Proceedings of Engineering & Technology -PET Vol 96, pp.119-126 **Advances in Energy Transition and Environmental Impacts**

Smart Control of PV–Battery–Electrolyzer Systems

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***Abstract*—This work proposes an integrated renewable energy system that combines a photovoltaic (PV) panel, battery storage, an electrolyzer, and a fuzzy logic-based Maximum Power Point Tracking (MPPT) controller. The PV panel captures solar energy and converts it into electricity, which is stored in a battery to ensure a stable energy supply, even during low irradiation periods. This setup enhances system autonomy and reliability.**

Excess energy is utilized by the electrolyzer to produce hydrogen via water electrolysis, offering an effective long-term energy storage solution and reducing losses linked to conventional energy conversion. The stored hydrogen serves as an additional energy carrier, contributing to greater system flexibility and sustainability.

To optimize energy harvesting, a fuzzy MPPT controller dynamically adjusts the operating point of the PV panel in response to changing environmental conditions. It also manages transitions between energy generation, battery charging, and hydrogen production, ensuring seamless system performance. Together, these components create a robust, adaptive, and efficient energy management architecture suitable for future renewable energy applications.

***Keywords*— PV panel, Fuzzy control, electrolyzer, batteries, energy management**

I. Introduction

Recent concerns related to global warming and the depletion of fossil fuel resources have emphasized the need to transition toward clean, sustainable, and accessible renewable energy sources. These alternatives are essential to meet the world's long-term energy demands while minimizing environmental impact. In this context, Algeria's significant solar potential represents a promising opportunity for economic growth and for reducing the negative effects associated with diesel-based installations [10], [11]. Among renewable energy technologies, photovoltaic (PV) systems have gained substantial attention due to their modularity, reliability, and decreasing cost. However, their efficiency strongly depends on environmental conditions such as irradiation and temperature. To ensure optimal operation, maximum power point tracking (MPPT) algorithms are employed to continuously extract the maximum available power from PV modules [1–3], [15], [16]. Traditional MPPT methods, such as Perturb and Observe (P&O) and Incremental Conductance (IncCond), are widely used due to their simplicity, but they often suffer from oscillations around the maximum power point and poor performance under rapidly changing atmospheric conditions [4], [22]. To overcome these limitations, intelligent control strategies—such as those based on Fuzzy Logic Controllers (FLCs), Genetic Algorithms (GAs), and Particle Swarm Optimization (PSO)—have been introduced [8], [9], [12], [13]. Fuzzy-based controllers are particularly attractive because of their ability to handle nonlinearities and uncertainties without requiring an exact mathematical model of the system [8], [9], [15]. Recent works have demonstrated their effectiveness in improving the dynamic response and energy conversion efficiency of standalone and hybrid PV systems [9], [14], [17], [18]. Moreover, integrating PV systems with complementary technologies, such as fuel cells, batteries, and hydrogen storage units, allows for reliable energy supply and enhanced autonomy in hybrid configurations [11], [17], [19],[24]. Proper system sizing and energy management strategies are crucial to optimize performance, reduce costs, and prolong component lifetime [13], [19], [25]. In this study, a hybrid renewable energy system is considered, where a fuzzy logic–based MPPT controller is implemented to optimize power extraction. A supervisory control structure is also proposed to manage the power flow between the PV generator, the electrolyzer, and the battery bank, ensuring battery protection against deep discharge and overcharge while maintaining supply continuity under variable irradiation conditions. The simulation

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results obtained in MATLAB/Simulink validate the proposed control and energy management strategies, showing improved tracking performance and system efficiency under diverse operating conditions.

II. THE PROPOSED SYSTEM MODELLING

The system architecture illustrated in Fig. 1 comprises a photovoltaic (PV) generator, three DC/DC converters, a battery bank, a fuel cell generator, an electrolyzer, and an inverter supplying the AC load. The overall power flow and energy management are controlled by the operating states of the five switches (R1–R5), ensuring coordinated interaction among the different subsystems.

