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Intelligent Management and Optimization of Renewable Sources for Remote Off-Grid Areas

This work presents a study of a microgrid that includes an electrochemical battery storage system. The system is Mainly powered by two renewable energy sources. The main source is a PV system, which is the most favorable for energy production in sunny regions, for which we propose a power optimization by analyzing two maximum power point tracking algorithms, namely the perturb and observe technique and the adaptive fuzzy logic, followed by a mixed technique between the two. A fuel cell is added to the system to enhance the power availability during poor PV production periods to ensure uninterrupted operation. A management system is proposed to reduce dependence on batteries and maximize energy distribution according to consumer needs. The integration of hydrogen fuel cells increases the overall lifespan of the system by minimizing the demand on the batteries, thus avoiding deep discharge. Sim-Power-System models from the Matlab/Simulink library were used in the system modeling. After several simulations, the rigorous analysis of the simulated results revealed that every PV system needed to be optimized in order to extract the maximum power. The mixed technique shows good results with less oscillation. Moreover, better performance of the multi-source system is achieved through a well-defined hierarchy of priorities.

Keywords: PEM Fuel cell; photovoltaic; battery; microgrid; MPPT controller.

1. Introduction

Electricity production systems are continuously improved byincreasing their efficiency and reducing emissions of harmful substances. Indeed, on the international level, various energy strategies are being implemented, not only to reduce or eliminate these harmful wastes, but also to maximize energy production. In this context, countries are increasingly turning to energy alternatives, particularly renewable energy. [1,2] Currently, researchers are discovering several renewable energies, with some exhibiting more promising prospects than others. Photovoltaic energy stands out as a particularly promising option for the future. However, it requires improvements, particularly regarding optimization and energy storage systems, to compensate for the lack of power production during non-sunny or partially sunny periods[3–7].

Previously limited by technical constraints such as intermittent production and high initial costs, photovoltaic systems have undergone significant improvements thanks to

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advancements in power electronics converters and computerized management [8–10] .This transformation has resulted in a decrease in production costs and a significant improvement in performance, thereby revolutionizing the field of solar energy. In this new perspective, power maximization (MPPT) methods have been essential. When they are associated with a DC/DC converter, they facilitate the power and optimal energy transfer of a photovoltaic device by simultaneously optimizing the current and voltage. The literature covers numerous techniques, ranging from fundamental ones to advanced, even intelligent ones.

Several elements define the performance of the MPPT algorithm: execution cost, convergence speed, computational simplicity, power demand, sensitivity to environmental changes, and general operational characteristics. The Perturb and Observable (P&O) algorithm is among the first and most often used MPPT techniques. Although it offers fairly fast performance, it also usually oscillates about the maximum power point (MPP) of the photovoltaic (PV) panel [10–12] . Using fuzzy logic approaches and state transition algorithms has helped this method to be improved in terms of efficiency and implementation expenses[10,13–18].

Despite its progress, photovoltaic solar energy still heavily relies on weather conditions like sunlight and temperature. These two factors have a significant influence on the production of electrical energy, which decreases the reliability of the system in case of a failure. Therefore, it is crucial to have supplementary sources to compensate the production deficit during periods of low or absent daylight [16,19,20]. In order to meet this challenge, several scientists first suggest the hybridization of random energy sources. Subsequently, other options leverage the advantage of decentralizing these resources to design microgrid production solutions directly integrated with consumers [21–23] . Researchers recognize hydrogen fuel cells as a viable way to get around the variability of photovoltaic solar energy production [3,24,25] . Proton exchange membrane hydrogen fuel cells provide numerous advantages compared to conventional storage batteries. Conventional batteries necessitate many hours for complete recharging, and their capacity is challenging to degradation due to fluctuations in their state of charge. In this context, hybrid systems that integrate photovoltaic solar energy and fuel cells are highlighted as a highly promising method for supplying electricity to remote areas, and sometimes supported by a battery storage system to improve overall efficiency[26–28].

