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Influence of Temperature and State Of Charge on Lithium-Ion and Lead Acid Batteries Performance in a Photovoltaic Application

Eric Korsaga, Dominique Bonkougou, Eric Simonguy, Zacharie Koalaga, Charles Wêpari Yaguibou, Nongma Ouiya and François Zougmoré

Laboratoire de Matériaux et Environnement, UFR/SEA, Université Ouaga 1 Prof Joseph Ki- Zerbo, 03 BP 7021 Ouagadougou 03, Burkina Faso.

Abstract: The storage of energy is a very important part of a photovoltaic system. Lithium-ion and lead-acid batteries are generally used for this purpose. This article compares the performance of these two types of batteries in a photovoltaic (PV) system under variation of temperature and state of charge. The PV generator, the lead-acid battery or the lithium-ion battery were modelled and then simulated using the Matlab / Simulink simulation environment. By taking into account the influence of temperature and state of charge, the simulation results show that lithium-ion technology is the most suitable for the storage of energy in a photovoltaic system.

Keywords: Temperature; photovoltaic; energy; storage; battery.

I. Introduction

Solar energy is a good alternative to conventional energy. Indeed, it is a non-polluting energy, available on the entire globe and also the best shared resource on earth. Thanks to solar photovoltaic modules, part of this solar energy is transformed into electrical energy. Stand-alone photovoltaic systems make it possible to consume electricity directly and permanently at the site of its production. The availability of energy is assumed by storage devices.

Indeed, lead-acid and lithium-ion batteries are very often used as storage technologies in photovoltaic installations. However, the temperature and the state of charge have important effects on their performance. For better understanding of the behaviour these batteries and improving their performance, numerous authors have developed various models [1-6]. Despite being prosperous in many aspects, most of them still have several drawbacks. Some of them ignore the temperature effects [2,7] while others only work for a fixed state of charge [8] which is an important factor for increasing the batteries performance. The aim of this work is to study the behaviour of lithium-ion and lead-acid batteries under the influence of temperature and state of charge in order to determine the best battery for energy storage in PV system.

This paper is organised as follows. In the first part, we will describe the mathematical equations used in the developed photovoltaic module and batteries. The second part represents the Matlab / Simulink modelling of lead-acid and lithium-ion batteries. The results of simulations and comparisons are given in the last part.

II. Material and Methodology

II.1. Modeling a photovoltaic generator

A photovoltaic generator makes it possible to convert solar energy into electrical energy. It usually consists of several modules connected in series and in parallel to obtain the desired peak power. Each module is in turn formed of several cells connected also in series and / or in parallel [8-13].

The mathematical model, which characterizes a photovoltaic module consisting of Np cells in parallel and Ns cells in series is given by the following equation [10-13] :

$$I = N_p.I_{ph} - N_p.I_s\left(exp\left[\frac{q\left(\frac{V}{N_s}+\frac{IR_s}{N_p}\right)}{nkT}\right]-1\right) - N_p\left(\frac{\frac{V}{N_s}+\frac{IR_s}{N_p}}{R_{sh}}\right) \quad (1)$$

where:

$$I_{ph} = \left[I_{sc} + K_i\left(T - T_{ref}\right)\right]\frac{G}{1000} \quad (2)$$

$$I_s = I_{s,ref}\left(\frac{T}{T_{ref}}\right)^3 exp\left[\left(\frac{qE_G}{nk_B}\right)\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (3)$$

I_{ph} : is the photocurrent, I : the total output current. I_s : is the saturation current of the unlighted junction (A), q : the elementary electric charge ($1.6.10^{-19}$ C), k_B : the Boltzmann constant ($1.381.10^{-23}$J/K), T : the absolute temperature of the cell (K), T_{ref} : : reference temperature (K), n : the ideality factor of the junction, G : the solar irradiation (W/m^2) and E_g : the gap energy of the semiconductor.

