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Solar charge controller for battery using buck-boost converter

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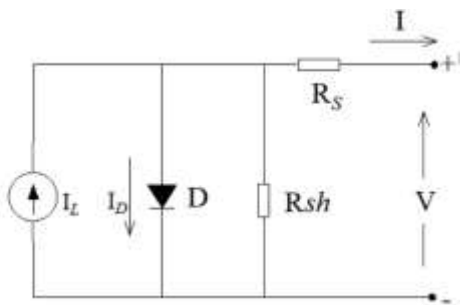
ABSTRACT: Charger controllers for solar batteries are becoming more and more popular these days. However, these controlstructures are generally divided into two categories: maximum power point tracking (MPPT) control and charge control.
This leads to considerable losses in small capacity equipment. On the other hand, when using a onverter, it will bechallenging to implement MPPT algorithms. This paper presents a control solution using a buck-boost converter thatcan satisfy multiple voltage ranges of batteries and solar cells while still optimizing the working capacity of the system.

KEYWORDS:MPPT, P&O Algorithm, Buck - Boost Converter & DC - DC Converter.

I. INTRODUCTION

Solar panels, including many solar cells, are semiconductor elements containing on the urface a large number oflight sensors, photodiodes, onverting light radiation into electrical energy. This conversion is done according tothe photoelectric effect. Solar cells operate according to the I-V and P-V nonlinear properties, which vary linearlywith solar radiation and operating temperature of photovoltaic (PV) cells [1-5].



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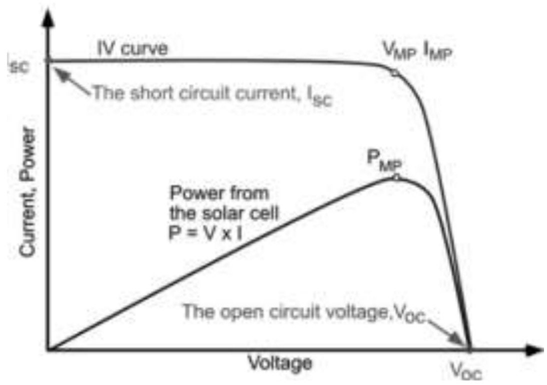

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Figure 1: a) Equivalent circuit of Photovoltaic Cells.
b) IV and PV Working Characteristics of Solar Cells.

Figure 1a. depicts an equivalence circuit of a photovoltaic cell. The voltage-current equation of a photovoltaic cell in a solar cell is given as below:

$$I_{PV} = I_{PH} - I_S\left[\exp\left(\frac{q(V_{PV}+I_{PV}R_S)}{kT_cA}\right)-1\right]-\frac{V_{PV}+I_LR_S}{R_{SH}} \tag{1}$$

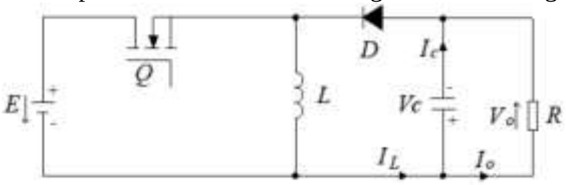
The I_{PH} photovoltaic current of a PV cell depends on the solar radiation and the working temperature ofthe PV cell, which is determined as follows:

$$I_{PH} = I_{SC}^{STC} + K_i\left(T_{PV} + T_{PV}^{STC}\right)\frac{\lambda}{\lambda^{STC}} \tag{2}$$

The saturation current of the PV cell,IS varies with the temperature of the PV cell, which is determined by thefollowing formula:

$$I_S = I_{RS}\left(\frac{T_C}{T_{PV}^{STC}}\right)^3\left[\exp\frac{qE_\lambda\left(\frac{1}{T_{PV}^{STC}}-\frac{1}{T_C}\right)}{kA}\right] \tag{3}$$

The MPPT algorithm [6-10] has obtained very satisfactory results and has been widelyapplied. One of thealgorithms that has a remarkable feature is the P&O algorithm. The power electronic converters make the adjustment of thesystem working point more flexible.With chargers, the output voltage of the converter is assumed to be fixed and equal tothe battery voltage, so the problem becomes complicated. Most converters mentioned in the literature [12-14] only focuson solving the MPPT problem without mentioning valve switching.



