its performance has been validated with experiments in the literature (Pereira et al., 2015), and it takes into account of the growing stage of the crops. Indeed, in this model, the reference crop evapotranspiration ET_0 depends on the ratio of the mean daily daytime hours for a given month to the total daytime hours in the year p and the mean monthly air temperature T for the corresponding month, as it is described now (Pereira et al., 2015) (1):

$$ET_0 = K\,p(0.46\,T + 8.13) \qquad (1)$$

where ET_0 is the crops evapotranspiration (mm) and K is the correction factor, expressed by (Pereira et al., 2015):

$$K = 0.03T + 0.24 \qquad (2)$$

To obtain the necessary gross water, it is essential to estimate the irrigation losses. For this, an additional water quantity must be provided for the irrigation to compensate for those losses. Thus, the final water volume V needed to irrigate tomatoes is given by (3) (Pereira et al., 2015; Wichelns et al., 2015):

$$V = (k_c E_{To} - r_m)\left(1 + \frac{1 - l_f(1 - L_R)}{l_f(1 - L_R)}\right) \qquad (3)$$

where:

r_m : the average monthly rain volume (mm),

l_f : leaching efficiency coefficient as a function of the irrigation water applied

L_R : the leaching fraction given by the humidity that remains in the soil, expressed by (Wichelns et al., 2015):

$$L_R = \frac{EC_w}{5EC_e - EC_w} \tag{4}$$

where:

EC_w : the electrical conductivity of the irrigation water (dS. m^{-1}).

EC_e : the crop salt tolerance (dS. m^{-1}).

3. System components modelling

As it has previously been mentioned, the studied plant is composed of PV panels, a battery bank interconnected via controllable relays (Fig.1). The power generated supplies a centrifuge pump, which pump water to a reservoir. The system components models are now explained:

3.1 PV panels model

A one-diode based non-linear model is used for the management algorithm, using an ideality factor to describe the diode's performance (Adamo et al., 2011). The model uses the radiation *G(t)*, the ambient temperature $T_a(t)$ at the panel surface, and the panel parameters to evaluate the photovoltaic power P_{pv}. The model is described by (1)-(5) (Adamo et al., 2011):

$$P_{pv}(t) = n_s n_p V_c(t)\left(I_{ph}(t) - I_r(t)\left(exp\left(\frac{V_c(t) + R_s I_c(t)}{V_{t\_T_a}} \right) - 1 \right) - \frac{V_c(t) + R_s I_c(t)}{R_p} \right) \tag{5}$$

$$I_{ph}(t) = \frac{G(t)}{G_{ref}} I_{sc}(t) \tag{6}$$

$$I_{sc}(t) = I_{sc\_T_{ref}}\left(1 + a\left(T_a(t) - T_{ref}\right)\right) \tag{7}$$

$$I_r(t) = I_{r\_T_{ref}}\left(\frac{T_a(t)}{T_{ref}}\right)^{\frac{3}{n}} \exp\left(\frac{-qV_g}{nK_B}\left(\frac{1}{T_a(t)} - \frac{1}{T_{ref}}\right)\right) \tag{8}$$

$$I_{r\_T_{ref}} = \frac{I_{sc\_T_{ref}}}{\exp\left(\frac{qV_{c\_T_{ref}}}{nK_B T_{ref}}\right) - 1} \tag{9}$$

3.2 Battery model

The photovoltaic panel produces electric energy only when the solar radiation is available. Hence, the use of a battery bank is necessary to complete the remaining power to the load supply on the one hand, and to store the excess photovoltaic energy, on the other.

In this paper, a non-linear model for modeling the lead- acid battery is used (Chaabene., 2009; Yahyaoui et al., 2015, c). In addition to its simplicity, this model has the advantage of using both the battery current and voltage to describe precisely the battery behavior when charging or discharging. Its performance is then evaluated from its depth of discharge *dod* given by:

The stored charge in the battery C_R is given by (Chaabene., 2009):

$$dod_{(k)} = 1 - \frac{C_{R_{(k)}}}{C_p} \quad (10)$$

where:

$$C_{R(k)} = C_{R(k-1)} + \frac{\partial k}{3600} I_{bat_{(k)}}^{\;k_p} \quad (11)$$

where ∂k is the time between instant *k*-1 and *k* and k_p is the Peukert, and C_p is the Peukert capacity, considered constant (A.h).

3.3 Pump

Generally, water pumps supplied by induction machines (IM) are commonly used, thanks to the simplicity in control and its cheap price. Hence, the mechanical power P_{pump} of the water pump is given by (Zulkifli et al., 2015):

$$P_{pump} = \frac{Vg\rho H}{\eta_p \Delta t} \quad (12)$$

where:

P_{pump}: the pump power (W),

V: the pumped water volume (m^3),

g: the gravity acceleration (m/s^2),

ρ : the water density (Kg/ m^3),

H_h: the head height (m),

η_p : the pump efficiency,

Δt : the water pumping duration (h).

4. Energy Water Management Algorithm

To ensure pumping the water volume needed to the crops irrigation and a safe operation for the system, an Energy Water Management Algorithm (EWMA) is proposed here. The EWMA aims to fulfill the water volume needed to irrigate the crops and optimize the use of the electrical energy produced from the photovoltaic system (Fig.1). Since the management is based on a case study, therefore, it is obvious to choose fuzzy logic as a control tool. The Fuzzy Management Algorithm (FMA) is explained now (Yager et al,. 2012; Yahyaoui et al., 2014).

4.1 Management Strategy

A management algorithm is established to meet the crops' water need through the control of the relays, which link the system' components (Fig.2). Hence, the fuzzy algorithm is to decide the interconnection time of the system elements using only the expert knowledge (Yager et al,. 2012).

In fact, the EWMA is based on four steps: the knowledge base of the expert, the fuzzification, the inference diagram and the defuzziyfication (Yager et al,. 2012; Yahyaoui et al., 2014). The interconnection time decision of the system components is made by means of fuzzy rules that fulfill the following objectives:

O1) Provide the required irrigation when needed, by storing water in the reservoir.

O2) Ensure a continuous power supply, especially during weather changes.

O3) Minimize the use of the battery bank.

O4) Protect the batteries against the excessive charge and discharge, by disconnecting them, respectively, from PVs and the pump when they are not used.