From equation (1), we establish a mathematical modelling under Matlab / Simulink of the photovoltaic generator given in Figure 1:

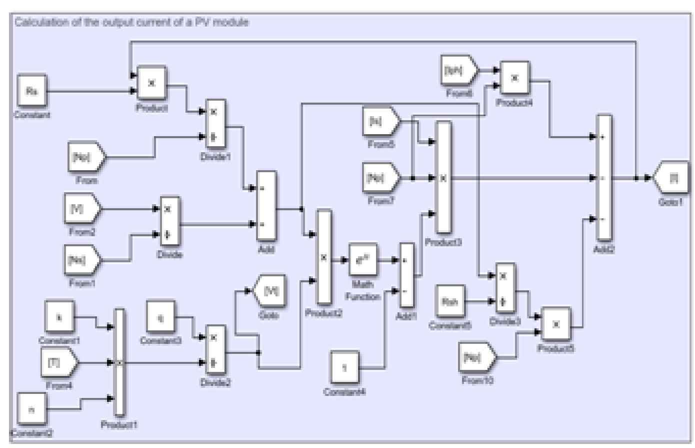

Figure 1: Simulation model of PV generator.

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II.2. Storage modeling

A battery is made up of a set of elements of 2 V connected in series to obtain the desired operating voltage. The batterie converts chemical energy into electrical energy and vice versa.
The general equation for the used battery model is the following equation [2,17,18]:

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i - R \cdot i + C \quad (4)$$

Where V: is the actual battery voltage (V), E_o: the battery constant voltage (V), K : the polarization resistance (Ω), Q : the battery capacity (Ah), it : the actual battery charge (Ah), R : the battery internal resistance (Ω), I : the actual battery current (A) and C : the exponential voltage (V).
From the discharge curve of a battery, we obtain the following equations [2,16,18] :

$$A = V_{full} - V_{ex} \quad (5)$$

$$B = \frac{3}{Q_{ex}} \quad (6)$$

with, A : exponential zone amplitude (V) and B : exponential zone time constant inverse (Ah^{-1})
The voltage constant (E_o) is deducted from the fully charged voltage (V_{full}):

$$E_o = V_{full} + K + R.i - A \quad (7)$$

A typical battery cell contains three main parts: a negative electrode, a separator, and a positive electrode. All these three components are immersed in an electrolyte solution [6]. Due to the different nature of the chemical materials, we have different types of batteries, which most use are: Lead Acid Batteries, Nickel-Cadmium (Ni-Cd) Batteries, Nickel-Metal Hydride (Ni-MH) batteries, Sodium Sulfur batteries, Zinc-Air batteries, Lithium Ion batteries [18]. The most used in photovoltaic systems are: lead acid batteries and lithium-ion batteries.

II.2.1. Modelling of lithium-ion batteries

This part shows the charge and discharge modes of operation by terms of mathematical expressions and a simulation model. The equations for the simulation of lithium-ion battery are as follows [2,17,18]:

- Discharge ($i^* > 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i^* - R \cdot i + A \cdot \exp(-B \cdot it) \quad (8)$$

- Charge ($i^* < 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{it-0{,}1 \cdot Q}i^* - R \cdot i + A \cdot \exp(-B \cdot it) \quad (9)$$

The impact of temperature on the model parameters is represented by the equations [19] :

- Discharge ($i^* > 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am})-it} \cdot (i^* + it) + A \cdot \exp(-B \cdot it) - R(T) \cdot i - C \cdot it \quad (10)$$

- Charge ($i^* < 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{0{,}1Q(T_{am})+it} \cdot i^* - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am})-it} \cdot it + A \cdot \exp(-B \cdot it) - R(T) \cdot i - C \cdot it \quad (11)$$

where:

$$E_o(T) = E_o|_{T_{ref}} + \frac{\partial E}{\partial T}(T - T_{ref}) \quad (12)$$

$$K(T) = K|_{Tref} \cdot \exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (13)$$

$$Q(T_{am}) = Q|_{T_{am}} + \frac{\Delta Q}{\Delta T}(T_{am} - T_{Ref}) \quad (14)$$

$$R(T) = R|_{T_{ref}} \cdot \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (15)$$

i^* is the filtered current (A) and C is the nominal discharge curve slope (V/Ah).