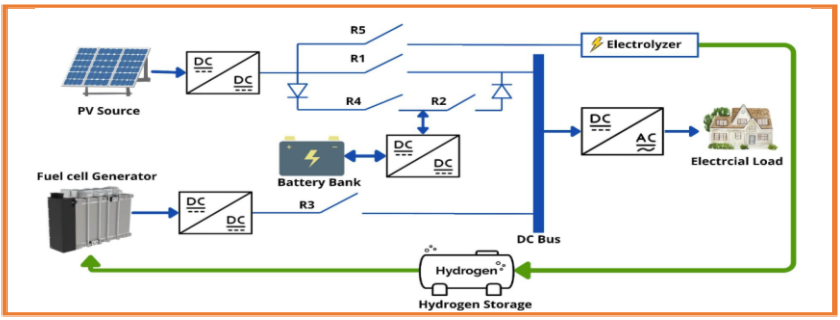

Fig. 1 The studied configuration with variable load

A. *Photovoltaic panels model*

The behaviour and functioning of the PV are described by a number of mathematical models. This study examines the model shown in Figure 2 [9–11]:

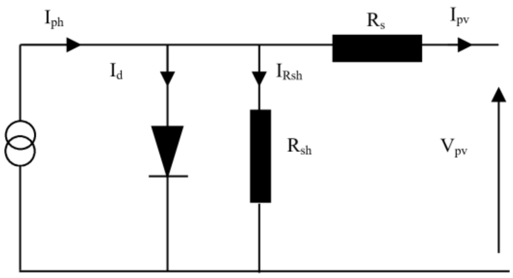

Fig. 2 Equivalent photovoltaic cell circuit

where I_{pv} denotes the PV output current, I_{ph} the photocurrent, I_d the diode current, and I_{Rsh} the shunt leakage current. *Rs* and *Rsh* represent the series and shunt resistances, respectively, while *G* is the solar irradiance. The I_{pv}–V_{pv} relationship of the model is given by:

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \tag{1}$$

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

The obtained model provides an accurate representation of the PV generator, allowing efficient evaluation of its dynamic response to variations in irradiance and temperature.

TABLE I PARAMETERS OF THE SUNTECH STOP 80S- 12/BB PV PANEL

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

B. *Modelling of batteries*

A battery can be modeled by a voltage source Eb and an internal resistance R_b [10–12]. The battery capacity C_{bat} is defined as:

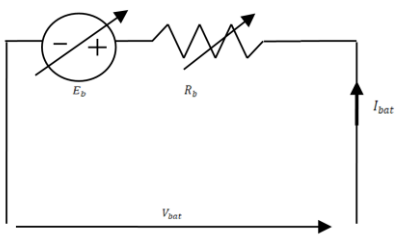

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Fig. 3 Battery model

$$C_{bat} = f(T, C_{10}) \quad (3)$$

where T is the temperature and C_{10} the rated capacity at I_{10}. The state of charge (SOC) is expressed as:

$$SOC(\%) = 100.(1 - \frac{Q}{C_{bat}}) \quad (4)$$

With:

$$Q = I_{batt} \times t \quad (5)$$

Where: t is the discharging time

III. MPPT FUZZY TECHNIQUE

The Fuzzy Logic Controller (FLC) comprises three main stages—fuzzification, inference, and defuzzification. In the MPPT control scheme illustrated in Fig. 4, the controller uses the error (E) and the change in error (CE) as input variables, which are computed at each sampling instant k as follows:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (6)$$

$$CE(k) = E(k) - E(k-1) \quad (7)$$

where P(k) and V(k) represent the instantaneous power and voltage of the photovoltaic module at the sampling instant k.

