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Influence of Temperature and Solar Irradiation on the Performance of Electrochemical Batteries in an Autonomous Photovoltaic System in Burkina Faso

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Abstract

Electrochemical batteries are very often used in photovoltaic systems as storage technologies to ensure a permanent supply of electrical energy to the load. However, these batteries are not always adapted to the different climatic conditions in Burkina Faso and to load demand. As a result, battery life is shortened and the overall cost of PV systems increases. The aim of this article is to study the influence of temperature and irradiation on the performance of lithium-ion (Li-ion), lead-acid (Pb-ac) and nickel-cadmium (Ni-Cd) batteries in a photovoltaic system. To achieve this objective, mathematical and electrical modelling of a PV system and of the different battery types was carried out, taking into account solar temperature and irradiation, in the Matlab/Simulink environment. The results obtained from the simulations show that the temperature of the batteries increases as the charging current increases. Also, the voltage and temperature of Lithium-ion and Nickel-Cadmium batteries show better stability during charging and discharging than Lead-acid batteries. This stability could increase the number of cycles of Li-ion batteries and thus increase their lifespan [1]. This work will eventually enable the spread of PV systems and their accessibility to all sections of the population of Burkina Faso.

Keywords

Batteries, Solar Photovoltaic Systems, State of Charge, Temperature, Matlab/Simulink

1. Introduction

Nowadays, faced with environmental problems caused in part by the exploitation of fossil fuels, solar photovoltaic energy is a viable alternative to fossil fuels. Photovoltaic solar energy has become one of the main alternatives for producing electricity in the Sahelian zone. However, this energy is not permanently available.

Batteries are generally used in photovoltaic systems as storage technologies to ensure a permanent supply of electrical energy to the load. However, existing photovoltaic systems in the Sahelian zone are very often defective. This is due, among other things, to the batteries used, which are not adapted to the climatic conditions of this region or to the load [2] [3].

This study will examine the influence of solar irradiation and temperature on the performance of lithium-ion (Li-ion), lead-acid (Pb-ac) and nickel cadmium (Ni-Cd) batteries in Burkina Faso. The aim is to increase the performance of the storage system, thereby reducing its cost and making electrical energy accessible to all sections of the population.

To achieve this objective, this article will be divided into two parts. In the first part, mathematical and Matlab/Simulink modelling of the main components of the PV system with Li-ion, Pb-ac and Ni-Cd batteries will be carried out, taking into account temperature and solar irradiation. In the second part, we will present and analyse the results obtained.

2. Modelling

2.1. Modelling a Field of Photovoltaic Modules

A photovoltaic cell is made from semiconductor materials. It transforms the energy from sunlight into electrical energy. The equivalent circuit of an ideal PV cell can be represented by a current generator (Iph) in parallel with a diode. Its equivalent electrical circuit is shown in **Figure 1** [4].

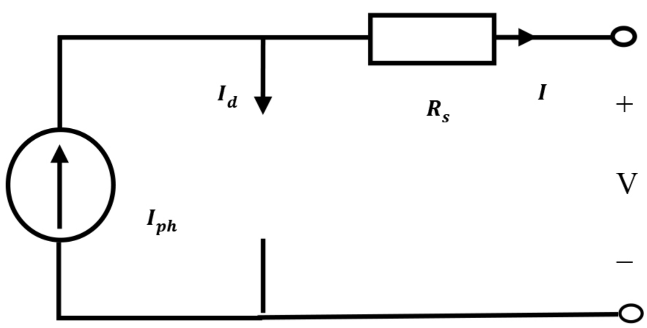

Figure 1. Equivalent electrical diagram of an ideal PV cell.