This article presents the study of a multi source, renewable energy base, electric power production system, designed to meet the energy needs of rural area far from distribution networks. The proposed system consists of photovoltaic panels, which constitute the main source of energy [29–33] . The efficiency and operation of the photovoltaic system are optimized through the use of power maximization techniques [27], [28], [29]. These techniques were chosen for their ease of implementation, low cost, and ability to ensure rapid convergence as well as optimal response time. The integration of MPPT algorithms, such as the P&O method, allows for maintaining an oscillation around this point[11,12,18,34]. These oscillations are reduced by using a fuzzy logic controller (FLC), thus ensuring more stable operation. In addition, hydrogen fuel cells are used as a supplementary energy source to satisfy power demand in low production periods. A battery storage system is also being implemented to store and deliver this energy according to the grid customers energy demand. Energy management is developed to prioritize sources according to user needs and the availability of the energy flow. This study evaluates the feasibility of the installation, particularly in terms of meeting the energy needs of small off-grid homes. This article highlights the advantages of hydrogen fuel cells in hybrid or multi-source systems to mitigate the intermittency issues of solar energy and their impact on battery stability.

This work is organized as follows: in Section 2, we discuss the system configuration and the modeling of the battery, fuel cell, and photovoltaic panel with MPPT controller. Section 3 explains the power control technique and the system simulation carried out with MATLAB/Simulink Sim-Power-Systems. Section 4 presents and discuss the simulation results. At last, in Section 5, we discuss the findings of this study.

2. System description and modeling

An overview of the studied system is presented in **Fig. 1**, it presentsthe detailed configuration intended to meet the energy needs of a direct current (DC) micro-grid. The system includes a set of photovoltaic panels, supportedby a hydrogen fuel cell as a backup source. Batteries are integrated to ensure energy storage. The chopper converter allows photovoltaic panels to operate at their maximum power point thanks to the MPPT technique, which optimizes the duty cycle. Furthermore, another step-up DC-DC converter, controlled to provide an additional current source, connects the hydrogen fuel cell to the DC bus. This architecture ensures a reliable and efficient distribution of energy, maintaining service continuity even under extreme conditions.

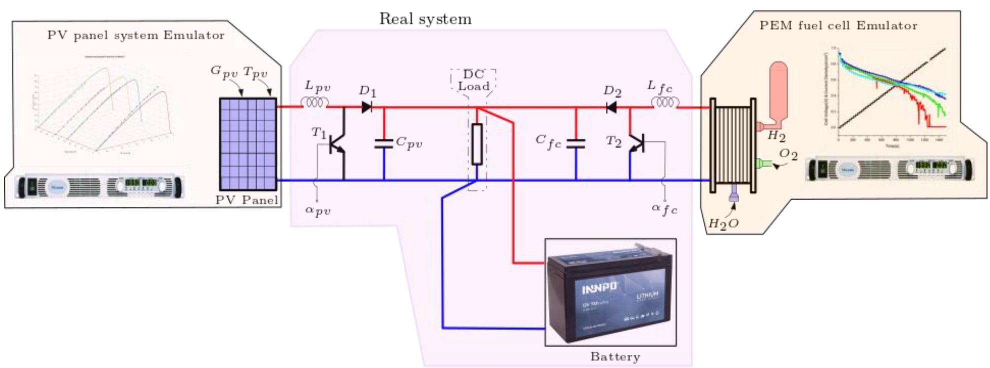

Fig. 1. Power system topology

2.1. PV model and MPPT controller

a. PV model

Photovoltaic single-diode equivalent circuit model, as shown in Fig. 2, is widely adopted for PV cell modeling,because of its simplicity and satisfactory accuracy. The model utilized in this study is the same as the one used in our previousresearchs[25,35,36].

