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A robust fuzzy logic PI controller for solar system battery charging

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ABSTRACT

This article discusses a design of a photovoltaic (PV) system that allow charging a battery under variable climatic circumstances. The system under study is composed of two DC-DC converters a boost and Buck converter. The first one is used to extract the maximum power from the PV array through a novel variable step size P&O based MPPT offering a high tracking accuracy compared to classical approaches such PO and INC. The second converters aim at regulating the output voltage and current that feeds the battery using a robust optimal PI (O-PI) which has a faster time response and high accuracy compared to classical PI and PID controllers. The overall system and the control strategies are tested and validated in MATLAB/Simulink environment. The simulations results show the effectiveness and the robustness of the system.

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1. INTRODUCTION

The global need for electricity has increased dramatically, especially in remote rural areas and mountains. Coal, oil, gas and other fossil fuels are still needed to provide electricity and heat. However, they are the main emitters of CO_2 and their stocks, unlike renewable sources, are finite. Photovoltaic (PV) systems have attracted the interest of many people due to their low cost. These systems have several advantages, such as being environmentally friendly and offering a higher degree of immunity. If not consumed directly the generated energy will be stored in batteries for later use. However, these panels have low efficiency range [1] as well as a current and voltage that are influenced by varying environmental circumstances such as temperature degree and the amount of radiation coming from the sun [2]. Due to the PV's nature of nonlinearity concerning the electrical energy production, there is merely one point on its curve where the PV cell generates the greatest amount of electrical power. A special control algorithm is needed to keep tracking of the maximum power point MPP and here where the technique of maximum power point tracking interferes to enhance the performance of solar generators. Traditional procedures such as fractional open circuit (FOCV), perturb and observe (P&O), fractional short circuit (FSCC), conductance increment (INC) [2] and innovative strategies such as perturb and observe (P&O) [3] are divided into two main groups in the literature. However, techniques such as fuzzy logic (FLC), sliding mode controller (SMC), neural network (ANN) and others can be discovered [4].

For charging the batteries, several control techniques are proposed, Latif and Hussain [5] investigated a system to charge a battery using an MPPT incremental conductance strategy that employs a SEPIC converter and PI control deployed to a Buck converter to compare the explored system with similar work. In order to charge a battery, a DC-DC Boost converter uses fuzzy logic as an MPPT approach, and a Buck converter uses a PI controller. This system was explored by Yilmaz *et al*. [6], however, using PI controllers are not suitable for this process since the gains are tuned manually or by optimization techniques and fixed, so it is more suitable to develop other techniques where the gains are variable during nonlinear variations. Sliding mode and model predictive controllers are proposed as solution of lacks and drawbacks of PI controllers, but the implementation of these is difficult; since the sliding mode need to define the sliding surface which is a part of the control law [7], [8]. Moreover, the model predictive, require programming of system parameters, which increases the number of sensors used and leads to high implementation costs.

Fuzzy control, which is a part of fuzzy logic, appeared very effective given the advantages such the non-necessity of a mathematical model and the input variables are considered as fuzzy linguistic inputs [9]. So, this concept allows to improve the behavior of PI controller whit the conservation the same easiness of implementation, with generation of variable gains with better set point control (constant current and voltage). The studied system consists of a solar generator, connected to a DC-DC boost converter controlled by a novel MPPT known as a variable step size P&O (VSS P&O). The concept is to adjust the step size of the MPPT P&O algorithm using fuzzy logic controller. A DC-DC Buck converter is controlled by a PID controller to target the necessary voltage in order to charge a battery by adjusting the Kp, Ki and Kd coefficient. The main contribution of this paper is proposing a robust PI-FL controller to adapt the PI parameters called "optimal PI". Figure 1 illustrates the configuration of the system.