The output current I is obtained by applying Kirchhoff's law:

$$I = I_{ph} - I_d \tag{1}$$

Where I_{ph} is the photocurrent and I_d is the diode current, which is proportional to the saturation current. They are given by Equations (2) and (3):

$$I_{ph} = \left[I_{ph,n} + ki\left(T - 298\right) \right] \frac{G}{1000} \tag{2}$$

$$I_d = I_s \left[\exp\left(\frac{qV}{nk_BT} \right) - 1 \right] \tag{3}$$

The current delivered by an ideal PV cell is then represented by Equation (3):

$$I = I_{ph} - I_s \left[\exp\left(\frac{qV}{nk_BT} \right) - 1 \right] \tag{4}$$

where: $I_{ph,n}$ is the photo-current under standard test conditions (STC); *ki*, short-circuit current of the cell at 25˚C and 1000 W/m²; *G* solar irradiance (W/m²); I_s, the reverse saturation current of the diode; *q*, the electron charge (1.6 × 10^{-19} C); K_B, Boltzmann's constant(1.38 × 10^{-23} J/K); *n*, the diode ideality factor (1 < *n* < 2); *T*, the junction temperature in K; I_d, the current flowing through the diode; *I*, the output current, and *V* the output voltage [4] [5].

The electrical model of the cell (**Figure 2**) is obtained by adding a parallel resistor (R_{sh}) to the equivalent diagram in **Figure 1**, when we take into account contact resistances and ohmic losses [4] [6] [7].

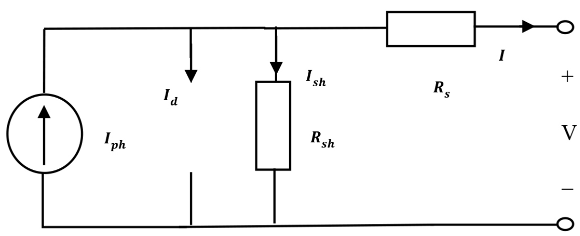

Figure 2. Equivalent electrical diagram of a PV cell.

Applying Kirchhoff's law, we obtain the following relationship:

$$I = I_{ph} - I_d - I_{sh} \tag{5}$$

$$\text{With: } I_{sh} = \frac{V + R_s I}{R_{sh}} \tag{6}$$

This gives Equation (7):

$$I = I_{ph} - I_s \left[\exp\left(\frac{q\left(V + R_s I\right)}{nk_BT} \right) - 1 \right] - \left[\frac{V + R_s I}{R_{sh}} \right] \tag{7}$$

The voltage at the terminals of a cell and the current supplied by a cell are generally insufficient to supply a load. It is therefore necessary to combine cells in series (N_S) and in parallel (N_P) in order to obtain higher voltage and current values, respectively [8]-[11]. Equation (7) then becomes:

$$I = N_p \cdot I_{ph} - N_p \cdot I_s \left[\exp\left(\frac{q\left(\frac{V}{N_s} + \frac{R_s \cdot I}{N_p} \right)}{nk_BT} - 1 \right) \right] - N_p \left[\frac{\frac{V}{N_s} + \frac{I \cdot R_s}{N_p}}{R_{sh}} \right] \tag{8}$$

with:

$$I_s = I_{s,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{nk_B}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \tag{9}$$

Where: E_g the energy of the band gap of the semiconductor (in eV) and $I_{s,n}$, is the nominal saturation current (A).

Equation (8) allows us to establish the Matlab/Simulink model of a photovoltaic module. In this model, irradiation and temperature are the input parameters and current, voltage and power are the output parameters (**Figure 3**).

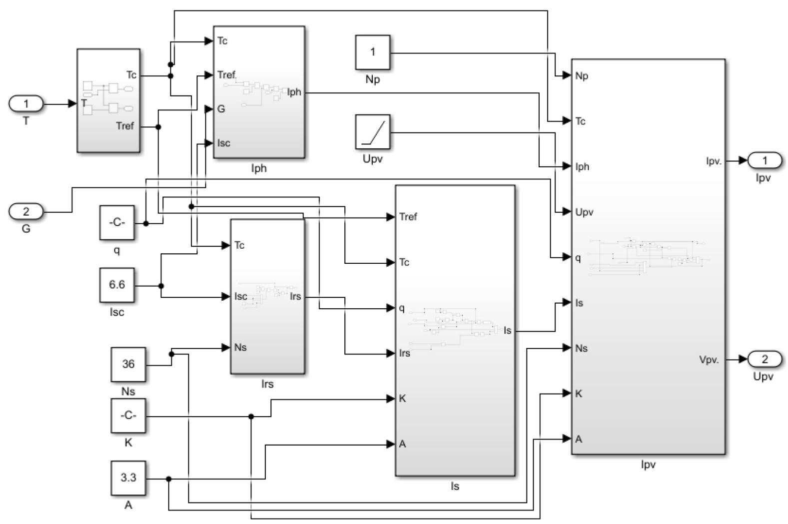

Figure 3. Simulink model of a PV module.