As photovoltaic power is used to supply the pump and the batteries, the water pumping is normally performed during the daylight, to minimize the battery use. This facilitates are to keep the depth of discharge of the battery bank (dod) between two fixed values dod_{min} and dod_{max}, for a continuous pump operation (that stops when the tank is full or the battery discharged).

Hence, the management algorithm decides the switching times of the three relays R_b, R_l and R_{lb}, which connect the photovoltaic system elements (Fig. 3). Thus, it is necessary to establish some criteria that define the algorithm efficiency. These criteria are related to:

i. The water volume in the reservoir L.

ii. The photovoltaic energy produced by the panel P_{pv}.

iii. The battery depth of discharge dod.

The management criteria are defined as follows:

a) When the reservoir contains enough water, store the excess of photovoltaic energy in the batteries.

b) Maintain a high water level in the reservoir to guarantee the water volume needed for the crop irrigation.

c) Ensure a depth of discharge dod less than dod_{max} to protect the battery against deep discharge, and greater than dod_{min} to protect it from excessive charge.

d) Ensure a margin of 10% of the photovoltaic power: the pump can be connected only to the panel if the measured photovoltaic power is 10% higher than the required power by the pump, to guarantee a continuous power supply for the pump.

During the day, the instantaneous power P_{pump} verifies that:

$$P_{pump} = P_{pv} + \bar{P}_{Bat} \tag{13}$$

According to the fourth criterion, the panel supplies the load alone if it can provide at least 110 % of the demand. This criterion is to guarantee the stability of the supply. Thus:

$$P_{pv} \geq 1.1 P_{pump} \tag{14}$$

When the water volume in the reservoir is not sufficient for the tomatoes irrigation, water pumping is also performed during the night using the battery bank. Hence, the pumping duration Δt is evaluated based on the water pumping flow and the water volume to be pumped. This is can be described by:

$$\Delta t = t_f - t_{on} = (L - V_i)/Q \tag{15}$$

where:

t_f : the time of finishing the water pumping (h),

t_{on} : the time of starting the water pumping (h),

L : the water need for the tomatoes irrigation (m^3),

V_i : the initial water volume in the tank (m^3),

Q**:** the water flow of the pump (m^3 / h).

Fig. 2. The structure of the proposed energy management algorithm

4.2 Switching Mode

The proposed energy management algorithm is performed via two steps: The first step consists in the acquisition of the climate-related installation site parameters, which allows the photovoltaic power P_{pv} to be estimated. The second step is to deduce the load connection times and duration to the power sources (Fig. 3).

Hence, following the objectives listed above, six operating modes for the three relays R_b, R_l and R_{lb} have been defined:

1/ At night, in normal conditions, the volume in the tank is full, so all the switches are off (mode 1). This mode is maintained during the irrigation period where the tank volume decreases.

2/ In the early hours of the morning, mode 2 is possible since the battery and the panels provide the pump with electric power to ensure the water pumping. In this case, the relays R_l and R_{lb} are on.

3/ The third mode (mode 3) consists in pumping water and charging the battery with the energy in excess. In this case, the relays R_l and R_b are on.

4/ When the reservoir is full, the photovoltaic energy produced by the panel is used in total to charge the battery. This is possible when the battery is discharged and it corresponds to mode 4.

5/ The relay R_l is switched on during the fifth mode (mode 5), to allow the pump supplying. This is possible when the panel produces the sufficient power to the pump with an excess of 10%.

6/ During mode 6, only the relay R_{lb} is switched on. This mode is possible during the night when the water volume in the reservoir is less than the volume needed to irrigate the crops for the corresponding month.

Fig. 3. Energy and water management strategy

4.3 Fuzzy Management Algorithm

Fuzzy decisions are built upon four steps (Yager et al., 2015; Yahyaoui et al., 2014): the creation of the knowledge base, the fuzzification, the inference diagram, and the defuzzification. These four steps are now presented in detail.

4.3.1 Knowledge Base

The knowledge base is generated on the basis of specifications analysis:

- *Photovoltaic power* P_{pv}

The photovoltaic generated power P_{pv} is periodically measured and then partitioned in three fuzzy sets that cover the interval $X = \left[0, P_{pv\ max}\right]$ at *low*, *medium* and *high* generation levels, respectively:

$$\forall x \in X\,,\ \mu_L(x) + \mu_M(x) + \mu_H(x) = 1 \qquad (16)$$

where $\mu_L(x)$, $\mu_M(x)$ and $\mu_H(x)$ are, respectively, the *low*, *medium* and *high* membership functions at the measured power level x.

- *Battery dod*

It is composed of three fuzzy sets that cover the interval $D = \left[0, dod_{max}\right]$ at *low*, *medium* and *high* production levels, respectively, and verify:

$$\forall d \in D, \mu_{dL}(d) + \mu_{dM}(d) + \mu_{dH}(d) = 1 \tag{17}$$

where $\mu_{dL}(d)$, $\mu_{dM}(d)$ and $\mu_{dH}(d)$ are, respectively, the *low*, *medium* and *high* membership functions of dod d.

- *Stored water v*

The third partition is composed of three fuzzy sets in the interval $V = \left[0, V_{max}\right]$ which verify:

$$\forall v \in V, \mu_{vL}(v) + \mu_{vM}(v) + \mu_{vH}(v) = 1 \tag{18}$$

where $\mu_{vL}(v)$, $\mu_{vM}(v)$ and $\mu_{vH}(v)$ are, respectively, the membership functions of v.

As the definition of low, medium and high depends on the use of the auxiliary sets, the following fuzzy variables are defined:

- ***Month M*:**

This partition is composed of as many fuzzy sets as months, given by the interval $M = (m_1, m_2, ..., m_t)$ and verify:

$$\forall m \in M, \mu_{m_1}(m) + \mu_{m_2}(m) + ... + \mu_{m_t}(m) = 1 \tag{19}$$

where $\mu_{m_i}(m)$ are the membership functions corresponding to the month m.

- ***Water level** L*

This partition is composed of as many fuzzy sets as months, denoted by the interval $L = (l_1, l_2, ..., l_t)$. The interval of the possible water $L = \left[0, L_{max}\right]$ is covered by these sets and verify:

$$\forall l \in L, \mu_{l_1}(l) + \mu_{l_2}(l) + ... + \mu_{l_t}(l) = 1 \tag{20}$$

where $\mu_{l_i}(l)$ is the membership function corresponding to l_i evaluated at l.