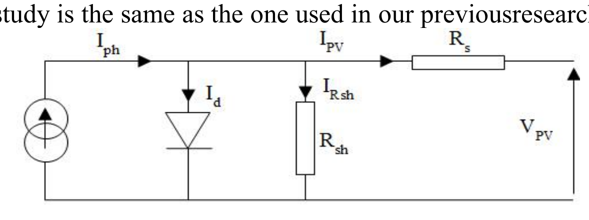

Fig. 2. Equivalent circuit of solar cell

In accordance with Kirchhoff's theorem applied to the presented model, the currents within the photovoltaic cell can be expressed as follows[37]:

$$\boldsymbol{I_{PV} = I_{ph} - I_d - I_{Rsh}} \qquad (1)$$

Where: $\boldsymbol{I_{ph}}$, the photo-current, $\boldsymbol{I_d}$ the diode-current and $\boldsymbol{I_{Rsh}}$ the shunt current[25,34,37,38].

After substituting the currents $\boldsymbol{I_d}$ and $\boldsymbol{I_{Rsh}}$ with their expressions in equation (1), the photovoltaic current is obtained as expressed in equation (2)[35], [36].

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

Table 1. photovoltaic panel Parameters

Symbol	Parameters	Values
P_{pv}	Photovoltaic Power	**80 Wp**
I_{mppt}	Maximum Current at MPP	**4.65 A**
V_{mppt}	Maximum Voltage at MPP	**17.5V**
I_{sc}	Short Circuit Current	**4.95A**
V_{oc}	Open Circuit Voltage	**21.9V**
α_{sc}	Temperature Coefficient at Short-Current	**3 mA/°C**
β_{oc}	Voltage Temperature Coefficient of Short-Current	**150mV/°C**

The equations (1) and (2) represent a mathematical model of a PV panel, able to describe the behavior of the module in Simulink. Several simulations were carried out. Fig. 3 illustrates the characteristics obtained under varying levels of solar irradiance, ranging from 1000 W/m² with an increment of 200 W/m². The maximum power points are indicated by red asterisks (*).

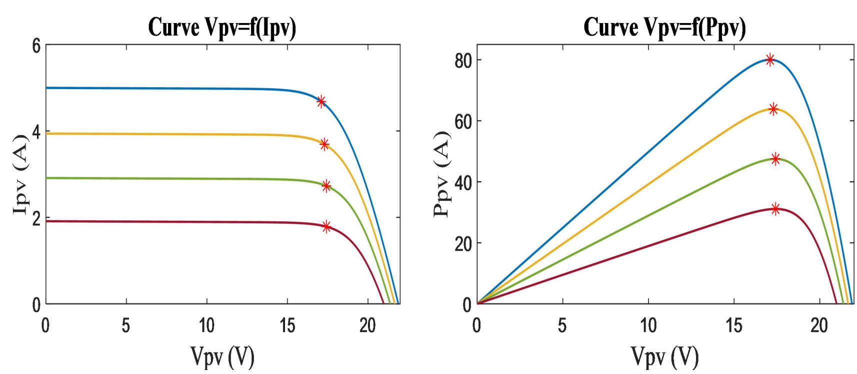

Fig. 3.Electrical IV and PV Curves for photovoltaic panel

b. MPPT Controller

➢ *P&O MPPT*

Perturb & observe algorithm (P&O) is the most used MPPT technique; it consists of disturbing the voltage by increasing or decreasing the duty cycle, and observe the behavior of the generated power (**Fig. 4.A**), and then decide whether to increase or to decrease the duty cycle in order to move toward the MPP.The flow chart represented in **Fig.4.B** describes the operation of this algorithm.