2.2. Battery Modelling

i) General model

Batteries are electrochemical converters capable of storing energy in chemical form and returning it in electrical form. The basic equivalent circuit of an electrochemical accumulator can be modelled by a voltage generator in series with a resistor (**Figure 4**) [12] [13].

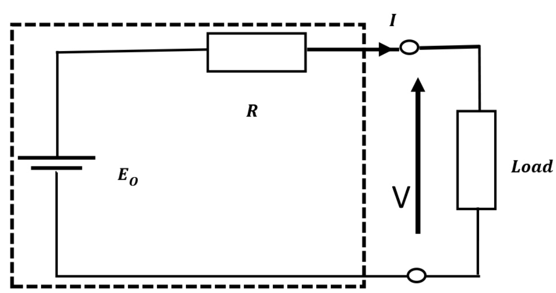

Figure 4. Basic circuit of an electrochemical accumulator.

Applying Kirchhoff's law, we obtain Equation (10)

$$E_O = V + R \times I \tag{10}$$

$$V = E_O - R \times I \tag{11}$$

with: E_O : the voltage of an electrochemical accumulator, *V*: the output voltage of the accumulator; *R*: the internal resistance of the accumulator and *I* the current supplied by the accumulator.

Taking the current density into account, we obtain the general mathematical model of the battery given by Equation (10) [12] [13].

$$V = E_o - K\frac{Q}{Q - it}it - K\frac{Q}{Q - it}i^* - R \cdot i + C \tag{12}$$

With $C = A \times e^{-B \times it}$

V: actual battery voltage (V)

E_o: battery constant voltage (V)

K: polarization resistance (Ω)

Q: battery capacity (Ah)

it: actual battery charge (Ah)

A: exponential zone amplitude (V)

B: exponential zone time constant inverse (Ah^{-1})

R: battery internal resistance (Ω)

i: actual battery current (A)

i^* : low-frequency current dynamics (A)

C: exponential voltage (V)

The state of charge (SOC) of a battery is given by Equation (13) [13] and [14].

$$\text{SOC} = \text{SOC}_0 - \int \frac{i * 100}{\alpha^U * 3600} \text{d}t \tag{13}$$

where SOC_0 is the initial SOC, *i* is the current and α^U is the capacity that can be used.

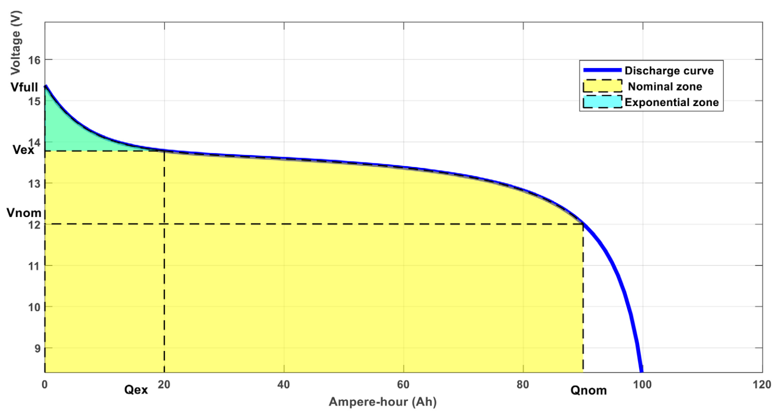

Figure 5. Discharge characteristics curve of battery.