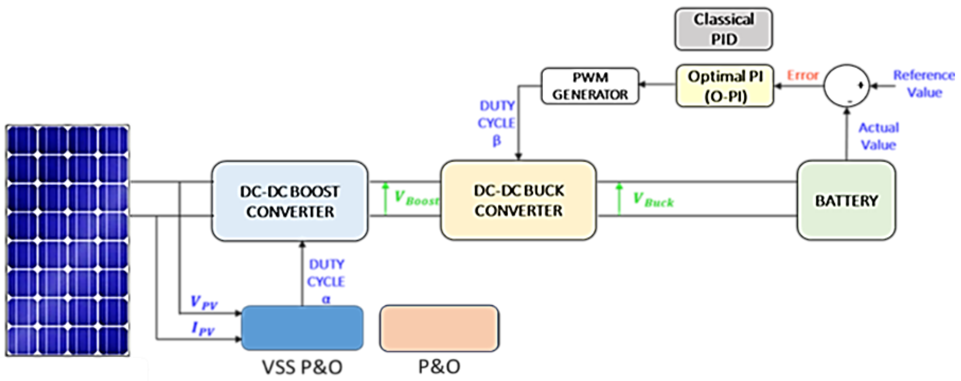

Figure 1. Functional representation of the suggested system

2. MODELING AND FEATURES OF THE PV PANEL

Solar radiation is converted to an exploitable energy thought photovoltaic panels. Several equivalent circuits are distinguished in the literature, differentiated in the number of the used components. The most used is based on a single diode. This circuit is used due to its simplicity and ability the describe the non-linear behavior of PV panels [10]. Figure 2 displays the electrical model.

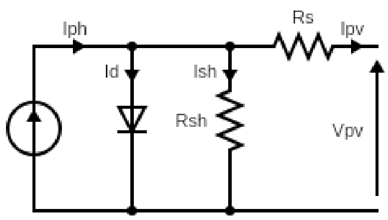

Figure 2. A PV cell's equivalent circuit

The output current Iph is described through as (1) [11]:

$$I_{ph} = [I_{sc} + K_I(T_c - T_{ref})]\frac{G}{G_{ref}} \quad (1)$$

The current at the junction is expressed by (2) [11]:

$$I_d = I_s(exp(\frac{q.(V+R_sI)}{N.K.T} - 1) \quad (2)$$

Using the following equation, Ipv is defined by (3) [11]:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (3)$$

where, I_{ph}, I_d and I_{pv} are
I_{ph}: The short circuit currents
I_d : The reverse saturation current
I_{pv} : The photovoltaic current
The sizing of the PV panels is done by referring to the equations presented in [12]. Table 1 summaries the specifications of the adopted PV panel.

Table 1. 1Soltech 1STH-350-WH PV generator table of parameters

Parameters	Value
The maximum power (Pmpp)	350 W
The maximum voltage (Vmpp)	43 V
The maximum current (Impp)	8.13 A
Short-circuit current (Isc)	9.4 A
Open circuit voltage (Voc)	51.1 V
Temperature coefficient of open circuit voltage	-0.36
Temperature coefficient of short-circuit current	0.09

2.1. Effect of solar radiation

Photovoltaic (PV) systems appear to have nonlinear characteristics that are affected by many variables such temperature and solar radiation. Panel efficiency increases with the amount of solar radiation at a given temperature, also the current emitted by the panel essentially depends on the sun radiation intensity as depicted in Figure 3.

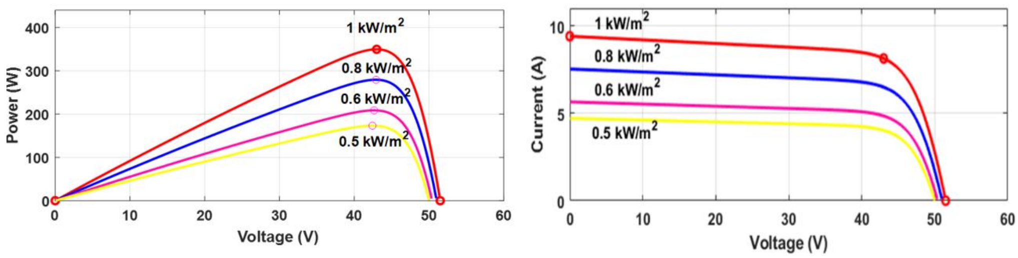

Figure 3. Curve of P-V and I-V with solar radiation changing

2.2. Effect of temperature

The PV panel's output power is negatively impacted by the temperature for a fixed amount of solar radiation. As the temperature of the cells increases. Figure 4 illustrates that the panel has output power decrease.

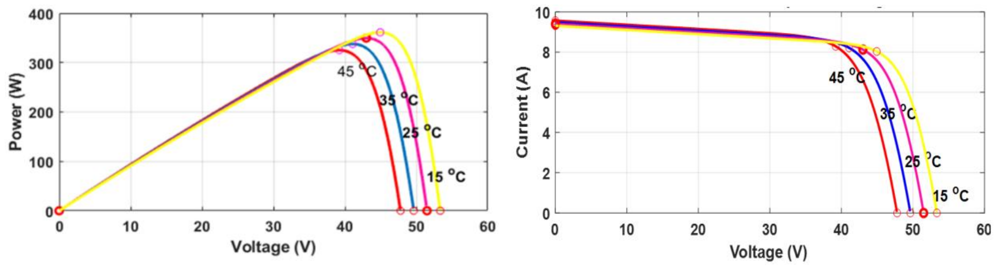

Figure 4. Curve of P-V and I-V with temperature changing

3. DC-DC CONVERTER
3.1. DC-DC boost converter
The figure above shows the boost converter's fundamental circuit. This particular converter is generally used as adaptation circuit, to provide a high output voltage [13]. It's composed of an inductor, a controlled switch, a diode and a capacitor. Figure 5 illustrates the equivalent circuit.

