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COMPARATIVE STUDY OF LEAD ACID BATTERY MODELLING

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ABSTRACT

In the electric circuit of combustion cars, the electric energy is produced by the internal alternator, Therefore, in the case of use of the accessories during its stops or in the cranking phase, it is essential to put a battery to store the energy captured to provide power. We have proposed in this paper to study the modeling of a lead acid battery to highlight the physical phenomena that govern the operation of the storage system. This work is devoted to the modeling and simulation of two battery models namely the model CIEMAT and the simplified electric model PSpice under the MATLAB environment. A pulse discharge and charge test are performed on a commercial automotive lead acid battery in order to collect data to evaluate those models, results are presented and compared.

Keywords: lead acid battery, storage system, modeling, CIEMAT model, PSpice model, TUDOR TB620.

1. INTRODUCTION

The storage of electrical energy represents a major challenge. At present, however, only supercapacitors and accumulator batteries are capable of having an autonomous energy reserve. There are several types of accumulators and several electrical and chemical factors that can affect their performance. Hence the idea of looking for models to represent them to ensure a rigorous design. However, the difficulty for modeling an accumulator lies in the nature of the electrochemical and/or dynamic phenomena that occur during its operation. Indeed, to understand the behavior of an accumulator such as a battery, it is necessary to build a model capable of predicting and simulating its operation. This modeling proves, according to several authors very complex [4, 5]. Despite this, at the level of literature, there is a wide variety of drumming models described by several authors as [6] [7] [8][9]. Most often, in these models the battery is represented by an equivalent electrical circuit consisting of resistors, capacitors and other elements of fixed value or varying with parameters, such as state of charge and temperature [10].

To establish a reliable model capable of predicting operation, in solar energy applications photovoltaic, in this paper we propose to design, under the MATLAB / Simulink environment, two battery models; that is, based on the universal CIEMAT model [11,12,13]. and the one built according to the simplified classical model PSpice [14]. Then, we compared these two models with the experimental curves of the commercial automotive 62Ah, 12V, 540A (TUDOR TB620) lead acid battery.

Our paper is organized as follows: after a brief introduction, in section 2, we briefly present the structure and principle of operation of the batteries. In section 3 we introduce the modeling of lead batteries, focusing on both so-called CIEMAT and PSpice models. In section 4, we expose and interpret the results of simulations of the models developed. This section concludes with a comparative study of our simulations with the experimental measurements of the manufacturer of TUDOR lead acid battery. Finally, our conclusions and perspectives are presented.

2. STRUCTURE AND FUNCTIONING OF BATTERIES

A battery consists of a set of electrochemical cells, capable of storing electrical energy in chemical form, then of restoring it partially afterwards, thanks to the reversibility of the reactions involved. These reactions consist of oxidation and reductions in the electrodes. The current is produced by the circulation of electrons between two plates or electrodes, a positive electrode composed of an oxidizing body, capable of attracting electrons, and a negative electrode composed of a reducing body, capable of giving off electrons.

A battery is therefore characterized first of all by a couple "Oxidizer-Reducer", exchanging electrons, for example "Lead / Lead Oxide - Nickel / Cadmium". The association of two plates constitutes the primary entity of a battery. Both plates are immersed in a liquid electrolyte solution or gel (Electrolyte). It is a chemical reaction between the solution and the electrodes that causes the displacement of electrons and ions in the solution. Thus, the function of the electrolyte is to provide ionic conduction and, more generally, to participate in the chemical reaction. A porous insulator (separator) separates the two plates while allowing the passage of ions [16]. In the case of lead-acid batteries, they are based on the following oxidation-reduction reaction [15]:

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2Pb^{2+} + 2SO_4^{2-} + 2H_2O \quad (1)$$

3. MODELING LEAD-ACID BATTERIES

In this part, we expose the models chosen to perform simulations.