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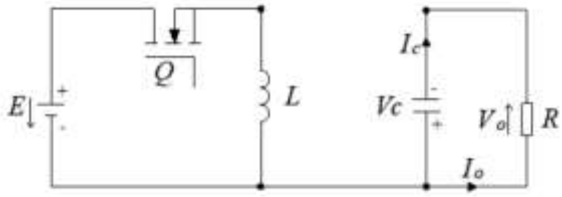

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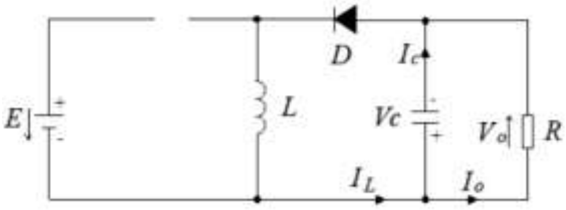

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Figure 2: a) Principle Diagram of Buck – BoostConverter, b) Q on and D off, c) Q off and D on

A DC-DC buck-boost converter is shown in Figure 2a. The buck-boost converter works with two states of thevalveQ. In the first half-cycle, when Q is closed, the source energy E is accumulated for inductor L, as shown in Figure 2b.In the second half-cycle, when Q is open, inductance L discharges and accumulates energy through diode D into the load,as shown in Figure 2c. The buck-boost converter that is being studied only considers the converter's operation in thecontinuous mode (CCM). When the valve is closed, the current in the circuit follows the following equation:

$$L\frac{di_L}{dt} = V_{\text{in}}(t) \qquad (4)$$

The amount of the currentincrease is determined as below:

$$\Delta I_{L\_\text{on}} = \int_0^{T_{\text{on}}} di_L \qquad (5)$$

From (4) and (5) we have:

$$\Delta I_{L\_\text{on}} = \int_0^{T_{\text{on}}} \frac{V_{\text{in}}(t)}{L}dt \qquad (6)$$

Operation of the converter when the valve is closed is given by

$$L\frac{di_L}{dt} = V_{\text{out}} \qquad (7)$$

The amount of the current drop during this period is calculated as

$$\Delta i_{L\_\text{off}} = \int_0^{T_{\text{off}}} di_L \qquad (8)$$

From (7) and (8) we have:

$$\Delta i_{L\_\text{off}} = \int_0^{T_{\text{off}}} \frac{V_{\text{out}}}{L}dt = \frac{V_{\text{out}}T_{\text{off}}}{L} \qquad (9)$$

The total current variation in the steady-state is zero. Therefore, $\Delta i_{L\_\text{on}} = \Delta i_{L\_\text{off}}$. From (6) and (9), we have:

$$\int_0^{T_{on}} \frac{V_{\text{in}}(t)}{L}dt = \frac{V_{\text{out}}T_{\text{off}}}{L} \qquad (10)$$

From (10), we see that Vout is the voltage of the applied battery.Due to the variation of the battery voltage is slow, Vout= VBAT = const can be considered. Accordingly, have:

$$\int_0^{T_{on}} V_{PV}(t)dt = V_{BAT}T_{off} \qquad (11)$$

The relationship between VPV and IPV is shown in (1). In other words, VPV is a variable depending on the workingpoint on the P-V curve, as shown in Figure 1b.

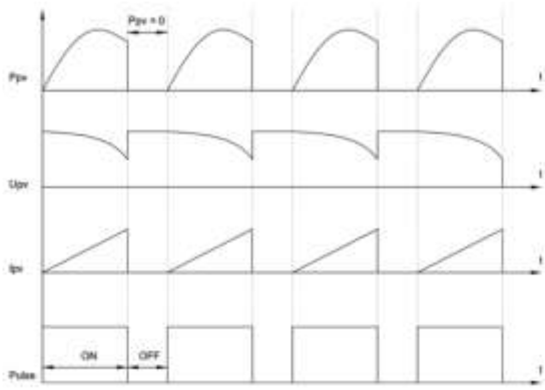

Figure 3: Operation of a Buck-Boost Converter Connected to Solar Cells.