The performance of the DC-DC converter is influenced by the size of the inductor and capacitor. You can determine their values by (4) [14].

$$L = \frac{D.V}{\Delta I_L.f} C = \frac{I_0.D}{\Delta V_0.f} \tag{4}$$

3.2. DC-DC Buck converter
A switching power supply called a buck converter or series chopper changes one DC voltage into a lower DC voltage. A well-designed buck converter can control the output voltage and operate at high efficiency (up to 95%). The input voltage can be decreased. The electrical circuit equivalent is depicted in Figure 6 [15]. Still for the Buck converter, the inductance and capacitance values can again be given as (5) [16], [17].

$$L = \frac{V_0.(1-D)}{\Delta I_L.f} C = \frac{(1-D)\,V_0}{8\Delta V_0.f} \tag{5}$$

With: ΔI_L, ΔV_0 which stand for the ripple rates of the output voltage and the current flowing through the inductor, respectively.

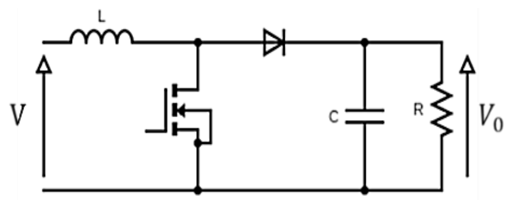

Figure 5. Boost DC-DC converter

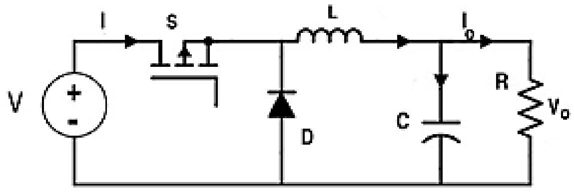

Figure 6. Buck converter topology

4. CONTROL OF STUDIED SYSTEM
MPPT is an algorithm that allow tracking the maximum power point and extracts the available power in the solar generator under all environmental conditions. As previously stated, the major goal of this research is to compare the classic P&O with the proposed variable step size P&O constructed using a fuzzy logic controller to boost the power output from a solar panel. The output voltage of the Buck converter, which charges the battery, is controlled by the PID regulator. The implementation of a novel fuzzy logic-based Optimal PI is one benefit of our research.

4.1. Command MPPT
4.1.1. Perturb and observe algorithm (P&O)
The P&O is the most popular technique due to its simplicity and easiness of implementation. The idea is to perturbed the system and observe the system responds. In this case, changing the duty cycle will change the solar panel voltage. As a result, the power provided by the solar panel at time k is measured and placed in a comparison with the previous time (k-1). As the power increases, the duty cycle variation remains constant and the system approaches MPP. As the power drops, the maximum power point shifts, requiring a duty cycle inversion. The P&O algorithm's flowchart is displayed in Figure 7 [18], [19].

4.1.2. Variable step size P&O (VSS P&O)
As with this traditional P&O method normally employs a univariate step size, employing a fixed MPPT step size efficiently confines the PV module output power variance to the MPP and its rise time. There is a cost associated with convergence to a point. A big step reduces response time to abrupt changes in solar radiation, but generates huge oscillations in steady-state PV array output power in the MPP, leading in power loss. A moderate step, on the other hand, minimizes the fluctuation in PV system output power around the MPP while slowing the increase time.

Therefore, to eliminate steady-state oscillations and accelerate dynamic responsiveness, a dynamic MPPT step is required. In this paper, we developed a fuzzy logic technique can modify the size of the step of the MPPT P&O algorithm (VSS P&O), overcoming the constraints of the standard fixed step size of MPPT P&O [20]. Figure 8 shows a schematic of the variable-step fuzzy logic MPPT P&O algorithm (VSS P&O).