3.1 Description of the CIEMAT model

The first model used for the simulation was developed by CIEMAT in Spain (Centro de Investigaciones Energéticas, Mediombientales y Technologicas) [12]. This model is based on the electrical

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diagram of Figure-1. It defines the voltage across the battery according to some parameters, such as the imposed current, its state of charge and its temperature. This model takes into account the faradic efficiency in charge to calculate the evolution of its state of charge, while integrating the phase of degassing (hydrogen release) which is a phenomenon peculiar to lead batteries, causing a significant rise in voltage at the end of charge [17].

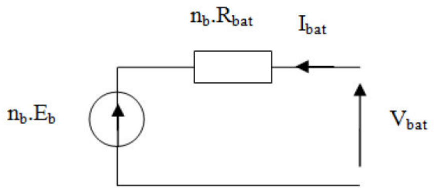

Figure-1. Equivalent circuit of the CIEMAT battery.

In this model, for n_b cells in series, the voltage across the battery is given below:

$$V_{bat} = n_b\, E_b + n_b R_{bat} I_{bat} \quad (2)$$

Where V_{bat} and I_{bat} are the voltage and current of the battery, Eb is the e.m.f (electromotive force) of a cell of the battery and R_{bat} its internal resistance.

The description of the behavior of the battery according to the CIEMAT model requires three equations corresponding to the three modes of operation: the discharge regime, the charging regime and the battery overload regime. The set of these equations takes into account the standardized expression of the battery capacity C_{bat}. The SOC state of charge of the battery is a function of the residual charge and the charging or discharging regime [4].

3.1.1 Modeling CBAT capacity

The model of the capacitance C_{bat} gives the amount of energy that can be restored by the battery according to the average discharge current $I_{bat,\, moy,\, disc}$. This capacity is given by (3).

$$C = \frac{1.67\ \times C}{1 + 0.67 \times \left(\frac{I_{bat,\, moy,\, disc}}{I_{10}}\right)^{(1+0.005\Delta T)}} \quad (3)$$

With:

- **I_{10}:** Nominal battery current (in A) given by the manufacturer.
- **C_{10}:** Nominal capacity of the battery (in Ah) in a constant current discharge regime for 10 hours. It is given by the manufacturer and is such that:

$$C_{10} = 10 \times I_{10} \quad (4)$$

- **ΔT:** The heating of the battery compared to the ambient temperature of 25 ° C. It is assumed to be identical for all elements of the battery.

The state of charge of the battery SOC is a function of the capacitance C_{bat} and the amount of charge missing at the battery Q_m which depends on the operating mode of the battery, it is defined by (5):

$$Q_m = I_{bat} \times t \quad (5)$$

Where t is the operating time of the battery with an I_{bat} current. The expression of the state of charge of the battery SOC is given by (6):

$$SOC = 1 - \frac{Q_m}{C_{bat}} \quad (6)$$

The charge quantity Q_{bat} at a time t, is obtained as a function of the value of the current I_{bat}, the Faradic efficiencies (charge and discharge) and the charge state SOC calculated at the previous instant Qt-1, according to:

$$Q_{bat} = \begin{cases} Q_{t-1} + \eta_{charge} \times Q_{exch}(t) & if\ I_{bat} > 0 \\ Q_{t-1} + \eta_{discharge} \times Q_{exch}(t) & if\ I_{bat} < 0 \end{cases} \quad (7)$$

Where the amount of charge exchanged Q_{exch} is:

$$Q_{exch}(t) = \int_0^t I_{bat}\,(t)dt \quad (8)$$

3.1.2 Modelling faradic performance

Faradic performance is efficiency that relate to the capacity of the battery to store energy. They do not involve Joule losses in the internal resistance. For the CIEMAT model, the faradic efficiency is taken into account in the case of the load and is assumed equal to 1 in the discharge regime.

$$\eta_{disch} = 1 \quad (9)$$

The faradic efficiency under load depends on the charge rate; it has a value close to 100% for low load currents and a low state of charge. Then, it gets worse as we approach full load. η_{charge} is given by (10):

$$\eta_{charge} = 1 - exp\left[\frac{20.73}{\frac{I_{bat}}{I_{10}}+0.55}(SOC - 1)\right] \quad (10)$$