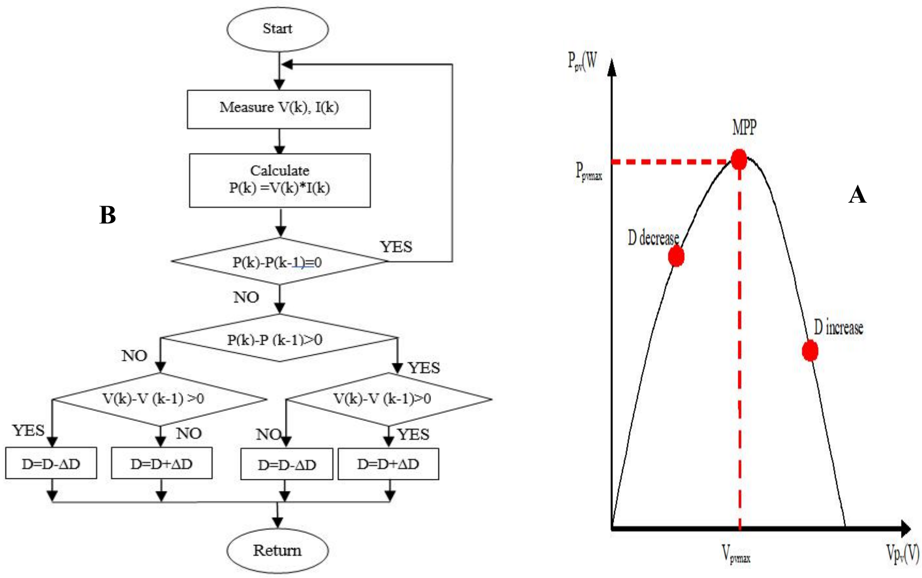

Fig. 4.Flow chart of P&O algorithm.

P&Ois commonly useddue to its simplicity and ease of implementation. Nevertheless, this system has limitations, such as the presence of oscillations around the MPP and adecrease in efficiency in case of low sunlight or rapid changes in environmental conditions.

- *FLC MPPT*

Suggested FLC controllers are characterized by two inputs, power variation (ΔP) and current variation (ΔI) at sample time k. The output the duty cycle of the converter (***Fig. 5***). The three primary steps of FLC are fuzzification, fuzzy logic inference system, and defuzzification. A basic Mamdani-type system utilizing the Min-Max approach has been employed, featuring two inputs and a single triangular-shaped membership function. Upon sampling the voltage and current of the PV array, $\Delta P\ (k)$ and $\Delta I\ (k)$are calculated using equations (3) and (4), [25,37]:

$$\boldsymbol{\Delta P(K) = P(K) - P(K-1)} \qquad (3)$$

$$\boldsymbol{\Delta I(K) = I(K) - I(K-1)} \qquad (4)$$

Table 2 describes the inference table of the FLC, where letters P, N, B, M, S and ZE stand for Positive, Negative, Big, Medium, Small, and Zero respectively.

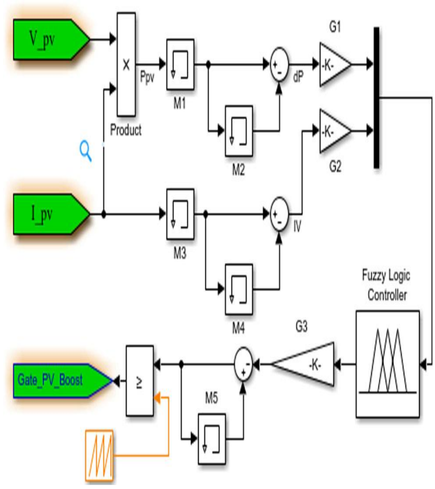

Fig. 5. FLC-MPPT bloc diagram

***Table 2.* fuzzy control rules**

ΔI \ ΔP	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	NM	NM	NB	NB
NS	PB	NS	ZE	NS	NS	NM	NB
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NB	NM	NS	PS	ZE	PS	PB
PB	NB	NB	NM	PM	PM	PB	PB

P(k) and *I(k)* represent the instantaneous power and current of the solar panel, respectively. The controller value (*ΔD*) represents the output of the fuzzy controller.