Therefore, during one valve's opening and closing cycle, the power of the system varies continuously and does notwork steadily at the maximum, as shown in Figure 3. When the valve is open, the battery's energy is accumulated into theinductor. When the valve is closed, the solar panel is disconnected from the converter. This reduces the actual workingcapacity of the PV panels. The average capacity of the PV panels depends on Ton and Toff. If Ton>>Toff, the operating time ofthe battery would take up most of the working cycle, so the maximum power is

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achieved. To solve this problem, a largeenough capacitor is added to store the panel's energy while the valve was in closed mode. Such a capacitor, however,would not be suitable for compact systems that require flexibility. This paper proposes amethod of controlling the valveopening and closing process so that the power of the system is optimal.

II. CONTROL STRUCTURE

1. System Structure

The proposed system structure is depicted in figure 4. The solar panels are connected to a buck-boost converter with aninverting topology. Theconverter output is connected to a battery. DC loaders may be connected in parallel with thebattery for other purposes.

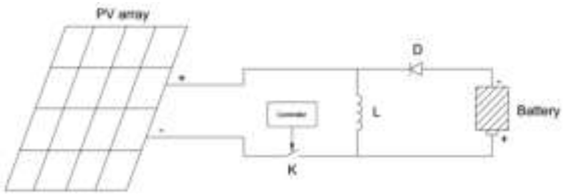

Figure 4: The Charging System Structure uses a Buck-Boost Circuit.

The control method for the K-switch is similar to the peak current control method described in the literature [15,16]. Techniques forimplementing such a system are simple and implemented in many power electronic converter systems[17].

2. Peak Current Control Algorithm

DC-DC controllers can all be controlled by the peak current method [6]. The principle of this approach is that the valveswitching occurs when the current on the inductor reaches a preset peak value. With this method, the control frequencywill vary depending on the load and inductor of the converter. This method is quite simple and is often implemented onhardware rather than on digital platforms. Hence, its fabrication is quite simple. The control algorithm of this method isdescribed in figure 5. The principle of this method uses an inductor current feedback, IL. When the current IL is less than apreset value, Iset the valve will switch from closed to open state. When the voltage Upv is less than a preset value, Uset thevalve will switch from an open to a closed state.

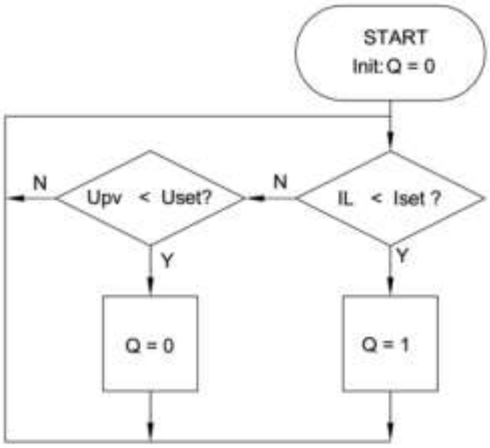

Figure 5: Peak Current Control Algorithm.

The advantage of this approach is that it does not consider the operating mode of the converter. The converter canoperate in a buck or boost mode depending on battery voltage. The Uset and Iset values provided by the improved P&O algorithm will be presented in the following sections.

3. Improved P&O Algorithm

The improved P&O algorithm relies on the change of power and voltage before and after correction to predict the currentoperating point of the solar panel. This algorithm has many variations by adding or changing several evaluation criteria,thereby changing the amount of control error in order to quickly approach the maximum power point [18,19,20].

Table 1:Interpret the Meaning and Control Method of P&O Algorithm.

Position	Variation of Operating Power (ΔP)	Variation of Operating Voltage (ΔV)	System Working Tendency	Control Tendency
1	$\Delta P < 0$	$\Delta V < 0$	Position 1	D decreases
2	$\Delta P < 0$	$\Delta V > 0$	Position 2	D decreases
3	$\Delta P > 0$	$\Delta V < 0$	Position 3	D increases
4	$\Delta P > 0$	$\Delta V > 0$	Position 4	D increases

This algorithm can be easily implemented on practical embedded systems [11]. Table 1 describes how the basic P&O algorithm works.