II.2.2. Modelling of lead acid

The charge and discharge of the lead-acid battery can be modelled from the following equations [17,18] :

- Discharge ($i^* > 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{Q-it}i^* - R \cdot i + \exp(t) \quad (16)$$

- Charge ($i^* < 0$)

$$V = E_o - K\frac{Q}{Q-it}it - K\frac{Q}{it-0{,}1 \cdot Q}i^* - R \cdot i + \exp(t) \quad (17)$$

When we take into account the effect of temperature, we have the following equations:

- Discharge ($i^* > 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am})-it} \cdot (i^* + it) + \exp(t) - R(T) \cdot i - C \cdot it \quad (18)$$

- Charge ($i^* < 0$)

$$V(T) = E_o(T) - K(T) \cdot \frac{Q(T_{am})}{Q(T_{am})-it}it - K(T) \cdot \frac{Q(T_{am})}{it-0.1\,Q(T_{am})}i^* - R(T) \cdot i + \exp(t) - C \cdot it \quad (19)$$

The different mathematical formulations presented above, allowed us to develop under the Matlab / Simulink environment, the model of lead-acid battery, whose block diagram is shown in Figure 2. The ambient temperature and the charging current represent the input parameters. An oscilloscope placed at the output of the accumulator makes it possible to observe the state of charge, the voltage and the evolution of the internal temperature of the battery.

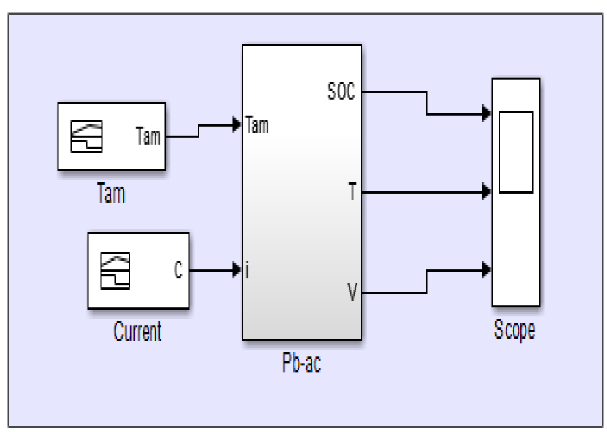

Figure 2 : Simulink model of lead-acid battery.

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III. Simulation results

III.1 Influence of temperature on I (V) and P (V) characteristics of a photovoltaic generator

The temperature affects the characteristics of a 30 W photovoltaic generator (Ns=36 and Np=1). When the temperature increases, the voltage decreases, while the current increases slightly. I(V) and P(V) characteristics are then presented in Figure 3 for temperatures from 25 ^{o}C to 50 ^{o}C and irradiance of 1000 W/m^2.

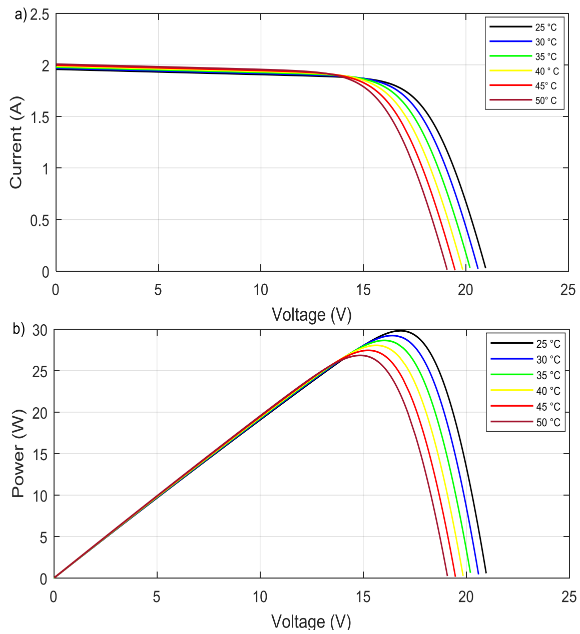
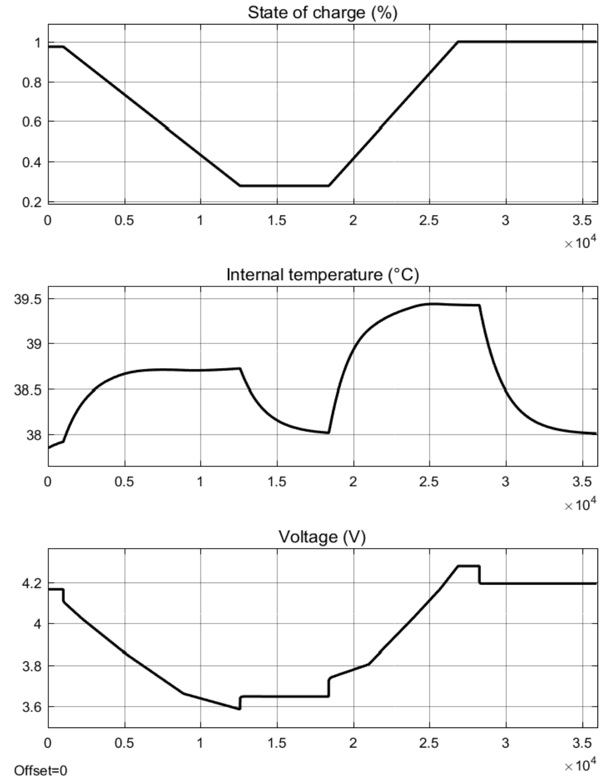


