Parameters Modelling of A Lead-Acid Battery and its Operation in A Wind/Photovoltaic Hybrid System in Autonomous Mode

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***Abstract*— Renewable energy, particularly solar and wind, has an intermittent nature. For this purpose, a storage module is recommended for a power generation system. This document shows the modeling of the lead-acid battery integrated in a hybrid system. The aim is to determine the internal characteristics of the battery and the influence of temperature and the influence of the charge and discharge time on one hand, and to visualize their behavior towards the various energy flows of the hybrid system on the other hand. In this study, we modelled the battery according to the CIEMAT model (Centro de Investigaciones Energéticas, Mediombientales y Technologicas). The system is composed of a photovoltaic and a wind sources. The power delivered by each source is controlled by incorporation of tracking control of the point of maximum power. Therefore, the hybrid set is optimized. The battery has been integrated into the system for energy storage, whose operation (charge and discharge) is managed by a supervision module. In the hybrid system, the operation of the battery generally depends on the energy input from the sources and the charge demand. The veracity of the CIEMAT model is shown on the simulation results that we performed using Matlab Simulink software.**

Keywords—Battery, CIEMAT, Photovoltaic, Wind, Hybrid, SOC, MPPT, Matlab and Simulink

I. INTRODUCTION

In a country, energy is a key sector for development. Since the last decades, energy consumption has increased significantly [1], [2]. Currently, 80% of the world's energy production is fossil energy [1]. The continued use of fossil energy is leading to the progressive depletion of its resources. In this context, renewable energy is the subject of an alternative trend solution [3]. They are generally intermittent in nature, as a single source cannot indeed solve the energy problem. Thus, a hybrid system combining several sources improves production efficiency. In this work, the hybrid system studied consists of a photovoltaic and a wind conversion chain. The system thus uses solar and wind energy, each of which is dependent on weather conditions. Thus, the continuity of production of these two energy sources is not guaranteed at all. It is for this reason that the need for the battery becomes paramount for the system in autonomous mode, in order to reduce the risk of disruption of energy production. In the literature, several battery models are available [4], [5], [6]. In this study, the CIEMAT model was chosen and used in our system. The work thus consists in modelling a battery using the CIEMAT model. The aim of this study is on one hand to verify the veracity of this model with the help of simulation results using Matlab Simulink software, and on the other hand to visualize their mode of operation in a hybrid wind/photovoltaic system for different possible cases. This document will first show the modeling of the CIEMAT model parameters and then, in the second step, their operating mode in a hybrid system. EASE OF USE

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II. PRESENTATION OF THE HYBRID SYSTEM

The electric production chain of the hybrid system is composed of the following cells:

- 11 photovoltaic panels of 720W, connected to the DC bus
- 01 3KW power wind turbine, connected to the DC bus via a rectifier and a voltage regulator.

The energy storage device implemented in this hybrid system is directly connected to the DC bus whose voltage is fixed at 48V. Thus, there are 24 accumulator cells, each 2V connected in series. The hybrid system is used in autonomous mode in isolated sites. It is used to supply a specific charge on a specific site. The DC bus is therefore connected directly to the charge. The power delivered by each of the sources is controlled by incorporation of tracking commands of the maximum power point. Consequently, the hybrid set is optimized. The topology of the studied system is shown in figure (1).

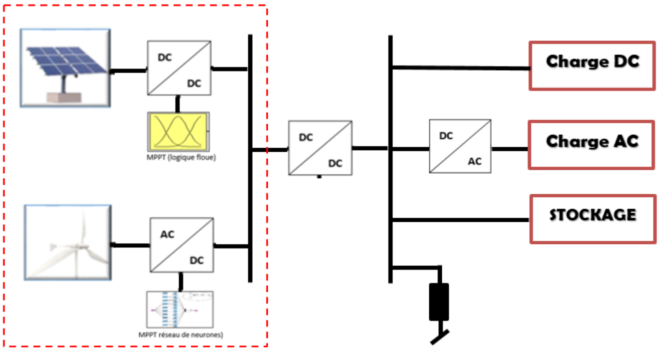

Figure 1 – Topology of the dual-source hybrid system

III- PRESENTATION OF THE CIEMAT MODEL

The operating conditions produced by hybrid systems are related to the state of the storage system. A good balance between precision and simplicity is achieved by using a model generally based on the observation of the physico-chemical phenomena of charging and discharging, of the storage system [5], [6]. The model is based on the equivalent circuit of figure (2). The battery is described by a voltage source and its variable internal resistance.