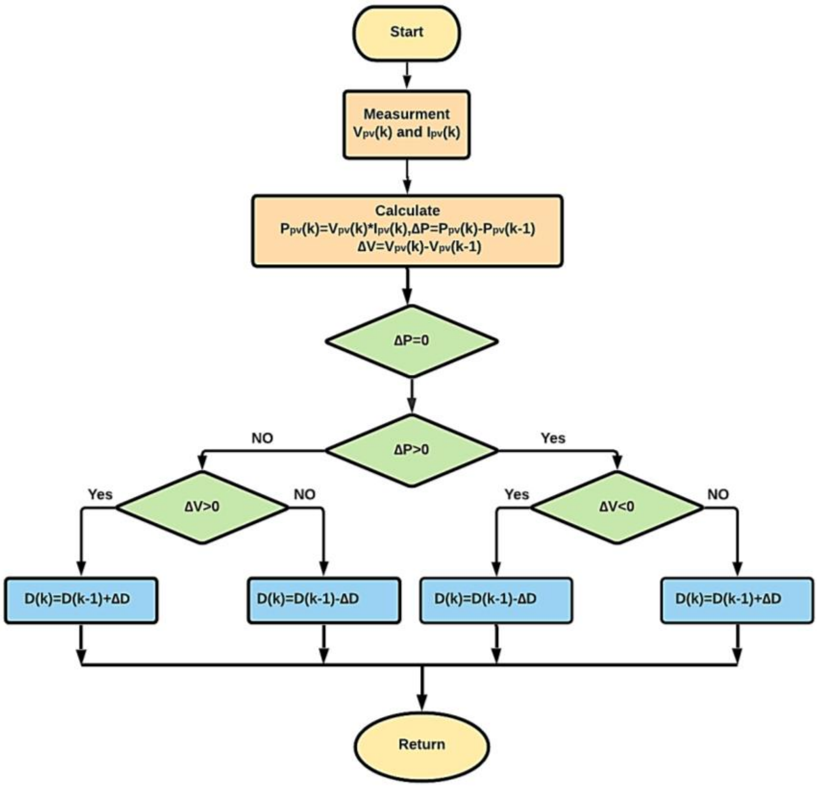

Figure 7. The P&O algorithm flowchart

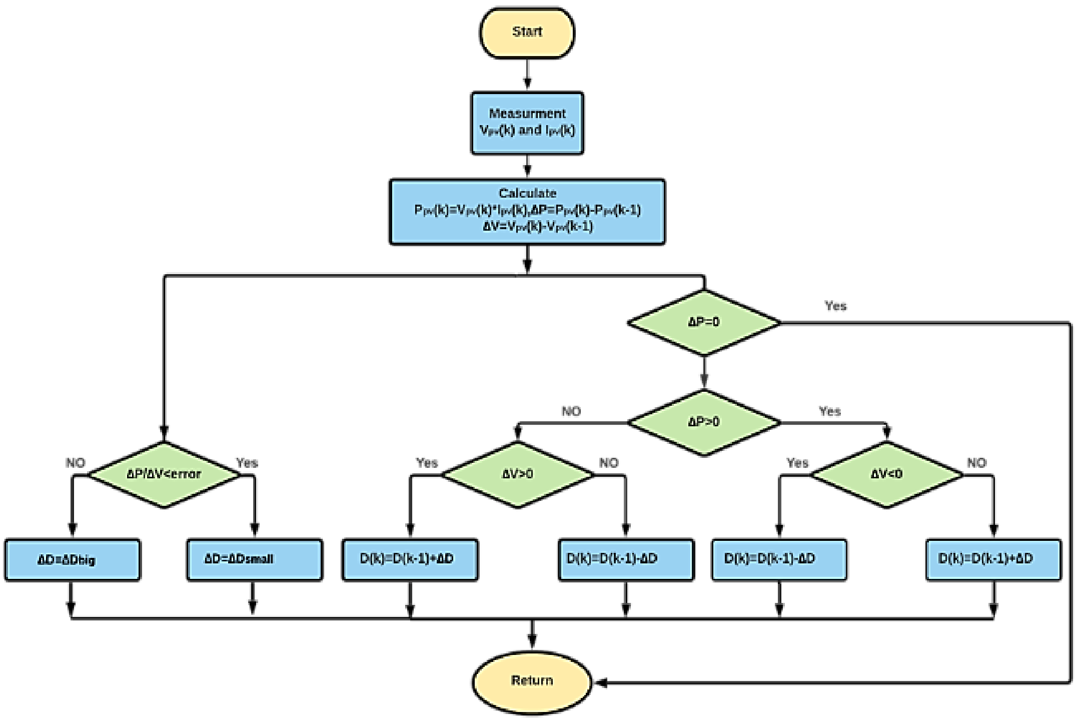

Figure 8. The flowchart for variable step size P&O (VSS P&O)

The rules that guide the VSS P&O algorithms are:
- If dP/dV is negative big (NB) then the duty cycle D is NB
- If dP/dV is negative small (NS) then the duty cycle D is (NS)
- If dP/dV is zero (ZE) then the duty cycle D is (ZE)
- If dP/dV is positive small (PS) then the duty cycle D is PS
- If dP/dV is positive big (PB) then the duty cycle D is PB

