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Optimized and smart control of photovoltaic system with batteries in a standalone application

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ABSTRACT

The subject of our study is the optimization and smart control of an isolated photovoltaic system. To achieve this goal, we have used a power management control (PMC) system to govern the examined system, relying on fuzzy logic control (FLC) and specified decision criteria. The PMC protects the batteries against deep discharges and overloads, ensuring that the load receives uninterrupted power. Using fuzzy logic control, the PMC can efficiently adapt to changing conditions and make decisions to improve system performance. The studied system consists of solar panels and batteries interconnected with a converter enabling the bi-directional flow of current. This feature facilitates the charging and discharging of the batteries under various meteorological conditions. Two different algorithms have been used for power optimization. The findings demonstrate good performance of the proposed approach utilizing the fuzzy logic control method. These findings were consistent across two diverse profiles, underscoring the efficacy of our approach in diverse operating conditions.

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1. INTRODUCTION

Solar energy is important in many applications since it is renewable is renewable and environmentally friendly. However, its efficiency is dependent on solar irradiance, which can fluctuate based on factors such as weather variations. Photovoltaic (PV) panels are typically integrated with maximum power point tracking (MPPT) algorithms to improve solar energy efficiency [1-4]. In the literature, various MPPT algorithms have been developed. They include both traditional strategies, such as perturb & observe (P&O) and incremental conductance (Inc Cond), as well as modern techniques, such as fuzzy logic controllers (FLC) and sliding mode controllers (SMC) [5].

When many energy sources are used in a system, implementing a power management control is critical. This control mechanism guarantees that available energy sources are used efficiently and that the system operates optimally. Numerous publications are dedicated to power management in PV systems, addressing a wide range of applications and issues. These studies have concentrated on applying smart power management strategies [6- 12], demonstrating the systems efficiency in the face of climatic and load demand changes. Specifically, in references [5-7], researchers created energy management methods for self-sufficient renewable energy sources.

Meanwhile, references [9-14] discuss fuzzy energy management approaches for electrifying rural families, demonstrating their potential to improve access to electricity in underserved areas. Furthermore, in references [12-13], the authors present an application for electric vehicles that includes a supervisory control system for a photovoltaic/hydrogen/battery bank hybrid configuration. These numerous studies demonstrate the versatility of power management approaches for PV systems and their usefulness in enabling dependable and sustainable energy solutions in a variety of scenarios [14-19].

A power management system applied to the PV system is developed in this work. The system is based on FLC, which allows it to successfully handle unpredictable changes in climatic variations conditions and load demand. To maximize energy extraction, we use the MPPT strategy, which combines the P&O method with an FLC. Our proposed power management system ensures that the PV generator produces maximum power while also protecting the batteries from overcharge and deep discharge, as well as satisfying the load's energy requirements. Simulation findings performed using MATLAB/Simulink show that the suggested energy management system is more operable, verifying its effectiveness in applications. The most important points of this work can be summarized as follows:

1. High-performance PMC by development of a smart PMC system for an isolated PV system with battery storage.
2. Use of artificial intelligence techniques by implementation of FLC for intelligent power management.

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3. Precise battery control by providing precise control to protect against overcharge and deep discharge.
4. Integration of the P&O and FLC methods to maximize energy extraction from the PV system and validation through simulation by demonstrating the effectiveness and operability of the proposed MPPT system through simulation results using MATLAB/Simulink.

2. SIZING OF THE STUDIED SYSTEM

A PV generator, a battery bank, two DC/DC converters, and an inverter that provides power to an AC load make up the proposed structure seen in Figure 1. The efficacy of the power management system is determined by the operation of three switch states, indicated as K_1, K_2, and K_3. Following the sizing process, the results are summarized and shown in Table 1.