3.1.3 Battery voltage in discharge regime

In discharge regime, the e.m.f and the internal resistance are determined by (11) and (12):

$$E_{b-disch} = 1.965 + (0.12\ \times SOC) \quad (11)$$

$$R_{b-disch} = R_{bat} = \frac{1}{C_{10}} \times \left(\frac{4}{1 + |I_{bat}|^{0.3}} + \frac{0.27}{SOC^{1.5}} + 0.02\right) \times (1 - 0.007\Delta T) \quad (12)$$

then the expression of the battery voltage, for this discharge regime:

$$V_{bat-disch} = (n_b E_{b-disch}) - n_b R_{b-disch}|I_{bat}| \quad (13)$$

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3.1.4 Battery voltage in charge regime

In the charging regime and before the appearance of the phenomenon of "Gassing" (gaseous release of hydrogen and oxygen), the electromotive force and the internal resistance are determined by (14) and (15):

$$E_{b-charg} = 2 + 0.16 \times SOC \quad (14)$$

$$R_{b-char} = R_{char} = \frac{1}{C_{10}}\left(\frac{6}{1+(I_{bat})^{0.86}} + \frac{0.48}{(1-SOC)^{1.2}} + 0.036\right)(1 - 0.025\Delta T) \quad (15)$$

The expression of the voltage of the battery before the overcharge (16):

$$V_{bat-char} = n_b E_{b-char} + n_b R_{b-char} I_{bat} \quad (16)$$

3.1.5 Battery voltage in overcharge regime

In overload mode, the expression of the voltage of the battery takes into account two physical phenomena which are:

- The "Gassing" whose tension is V_g.
- The saturation that expresses the rest of the battery, when its state of charge no longer varies. the battery voltage called end of charge voltage V_{ec}.

For this overcharge regime, the expression of the battery voltage is then given by (17):

$$V_{bat-overch} = n_b V_g + n_b(V_{ec} - V_g)\left[1 - exp\left(\frac{t-t_g}{\tau_g}\right)\right] \quad (17)$$

With:

- t_g: the instant after which $V_{bat-char} = V_g$.
- V_g: "Gassing" tension expressed by (18).
- V_{ec}: end of charge voltage expressed by (19).
- τ_g: Time constant expressed by (20).

$$V_g = \left[2.24 + 1.97\, ln\left(1 + \frac{I_{bat}}{C_{10}}\right)\right](1 - 0.002\Delta T) \quad (18)$$

$$V_{ec} = \left[2.45 + 2.01\, ln\left(1 + \frac{I_{bat}}{C_{10}}\right)\right](1 - 0.002\Delta T) \quad (19)$$

$$\tau_g = \frac{1.73}{1 + 852\left(\frac{I_{bat}}{C_{10}}\right)^{1.67}} \quad (20)$$

The different mathematical formulations presented above, allowed us to develop, under the MATLAB / Simulink environment, the model of the CIEMAT battery, whose block diagram is represented in Figure-2.

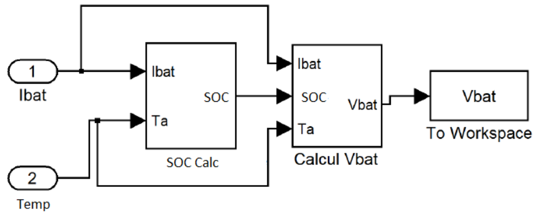

Figure-2. Diagram of the CIEMAT model of the lead-acid battery under MATLAB-Simulink.

3.2 Description of the PSPice model

The second model of the lead battery has been implemented on the basis of the so-called PSpice model [14]. It has two operating modes of charging and discharging. When the battery current is positive, then it is in charge mode. While it is in the discharge mode, if this current is negative. Figure-3 illustrates the equivalent diagram of the lead battery according to the PSpice model.

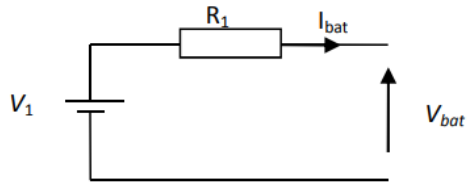

Figure-3. Equivalent diagram of the PSpice battery.