Figure 9 show the membership faction of the output and input of the fuzzy logic controller

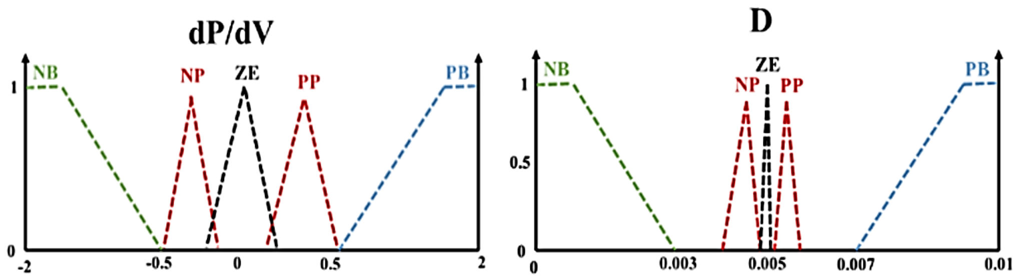

Figure 9. D and the dP/dV and membership functions

4.2. Voltage loop control
4.2.1. PID controller

A common closed loop control method used in a variety of industrial applications is the PID controller. This is mostly due to its straightforward design, which is easy to comprehend and put into practice. As shown in Figure 10, the PID regulator controls the output voltage and current of the Buck converter to charge the battery. The three gains, Kp, Ki, and Kd, are estimated using the Ziegler-Nicols method [21].

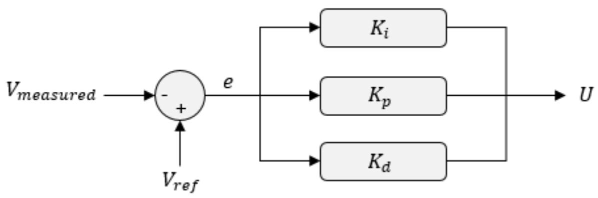

Figure 10. The PID controller's block

4.2.2. Optimal PI controller

There are many methods for fine-tuning the PI controller parameters [22] and in this study, the optimal PI controller calculates the best Kp and Ki while taking into account PI parameter tuning to produce a better responsiveness and reference voltage following. The suggested controller structure is shown in Figure 11, and an algorithm to change the parameters K_p and K_i is built using fuzzy logic.

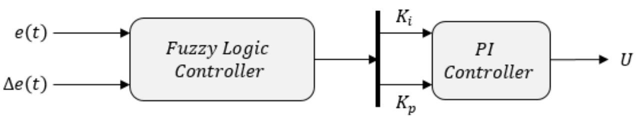

Figure 11. Block diagram for the optimal PI controller

The inputs e(t) and e of the ideal PI controller are represented by (6) and (7) [23].

$$e(t) = V_{buck} - V_{Ref} \tag{6}$$

$$\Delta e = e(t) - e(t-1) \tag{7}$$

This section will provide the ideal PI controller's e(t) and e input variables will be used as fuzzy block inputs. Ki and Kp will be the results. The Figure 12 presented membership function of e(t), e, KI, and Kp.

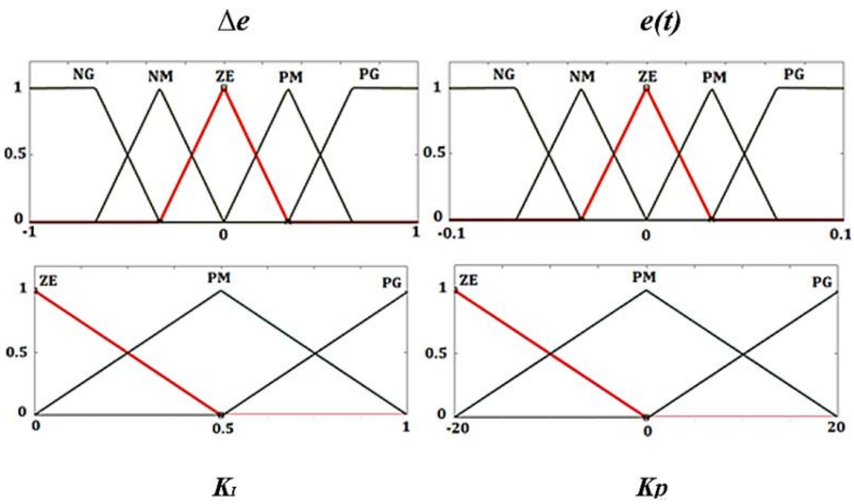

Figure 12. Membership of e(t), e, KI, and Kp functions

5. STORAGE MODELLING

The goal of employing batteries is to store extra energy and satisfy the need for charging during the night or inclement weather. Figure 13 provides an illustration of the proposed model of the battery model is defined [24], [25]. The following equation, which represents a battery's terminal voltage, is written as (8).

