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A proposal for off-grid photovoltaic systems with non-controllable loads using fuzzy logic

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ABSTRACT

A fuzzy-logic based methodology is proposed and evaluated for energy management in off-grid installations with photovoltaic panels as the source of energy and a limited storage capacity in batteries. The decision on the connection or disconnection of components is based on fuzzy rules on the basis of the Photovoltaic Panel Generation measurement, the measured power required by the load, and the estimation of the stored energy in the batteries (this last is obtained from the estimation of the Depth-of-Discharge). The algorithm aims to ensure the system's autonomy by controlling the switches linking the system components with respect to a multi-objective management criterion developed from the requirements (supply of the load, protection of the battery, etc.). Detailed tests of the proposed system are carried out using data (irradiation, temperature, power consumption, etc.) measured in a household at the target area at several days of the year. The results demonstrate that the proposed approach achieves the objectives of system autonomy, battery protection and power supply stability. Compared with a basic algorithm, the proposed algorithm is not sensitive to sudden changes in atmospheric parameters and avoids overcharging the battery.

1. Introduction

The demand for electrical energy supply systems in isolated areas is increasing around the world, for water pumping [1], desalination [2] and supplying remote dwellings with electricity [3]. This motivates the development of novel energy management methodologies to balance production with demand. Among the renewable energy sources that are being installed, photovoltaic panels (*PVPs*) is probably the most frequent, since it offers many advantages such as low maintenance costs, no polluting, and no noise.

The main disadvantage is that the electricity is produced only during the day, so if the electrical load cannot be fully controlled to balance with the electricity production, the use of batteries is essential.

These off-grid *PVP*-based systems, require specific solutions that are being researched, focusing on system modeling [4], *PVP* sizing [5,6], optimization [7], Maximum Power Point Tracking (*MPPT*) [8], etc. These issues are mainly deliberated in the literature and efficient standard tools have been advanced [9].

Fuzzy Management Algorithms (*FMAs*) have previously shown to offer adequate energy management of the photovoltaic systems [10]. Thus, starting from a preliminary study presented in [11], the management algorithm is refined here, with improved models, is generalized for generic non-adaptable loads, and its performance is demonstrated using measured data of a household in the target area.

Thus, this paper presents the development and tests of a management strategy for off-grid *PVP*-based systems that is advanced (in the sense that it is based on considering several measurements to find on-line a compromise between conflicting objectives), that can be adapted to different configurations and could be implemented using off-the-shelf hardware and software. To do so, Mamdani-type fuzzy logic is used within the management algorithm as it is simple to learn for operators with little technical training [12] and can be implemented using standard components, such as Programmable Industrial Controllers [13].

Following previous works [11], the estimated power produced by the photovoltaic panel is used by the algorithm. This estimation is used to decide when to connect the components of the system using a fuzzy-rules algorithm. The decisions taken ensure the autonomy of the system, the correct charge/discharge of the

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Nomenclature

a	temperature coefficient
AC	alternating current (A)
C_R	remaining battery capacity (A h)
C_p	Peukert capacity (A h)
DC	direct current (A)
dod	depth of discharge
FMA	Fuzzy Management Algorithm
G	solar radiation (W/m^2)
G_0	nominal solar radiation (W/m^2)
I_{Bat}	battery current (A)
I_i	instantaneous current supplied to the load (A)
I_{ph}	generated photo-current at a given irradiance G (A)
I_{pv}	current produced by the photovoltaic panel (A)
I_{PV}	current produced by the photovoltaic panel after the Maximum Power Point Tracking bloc (A)
I_r	reverse saturation current for a given ambient temperature (A)
$I_{r\_T_{ref}}$	reverse saturation current for the temperature of reference (A)
I_{sc}	short circuit current for a given temperature T_a (A)
$I_{sc\_T_{ref}}$	short circuit current for the temperature of reference (A)
$MPPT$	Maximum Power Point Tracking
K	Boltzmann constant
k_p	Peukert constant
$M_{1,2,3,4,5,6}$	function modes 1, 2, 3, 4, 5, 6
n	coefficient of ideality
n_p	number of parallel photovoltaic modules
P_{Bat}	battery power (W)
P_i	instantaneous power supplied to the load (W)
P_L	power of the load (W)
P_{PV}	photovoltaic power (W)
PVP	photovoltaic panel
$PVPG$	photovoltaic power generation
$P\&O$	Perturb and Observe method for $MPPT$
q	electron energy (C)
R_s	serial resistance of a photovoltaic module (Ω)
R_1, R_2, R_3	three switching relays
T_a	ambient temperature at the panel surface (°C)
T_{ref}	temperature of reference at the panel surface (°C)
V_c	open circuit voltage of a photovoltaic module (V)
V_g	gap energy (e V)
$V_{t\_T_a}$	thermal potential at the ambient temperature (°C)
.	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.