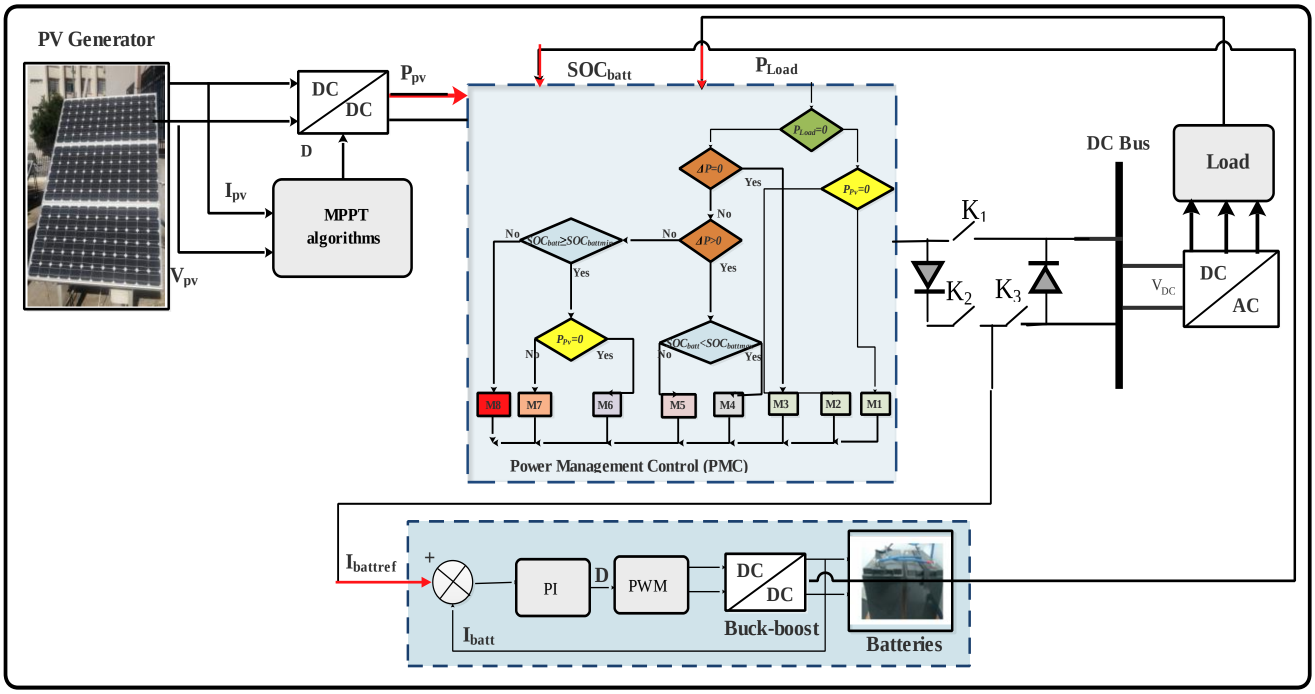


Fig. 1. Proposed optimized PV system with batteries and power management control.

Table 1. Sizing results of designed system.

Components	*Variables*	*Values*
PV Panels	$N_{PV\text{-}total}$	22
	$N_{PV\text{-}serial}$	2
	$N_{PV\text{-}parallel}$	11
	$P_{c\text{-}total}$	1.87 kWp
	$S_{PV\text{-}total}$	14.2 m²
	P_{MPP}	1678 Wc
	U_{MPP}	32 V
	I_{MPP}	53 A
Battery	$V_{batt\text{-}unit}$	12 V
	$C_{batt\text{-}unit}$	100 Ah
	$N_{batt\text{-}serial}$	2
	$N_{batt\text{-}parallel}$	5
	$C_{batt\text{-}total}$	500 Ah
	J_{aut}	1.5 day

3. SYSTEM MODELING

3.1. Modeling of Photovoltaic Panels

Different models are applied to PV panels. The following model is considered in this work as seen in Figure 2 [3, 7, 20].

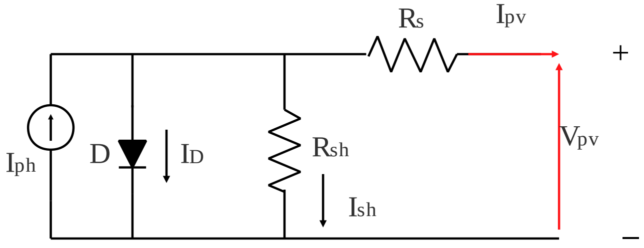


Fig. 2. PV cell model [4].

Where: I_{ph} is the photocurrent, I_d is the diode current, I_{Rsh} and R_{sh} are respectively the shunt current and resistance, I_{pv} is the PV current, and R_s is the serial resistance. The electrical characteristic is described by Equation (1) and (2) [21].

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

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

The electrical PV characteristics of a 80 Wp PV panel given in Table 2 have been determined using a test bench in the Figure 3 and the experimental results are compared to those obtained by simulations in Figure 4 (a) and (b) [4].

Table 2. PV solar parameters of 80 Wp [3].

Parameters	*Symbol*	*Values*
PV power	P_{PV}	80 Wp
Maximum current at MPP	I_{mpp}	4.58 A
Maximum voltage at MPP	V_{mpp}	17.5 V
Short circuit current	I_{sc}	4.95 A
Open circuit voltage	V_{oc}	21.9 V
Current temperature coefficient	α_{sc}	3.00 mA/°C
Voltage temperature coefficient	β_{oc}	-150.00 V/°C

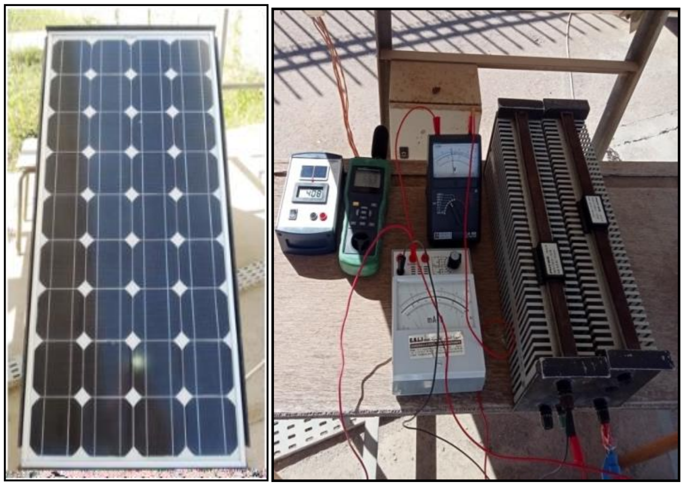
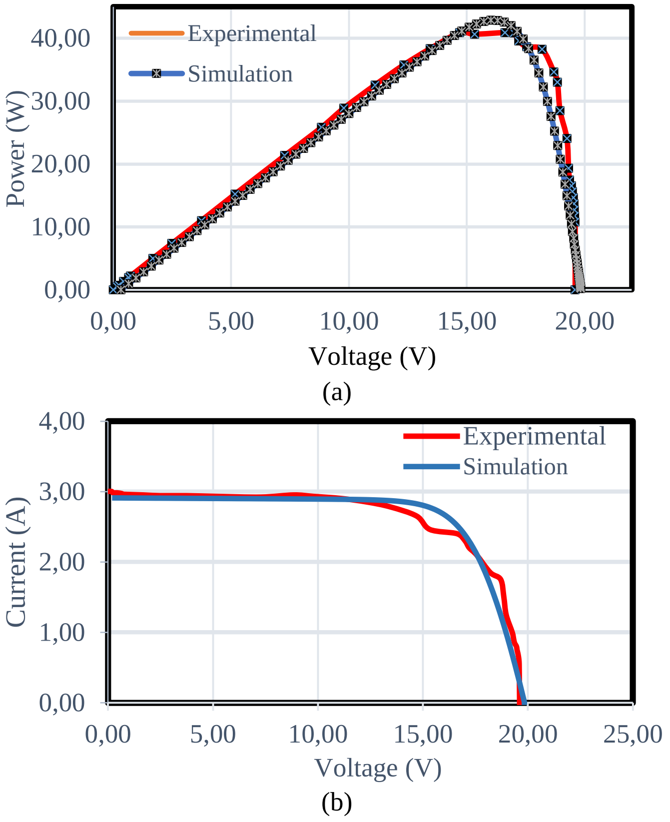