$$V = E_b \pm I_b \cdot R \tag{8}$$

R: internal resistance, I_b : battery current, andE_b: voltage source the following criteria define battery capacity C as (9).

$$C = \frac{E_d \cdot N_d}{V \cdot DOD \cdot \eta_b} \tag{9}$$

E_d: The load's daily electrical energy requirement, N_d:the number of days spent on your own. V: The battery electrical tension, and DOD is the discharge depth and η_b is the performance of the battery.

The battery current affects the battery's state of charge (SOC) (I_b). The following equation yields the SOC: [26].

$$SOC(k) = SOC(k-1) - \int_{k-1}^{k} \frac{I_b}{C_b} . dk \tag{10}$$

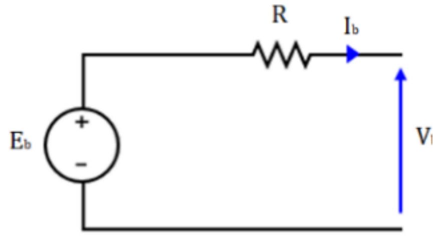

Figure 13. Batteries electrical model

6. RESULTS AND DISCUSSION

The overall system has been put to the test and assessed under the temperature and sun irradiation profiles depicted in Figures 14 and 15. The solar radiation varies every two seconds from 1000 W/m², 500 W/m², 800 W/m², and 600 W/m², while the temperature varies from 27°C to 25°C to 26°C to 23°C. Figures 16 and 17 show the extracted power profile and a comparison of P&O for time-varying radiation with a fixed temperature at 25°C and P&O for variable step size radiation. According to the simulation findings under MATLAB/Simulink comparing MPPT methodologies used to attain the maximum power point, the Variable Step Size P&O (VSS P&O) controller offers better performances in terms of response time and the produced power, as shown in Figures 16 and 17. However, the conventional P&O algorithm also has a problem with oscillation. As opposed to the PID controller, the proposed optimal PI based on fuzzy logic technique guarantees a better pursuit of the voltage set point without any overshoot for the second block of voltage regulation as shown in Figure 18, Figure 19 and Figure 20.