The battery discharge curve shown in **Figure 5** allows us to calculate the amplitude of the exponential zone *A*, the time constant of the inverse exponential zone *B* and the polarisation resistance *K* [15] and [16].

$$A = V_{full} - V_{ex} \tag{14}$$

$$B = \frac{3}{Q_{ex}} \tag{15}$$

$$K = \frac{V_{full} - V_{nom} + A\left[\exp\left(-B * Q_{nom}\right) - 1\right] * \left(Q - Q_{nom}\right)}{Q_{nom}} \tag{16}$$

$$V_{full} = E_0 - R * i + A \tag{17}$$

We can deduce the voltage (E_o) from the maximum charging voltage (V_{full}):

$$E_o = V_{full} + K + R \cdot i - A \tag{18}$$

$$V_{ex} = E_0 - K \frac{Q}{Q - Q_{ex}} * \left(Q_{ex} + i\right) - R * i + A\exp\left(\frac{-3}{Q_{ex}} * Q_{ex}\right) \tag{19}$$

$$V_{no} = E_0 - K \frac{Q}{Q - Q_{no}} * \left(Q_{no} + i\right) - R * i + A\exp\left(\frac{-3}{Q_{ex}} * Q_{no}\right) \tag{20}$$

The functional blocks of the Matlab/Simulink software can be used to construct the generic model of a battery (**Figure 6**) from Equations (12) and (13). In this model, current is an input parameter; voltage and state of charge are battery output parameters. The signals are displayed using an oscilloscope.

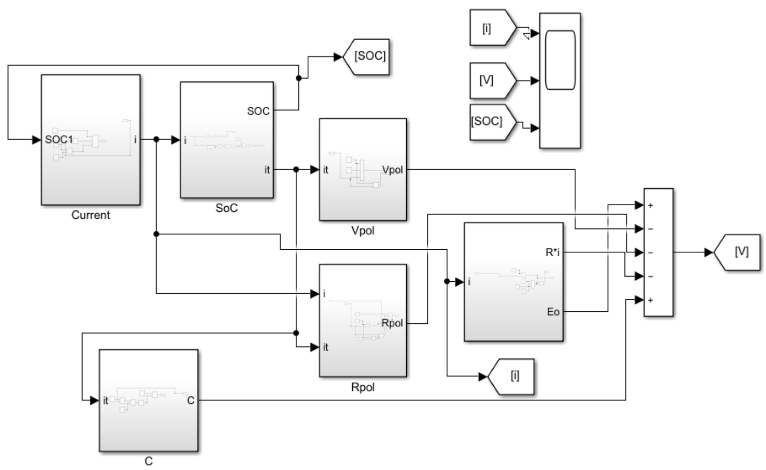

Figure 6. Generic model of a battery in Matlab/Simulink.

The batteries most commonly used in photovoltaic systems are lithium-ion, lead-acid and nickel-cadmium. From Equation (12), we can establish mathematical models for the different types of battery.

ii) Mathematical models of the main types of battery

During discharge and charge, we can model the different types of batteries using the following equations [11]-[13] [17]:

- Lithium ion

- Discharge ($i^* > 0$)

$$V = E_o - K \frac{Q}{Q - it} it - K \frac{Q}{Q - it} i^* - R \cdot i + A \cdot \exp\left(-B \cdot it\right) \tag{21}$$

- Charge ($i^* < 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{it-0.1\cdot Q}i^* - R\cdot i + A\cdot\exp(-B\cdot it) \tag{22}$$

- Lead acid
  - Discharge ($i^* > 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i^* - R\cdot i + \exp(t) \tag{23}$$

  - Charge ($i^* < 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{it-0.1\cdot Q}i^* - R\cdot i + \exp(t) \tag{24}$$

- Nickel-Cadmium
  - Discharge ($i^* > 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i^* - R\cdot i + \exp(t) \tag{25}$$

  - Charge ($i^* < 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{|it|-0.1\cdot Q}i^* - R\cdot i + \exp(t) \tag{26}$$

In an electrochemical accumulator, heat is dissipated only by conduction so that the thermal balance of its volume can be given by the following expression depending on the shape of the accumulator:

$$\rho C_P\frac{\partial T}{\partial t} = \dot{Q}_{generation} + kr\frac{\partial^2 T}{\partial x^2} + kr\frac{\partial^2 T}{\partial y^2} + kr\frac{\partial^2 T}{\partial z^2} \tag{27}$$

Where:

$$T = L^{-1}\left(\frac{P_{Loss}\times R_{th} + T_{am}}{1+t_c}\right) \tag{28}$$

$$P_{Loss} = \left(E_0(T) - V(T)\times i\right) + \frac{\partial E}{\partial T}\cdot i\cdot T \tag{29}$$

With, R_{th} is the thermal resistance, cell to ambient (˚C/W); t_c is the thermal time constant, cell to ambient (s) and P_{Loss} is the overall heat generated (W) during charge/discharge process.