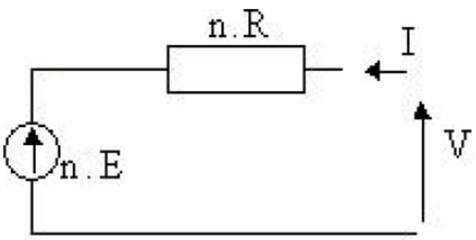

Figure 2 –Equivalent wiring diagram of the battery system

The mathematical model given by equation (1), which best describes the physical phenomena of charging and discharging, is given below [7]:

$$V = n.E \pm n.R.I \quad (1)$$

In our case, the battery is composed of 24 cells of 2V in series. The manufacturer's characteristic gives us for one cell a capacity C_{10} . (C_{10} is the capacity in Ah of the battery in constant current discharge regime I_{10} during 10h : $C_{10} = 10.I_{10}$)

The equations needed to describe the behavior of the battery depend on the charge and discharge regime. The formulation of these equations considers the standard expression of the battery capacity C. The state of charge (SOC) of the battery has a purpose on the residual charge and the charging or discharging regime.

A. *Direct Neural Power Control (DPC - ANN)*

In order to highlight the physical phenomena that govern the operation of the storage system, through capacity, temperature should be considered [6]. This is the reason why we propose the capacity model, giving the amount of energy that can be restored has a purpose of the average discharge current I given by equation (2).

The capacity model is based on the expression of the current, I_{10} corresponding to the operating regime C_{10} , in which ΔT is the accumulator heating (assumed to be identical for all cells) with respect to an ambient temperature equal to 25°C [5], [6], [8].

$$C = C_{10} \frac{1.67}{1 + 0,67\left[\frac{\bar{I}}{I_{10}}\right]^{0,9}} (1 + 0,005.\Delta T) \quad (2)$$

The capacity C is used as a reference in order to determine the state of charge of the battery (called « State Of Charge » or SOC).When the battery is fully charged, the SOC is 1 or 100%. When the battery is completely discharged, it is 0 or 0%. The latter will be formulated according to the amount of charge missing from the battery 'Q'.

$$SOC = 1 - \frac{Q}{C} \quad (3)$$

The time evolution of 'Q' depends on the operating mode of the battery.

$$Q = I.t \quad (4)$$

a. *Equation of Voltage in Discharge*

The expression of the battery voltage is established from equations (1) and (2) allow us to give a linked structure of the internal cells of the battery as a function of the electromotive force, internal resistance and the influence of the parameters.

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$$V_d = n_b\left\{2.085+0.12(1-SOC)\right\} - n_b\frac{|I|}{C_{10}}\left[\frac{4}{1+|I|^{1.3}}+\frac{0.27}{(SOC)^{1.5}}+0.02\right](1-0.007.\Delta T) \quad (5)$$

C. *The equation of Voltage in Charge*

The charge equation has the same structure as equation (5), which shows the influence of electromotive force and internal resistance, equation (6).

$$V_c = n_b\left\{2+0.16SOC\right\} + n_b\frac{|I|}{C_{10}}\left[\frac{6}{1+|I|^{0.86}}+\frac{0.48}{(1-SOC)^{1.2}}+0.036\right](1-0.025\Delta T) \quad (6)$$

For charge modeling, a set of two states such as overcharge and deep discharge must be considered. The expression of overcharge includes two physical phenomena :

- the gassing whose voltage is V_g
- the saturation which expresses the standby state of the battery, when its state of charge no longer changes. Then the battery voltage is V_{ec}