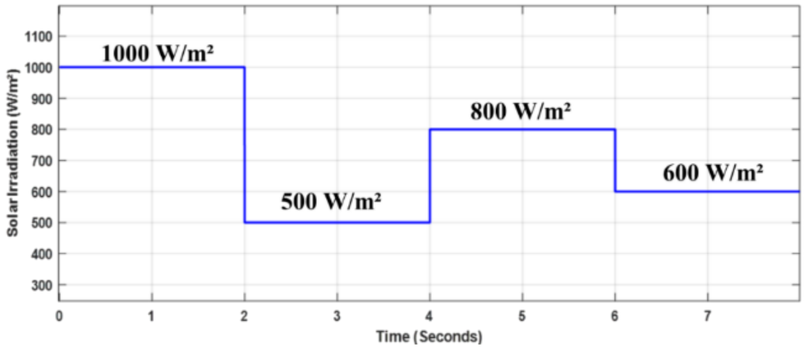

Figure 14. Evolution of radiation level

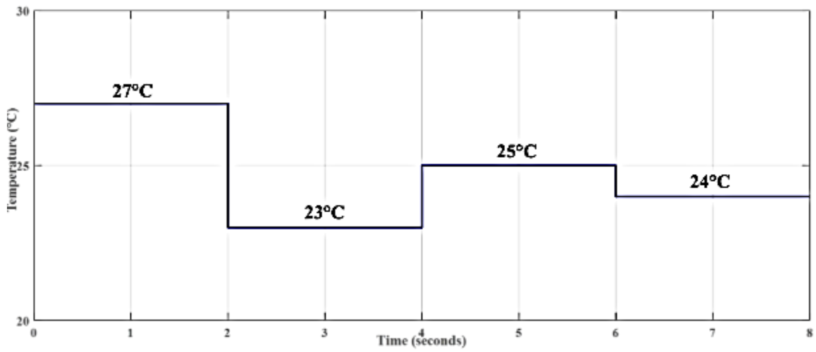

Figure 15. Evolution of temperature level

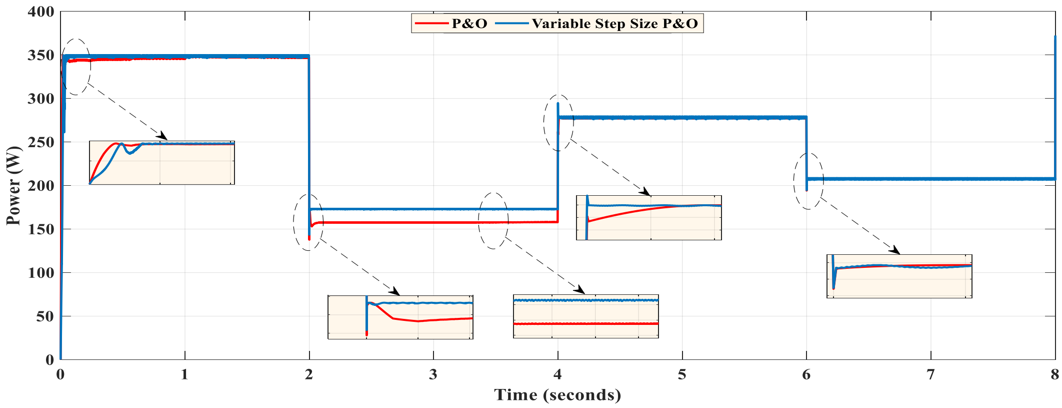

Figure 16. The evolution of the power generated by the P&O and VSS P&O algorithms

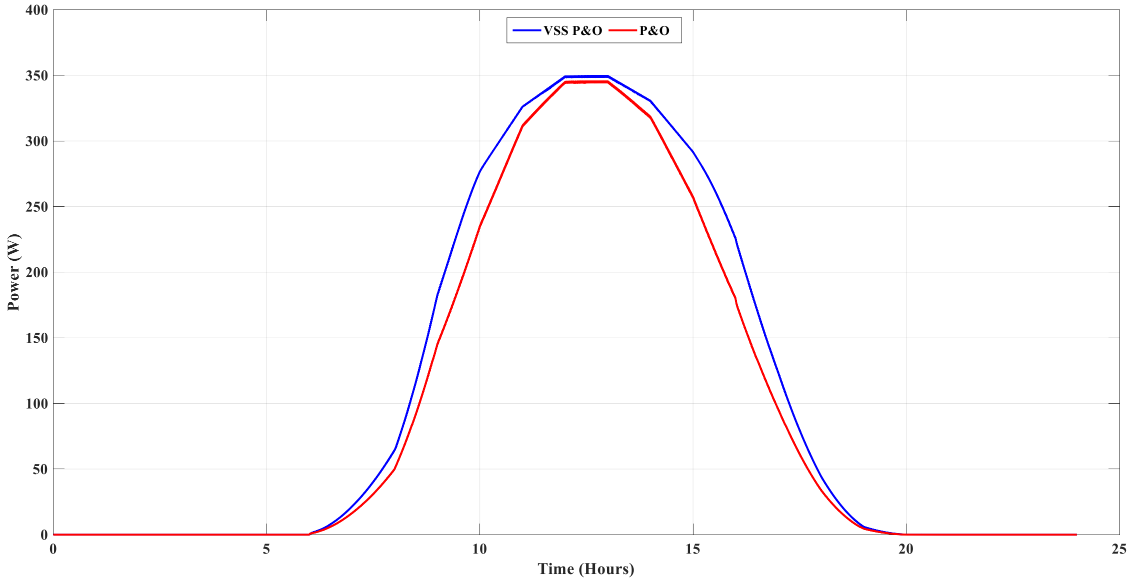

Figure 17. The evolution of the power produced for one day

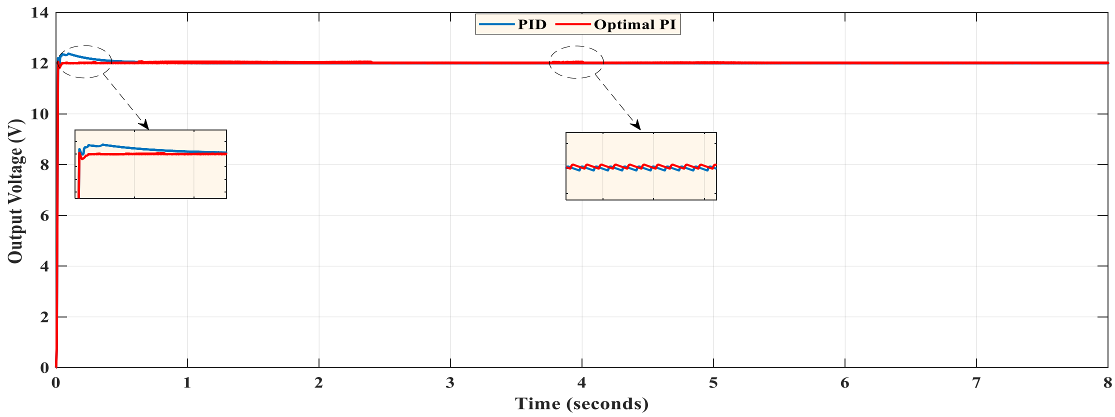

Figure 18. Compares the output voltage of a buck converter for a voltage of 12 volts with optimal PI and PID control for one day