Figure 3 : I(V) characteristic for different temperatures b) P(V) characteristic for different temperatures.

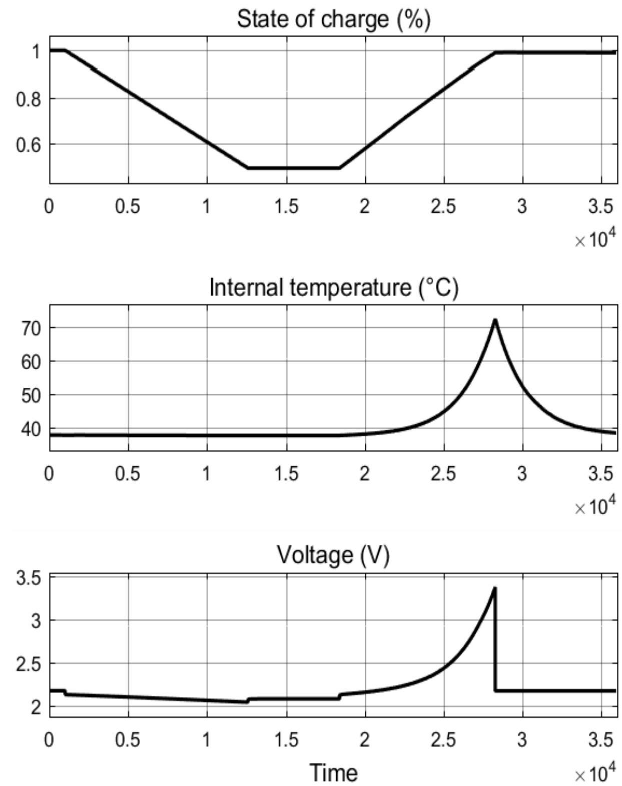
III.2. results of simulations and comparisons of accumulators

Both types of batteries were first simulated at an ambient temperature of 38 ^{o}C. In the second simulation, we varied the ambient temperature in order to observe the influence of the temperature on the state of charge and the voltage of the lithium-ion and lead-acid battery. The simulation results are presented in Figures 4-5 of one cycle (discharge/charge) for 10 hours.

The ambient temperature is set at 38^{o}C. During the discharge phase, there is a slight decrease in the internal voltage of the two types of batteries. Also, the temperature of the lithium-ion and lead acid batteries varies very little. During the charging phase, the internal voltage of both types of batteries increases. However, there is a peak voltage of the lead-acid battery that goes from 2.2 V to 3.4 V. Also, the internal temperatures of the two batteries increase. This increase in internal temperature is much greater for the lead-acid one (38 to over 70 °C) than the lithium-ion battery (38 to 39.4 °C). The strong increase in temperature decreases the life of lead-acid batteries (Figures 4).



a) dynamic charge-discharge of a 15 Ah, 3 V Li-Ion battery.



b) dynamic charge-discharge of a 15 Ah, 2.2 V lead-acid battery.

Figure 4 : Dynamic charge-discharge of lithium-ion and lead-acid batteries at constant ambient temperature (38 °C).