2.2. *Fuel cell model and controller*

PEM fuel cells offer a number of benefits, including high efficiency, low emissions, and the ability to generate electricity directly. the equations of the fuel cell are presented in (5), (6), (7), (8) and (9)[19,25,37,39]

The terminal voltage of a single cell can be expressed as given by equation (5):

$$V_{fc} = n_{fc}(E_{Nernst} - E_{Act} - E_{Con} - E_{Ohm}) \tag{5}$$

Each term of equation (5) can be calculated by the following equations:

$$E_{Nernst} = 1.229 - 8.5e^{-4}(T_{fc} - 298.15) + 4.308e^{-5}\left[ln\left(P_{H_2}\right) + \frac{1}{2}ln\left(P_{O_2}\right)\right] \tag{6}$$

$$E_{Act} = \frac{RT}{\alpha\, zF}\, ln\left(\frac{I_{fc}}{I_0}\right) \tag{7}$$

$$E_{Con} =- 0.016\, ln\left(1 - \frac{i_{fc}}{25}\right) \tag{8}$$

$$E_{ohm} = i_{fc}R_{ohm} \tag{9}$$

The parameters of the fuel cell are shown in Table 3.

Table 3. Fuel cell parameters

Symbol	Parameters	Values
P	Typical peak power	**500 (W)**
N_{fc}	Number of Cells in stack nfc	**48**
T	Operating temperature (T)	**278–308 (K)**
I_{fc}	PEM fuel cell stack Rated current ifc	**20 (A)**
E_0	Standard reference potential (E0)	**1.229 (V)**
a	Constant in Tafel equation (a)	**0.13 ($V.K^{-1}$)**
b	Constant in Tafel equation (b)	**$1.9e^{-4}$ ($V.A^{-1}.K^{-1}$)**

The fuel cell is regulated by a feedback control system, as seen in the block diagram in**Fig. 6.A**. The current of the PEM fuel cell must be adjusted to a specified reference value in order to match the consumption fluctuations. The reference value of the PEM fuel cell current, I_{fc_ref}, is compared tothe measured current, I_{fc_meas},and the error signal is used as an input to the PI controller, which in turn calculates the voltage reference value. This voltage is developed in equation (10) to derive the modulation ratio, which is then compared to a triangular wave to provide control pulses for regulating the boost DC-DC converter, we have illustrated its power circuit in the **Fig. 6.B**.

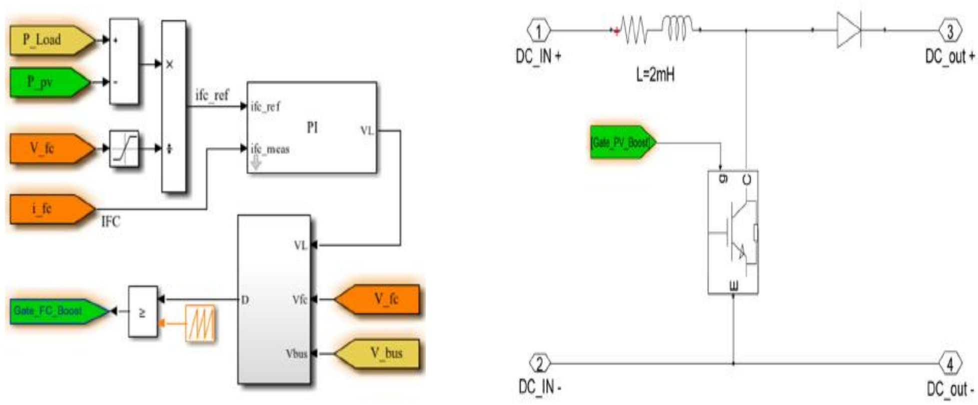

Fig. 6. fuel cell control block (A), Boost dc/dc converter (B)

$$\begin{aligned} V_{fc} &= V_L + (1-\alpha)V_{bus} \\ I_{fc}(1-\alpha) &= I_c + I_{bus} \end{aligned} \qquad (10)$$

2.3. DC-DC Converter

The power circuit of the DC-DC boost converter used for fuel cells or PV panels is illustrated in **Fig. 6.B**. The input voltage source energizes the coil when the IGBT switch is closed, and the Schottky diode is reverse-biased, there by providing isolation between the converter's input and output. When the switch is turned ON, the energy accumulated in the coil and the power source feed the load. The equation (11) gives averaged input and output values of current and voltage.

$$V_{out} = \frac{V_{in}}{(1-\alpha)}$$
$$I_{in} = \frac{I_{out}}{(1-\alpha)} \tag{11}$$

2.4. Lead-Acid Battery Model

Lead-acid batteries are popularly used due to their flexibility and affordability and are commonly found in uninterruptible power supplies and PVsystems. The main drawbackof this type of batteries is their low energy density, but they are known for their prolonged storage capacity[8,20,23]. The model used in this study is based on model available in the MATLAB/Simulink [40].