- *Power difference ΔP*

This partition is composed of two fuzzy sets $F = (f_1, f_2)$ and verify:

$$\forall f \in F, \mu_{f_1}(f) + \mu_{f_2}(f) = 1 \qquad (21)$$

where $\mu_{f_e}(f)$ is the membership function corresponding to f_e evaluated at f.

- *Relays* R_l, R_b, R_{lb}

To decide the switching of the relays R_l, R_b, R_{lb}, depending on the fuzzy variables *x*, *d* and *v*, two fuzzy sets are planned $O = (on, off)$. They cover the domain $O = [0,1]$ and verify $\forall\, o \in O$:

$$\begin{cases} \mu_{off\,\eta}(o) + \mu_{on\,\eta}(o) = 1 \\ \mu_{off\,\eta_b}(o) + \mu_{on\,\eta_b}(o) = 1 \\ \mu_{off\,\eta_{lb}}(o) + \mu_{on\,\eta_{lb}}(o) = 1 \end{cases} \qquad (22)$$

where the switching controls given to relays are provided by the membership functions corresponding to r_l, r_b, r_{lb} respectively, evaluated at o.

Based on this structure, the fuzzy rules for the relays' switching time are classified according to three intervals of dod:

$dod \in X = \left[0, d_{dL_{max}}\right]$: the panels and/ or the battery bank supply the pump,

$dod \in Y = \left[d_{dL_{min}}, d_{dM_{max}}\right]$: supplying the pump is preferred than charging the battery,

$dod \in Z = \left[d_{dM_{min}}, d_{dL_{max}}\right]$: charging the battery bank is preferred to supplying the pump, when the panel produces insufficient power to the pump.

4.3.2 Fuzzification

- *Photovoltaic power* P_{pv}

The membership functions of $\mu_L(x_{0i}), \mu_M(x_{0i}), \mu_H(x_{0i})$ corresponding to P_{pv} are expressed as follows:

$$\mu_L(x_{0i}) = \begin{cases} 1 & if \quad 0 < x < x_{L_{min}} \\ \dfrac{x_{0i} - x}{\varepsilon_{x_{0i}}} & if \quad x_{L_{min}} < x < x_{L_{max}} \\ 0 & otherwise \end{cases} \qquad (23)$$

$$\mu_M(x_{0i}) = \begin{cases} \dfrac{x - x_{0i}}{\varepsilon_{x_{0i}}} & if \quad x_{M_{min1}} < x < x_{M_{min2}} \\ 1 & if \quad x_{M_{min2}} < x < x_{M_{max1}} \\ \dfrac{x_{0i} - x}{\varepsilon_{x_{0i}}} & if \quad x_{M_{max1}} < x < x_{M_{max2}} \\ 0 & otherwise \end{cases} \qquad (24)$$

$$\mu_H\left(x_{0i}\right)=\begin{cases}1 & if \quad x>x_{H_{max}} \\ \dfrac{x - x_{0i}}{\varepsilon_{x_{0i}}} & if \quad x_{H_{min}}<x<x_{H_{max}} \\ 0 & otherwise\end{cases} \tag{25}$$

- *Battery depth of discharge* dod

The membership functions of $\mu_{dL}\left(d_{0k}\right), \mu_{dM}\left(d_{0k}\right), \mu_{dH}\left(d_{0k}\right)$ corresponding to dod are expressed as follows:

$$\mu_{dL}\left(d_{0k}\right)=\begin{cases}1 & if \quad 0<d<d_{dL_{min}} \\ \dfrac{d_{0k} - d}{\varepsilon_{d_{0k}}} & if \quad d_{dL_{min}}<d<d_{dL_{max}} \\ 0 & otherwise\end{cases} \tag{26}$$

$$\mu_{dM}\left(d_{0k}\right)=\begin{cases}\dfrac{d - d_{0k}}{\varepsilon_{d_{0k}}} & if \quad d_{dM_{min1}}<d<d_{dM_{min2}} \\ 1 & if \quad d_{dM_{min2}}<d<d_{dM_{max1}} \\ \dfrac{d_{0k}-d}{\varepsilon_{d_{0k}}} & if \quad d_{dM_{max1}}<d<d_{dM_{max2}} \\ 0 & otherwise\end{cases} \tag{27}$$

$$\mu_{dH}\left(d_{0k}\right)=\begin{cases}1 & if \quad d>d_{dH_{max}} \\ \dfrac{d - d_{0k}}{\varepsilon_{d_{0k}}} & if \quad d_{dH_{min}}<d<d_{dH_{max}} \\ 0 & otherwise\end{cases} \tag{28}$$

- *Water volume* v

The membership functions of $\mu_{vL}\left(v_{0j}\right), \mu_{vM}\left(v_{0j}\right), \mu_{vH}\left(v_{0j}\right)$ corresponding to the water volume v are expressed as follows:

$$\mu_{vL}\left(v_{0j}\right)=\begin{cases}1 & if \quad 0<v<v_{vL_{min}} \\ \dfrac{v_{0j} - v}{\varepsilon_{v_{0j}}} & if \quad v_{vL_{min}}<v<v_{vL_{max}} \\ 0 & otherwise\end{cases} \tag{29}$$

$$\mu_{vM}\left(v_{0j}\right)=\begin{cases}\dfrac{v - v_{0j}}{\varepsilon_{v_{0j}}} & if \quad v_{vM_{min1}}<v<v_{vM_{min2}} \\ 1 & if \quad v_{vM_{min2}}<v<v_{vM_{max1}} \\ \dfrac{v_{0j}-v}{\varepsilon_{v_{0j}}} & if \quad v_{vM_{max1}}<v<v_{vM_{max2}} \\ 0 & otherwise\end{cases} \tag{30}$$

$$\mu_{vH}\left(v_{0j}\right)=\begin{cases}1 & if \quad v>v_{vH_{max}} \\ \dfrac{v - v_{0j}}{\varepsilon_{v_{0j}}} & if \quad v_{vH_{min}}<v<v_{vH_{max}} \\ 0 & otherwise\end{cases} \tag{31}$$