As for the overcharge, we have equation (7):

$$V_{sc} = nV_g + n(V_{ec}-V_g)\left[1-\exp\left(\frac{t-t_g}{\tau_g}\right)\right] \quad (7)$$

$$V_g = \left[2.24+\ln\left(1+\frac{I}{C_{10}}\right)\right].(1-0.002.\Delta T) \quad (8)$$

$$V_{ec} = \left[2.45+2.011.\ln\left(1+\frac{I}{C_{10}}\right)\right](1-0.002\Delta T) \quad (9)$$

$$\tau_g = \frac{1.73}{1+858.\left(\frac{I}{C_{10}}\right)^{1.67}} \quad (10)$$

For storage systems, these phenomena can generally be summed up as a table describing the operation of batteries (Table 1) [5].

Battery voltage	Operating zone	Current	Operating condition	
V_{sc}	Saturation		$V=V_{ec}$	$\eta_c=0$
	Gassing	$I>0$	$V_{ec}\geq V\geq V_g$	$0<\eta_c<1$
V_c	Charge		$V<V_g$	
V_{edc}	Discharge/charge transition	$I=0$	$V_c\geq V\geq V_{dc}$	
V_{dc}	Discharge	$I<0$	$V>0.9V_N$	
	Over-discharge		$V_N\geq V\geq 0.7V_N$	
	Deep discharge		$V<0.7V_N$	

Table 1: Overview of the operating area of the batteries

The release of acid cause an increase of E_b and a decrease of R_b and thus a decrease of the charging current I_{ch} with R_b. The evolution of the voltage at the battery terminal is indicated by the discharge equation (5).

- When the charge is almost complete, the active ingredient becomes scarce. The current keeps on flowing although the battery no longer leads to chemical reactions. Instead, the current merely electrolyzes the water, breaking it down into oxygen at the positive electrode and hydrogen at the negative electrode.

D. *Charge Efficiency*

There are two types of efficiency: faradic (Coulombian) efficiency and energy efficiency. The first concerns the capacity of the battery to store energy and does not involve Joule losses in the internal resistance [6].

The energy efficiency includes the faradic efficiency and Joule losses. The Joule efficiency corresponds to the resistive losses, and the faradic efficiency (which has a value close to 100% for low charging currents and low state of charge).

$$\eta_c = 1-\exp\left[\frac{20.73}{\frac{I}{I_{10}}+0.55}.(SOC-1)\right] \quad (11)$$

The trend of the energy efficiency or overall efficiency is represented (Coulombian efficiency + losses by Joule effect) for the battery in charge, depending on how much energy is used.

IV- SIMULATION RESULTS OF CIEMAT MODEL

Simulations are carried out to study the internal resistance and the influence of temperature and charge and discharge time on the behavior of the electrochemical storage system. In the whole simulation we consider $C_{10} = 100Ah$ and the nominal voltage $V_b = 48$V.

A. *Internal Battery Resistance*

Figures (3) and (4) illustrate the internal resistance of the battery during charging and discharging.

During discharge, the resistance of discharge R_d corresponds to the considerable increase. This means that the current cannot easily flow through the battery. The second term of equation (6) shows us that the internal resistance is directly linked to the state of charge of the battery. When it is charged, the internal resistance is low and becomes significant for a state of charge close to zero. On the other hand, the charging resistance Rc has a higher value when full charge is reached (figure 4).

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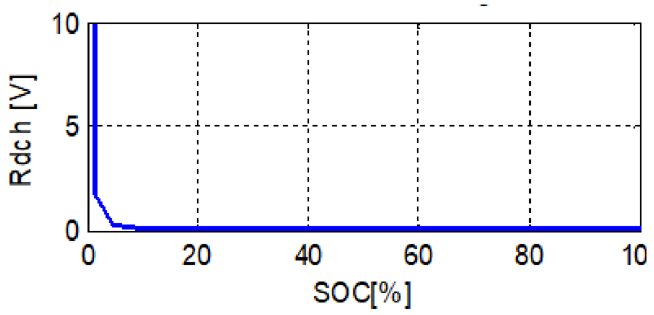

Figure 3: Battery resistance (discharge)