Fig. 3. Determination of the electrical characteristics.



(a)

(b)

Fig. 4. Electrical characteristics under different solar irradiance, (a) $P_{pv}=f(V_{pv})$, (b) $I_{pv}=f(V_{pv})$.

3.2. Battery Model

The model depicted in Figure 5 illustrates the framework utilized in this paper. It consists of two primary electrical components: a voltage source E_b and an internal resistance R_{Batt} [13-15].

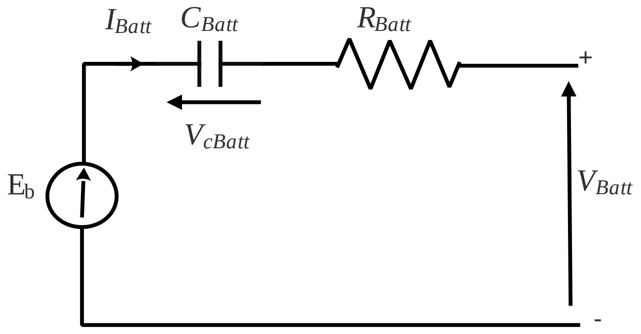


Fig. 5. Battery model.

$$V_{Batt} = E_b \pm R_{Batt} \cdot I_{Batt} \tag{3}$$

$$C_{Batt} = C_{10} \times \frac{1.76 \times (1 + 0.005 \times \Delta T)}{1 + 0.67 \times \left(\frac{I_{Batt}}{I_{10}}\right)} R_{Batt} \cdot I_{Batt} \tag{4}$$

$$SOC = (1 - \frac{Q}{C_{Batt}}) \tag{5}$$

$$Q = I_{Batt} \times t \tag{6}$$

Where: C_{Batt} battery capacity, C_{10} is the rated capacity, SOC is the battery state of charge, and t is current the discharging time.

The charge and discharge voltage battery are given as [13]:

$$\begin{aligned} V_{Batt-charg} &= n_{Batt-serial}.(1.965 + 0.12SOC) \\ &- n_{Batt-serial} \frac{I_{Batt}}{C_{10}} \left(\frac{4}{1 + I_{Batt}^{0.86}} + \frac{0.27}{SOC^{1.2}} + 0.02 \right).(1 - 0.007\Delta T) \end{aligned} \tag{7}$$

$$\begin{aligned} V_{Batt-dischareg} &= n_{Batt-serial}.(2 + 0.16SOC) \\ &- n_{Batt-serial} \frac{I_{Batt}}{C_{10}} \left(\frac{6}{1 + I_{Batt}^{0.86}} + \frac{0.48}{SOC^{1.2}} + 0.036 \right).(1 - 0.0025\Delta T) \end{aligned} \tag{8}$$

3.3. MPPT Control Methods

3.3.1. P&O method

The perturb and observe approach operation is based on the adjustment of the step size of the voltage reference. Figure 6 shows a flowchart describing the operation [3, 20].

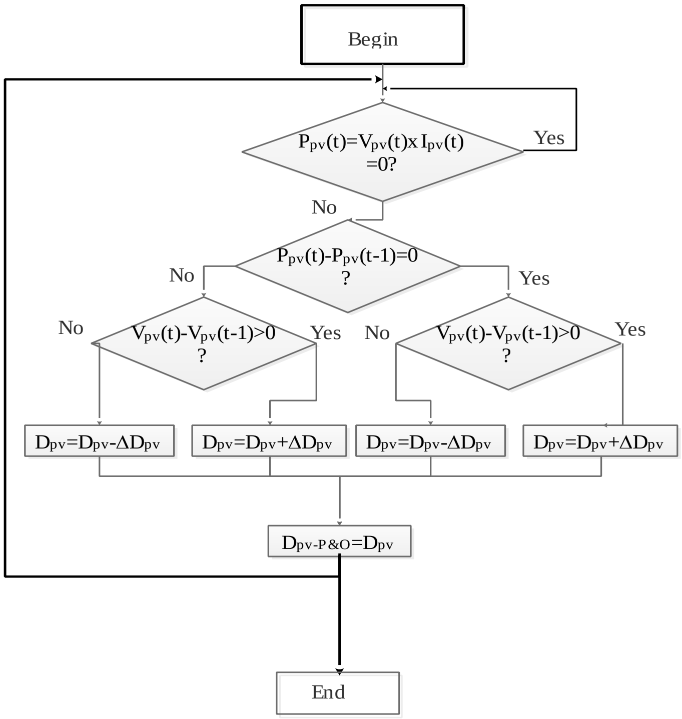


Fig.6. P&O algorithm flowchart.