During the charging and discharging phases of each type of battery, we will appropriately represent the influence of temperature on the voltage. Thus, taking into account the temperature, Equations (21)-(26) become respectively:

- Lithium ion
  - Discharge ($i^* > 0$)

$$V(T) = E_o(T) - K(T)\cdot\frac{Q(T_{am})}{Q(T_{am})-it}\cdot\left(i^* + it\right) + A\cdot\exp(-B\cdot it) - R(T)\cdot i - c\cdot it \tag{30}$$

  - Charge ($i^* < 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{0.1Q(T_{am}) + it} \cdot i^* - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am}) - it} \cdot it + A \cdot \exp(-B \cdot it) - R(T) \cdot i - c \cdot it \quad (31)$$

- Lead acid
  - Discharge ($i^* > 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am}) - it} \cdot (i^* + it) + \exp(t) - R(T) \cdot i - C \cdot it \quad (32)$$

  - Charge ($i^* < 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am}) - it} it - K(T) \cdot \frac{Q(T_{am})}{it - 0.1Q(T_{am})} i^* - R(T) \cdot i + \exp(t) - C \cdot it \quad (33)$$

- Nickel-Cadmium
  - Discharge ($i^* > 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am}) - it} \cdot (i^* + it) + \exp(t) - R(T) \cdot i - C \cdot it \quad (34)$$

  - Load ($i^* < 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am}) - it} it - K(T) \cdot \frac{Q(T_{am})}{|it| - 0.1Q(T_{am})} i^* - R(T) \cdot i + \exp(t) - C \cdot it \quad (35)$$

with:

$$E_o(T) = E_o\big|_{T_{ref}} + \frac{\partial E}{\partial T}(T - T_{ref}) \quad (36)$$

$$K(T) = K\big|_{T_{ref}} \cdot \exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (37)$$

$$Q(T_{am}) = Q\big|_{T_{am}} + \frac{\Delta Q}{\Delta T}(T_{am} - T_{ref}) \quad (38)$$

$$R(T) = R\big|_{T_{ref}} \cdot \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (39)$$

where: c is the nominal discharge curve slope (V/Ah); T is the internal temperature (K); α is Arrhenius rate constant for the polarization resistance; β is Arrhenius rate constant for the internal resistance and T_{am} is the ambient temperature (K).

3. Results and Discussion

3.1. Evolution of Battery Discharge Current

Based on the mathematical equations obtained in 2, Matlab/simulink models of the different battery types are constructed. The simulation results are shown in Figures 7-9. These figures show the discharge curves as functions of the discharge currents for the Li-ion, Pb-ac and Ni-Cd batteries, respectively.

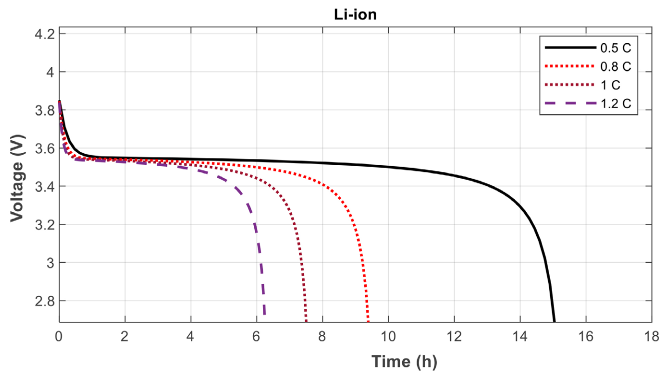

Figure 7. Li-ion battery discharge as a function of discharge current.