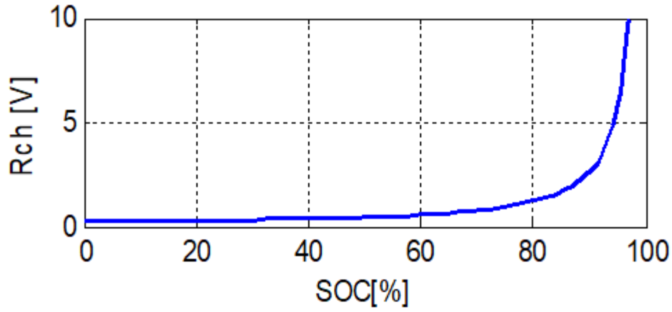

Figure 4 – Battery resistance (Charge)

B. Influence of Temperature

a. On capacity and State of charge

Figure (5) shows the influence of temperature on the capacity based on battery current. Figure (6) shows the state of charge based on capacity.

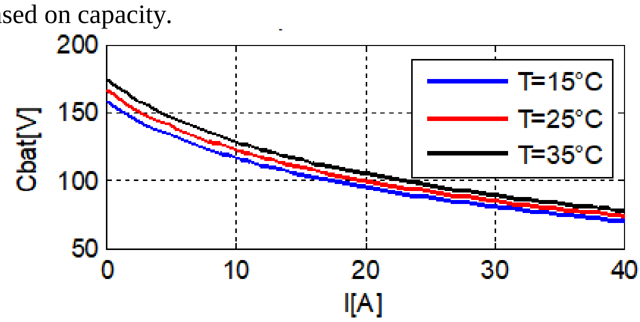

Figure 5 – Influence of temperature on capacity

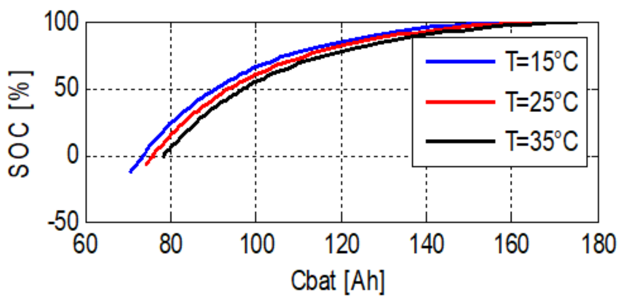

Figure 6 – Temperature influence on the state of charge

As we see, the increase in temperature causes a moderate rise in capacity. In the case of charging, the battery capacity corresponding to the minimum state of charge ($SOC = 0$) changes proportionally to the temperature.

b. On battery Voltage

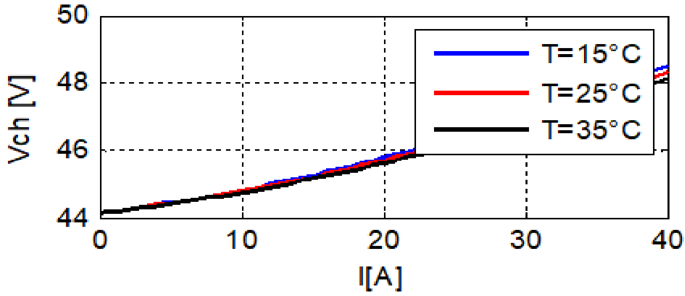

Figure 7 – Influence of temperature on voltage

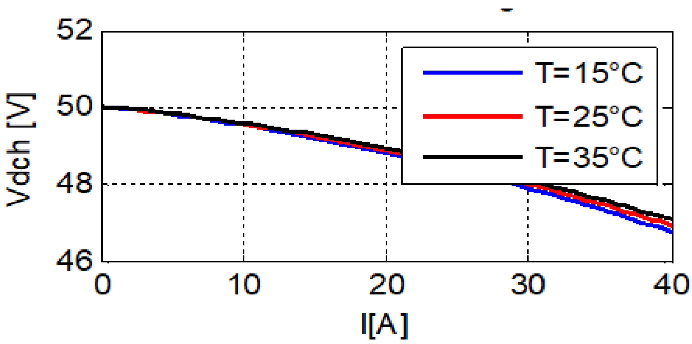

Figure 8 – influence of temperature on voltage

C. Influence of charging and Discharging Time

a. On Battery Voltage

The influence of time (duration of charge and discharge) on the battery voltage, illustrated in figures (9) and (10), makes it possible to study the case of charge and discharge.