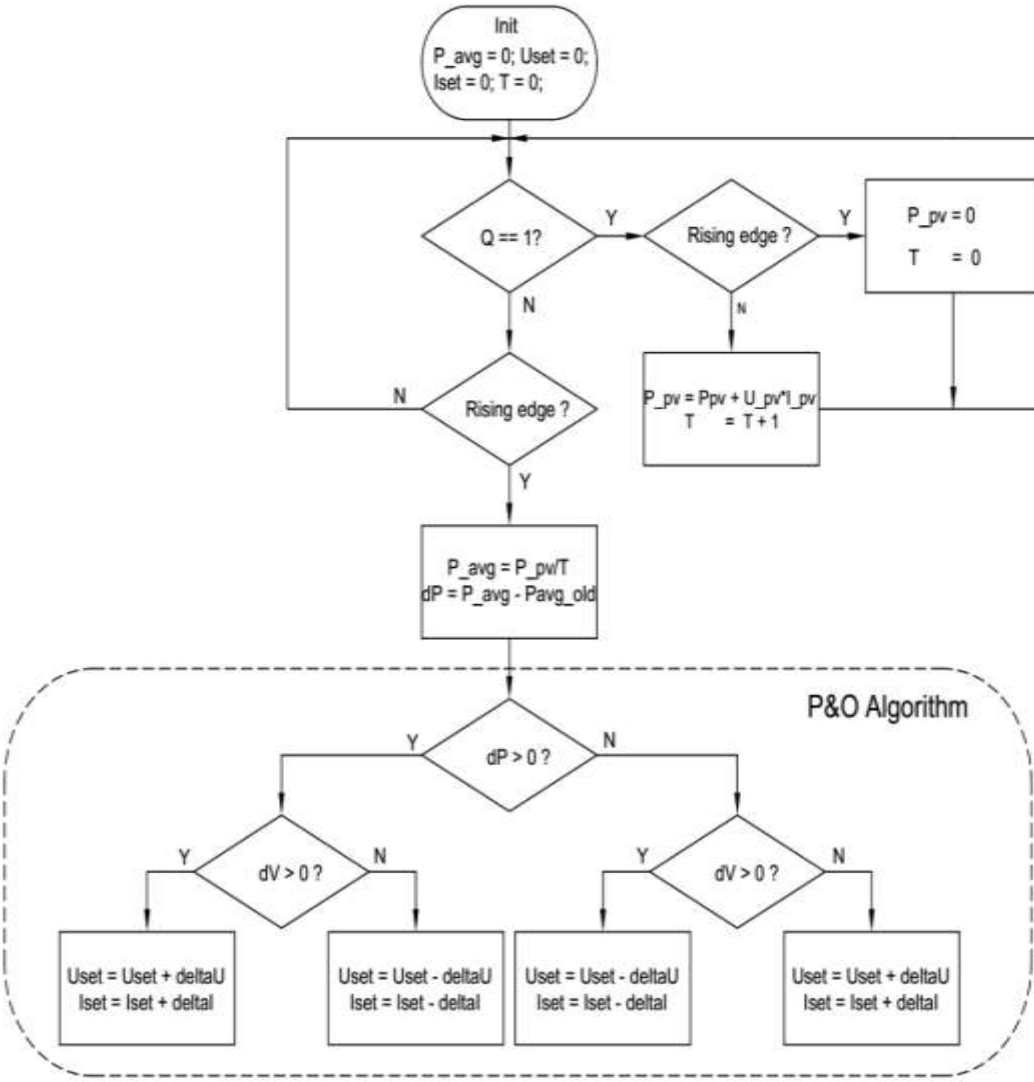

Figure 6: Customizable P&O Algorithm for Buck - Boost Converter.