- *Power difference* ΔP

The membership functions of $\mu_{fL}\left(f_{0e}\right), \mu_{fH}\left(f_{0e}\right)$ corresponding to ΔP are expressed as follows:

$$\mu_{fL}\left(f_{0e}\right)=\begin{cases} 1 & if \quad 0<f<f_{fL_{min}} \\ \dfrac{f_{0e}-f}{\varepsilon_{f_{0e}}} & if \quad f_{fL_{min}}<f<f_{fL_{max}} \\ 0 & otherwise \end{cases} \tag{32}$$

$$\mu_{fH}\left(f_{0e}\right)=\begin{cases} 1 & if \quad f>f_{fH_{max}} \\ \dfrac{f-f_{0e}}{\varepsilon_{f_{0e}}} & if \quad f_{fH_{min}}<f<f_{fH_{max}} \\ 0 & otherwise \end{cases} \tag{33}$$

- *Switching control of the relays* R_b, R_l, R_{lb}

The relay membership functions $\mu_{off\ r_l, r_b, r_{lb}}\left(o_{0z}\right)$ and $\mu_{on\ r_l, r_b, r_{lb}}\left(o_{0z}\right)$ corresponding to the relays R_b, R_l, R_{lb} are expressed as follows:

$$\mu_{off\ r_l, r_b, r_{lb}}\left(o_{0z}\right)=\begin{cases} 1 & if \quad 0<o<o_{off_{min}} \\ \dfrac{o_{0z}-o}{\varepsilon_{o_{0z}}} & if \quad o_{off_{min}}<o<o_{off_{max}} \\ 0 & otherwise \end{cases} \tag{34}$$

$$\mu_{on\ r_l, r_b, r_{lb}}\left(o_{0z}\right)=\begin{cases} 1 & if \quad o>o_{on_{max}} \\ \dfrac{o-o_{0z}}{\varepsilon_{o_{0z}}} & if \quad o_{on_{min}}<o<o_{on_{max}} \\ 0 & otherwise \end{cases} \tag{35}$$

Table 1 Fuzzification of the knowledge base

- *dod* is *dL*

- *dod* is *dM*

- *dod* is *dH*

4.3.3 Inference diagram

Based on the fuzzified inputs, the rules set serve to decide the relays' switching control, which are deduced using the modes explained previously. The control signals of the relays are given following this equation:

$$r_{0l,b,lb} = \frac{\int_0^1 r_{on}\,\mu_{r_{l\,on}}\,dr_{on}}{\int_0^1 \mu_{r_{l\,on}}\,dr_{on}} \quad (36)$$

4.3.4 Defuzzification

The control of the three relays is deduced by (Fig. 3):

$$If \quad r_{l,b,lb} \; < \; 0.5\, then \quad R_{l,b,lb} \quad is \quad off \quad (37)$$

$$If \quad r_{l,b,lb} \; > \; 0.5\ then \quad R_{l,b,lb} \quad is \quad on \quad (38)$$

5. Results and discussions

To test the EWMA efficiency, the algorithm is validated using measured climatic data of an agricultural land planted with tomatoes, situated in Northern Tunisia (latitude: 36.64°, longitude: 9.60°) and characterized by its semi-arid climate. This application is prompted by the fact that tomatoes must be irrigated regularly, especially during flowering and fruit formation. The irrigation is gravity-based: 200 m^3/h just before sunrise, to irrigate a 10 ha field by a low-pressure gravity-driven drip system.

5.1 Algorithm Parameterization

5.1.1 Photovoltaic Power P_{pv}

The photovoltaic power P_{pv} is classified as follows:

$$If \quad P_{pv} \; \in \; [0 \;\; 10] \;\; then \quad P_{pv} \quad is\ considered \quad low \;\; If \quad P_{pv} \; \in \; [10 \;\; 4500] \;\; then \quad P_{pv} \quad is\ considered \quad medium$$

$$If \quad P_{pv} \; \in \; [4500 \;\; 10000] \;\; then \quad P_{pv} \quad is\ considered \quad high$$

5.1.2 Battery depth of discharge dod

The battery' non-linear model detailed in the subsection 3.2 is used here to evaluate the dod, which is classified as follows:

$$If\ dod \; \in \; [0 \;\; 0.02] \;\; then \quad dod \quad is\ considered \quad low.$$

$$If \quad dod \; \in \; [0.02 \;\; 0.9] \;\; then \quad dod \quad is\ considered \quad medium.$$

$$If \quad dod \; \in \; [0.9 \;\; 1] \;\; then \quad dod \quad is\ considered \quad high.$$

5.1.3 Water Volume V needed for crops irrigation

Using the water need model given in Section 2, the water volume V corresponding to each month of tomatoes' vegetative cycle at the target location is described in Table 2. The values are measured and provided by the agriculture administry of Medjez El Beb, Tunisia.

Table 2. Daily water volume needed for tomatoes irrigation

The mean water volume of March (m_1) is $l_1 = 60$ m^3 / day.

The mean water volume of April (m_2) is $l_2 = 100$ m^3 / day.

The mean water volume of May (m_3) is $l_3 = 179$ m^3 / day.

The mean water volume of June (m_4) is $l_4 = 241$ m^3 / day.

The mean water volume of July (m_5) is $l_5 = 321$ m^3 / day.

The fuzzification of the water volume depends on the month and is described in Table 3.

Table 3. Water fuzzification corresponding to each month *M*

5.2 Results and discussion

The management algorithm was implemented and tested by simulations using measured data (solar irradiation, ambient temperature, rainfall, etc.) from the target location (Medjez El Beb, Northern Tunisia) for the irrigation season from *March* to *July* (Fig. 2). Obtained results (Fig. 4-10) prove that the algorithm fulfills the objectives: relays switching ensures the system autonomy. The water demand is fulfilled and the battery and load are correctly disconnected when not used. In fact, the case of unexpected water extraction between the instants t_{fi} and t_{fd} from the reservoir is studied here for *March* and *April* (Fig. 4 and Fig. 5). The missing water volume in the reservoir is less than the volume needed to irrigate the crops. Hence, the starting water pumping time is evaluated using equation (15). Then, the missed water volume is pumped using a constant water flow Q= 200 m^3 / h, and used to irrigate the crops. Thus, the developed algorithm allows the relay R_{lb} to be switched *on*, which connects the battery bank to the pump, so as to compensate the loss in water volume while the *dod* is less than 0.8. In this case, the pumping is performed to have the water needed for the plants irrigation. Hence, to minimize using the battery bank during the night and to keep it charged, the EWMA ensure pumping only the missing water volume needed for the crops irrigation. Hence, the EWMA fulfills the objectives O1 and O3.