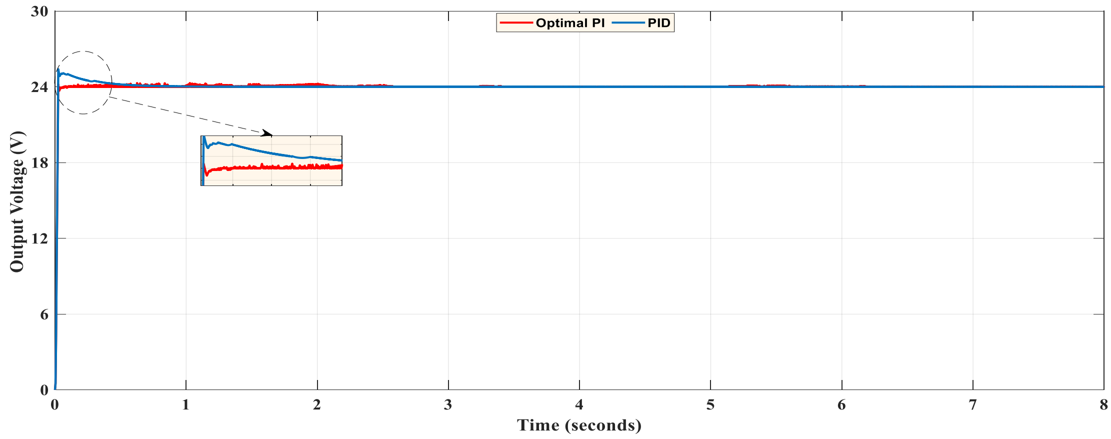

Figure 19. Compares the output voltage of a buck converter for a voltage of 24 volts with optimal PI and PID control for one day

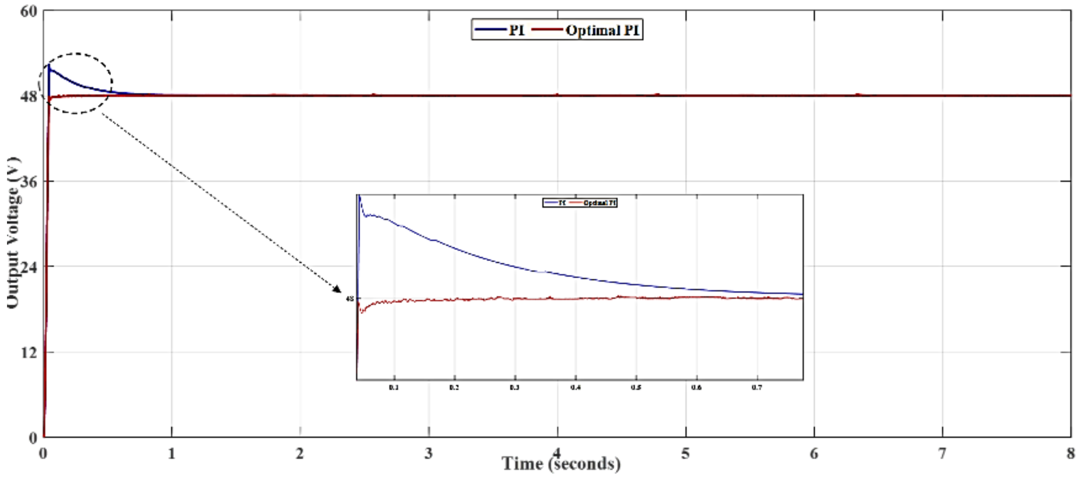

Figure 20. Compares the output voltage of a buck converter for a voltage of 48 volts with optimal PI and PID control for one day

7. CONCLUSION

The proposed photovoltaic system, which displayed a nonlinear feature, aims to harvest the most power possible utilizing P&O tracking techniques, in contrast to a Variable Step Size P&O (VSS P&O). The utilization of the second DC-DC converter for battery charging is controlled by the standard PID and the proposed Optimal PI. According to simulation studies, the latter guarantees a faster response time and greater voltage stability while controlling the voltage in the terminal's battery.

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