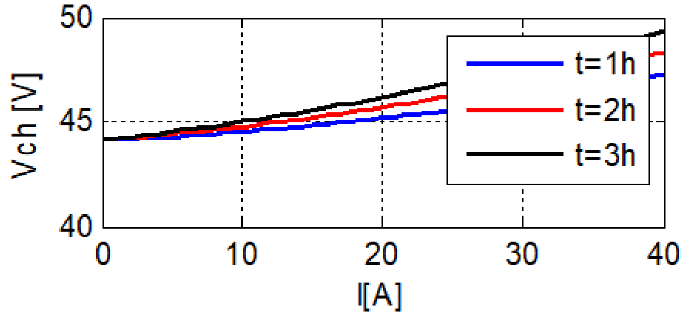

Figure 9 – influence on charging time on the voltage

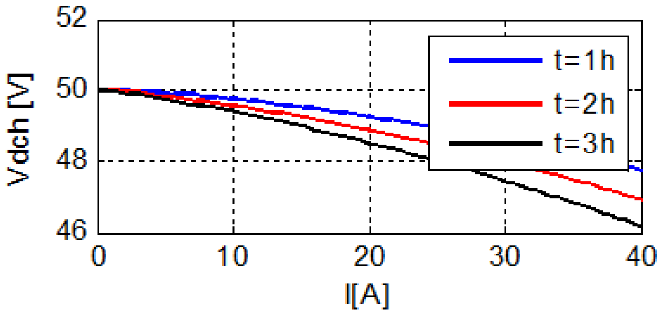

Figure 10 – influence on discharging time on the voltage

In the case of charging, the longer the charging time decreases, the further the maximum battery voltage is reached.

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In the case of discharging, the longer the discharge time, the deeper the voltage drops.

V. SIMULATION RESULTS OF THE COMPLETE SYSTEM

In this part, the simulation is carried out in order to study the behavior of the CIEMAT model in the complete system. In this case, we have set the temperature at 25°C, but the wind speed and solar radiation remain variable. The energy flow of our system is managed by a supervision module in such a way that if the state of charge is not between 20% and 80%, the battery is disconnected to protect it against overcharging and deep discharge. Initially, the state of charge was set at 50%. Figure () and () show the input of the system.

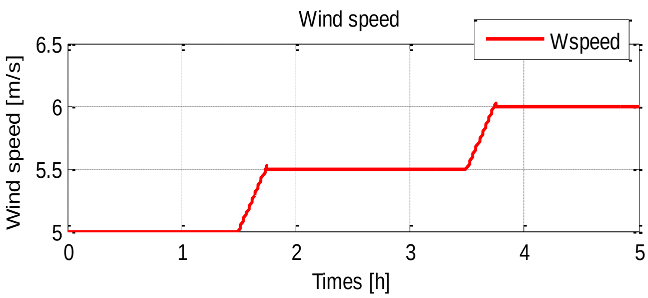

Figure 11 – System Input: Wind Speed

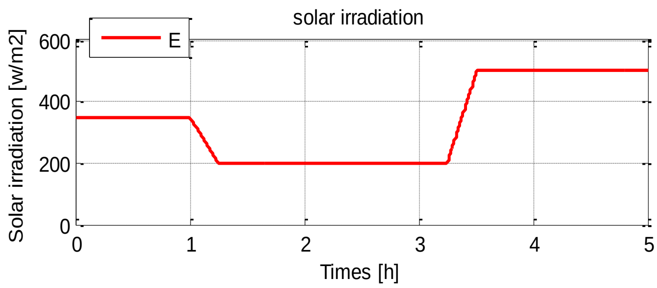

Figure 12: System Input: Insolation

From the wind speed and insolation as presented in figures (11) and (12), we obtained figures (13), (14), (15) and (16) showing respectively the power (hybrid power obtained and power demanded by the charge), the DC bus voltage, the state of charge and the battery voltage during its operating time.