3. POWER CONTROL METHODOLOGY

Figure 7 presents a flowchart illustrating the different operating modes of the Energy Management Strategies (EMS), designed to maintain energy balance and ensure the reliable operation of the DC micro-grid despite fluctuating conditions and load variations. The system primarily uses photovoltaic solar energy, andin case of low PV power production, it uses thePEM to compensate for power lack. The battery operates in charging mode during periods of high powerproduction, and switches to discharging mode during typical power deficits. The management strategy proposed in this work is achieved thanks to the two DC-DC converters, as they can allow the gradual isolation of a source by acting on the duty cycle to reduce the current and avoid electric arcs.

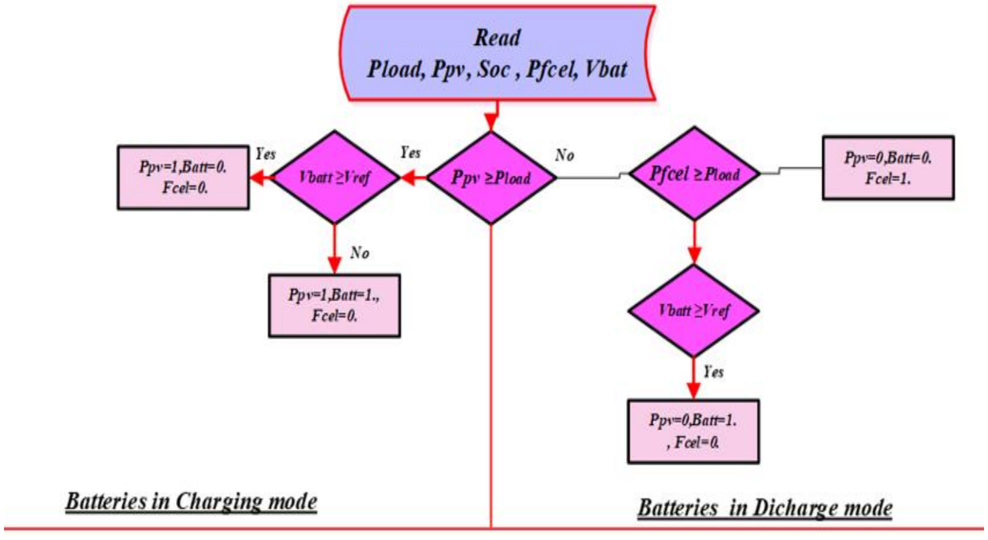

Fig. 7 . Proposed energy management strategy

4. SIMULATION RESULTS

To evaluate the effectiveness of the two MPPT techniques, namely FLC and conventional P&O, we use MATLAB/SIMULINK, conducting simulation tests that expose these algorithms to varying sunlight and temperature conditions. This section aims to compare the performance of the FLC-MPPT technique with P&O with FLC correction. We subject both techniques to simulation tests involving sudden variations in the incident sunlight on the photovoltaic panel.