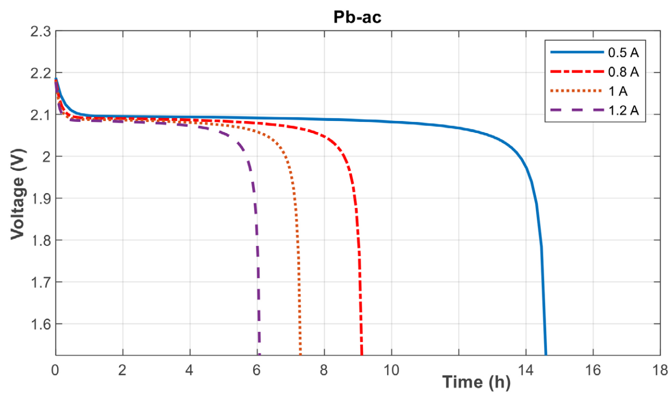

Figure 8. Pb-ac battery discharge as a function of discharge current.

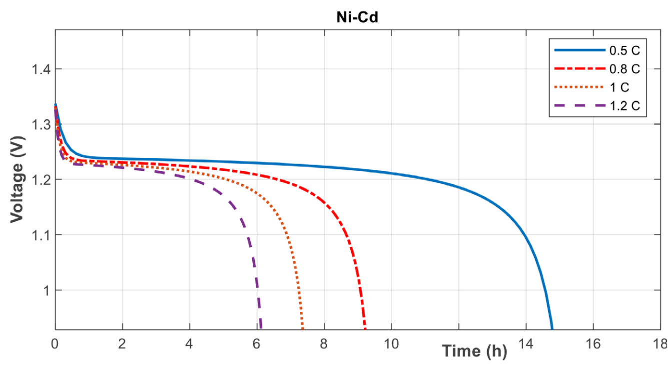

Figure 9. Ni-Cd battery discharge as a function of discharge current.

Figures 7-9 show that the higher the discharge current, the faster the battery discharges. Battery discharge is therefore dependent on discharge current. The results obtained are in agreement with those found by [18]-[21]. In the following, we will consider the case of a photovoltaic solar installation in Burkina Faso.

3.2. Influence of Temperature and Irradiation on a PV System

The batteries used in this work are used in photovoltaic systems. The characteristics of each battery are given in Table 1.

Table 1. Characteristics of each battery.

Parameters	Li-ion	Pb-ac	Ni-Cd
Capacity	130 Ah	130 Ah	130 Ah
Total cell number	4	6	10
Nominal cell voltage	3.3 V	2.0 V	1.2 V
Total voltage	13.2 V	12 V	12 V

For the sizing, we considered the average daily sunshine for the month of October in Burkina Faso, which is 5.72 kWh/m^2/day [22], a two-day autonomy, and a discharge depth of 65%. The results obtained show that the system is mainly composed of two PV modules (150 Wp each) connected in parallel, a 360 W DC/DC inverter, a 0.2 kVA DC/AC inverter, a 130 Ah battery (for each type), and the load. We consider these same characteristics for the simulations.

The energy balance is verified by considering the system losses at 0.65. The daily production thus amounts to 1115.4 Wh. This value is higher than that obtained for the load's daily requirements, which are estimated at 1000 Wh.

Figure 10 shows the modelling of the PV system.

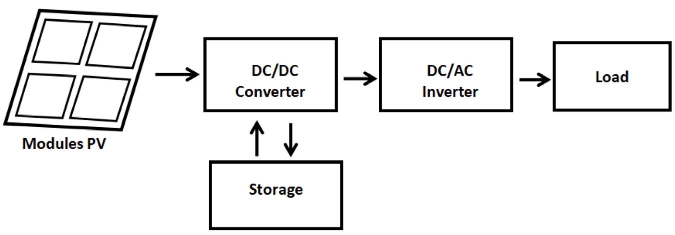

Figure 10. Block diagram of the photovoltaic system.

For the Matlab/Simulink simulations, we considered the daily average irradiation and temperature values for the month of October 2024 as input parameters (Figure 11).

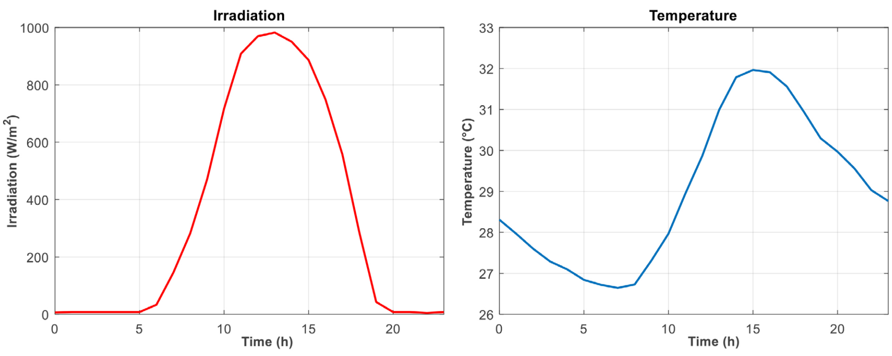

Figure 11. Sunshine and temperature curves as a function of time.