Fig. 4 Algorithm response in the case study for a day in *March*

Fig. 5 Algorithm response in the case study for a day in *April*

The FMA is also tested in case of empty reservoir and charged battery bank during *May* and *June* (Fig. 6 and Fig. 7). Indeed, the battery bank is used to pump water until the water volume needed to irrigate tomatoes is pumped. In this process, the irrigation starting and finishing times are taken into consideration: the irrigation is finished one hour before sunrise to allow a better absorption of the water by the crops. Thus, during irrigation, the water volume decreases, following the constant irrigation flow rate (200 m^3/h). In the sunrise, since the battery bank is discharged, the photovoltaic energy generated is used to charge the batteries. Then, when it is medium charged, the photovoltaic energy generated is used to supply the water pump and to charge the battery bank. Hence, the available photovoltaic energy is used to charge the battery since the battery bank is not full charged, so the relays R_l and R_b are switched *on*. During all of these modes, the *dod* is always maintained between the prefixed values (0.02 and 0.8), which guarantees the battery safety.

Fig. 6 Algorithm response in the case study for a day in *May*

Fig. 7 Algorithm response in the case study for a day in *June*

Using meteorological data of *July*, the case of full reservoir and empty battery bank is tested (Fig. 8 and Fig. 9). In fact, the since the battery bank is empty, the water pumping starts when there is an excess in the photovoltaic power generated. In this case, both the relays R_l and R_b are switched on, which corresponds to mode 3. Moreover, Fig. 9 shows that the control signals ensure relays complementary switching (relays R_b and R_{lb}) since each relay is considered *on* when the membership degree for the relay control signal is higher than 0.5 otherwise it is *off*, enabling then a continuous power supply for the pump and the system autonomy, where the EWMA ensures pumping the water volume expected for *July* and the *dod* is maintained less than 0.8. Moreover, the relays switching shows that even in rapid changing in atmospheric conditions, the panel is able to operate around the optimal value.

Fig. 8 Algorithm response in the case study for a day in *July*

Fig. 9 Algorithm response in the case study for three days in *July*

Using the global meteorological data of the solar radiation and the ambient temperature, the proposed algorithm is evaluated from *March* to *July*, as this is the growing season for tomatoes in the target location. The results show that the use average of batteries is minimized, since the battery bank maximum contribution in supplying the pump represents 26 % of the panels contribution (Fig.10). Moreover, it is clear that the EWMA ensures pumping more water volume than needed, especially during *March* and *April*. This proves the algorithm efficiency in keeping the battery bank charged and minimizing its use.

Fig. 4 Energy generation evaluation during the tomato vegetative cycle

6. Conclusion

A fuzzy algorithm for the water and energy management of an autonomous off-grid solar irrigation installation has been presented and tested. The algorithm makes decisions on the interconnection time of the main components (photovoltaic panels, batteries and water pumps) by controlling the switching of the relays, and taking into account some constraints related with the photovoltaic power generated, the battery depth of discharge, the operating month and the amount of stored water.

This algorithm has been tested for a specific installation for tomatoes' irrigation during the vegetative cycle months of tomatoes in Tunisia (from *March* to *July*), including extreme situations that cause insufficient water volume in the reservoir or a depleted battery bank. Using measured data from the target location, the results show that the algorithm ensures pumping the water volume needed by tomatoes, the system autonomy and the increases the batteries lifetime. Moreover, it is important to notice that the proposed algorithm is general, in the sense that it can be used for PV irrigation systems of different sizes, by providing the monthly water demand and the energetic requirements.

As a general conclusion, the efficiency of fuzzy logic has been demonstrated in combining energy and water management for off-grid pumping installation, and that a simple management algorithm system can improve the operation of off-grid PV systems.

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Santo (FAPES), Brazil. Pr. Tadeo is supported by a project from the Spanish ministry of economy and competitiveness (MiCInn DPI2014-54530-R, co-funded by FEDER). Pr. Segatto is partially supported by CNPq/Brazil (CNPq 307470/2012-1).

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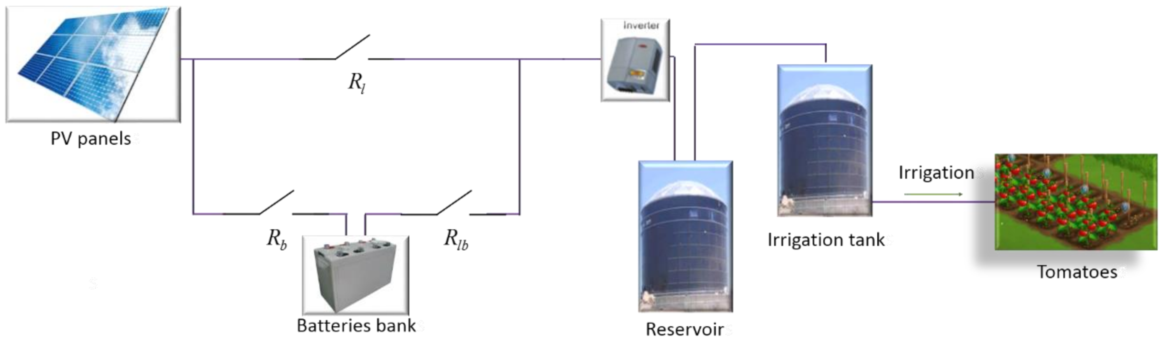