With the operating principle of the basic P&O algorithm, this paper proposes a peak-current (Ipeak) controlmethod for a buck-boost converter, as shown in figure 6. The algorithm identifies two switching points, Uset and Iset, bycalculating the average power in one open valve cycle, Pavg, and the average switching voltage, Uavg, at the beginning ofeach cycle, using the following formula:

$$\begin{cases} U_{\text{avg}} = U_{peak} - U_{\text{set}} \\ P_{\text{avg}} = \dfrac{\sum_{T=0}^{n} V_{pv} I_{pv}}{T} \end{cases} \quad (12)$$

The values obtained from (12) will be used to implement the P&O algorithm described in the previous section.

III. SIMULATION

1.Simulation Diagram

The simulation model was built onMatlab/Simulink software, as shown in figure 7. The simulated panels' parameters aredescribed in table 2.

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Table 2: Solar Panel Parameters

Parameter	Symbol	Value	Unit
Maximum power	Pmax	29	W
Open-circuit voltage	Uoc	7.2	V
Short-circuit current	Isc	4	A
Voltage at the maximum point	Vmp	6	V
Current at the maximum point	Imp	3	A
Number of serial panels	Ns	1	
Number of parallel panels	Np	1	

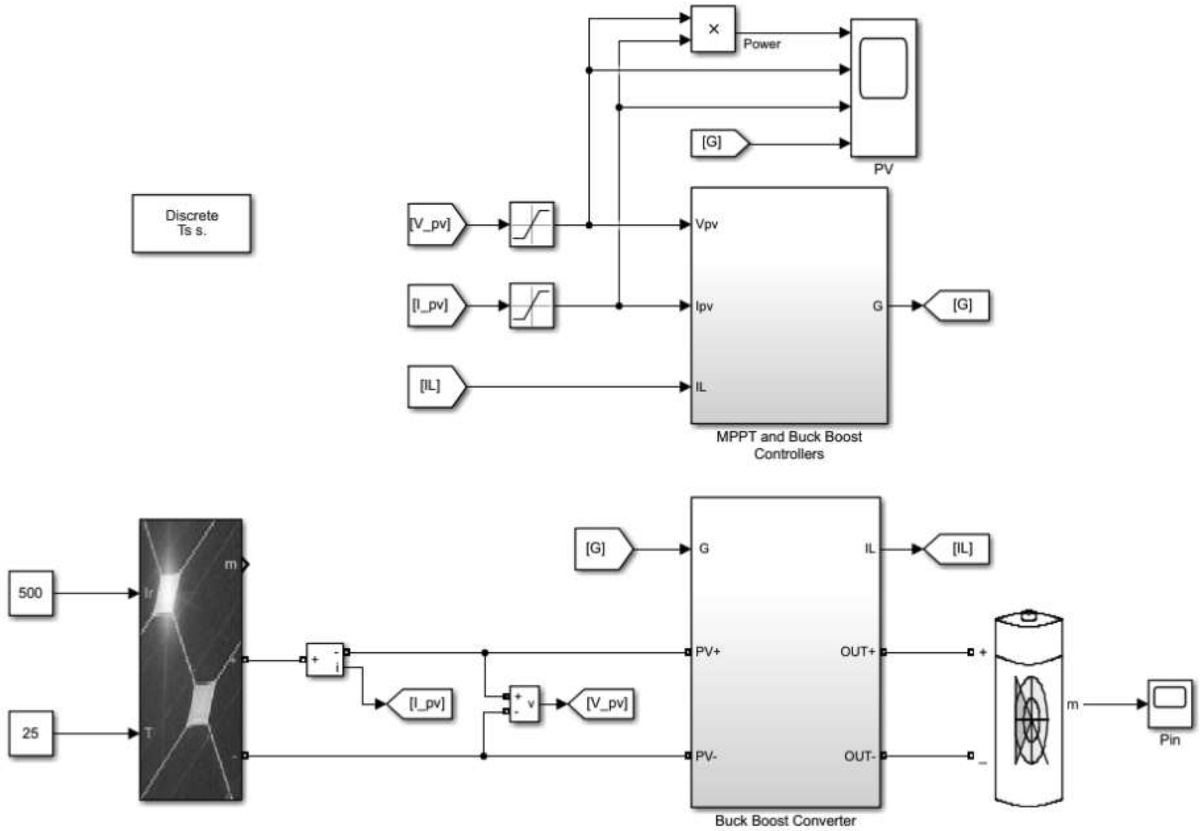

Figure 7: Simulation Diagram of the System.