The MPPT controller determines the switch's duty cycle (D) using the P&O technique and Equation (9) and (10) [4].

$$V_{out} = V_{pv}\left(\frac{1}{1-D}\right) \tag{9}$$

$$I_{out} = I_{pv}(1-D) \tag{10}$$

3.3.2. FLC method

Membership functions define how each input variable is mapped to a degree of membership within a fuzzy set. In our case, we have used the following seven membership functions for both input variables: Negative Big (NB), Negative Small (NS), Negative Medium (NM), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The fuzzy inference system evaluates all the rules in parallel to make a control decision.

1. *Fuzzification:* The input variables (*e* and *Δe*) are fuzzified using the membership functions
2. *Inference engine*: Each fuzzy rule is evaluated by applying the fuzzified inputs. The result is a set of fuzzy outputs.
3. *Defuzzification:* The aggregated fuzzy set is converted back.

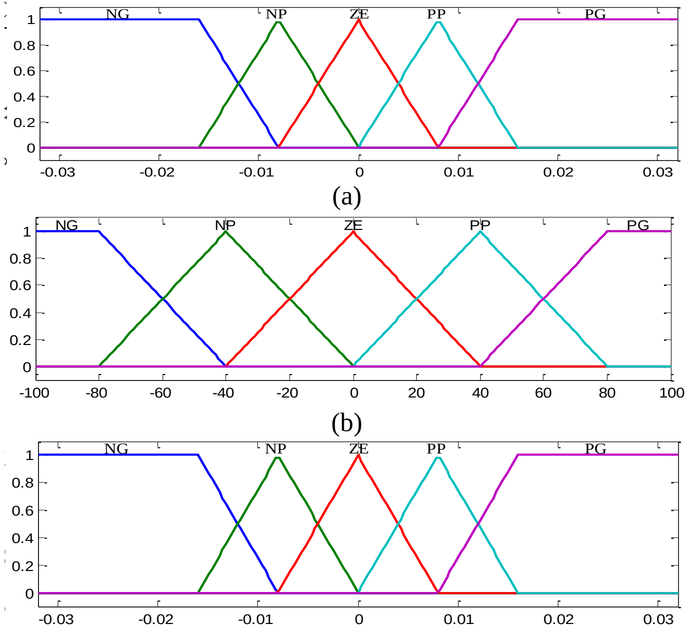
The MPPT FLC system is structured with two inputs as seen in Figure 7.

The error and the change in error are calculated using the following relations [22-24]:

$$e(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{11}$$

$$\Delta e(k) = e(k)-e(k-1) \tag{12}$$

These relations are defined by the various rules that link the inputs to the output decision of the FLC, as grouped in Table 4.



(a)

(b)

(c)

Fig.7. Membership functions (a) Input variable *e*, (b) Input variable DE, (c) Output variable D.

Table 4. Fuzzy logic controller rules.

e	*Δe*						
	NB	NM	NS	ZE	PS	PM	PM
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

3.3.3. Comparison results

A comparison of the two studied techniques is undertaken under standard test conditions (STC). As depicted in Figure 8, the FLC demonstrates a faster and more accurate response compared to P&O. While the P&O method exhibits oscillations in a steady state, the FLC ensures a smoother and more precise performance [25, 26].

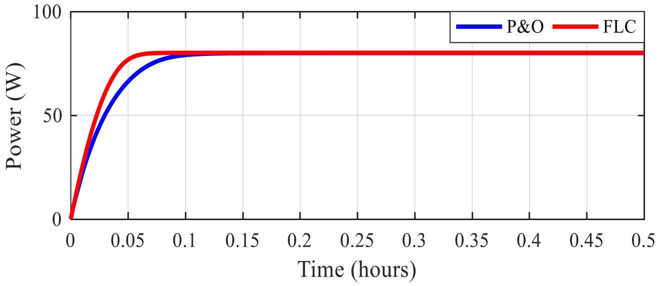


Fig.8. Photovoltaic power under P&O and FLC strategies.

4. EXPERIMENTAL STUDY

The study examines the application of the two studied techniques in the PV system. The experimental bench of the MPPT is given in Figure 9.

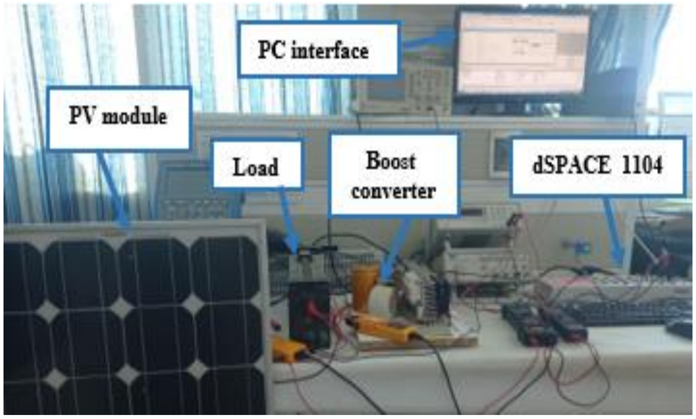


Fig. 9. The used experimental hardware.