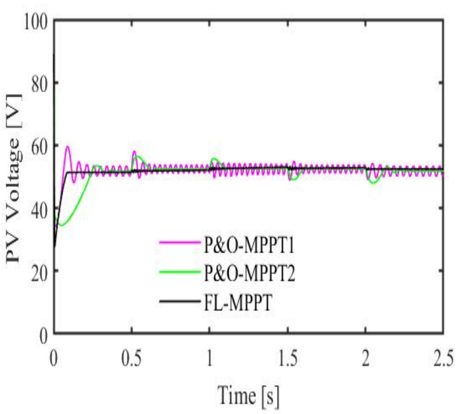

Fig. 8. PV Voltage

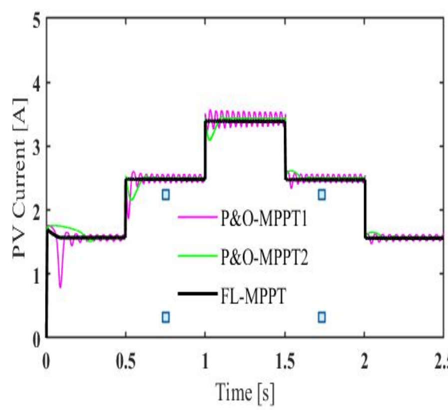

Fig. 9. PV current

We have tested the photovoltaic system with the MPPT controller under constant temperature and variable irradiation, and the results present the output PV voltage and current in**Fig.8** and **Fig.9** , respectively. In **Fig.8** , the PV voltage with fuzzy logic controller is constant and presents excellent signal quality, but with P&O MPPT 1 and 2(with FLC correction for **Δα**), the signal presents low oscillation. In **Fig.9** , the PV current with a fuzzy logic controller responds well to variations in irradiation and displays excellent signal quality without oscillation. However, when using P&O MPPT 1 and 2, the signal shows moderate oscillation.

The study's obtained result indicates that using a fuzzy logic controller significantly improves control over voltage and current signals, resulting in less oscillations and a more stable operating point compared to the P&O-MPPT1 and P&O-MPPT2 approaches.

We have simulated the global system with a proposed management energy strategy under variable irradiation and temperature after evaluating the proposed PV system and selecting the optimal MPPT controller.

The signals of irradiation and temperature are depicted in the figures, **Fig.10** and **Fig. 11**, respectively.

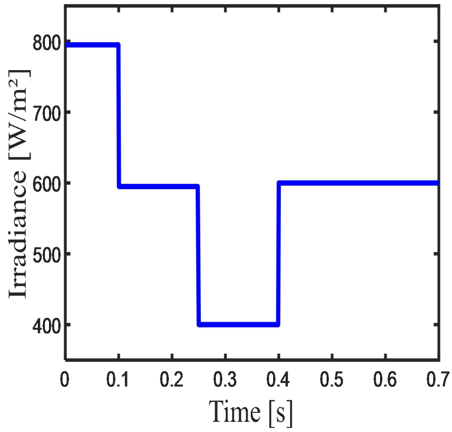

Fig. 10. Irradiation profile

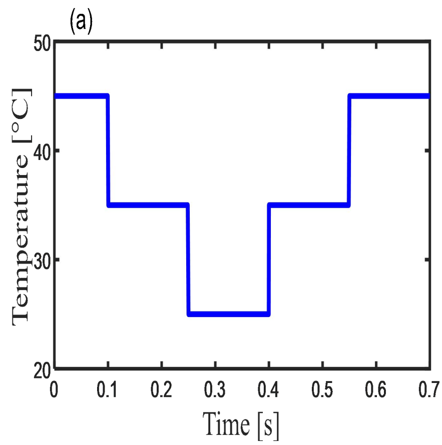

Fig. 11. Température profile

Once we inject the irradiation and temperature profiles into Matlab/Simulink, the management strategy controls the sources, leading to the simulation results shown below.

Fig. 12 presents the PV and FC voltages, with the PV voltage being Vmpp = 52.5V DC and the FC voltage being Vfc = 37V DC, both of which remain constant without any oscillations.

This voltages value is boosted to 102 volts with the DC chopper. Fig. 13 presents the DC bus obtained by the outputs of PV and FC sources.