2. Simulation Results

Case 1: In this simulation, the controller is evaluated withradiation intensity 500W/m2,ΔU = 0.1V, ΔI = 0.1A. The system reaches the steady-state after 1.05s (figure 8., figure 9.), with reference voltage Uset = 3V and referencecurrent Iset = 2.25A.

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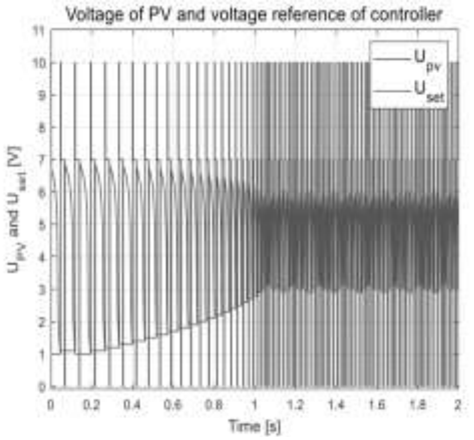


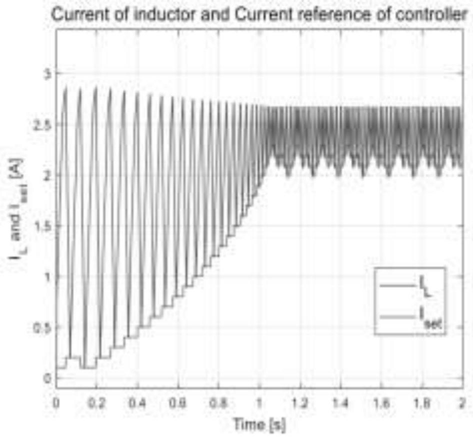
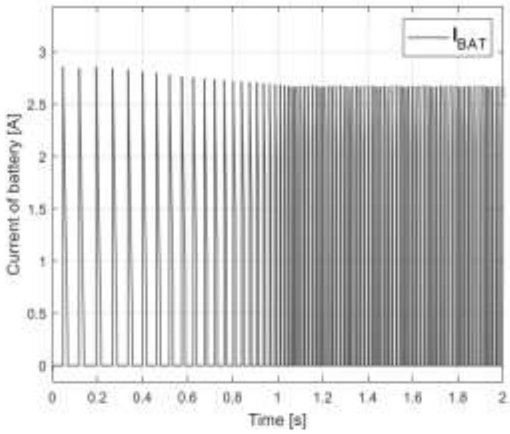


Figure 8: Voltage of the PV and Reference Voltage of the Controller.
Figure 9: Current of the Inductor and the Reference Current of the Controller.



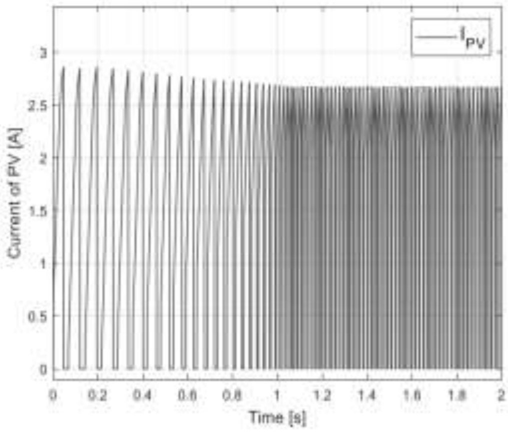
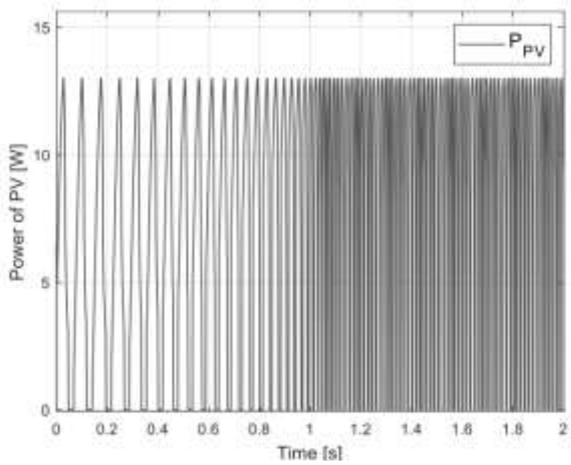


Figure 10: Current of the Battery.
Figure 11: Current of the PV.