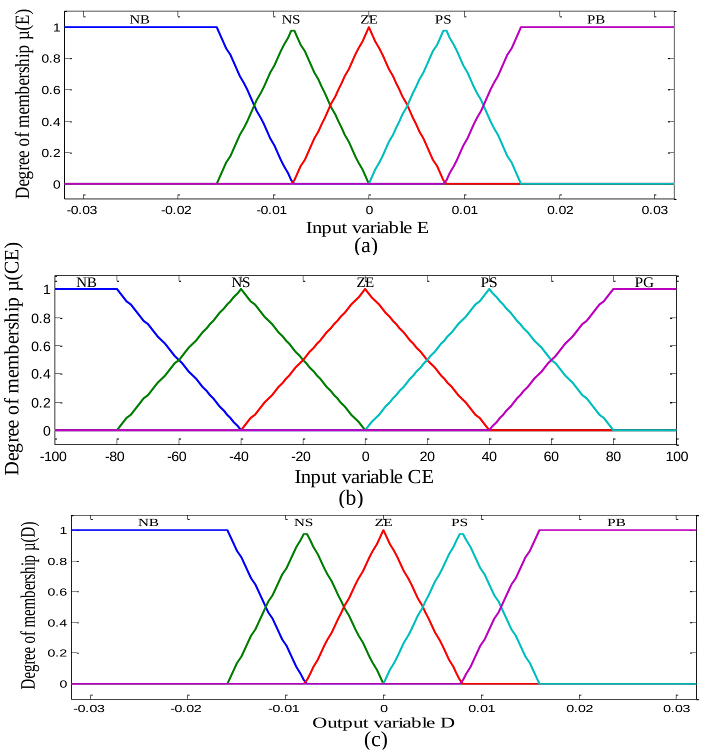


Fig.4 Membership functions for: (a) input variable E, (b) input variable CE, (c) output variable D.

The duty cycle (D) represents the system's output variable, which can be determined using the center of area (COA) method. The relationships between the input variables and the corresponding output decisions of the FLC are summarized in Table 2.

TABLE 2. RULES BASE TABLE FOR COMPUTATION D

ISSN: 1737-9334

CE / E	NB	NS	ZE	PS	PB
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

IV. SUPERVISION STRATEGY

The PV generator's power level and the batteries' state of charge (SOC) are the primary determinants of the supervision tactics. By using the supervisor, the PV generator can produce its maximum output, safeguard the batteries from deep drain and overcharge, and meet energy demands. The system functions in one of the following modes based on the various tests. The system works according to the operating modes summarized in table 3 as follow:

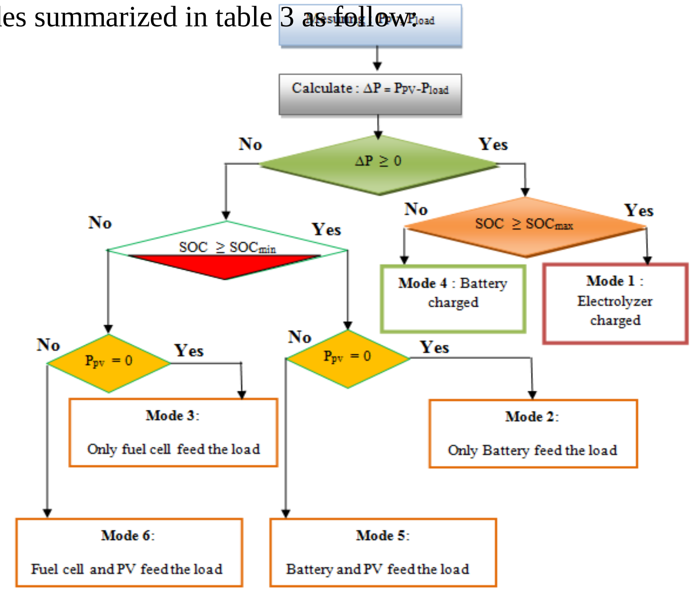


Fig. 5 Flowchart of the proposed management.

TABLE 3. SWITCHES STATE OPERATING MODES

Modes	Switches States				
	R_1	R_2	R_3	R_4	R_5
Mode1	On	Off	Off	Off	On
Mode2	Off	On	Off	Off	Off
Mode3	Off	Off	On	Off	Off
Mode4	Off	On	Off	On	Off
Mode5	On	On	Off	Off	Off
Mode6	On	Off	On	Off	Off

V. SIMULATION RESULTS

The simulated were performed under a seven-days profile, and the following configuration results were obtained: The photovoltaic power profiles obtained under the previously described irradiation and temperature conditions, for a household with variable and constant electrical loads. Are presented in figure 8.The following figure shows the succeed of different sources according to the climatic condition of the seven different days. Regarding the state of charge of the battery and hydrogen storage Fig. 10- 11, the system demonstrates stable performance throughout the operating period.