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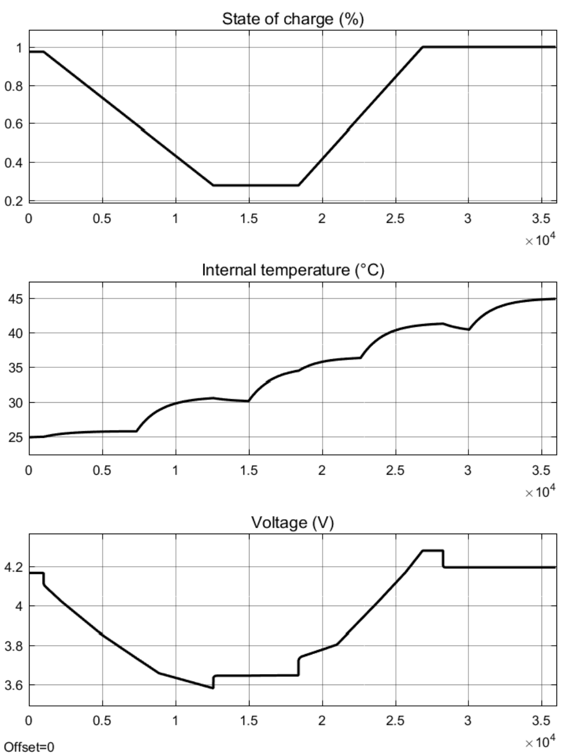
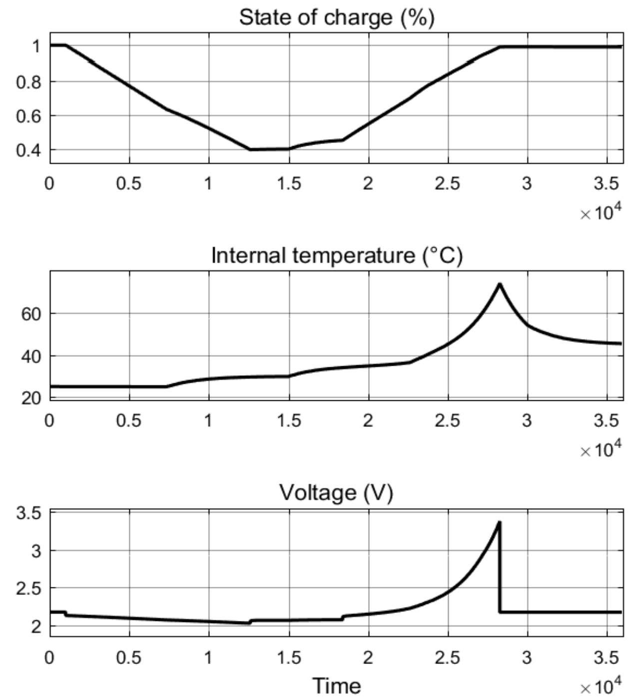
The figure 5 shows the performance of the temperature dependent Lithium-Ion and lead-acid batteries models. When the ambient temperature is varied from 25 °C to 50 °C with a pitch of 5 ^{o}C, it is observed that :

- the internal temperature of the lithium-ion battery changes with increasing ambient temperature during the discharge and charging phases. However, increasing the ambient temperature has very little effect on the internal voltage and the state of charge of this battery during these phases ;

- for the lead-acid battery, it is noted that the variation of the ambient temperature is accompanied by small disturbances on its state of charge while its internal voltage hardly varies. However, increasing the ambient temperature causes an increase in the internal temperature of the battery. During the charging phase, a peak of internal temperature up to 75 ° C is observed.



a) dynamic charge-discharge of a 15 Ah, 3 V Li-Ion battery at variable ambient temperature.



b) dynamic charge-discharge of a 15 Ah, 2.2 V lead acid battery.

Figure 5 : dynamic charge-discharge of lithium-ion and lead-acid batteries at variable ambient temperature.

According to our simulation results, the internal temperatures and voltages of both types of batteries increase during the charging phase. These results confirm those obtained by [20]. The increase of the internal temperature of the lead-acid battery is much higher than that of lithium-ion. Also, the variation of the ambient temperature causes internal temperature and voltage peaks as well as low disturbances of the state of charge of the lead-acid battery. However, this variation does not have enough impact on the internal voltage temperature and the state of charge of the lithium-ion battery. For example, lithium-ion batteries are more stable than lead-acid batteries in the face of temperature effects. The increase in ambient temperature causes an exponential increase in the internal temperature of both types of batteries. However, the increase of the internal temperature of the lead-acid battery is greater than that of lithium-ion. Thus, they are best suited as storage technology in a photovoltaic system especially in hot regions.

IV. Conclusion

This article describes the behavior of lithium-ion and lead-acid batteries under the influence of temperature and state of charge to determine the most efficient for energy storage in a PV application. From the simulation results, the temperature and the state of charge have a greater influence on the output voltage and state of charge of the lead-acid accumulators than those of the lithium-ion accumulators. However, these results need to be confirmed by an experimental study of lithium-ion and lead-acid batteries for stand-alone PV systems.

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