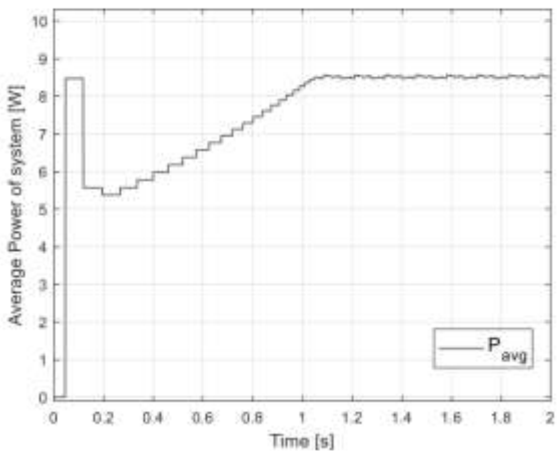


Figure 12: Power of the PV.
Figure 13: Average Power of Solar Panels.

The average power of the system is approximately Pagv = 12W (Figure 13.), while the maximum power of the PVpanels Pmax = 14.9W at radiation intensity Ir = 500W/m^2. The system achieves 80% efficiency.

Case 2: Power of the converter for different battery voltages. In this simulation, the operation of the system is evaluated with different battery voltage ranges. There are threebattery voltages to be used: 3.7V, 12V, and 24V. Figure 14. shows the operations of the controller for different batteryvoltages, where all three considered voltages result in an average power of about 12W. However, for systems with lowerbattery voltages, the convergence time of the algorithm is slower due to the longer inductor charging.

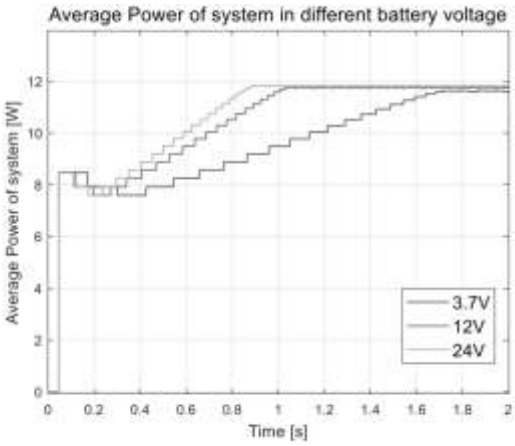


Figure 14: The Average PV Power Corresponds to Different Charging Voltages.

Conversion efficiency at different battery voltages is given in Table 3.

Table 3: Conversion Efficiency at Different Battery Voltages

Battery Voltages	Average Power	Efficiency
3.7V	11.5W	77%
12V	11.8W	79%
24V	11.9W	80%

IV. CONCLUSIONS

Simulation results show that the system is satisfied with different voltage ranges of batteries and solar panels. Besides, thealgorithm allows optimizing the system's power up to 80% of the maximum power of the PV panels. Theimplementedcontrol scheme has improved theworking capacity of the charging control system for batteries using solar panels.

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SYMBOLS

I_{PH}	Photoelectric current
I_S	Saturated current
q	Atomic charge
k	Boltzmann's constant
T_C	Working temperature of the photovoltaic cell
A	Ideal constant of semiconductor materials
R_{SH}	Parallel resistance (shunt)
R_S	Serial resistance
I_{SC}^{STC}	Short-circuit current of the photoelectric cells at 25^0C and 1kW/m^2
T_{PV}	The working temperature of the photovoltaic cells (^{0}C)
K_i	Short-circuit current temperature coefficient of photovoltaic cells
λ^{STC}	Solar radiation 1kW/m^2
I_{RS}	Current flows through the internal parallel resistance RSH
E_λ	Distance energy of semiconductors of photovoltaic cells
T_{PV}^{STC}	Standard temperature of the photovoltaic cell ^{0}C

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