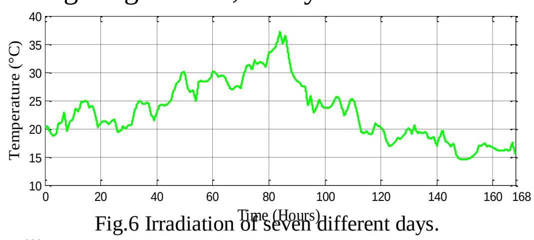
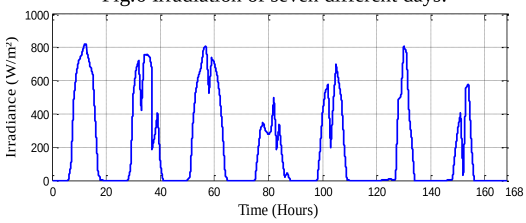


Fig.6 Irradiation of seven different days.



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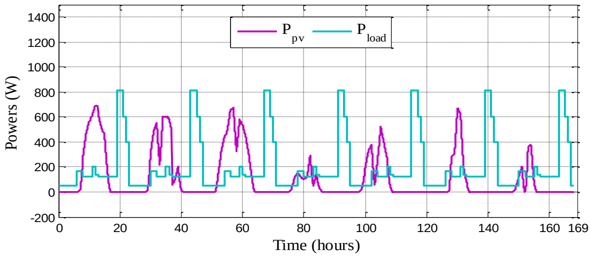

Fig.8 Photovoltaic and load power of seven different days.

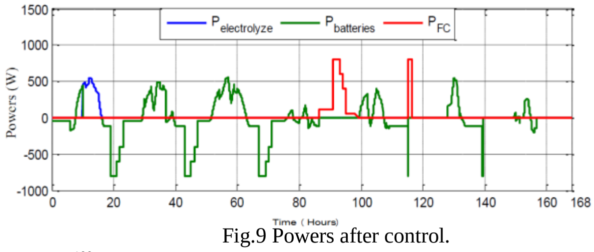

Fig.9 Powers after control.

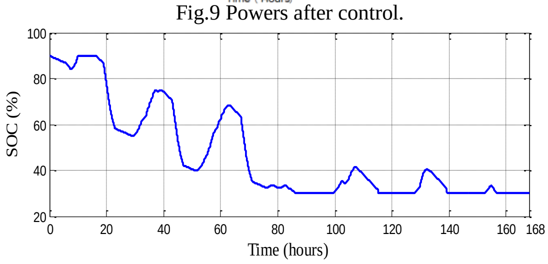

Fig.10 Batteries state of charge.

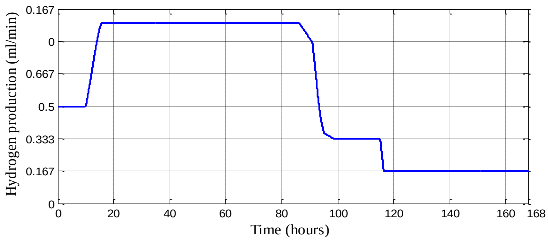

Fig.11 Hydrogen production.

The various operating modes are as follow:

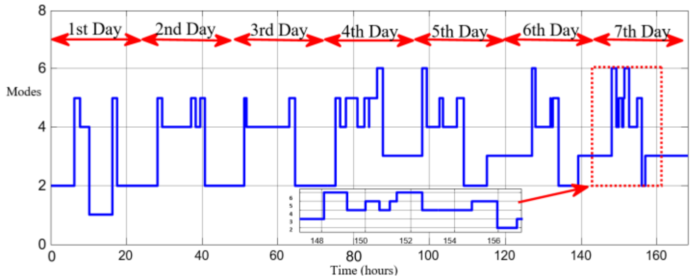

Fig.12 Modes operation.

VI. CONCLUSION

This research proposed a power management plan integrating off-grid solar PV, hydrogen fuel cells, and battery storage. Thanks to the effectiveness of fuzzy MPPT control and the proposed efficient energy management strategy.

ISSN: 1737-9334

The different modes are in first operates in a standby mode where energy consumption is minimal and the battery maintains its charge. Secondly, the normal operating mode involves powering the household load with photovoltaic energy, supplemented by the battery when needed. Finally, the backup mode activates when both the photovoltaic generation and battery charge are insufficient, relying on hydrogen storage to meet the demand. Each mode is designed to optimize energy usage and ensure continuous power supply under varying conditions. The results demonstrate the viability of the configuration for sustainable and autonomous energy systems.

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Proceedings of Engineering & Technology -PET Vol 96, pp.119-126 **Advances in Energy Transition and Environmental Impacts**

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