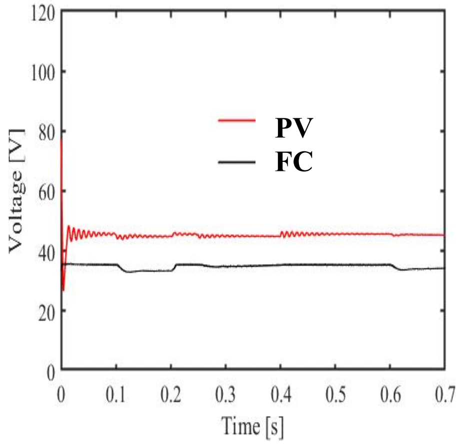

***Fig.12*. PV and FLC voltage**

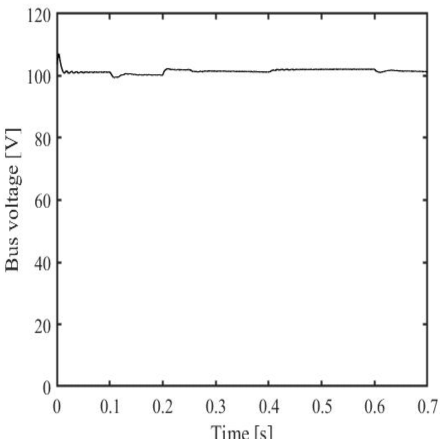

Fig. 13. Bus Voltage

Figures 14 and 15 show the variation of power for PV, FC, BAT sources, and the busDC (nano-grid). The nano grid (Bus power) receives power from thePV source in the interval 0 to 0.1s, with battery assistance. The FC is used to power the DC bus alongside with the PV panel in0.1 to 0.2s,with the battery compensating for any deficit.In unfavorable conditions, the FC and BAT feed the nano grid, with assistance from the PV panels. The presented results show that the solar panels, the fuel cell, and the batteries work together to supply power to the DC nano grid, regardless of sudden load changes or unfavorable irradiation and temperature conditions.

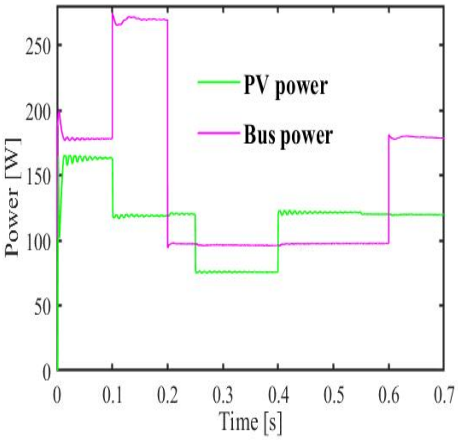

Fig. 14. Bus and PV power

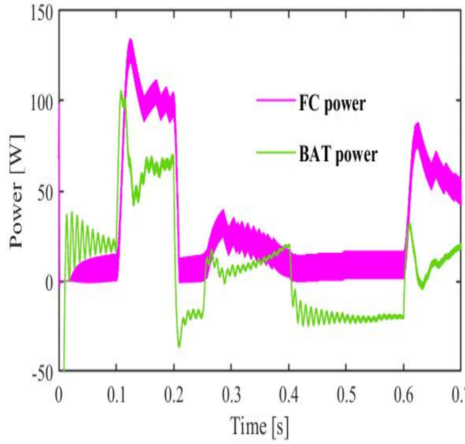

Fig. 8. FC and Battery Power

5. Conclusion

This paper presents an approach to manage renewable electric energy sources, focusing on rapid dynamic response through closed-loop system control. It highlights the potential response time of the fuel cell as the main backup source for the system. By comparing the Perturb and Observe Maximum Power Point Tracking (P&O-MPPT) technique with Fuzzy Logic Maximum Power Point Tracking (FL-MPPT), it is observed that the latter generates fewer oscillations and offers a more stable operating point. This results in accelerated convergence and response time of the system. Simulation results showed up the increased precision of the fuzzy controller for Maximum Power Point operation, as well as low bus voltage oscillations. Furthermore, in the event of sudden load changes, the results demonstrate that power is jointly supplied by solar panels, the fuel cell, and the batteries. In perspective, the experimental system is currently under construction, and promising results are being achieved.

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