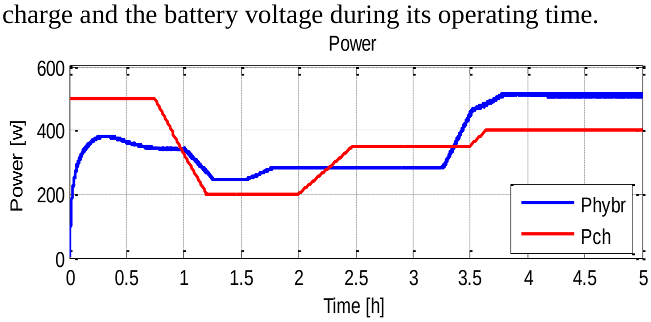

Figure 13 – Hybrid and load power

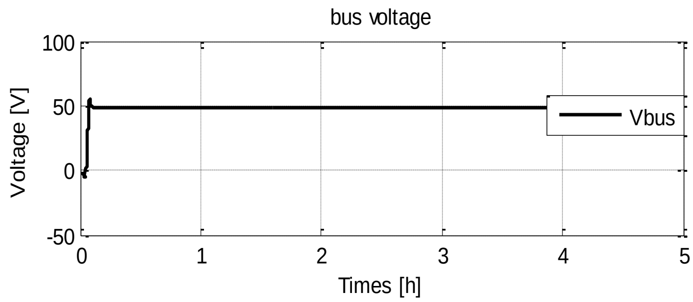

Figure 14 – DC bus Voltage

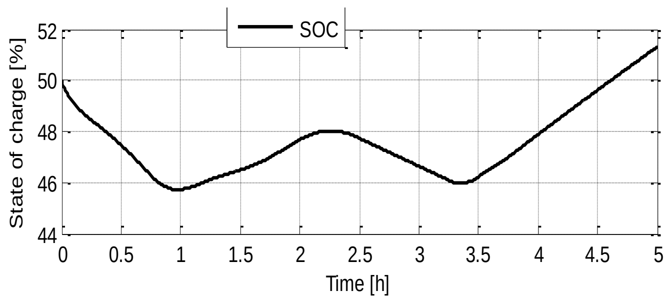

Figure 15– Stage of charge of the battery

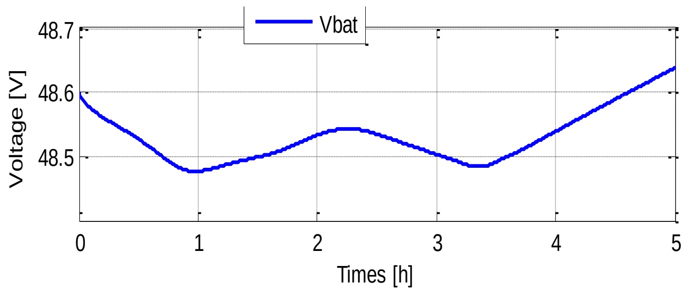

Figure 16– Battery Voltage

If the power supplied (hybrid power) is higher than the charge, the battery is charged, so the voltage increases. In the opposite case, the battery discharges and its voltage decreases.

VI. CONCLUSION

We mathematically modelled the battery based on the CIEMAT model. This model allowed us to observe the operating characteristic of the lead-acid battery (48V, 100Ah), particularly the variation in the internal resistance of the battery during charge and discharge and the influence of temperature and charge and discharge time on the battery. The simulation results describing the physical and internal behavior of the battery prove the accuracy of this model. In the overall system, the battery performs an important role. Their operation is managed by a supervision module. It comes into play when the hybrid power is lower than the power required by the charge (the battery is discharged). In the opposite case, the battery is charged (storage of electrical energy). If the state of charge is greater than or equal to 80% or less than or equal to 20%, the battery is automatically disconnected for safety against overcharging and deep discharge.

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