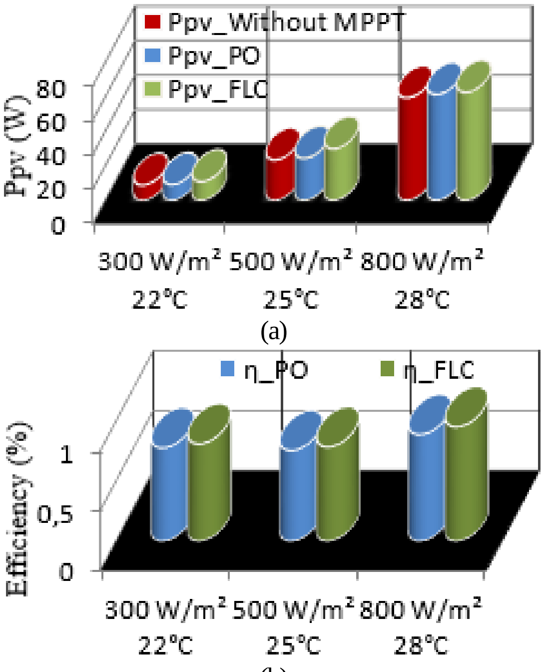
Data acquisition and MPPT control are conducted using dSPACE 1104 software, enabling real-time control. Sensors measure the voltage and current of the SUNTECH STPO80S-12/Bb solar panel, and the signals are processed by dSPACE hardware optimizing. Three tests were conducted to evaluate the effectiveness of the MPPT controller in Table 5.

Table 5. Tests for the MPPT controllers.

Tests	*G (W/m²)*	*Ta(°C)*
Test a	300	22
Test b	500	25
Test c	800	28

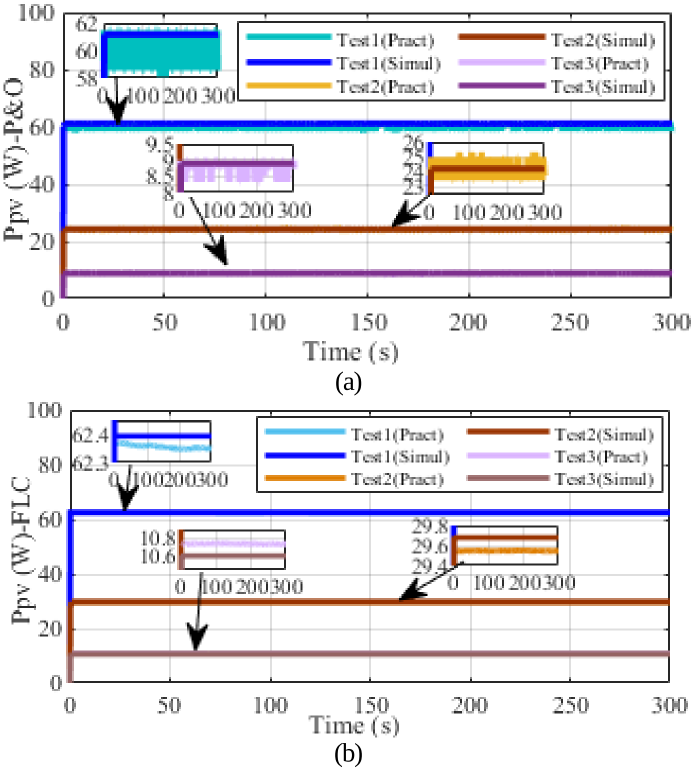
The PV powers and efficiencies for P&O and FLC are represented respectively in Figure 10(a, b). According to Figure 10(b) the FLC-based MPPT control method achieves a tracking efficiency rate of 95%, surpassing the 88% obtained with the P&O method. These tests aimed to calculate the amplitude of oscillations.

Figure 11(a, b) represents a comparison between practical and simulation results across various tests forthe two MPPT strategies. Figure 11(a) highlights a significant difference between the experimental and simulated results, characterized by a more pronounced oscillation amplitude in the practical data. The maximum power oscillation is 5 W for the P&O approach, but only 0.01 W for the FLC method as in Figure 11(b). These findings highlight the need to use experimental data to validate simulations.



(b)

Fig. 10. Evaluation of various powers and MPPT efficiency for each strategy, (a) PV power, (b) efficiency.



(a)

(b)

Fig.11. Comparison between practical and simulation results across various tests, (a) P&O, (b) FLC.

5. CONTROL OF THE STUDIED SYSTEM

The major decision elements for a PMC strategy are the PV generator's power output and the SOC. Implementing this management method allows the PV generator to provide the most power possible, protects the batteries, and guarantees that energy requirements are met [12]. The system operates as shown in Figure 12 in one of the following modes using the following Equation (13) and (14) [4].

$$\Delta P = P_{pv} - P_{Load} \tag{13}$$

$$SOC_{min-Batt} < SOC_{batt} < SOC_{max-Batt} \tag{14}$$

The fuzzy logic controller generates four control signals, K_1, K_2, and K_3, from four inputs: charging power P_{Load}, ΔP: excess power, the SOC, and PV power P_{PV}. Hence the output signals are: K_1: Control signal for the switch supplying the load with PV power, K_2: control signal for the switch that charges the battery with PV power, K_3: control signal for the switch that supplies the load, and battery.

Fuzzification is converting digital input/output variables into linguistic terms in Table 6.

Table 6. Linguistic variables.

Input and output variables	*Linguistic variables*		
SOC	MIN	MOY	MAX
	0-30	30-90	90-100
DP	P	Z	N
	>0	=0	<0
P_{Load}, P_{pv}	Z		NZ
	0		1
K_1,K_2, K_3	ON		OFF

From the fuzzy subsets corresponding to the fuzzification of the inputs, the inference mechanism calculates the fuzzy subset relating to the control of the system, using the SUGENO method, given that precise numerical outputs are required [8]. For PMC, FLC is used and the different inputs and outputs of Smart PMC are as follows in Figure 12.