Fig. 1. Scheme of the off-grid photovoltaic irrigation plant

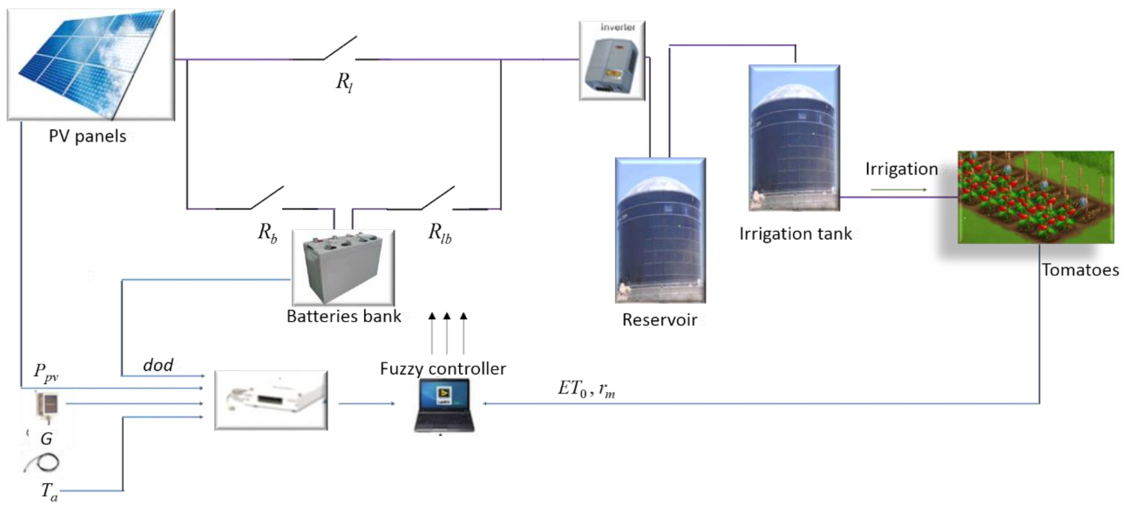

Fig. 2. The structure of the proposed energy management algorithm

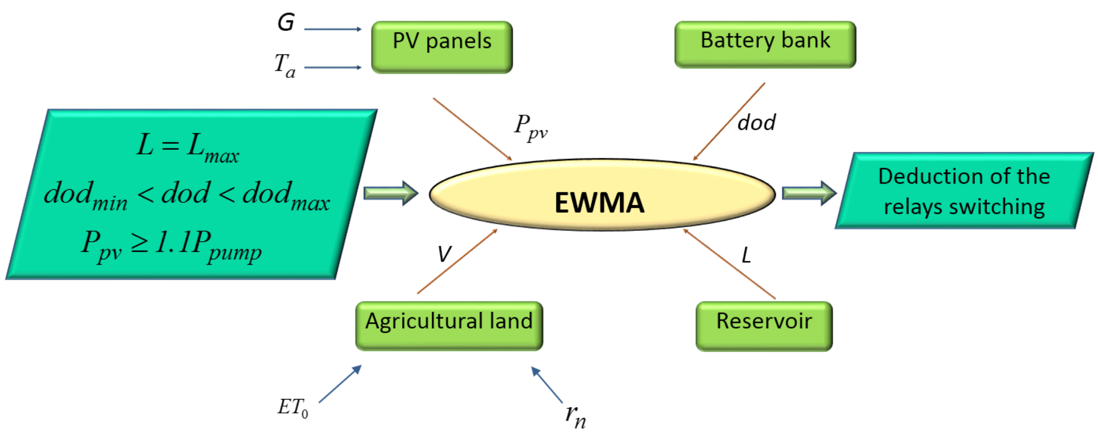

Fig. 3. Energy and water management strategy

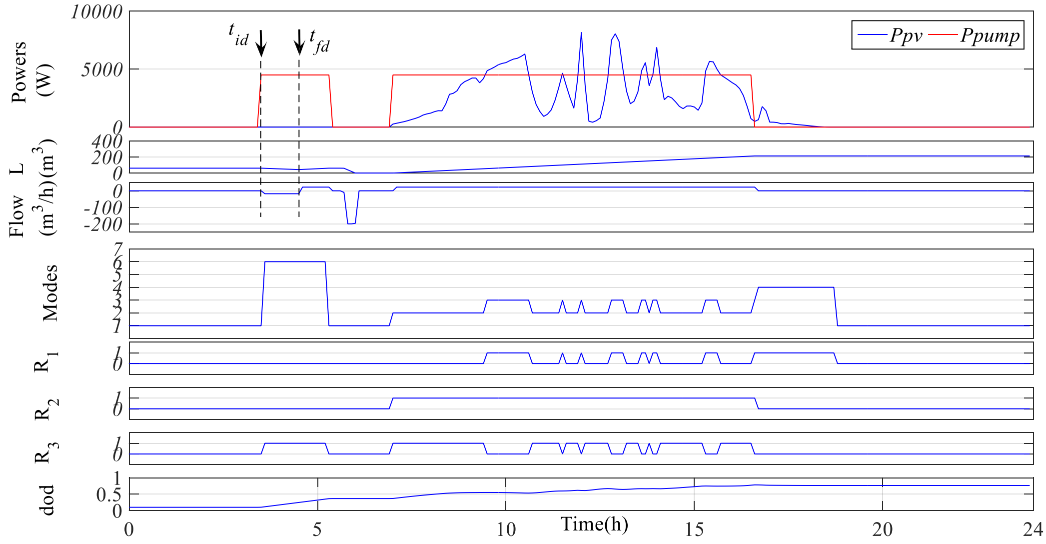

Fig. 4 Algorithm response in the case study for a day in *March*

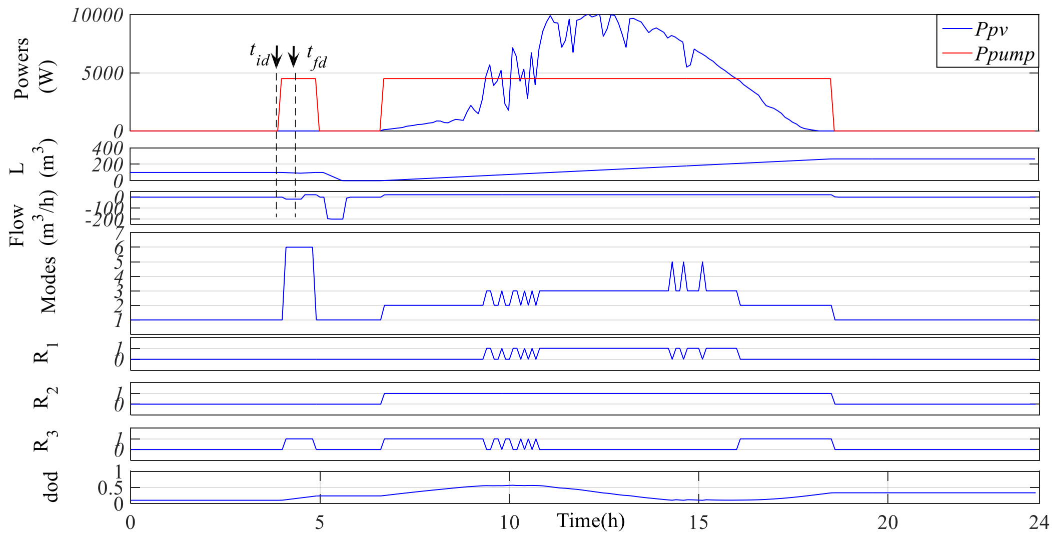

Fig. 5 Algorithm response in the case study for a day in *April*

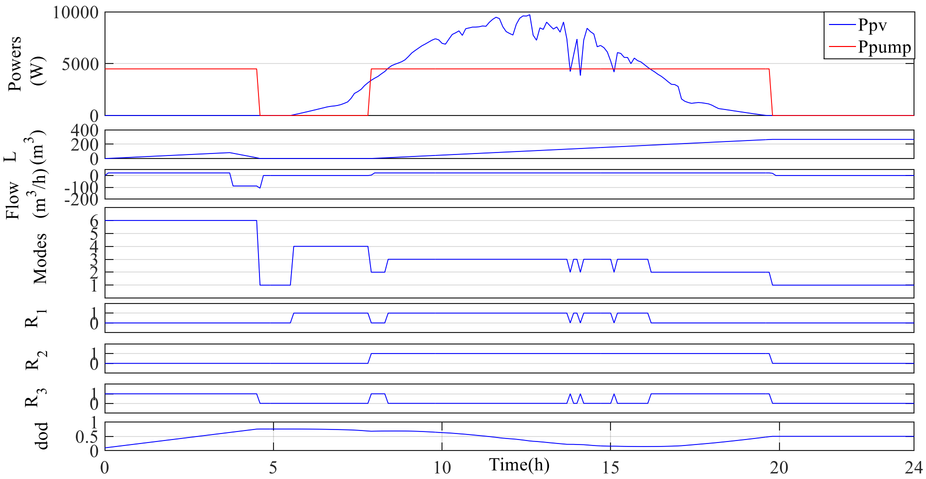

Fig. 6 Algorithm response in the case study for a day in *May*

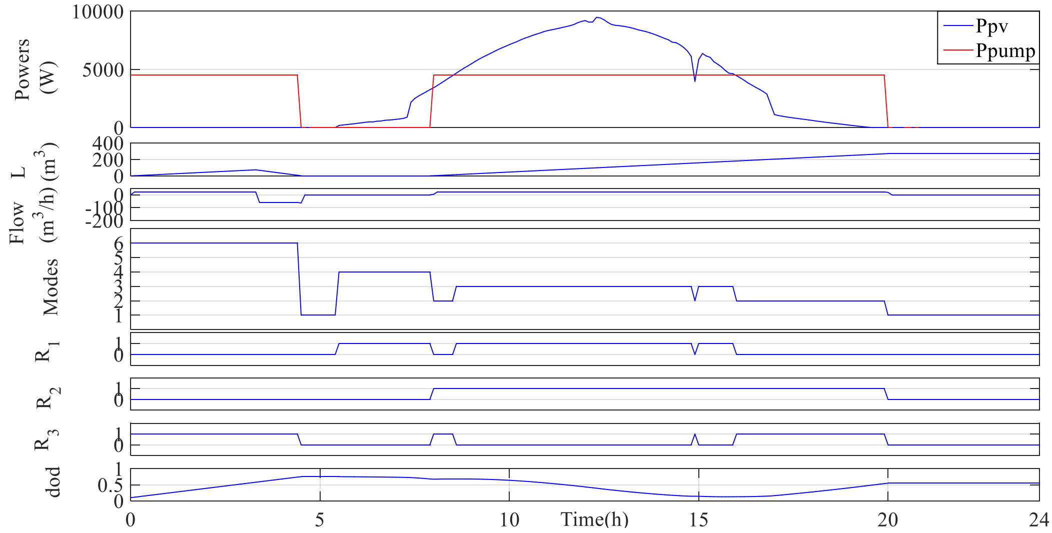

Fig. 7 Algorithm response in the case study for a day in *June*

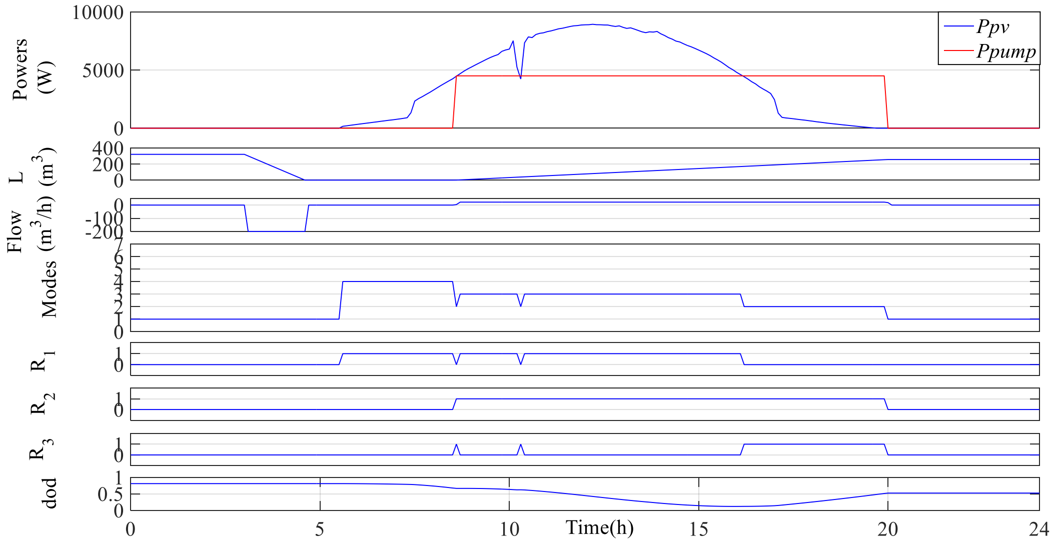

Fig. 8 Algorithm response in the case study for a day in *July*

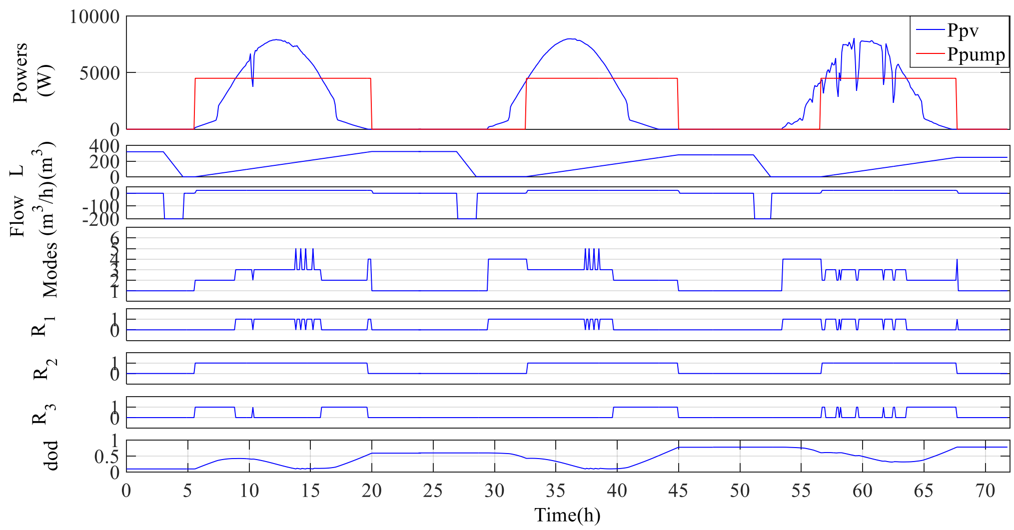

Fig. 9 Algorithm response in the case study for three days in *July*

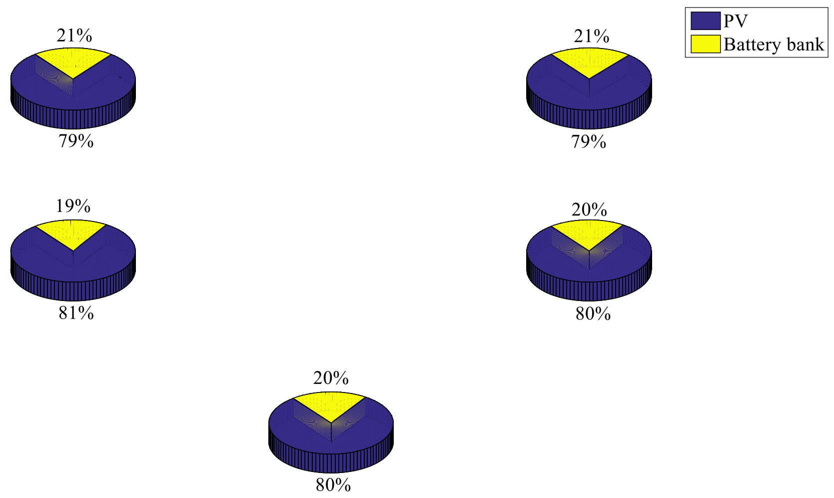

Fig. 10 Energy generation evaluation during the tomato vegetative cycle

Nomenclature

a	temperature coefficient K^{-1}	R_s	serial resistance of a photovoltaic module (Ω)
AC	Alternating Current (A)	R_p	the parallel resistance of the photovoltaic module (Ω),
C_R	remaining battery capacity (A.h)	k_p	Peukert constant
C_p	Peukert capacity (A.h)	$M_{1,2,3,4,5,6}$	function modes 1, 2, 3, 4, 5, 6
DC	Direct Current (A)	n	Coefficient of ideality
dod	depth of discharge	n_p	number of parallel photovoltaic modules