- The parameters listed below were used for modeling the lead-acid battery.
- SOC1 = SOC (0): initial state of charge (%);
- SOC (t): Available load (%);
- SOC_m: Maximum state of charge (Wh);
- n_b: Number of 2 V cells in series;
- D: Battery discharge rate (h^{-1});
- K_b: Efficiency of charge and discharge of battery.

As SOC varies linearly with the open-circuit voltage of the V_{ocb} battery, the relationship between the open circuit voltage of the battery and the SOC charge state can be determined using the following table [14].

Table-1. State of charge according to V_{ocb}.

Voltage V_{ocb}	State of charge(%)
12.64	100
12.53	90
12.46	80
12.40	75
12.26	60
12.16	50
11.98	25
11.75	0

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According to the PSpice model shown schematically in Figure-3 above, the voltage across the lead battery is then given by:

$$V_{bat} = V_1 + R_1 I_{bat} \quad (21)$$

V_1 and R_1 depending both on the operating mode of the battery; I_{bat} is positive when the battery is in charge mode (ch) and negative when it is in discharge mode (dch).

In charging mode, the resistor R_{ch} and the voltage V_{ch} of the battery can be written as follows:

$$R_1 = R_{ch} = \left(\frac{0.139}{(1.06 - SoC(t)) \times n_b} + 0.785\right) \times \frac{1}{SoC_m} \quad (22)$$

$$V_1 = V_{ch} = (0.148 \times Soc(t) + 2) \times n_b \quad (23)$$

In discharge mode, the resistance R_{dch} and the voltage V_{dch} of the battery are then written in the following manner:

$$R_1 = R_{dch} = \left(\frac{0.1037}{(SoC(t) - 0.14) \times n_b} + 0.785\right) \times \frac{1}{SoC_m} \quad (24)$$

$$V_1 = V_{dch} = (0.124 \times Soc(t) + 1.926) \times n_b \quad (25)$$

To estimate the value of SoC (t), the following equations will be used to describe the PSpice model [14].

$$SoC(t + dt) = SoC(t)\left(1 - \frac{D\,dt}{3600}\right) + \frac{K_b(V_{bat}I_{bat} - R_1 I_{bat}^2)dt}{3600} \quad (26)$$

In the previous equation, the time is expressed in seconds. Using equation (21) of V_{bat} and after integration, the value of SoC (t) can be determined as indicated by (27):

$$SoC(t) = SoC(t-1) + \frac{1}{3600}\int_{t-1}^{t}\left[\frac{K_b V_1 I_{bat}}{SoC_m} - SoC(t-1)\,D\right]dt \quad (27)$$

Following these mathematical formulations, we can develop, under the MATLAB / Simulink environment, the PSpice model of the lead-acid battery, whose block diagram is shown in Figure-4.

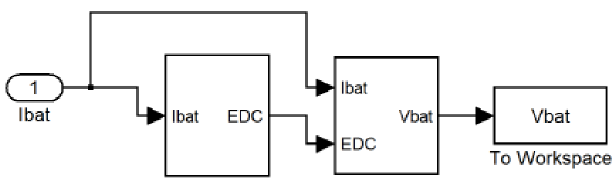

Figure-4. Simulink model of the PSpice battery.

4. ANALYSIS OF THE RESULTS

Under the MATLAB / Simulink environment we simulated the two models thus developed; namely that of CIEMAT and that of PSPice. The characteristics of the battery used for our simulations are as follows:

- Nominal capacity of the battery: C_{10} = 62 Ah;
- Nominal current of the battery: I_{10} = 10 A;
- Nominal voltage of the battery: $V_{bat\text{-}nom}$ = 12 V;
- Number of cells in series n_b = 6.

In order to validate the simulations and to have the results allowing evaluating the quality of the chosen model and that of the adopted approach, we used the experimental data presented by N. Achaibou and all. of reference [15]. The various results of simulations that we have reached are summarized in Figures 5 and 6.