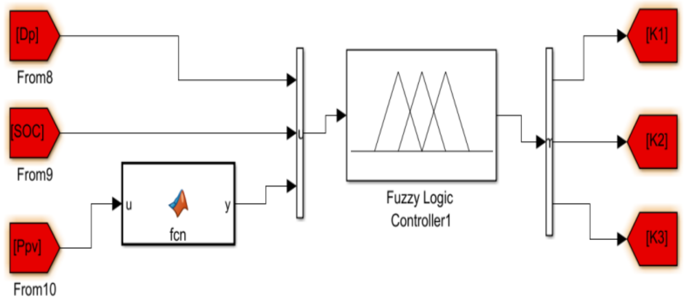


Fig.12. Different inputs and outputs of PMC.

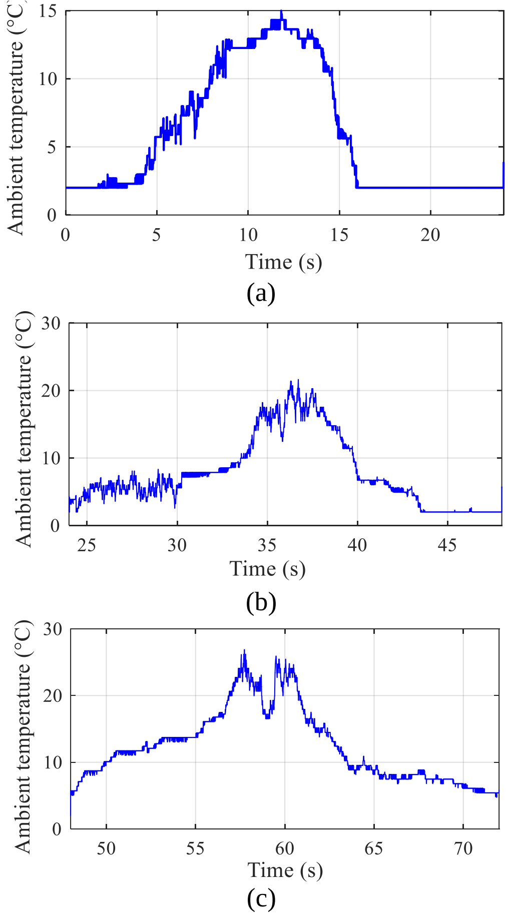
Table 7 presents the rule table of the fuzzy logic controller.

Table 7. States of the various switches.

Inputs				*Outputs*			
DP	*SOC*	P_{pv}	P_{Load}	K_1	K_2	K_3	*Mode*
Z	/	/	/	ON	OFF	OFF	1
P	MIN	/	/	ON	ON	OFF	2
P	MOY	/	/	ON	ON	OFF	2
P	MAX	/	Z	OFF	OFF	OFF	3
P	MAX	/	NZ	ON	OFF	OFF	4
N	MOY	Z	/	OFF	OFF	ON	5
N	MAX	NZ	/	OFF	OFF	ON	5
N	MOY	Z	/	ON	OFF	ON	6
N	MAX	NZ	/	ON	OFF	ON	6
N	MIN	Z	/	OFF	OFF	OFF	7
N	MIN	NZ	/	OFF	ON	OFF	8

6. STUDIED SYSTEM SIMULATION

The system comprises 22 PV panels of 80 W_p, 10 batteries (12 V and 100 Ah), and a load simulating a house with a daily consumption of 4869Wh/day. Each component of the system, including PV panels, DC/DC converter, batteries, and load, is modelled as separate blocks. The MPPT and the management system are controlled by fuzzy logic. The evaluation of the system's performance is made on different four days as seen in Figure 13(a-d) for measured ambient temperature and Figure 14 (a-d) for measured solar irradiance. The chosen load profile is represented in Figure15



(a)

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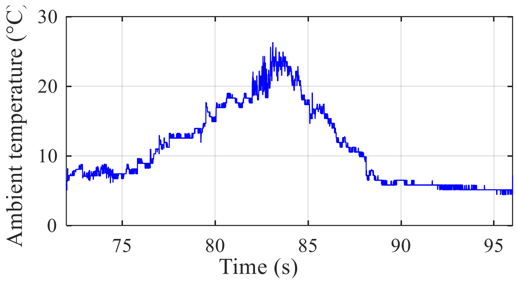
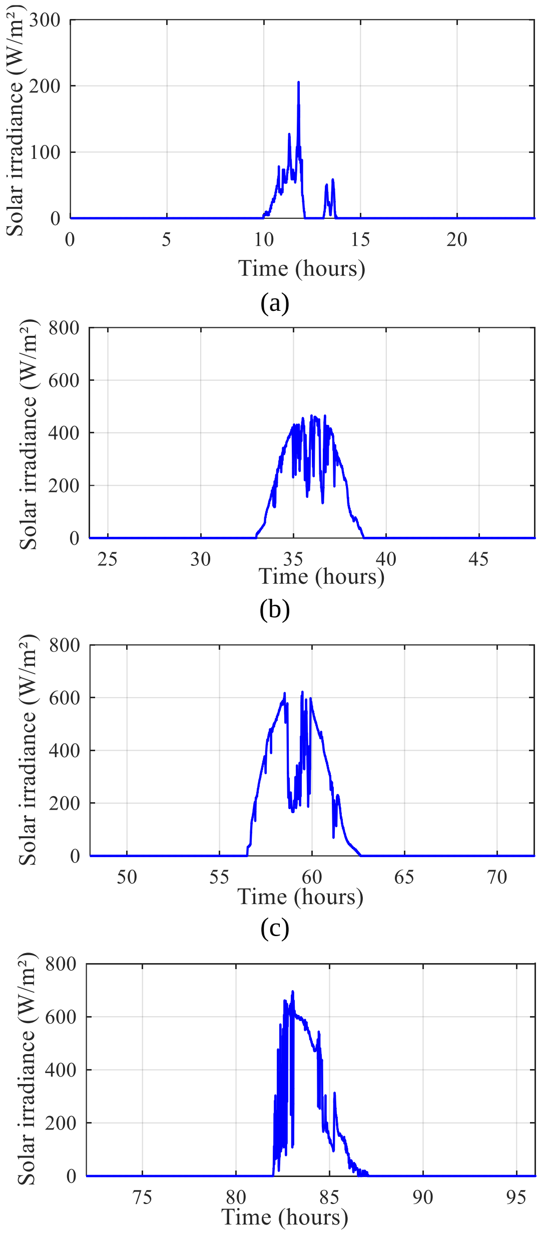