FMA	Fuzzy Management Algorithm	P_{bat}	battery power (W)
G	solar radiation (W/m^2)	P_i	instantaneous power supplied to the load (W)
G_{ref}	Reference solar radiation (W/m^2)	P_{pump}	power of the pump (W)
I_{bat}	battery current (A)	P_{pv}	photovoltaic power (W)
I_i	instantaneous current supplied to the load (A)	PVP	PhotoVoltaic Panel
I_{ph}	generated photo-current at a given irradiance G (A).	q	electron energy (C)
I_{pv}	current produced by the photovoltaic panel (A)	R_1, R_2, R_3	three switching relays
I_{pv}	current produced by the photovoltaic panel after the Maximum Power Point Tracking bloc (A)	T_a	ambient temperature at the panel surface (°C)
I_r	reverse saturation current for a given ambient temperature (A)	T_{ref}	temperature of reference at the panel surface (°C)
$I_{r\_T_{ref}}$	reverse saturation current for the temperature of reference (A)	V	pumped water volume (m^3)

I_{sc}	short circuit current for a given temperature T_a (A)	V_c	open circuit voltage of a photovoltaic module (V)
$I_{sc\_T_{ref}}$	short circuit current for the temperature of reference (A)	V_g	Gap energy (e.V)
K	Boltzmann constant	$V_{t\_T_a}$	thermal potential at the ambient temperature (ºC)
$MPPT$	Maximum Power Point Tracking	Δt	pumping duration (h)