battery, a good use of the generated power and a stable supply for the load.

The following section describes the system components models. The Fuzzy Management Algorithm is detailed in Section 3, where the management strategy and the algorithm's execution are explained in depth. Some results are presented and discussed in Section 4. Finally, Section 5 gives a conclusion.

2. System modeling

The system under study is composed of a set of photovoltaic panels (with *MPPT* controllers), connected through relays to a Lead-acid battery bank (which includes the batteries and their regulators), and a variable load, using a *DC* bus, as presented in Fig. 1.

2.1. The PVP generation model

A non-linear model is used to model the photovoltaic panel. It is based on the daily measured radiation G and the ambient temperature T_a at the panel surface, which are used as inputs to a *PVP* generation model to evaluate the photovoltaic current I_{pv}. Thus, it is given by these equations [14]:

$$I_{pv} = n_p\left(I_{ph} - I_r\left(exp\left(\frac{V_c + I_{PV}\ R_s}{V_{t\_T_a}}\right) - 1\right)\right) \quad (1)$$

$$I_{ph} = \frac{G}{G_0} I_{sc} \quad (2)$$

$$I_{sc} = I_{sc\_T_{ref}}\left(1 + \left(a(T_a - T_{ref})\right)\right) \quad (3)$$

$$I_r = I_{r\_T_{ref}}\left(\frac{T_a}{T_{ref}}\right)^{\frac{3}{n}} e^{\left(\frac{-qV_g}{nK}\left(\frac{1}{T_a} - \frac{1}{T_{ref}}\right)\right)} \quad (4)$$

$$I_{r\_T_{ref}} = \frac{I_{sc\_T_{ref}}}{e^{\frac{qV_c}{nKT_{ref}}} - 1} \quad (5)$$

where I_{pv} is the estimated photovoltaic current (A), I_{ph} is the generated photo-current at a given irradiance G (A), I_{sc} is the short circuit current for a given temperature T_a (A), I_r is the reverse saturation current for a given temperature T_a (A), $I_{r\_T_{ref}}$ is the reverse saturation current for the reference temperature T_{ref} (A).

The efficiency of the photovoltaic generation is ensured via the use of the *MPPT* bloc, where we adopted the *P&O* method for the extraction of the maximum electric power [8]. Hence, we obtain I_{PV}, the optimum photovoltaic current.

2.2. The battery model

For the Lead-acid battery, we adopt the nonlinear model given by [7]. Fig. 2 describes the equivalent circuit used for the lead acid battery, where I_{Bat} is positive when charging and negative when discharging and V_{Bat} is the battery output voltage. The charge of the battery (at instant k) is given by:

$$C_{R_{(k)}} = C_{R_{(k1)}} + \frac{\partial t}{3600} I_{Bat_{(k)}}^{k_p} \quad (6)$$

where ∂t is the time between instant $k-1$ and k, and k_p is Peukert constant.

Thus, the depth of discharge dod is given by the following equation ($dod = 0$ when the battery is fully charged and $dod = 1$ when the battery is empty):

$$dod_{(k)} = \frac{C_{R_{(k)}}}{C_p} \quad (7)$$

where C_R is the charged capacity and C_p is the capacity of Peukert, considered constant.

2.3. The load

To take into account the use of the expected electricity, we used a profile based on the consumption patterns of a typical family in Tunisia. Fig. 3 shows an hourly pattern for a typical day.