(d)

Fig.13. Ambient temperature, (a) profile 1, (b) profile 2, (c) profile 3, (d) profile 4.



(a)

(b)

(c)

(d)

Fig. 14. Solar irradiance, (a) profile 1, (b) profile 2, (c) profile 3, (d) profile 4.

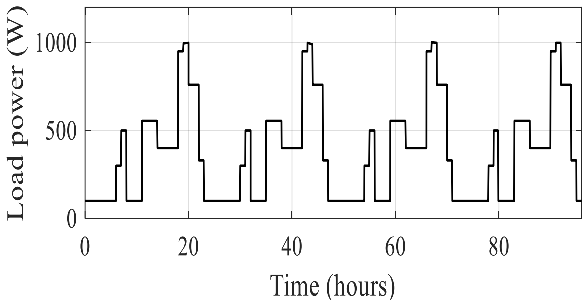


Fig.15. Load power variations.

After simulation under MATLAB/Simulink,the different results are shown in Figures 16-20. The variation of the SOC is shown in Figure 16. It can be observed that the use of management protects batteries against overcharging. It varies between 44.25% and 90%. The DC bus voltage at the inverter input aligns with its reference as in Figure 17, maintaining it at the required level (V_{DC_ref}=24 V) with minor fluctuations.

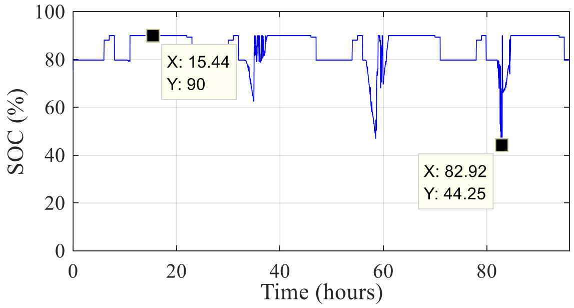


Fig. 16. Battery state of charge.

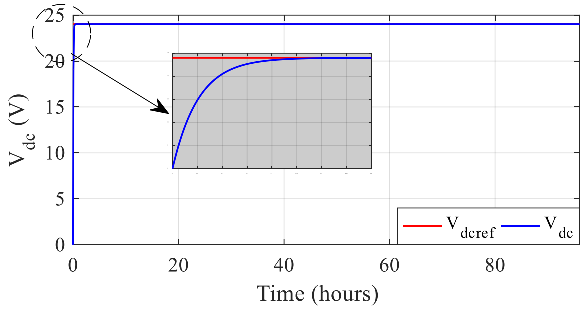
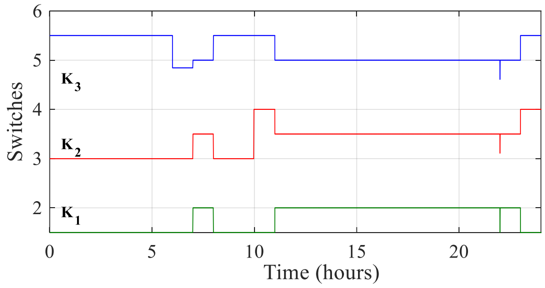
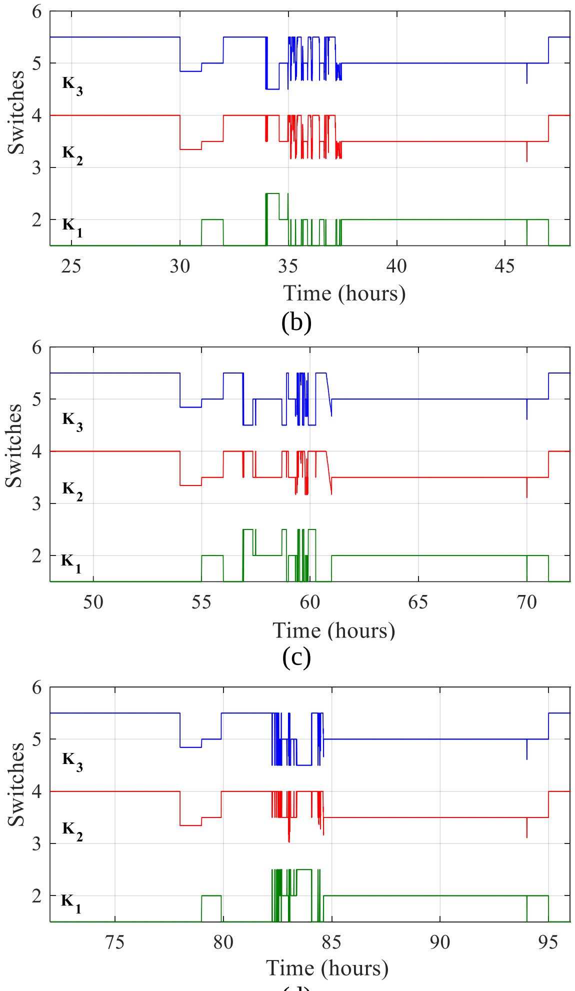


Fig. 17. DC bus voltage at the inverter input.