x_{0i} , d_{0k} , y_{0j} , f_{0s} , e_{0n} and O_{0l} are, respectively, the values of the variables *x*, *d*, *y*, *f* ,e and *O* in the membership intervals; and $\varepsilon_{x_{0i}}$, $\varepsilon_{d_{0k}}$, $\varepsilon_{y_{0j}}$, $\varepsilon_{f_{0s}}$, $\varepsilon_{e_{0n}}$ and $\varepsilon_{O_{0l}}$ are the range values of x_{0i} , d_{0k} , y_{0j} , f_{0s} , e_{0n} and O_{0l} , respectively.

Table 1 Fuzzification of the knowledge base

- *dod* is *dL*

v \ P_{pv}	*L*	*M*	*H*
vL	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is off* r_l *is on* r_b *is on*
vM	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is off* r_l *is on* r_b *is on*
vH	r_{lb} *is off* r_l *is off* r_b *is off*	r_{lb} *is off* r_l *is off* r_b *is off*	r_{lb} *is off* r_l *is off* r_b *is off*

- *dod* is *dM*

	L	*M*	*H*
vL	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is on* r_l *is on* r_b *is off*	r_{lb} *is off* r_l *is on* r_b *is on*

vM v	P_{pv}	r_{lb} is on r_l is on r_b is off	r_{lb} is on r_l is on r_b is off	r_{lb} is off r_l is on r_b is on
vH		r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on

- *dod is dH*

v \ P_{pv}	L	M	H
vL	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is on r_b is on
vM	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is on r_b is on
vH	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on	r_{lb} is off r_l is off r_b is on

Table 2. Daily water volume needed for tomatoes irrigation

Month	*March*	*April*	*May*	*June*	*July*
ET_0 (mm)	3.8	4.44	5.31	6.5	6.56
r_m (mm)	0.68	0.88	0.65	0.38	0.14
k_c (%)	50	65	80	80	100
V (m^3/ha)	6	10	17.9	24.1	32.1