The output parameters are mainly the current, state of charge, voltage and temperature of each type of battery. The simulation results for each type of battery are shown in Figures 12-14.

- Li-ion battery

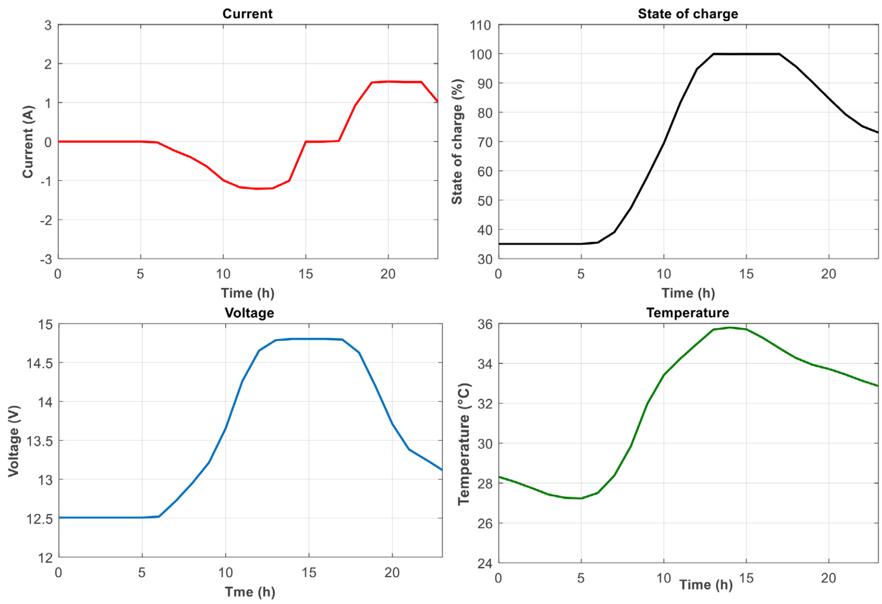

Figure 12. Influence of irradiation and temperature on the current, state of charge, voltage and temperature of a 130 Ah Li-ion battery in a PV system.

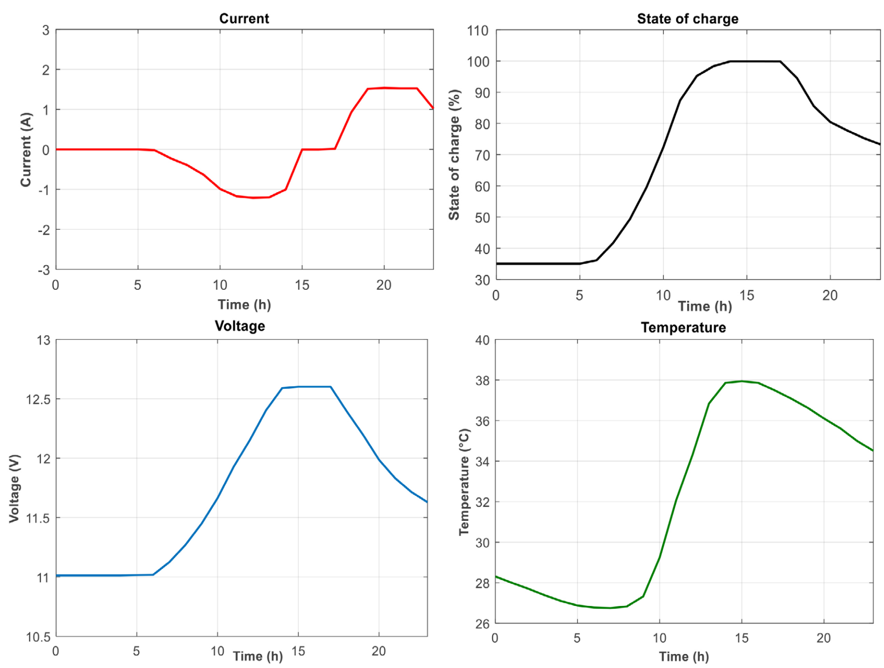

Figure 13. Influence of irradiation and temperature on the current, state of charge, voltage and temperature of a 130 Ah Pb-ac battery in a PV system.