The different switches during each day profile, obtained when the proposed PMC is executed are given in Figure 18 (a-d).



(a)



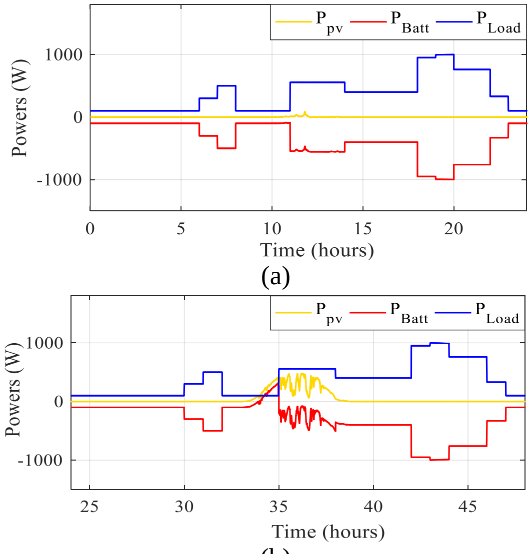
(b)

(c)

(d)

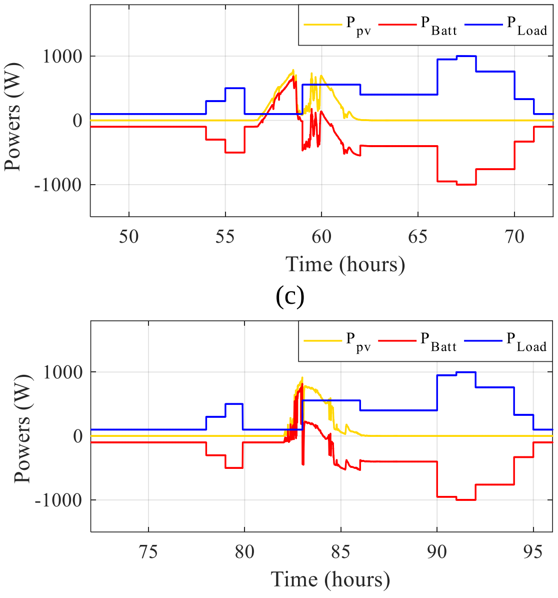
Fig. 18. The different switches; (a) profile 1, (b) profile 2, (c) profile 3, (d) profile 4.

The powers during each day profile are given in Figure 19.



(a)

(b)



(c)

(d)

Fig. 19. The different obtained powers; (a) profile 1, (b) profile 2, (c) profile 3, (d) profile 4.

The findings obtained demonstrate the advantages of this method for controlling and optimizing energy flows. The simulation highlights the system's ability to switch to different modes depending on load conditions and solar energy availability.

4. CONCLUSION

In this paper, a smart control of a PV system with battery storage has been presented. Simulation findings show good performances using the adopted control**.** The paper effectively highlights the advantages of intelligent management systems over traditional approaches, particularly in their ability to precisely control the SOC across multiple states. Traditional management approaches often use only two SOC levels. Intelligent management systems are shown to operate over a wide range of SOC states, offering greater flexibility and adaptability compared to traditional methods. The study includes applications for four different solar irradiance profiles, which correspond to different geographical locations. This ensures that the method, tested under varying solar conditions, demonstrates its applicability and reliability in diverse environments. By presenting these findings, the paper contributes valuable insights to the existing body of research on photovoltaic systems and smart power management. In the perspectives of this work, it is intended to implement the proposed system in real-time.

Nomenclature

C_{10}	Rated capacity, Ah
D	Output variable
e	Error
E_b	Voltage source
I_{batt}	Current battery, A
I_d	Diode-current, A

I_{MPP}	Maximum power point current, A
I_{out}	Output current, A
I_{ph}	Photocurrent, A
I_{pv}	PV current, A
I_{Rsh}	Shunt current, A
G	Solar radiation, W/m^2
K_1, K_2, K_3	Switches state
CE	Change in error
$N_{PV\text{-}total}$	PV panel number
$N_{PV\text{-}serial}$	Serial PV panel number
$N_{PV\text{-}parallel}$	Parallel PV panel number
$P_{c\text{-}total}$	Total photovoltaic power, W_c
P_{Load}	Load power, W
P_{pv}	PV power, W
P_{MPP}	Maximum power point, W
R_{bat}	Internal resistance, Ω
R_s	Series resistance, Ω
R_{sh}	Shunt resistance, Ω
$S_{PV\text{-}total}$	Total PV area, m^2
U_{MPP}	Maximum power point voltage, V
t	Discharging time, h
V_{out}	Output voltage, V
α_{sc}	Current temperature coefficient
β_{oc}	Voltage temperature coefficient
Δe	Input variable
ΔT	Accumulator's heat, °C
ΔP	Excess power, W
FLC	Fuzzy logic controller
MPP	Maximum power point
MPPT	Maximum power point tracking
P&O	Perturb and Observe
SMC	Sliding mode controller
SOC	Battery state of charge

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