- Ni-Cd battery

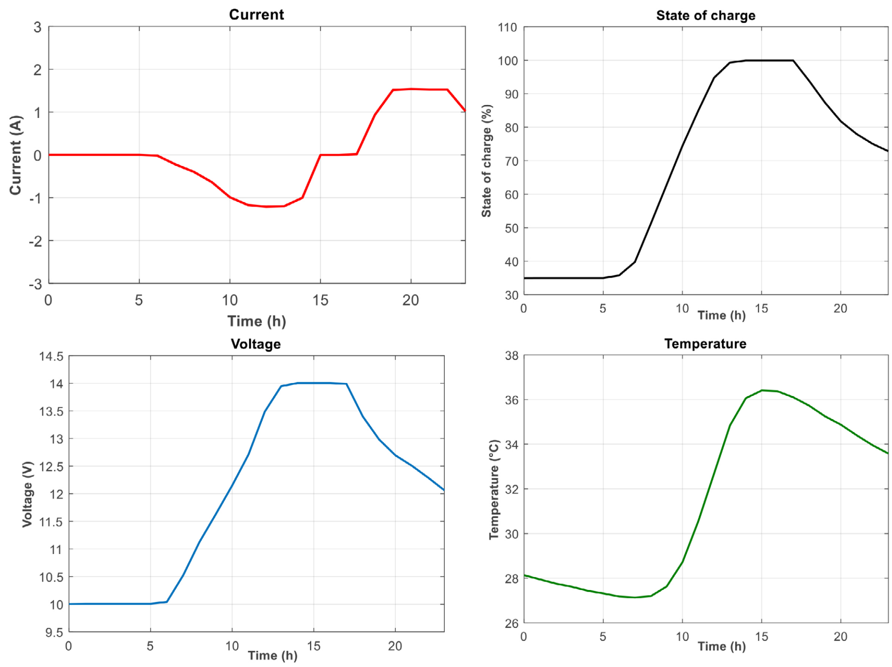

Figure 14. Influence of irradiation and temperature on the current, state of charge, voltage and temperature of a 130 Ah Ni-Cd battery in a PV system.

Figures 12-14 show that current intensity changes as a function of irradiance and load demand. These figures also show that the voltages and states of charge of the different types of battery increase as the charge/discharge current changes. However, we note that Li-ion and Ni-Cd batteries charge faster than Pb-ac batteries.

Internal battery temperatures increase as the ambient temperature rises. In fact, they change very quickly during the charging phases, forming a higher peak for the lead-acid battery (38˚C) than for the lithium-ion (35.8˚C) and Ni-Cd (36.4˚C) batteries. The increase in internal temperature for lead-acid batteries is greater than for Li-ion and Ni-Cd batteries.

As a result of these various simulations, the slower charging rate of Pb-ac batteries compared with Li-ion and Ni-Cd batteries is due, among other things, to the fact that the electrolyte is involved in the chemical reactions by varying the concentration of the solution. Also, the increase in internal temperature during charging is mainly due to the exothermic reactions that take place in electrochemical batteries. The kinetics of these reactions are favoured by the increase in ambient temperature. These reactions are more pronounced in Pb-ac batteries than in Li-ion and Ni-Cd batteries. These results obtained for the case of Burkina Faso are in agreement with those found by [1] and [23].

4. Conclusion

In this work, we have modelled an autonomous photovoltaic system with different types of batteries. The results obtained show that the current, voltage and state of charge depend on the amount of sunlight, the temperature and the receivers used.

Furthermore, the state of charge, voltage and internal temperature of lithium-ion and nickel cadmium batteries are more stable than those of lead-acid batteries in Burkina Faso's climate. As a perspective, it would be important to carry out a global study taking into account the number of cycles of the different types of batteries.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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