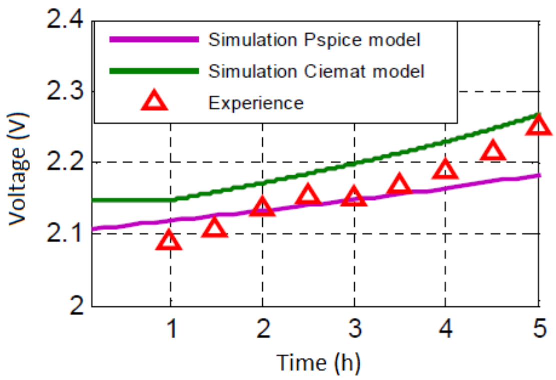

Figure-5. Comparison, in load mode, of the two CIEMAT and PSpice models, with experimental TUDOR TB620 readings for a capacity of 62 Ah and for a current setpoint I = 10 A.

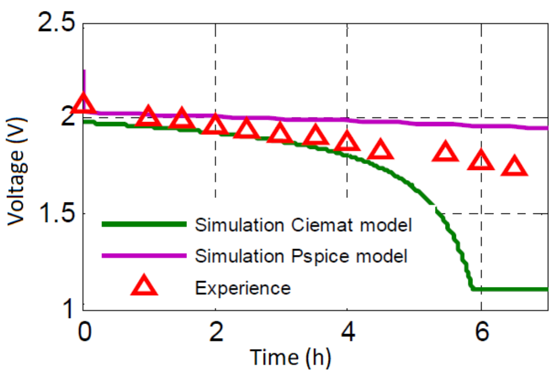

Figure-6. Comparison, in discharge mode of both CIEMAT and PSpice models, with experimental TUDOR TB620 readings for a capacity of 62 Ah and for a current setpoint I = 10 A.

These Figures 5 and 6 show well, in load mode, that despite the difference in the modeling approaches adopted, there is a certain similarity between the two battery models in comparison with the experimental readings of the TUDOR TB620 battery.

In discharge mode, we note that the CIEMAT model shows a rapid discharge, after 4.5 h, compared to that of PSpice. In addition, the response of the PSpice model is close to the experimental readings of the TUDOR TB620 battery. Finally, following our investigations presented above, we can confirm the superiority of the PSpice model over that of CIEMAT.

5. CONCLUSIONS

In this work, we presented one of the main components of electrical energy storage namely the battery. Two behavioral models were presented. After simulation of these models, we chose, for the rest of our study, the PSpice model because of its characteristics quite similar to that of the experimental readings of the TUDOR TB620 battery.

In perspective to our current work, we will proceed to insert the model of the chosen battery, PSpice, into a hybrid system composed of several renewable energy sources. The management of this system can be ensured by different methods such as that which is based on multi-agent systems.

REFERENCES

[1] El Mehdi Laadissi, A. E. F. & Zazi M. 2018. A Nonlinear TSNN Based Model of a Lead Acid Battery. Bulletin of Electrical Engineering and Informatics. 7(2): 169-175.

[2] L. Elmahni, L.Bouhouch and A. Moudden. 2016. Gestion intelligente d’une station de pompage photovoltaique situé dans la région d’Agadir, IJIAS. 18(4) : 1216-1227.

[3] Rizwana Rownak, Kazi Firoz Ahmed and Mohammad Shajibul-Al-Rajib. 2017. Solar-Biomass-CAES Hybrid System: Proposal for rural commercial electrification in Bangladesh, IJIAS. 19(3): 556-571.

[4] Laadissi E. M., Anas E. F. & Zazi M. 2016. Nonlinear Black Box Modeling of a Lead Acid Battery Using Hammerstein-Wiener Model.Journal of Theoretical &Applied Information Technology. 89(2).

[5] A. Ould Mahmoud Yahya, A. Ould Mahmoud, I. Youm. 2007.Modélisation d'un système de stockage intégré dans un système hybride (PV / Eolien / Diesel). Revue des Energies Renouvelables. 10(2) : 205-214.

[6] B. M. Shepherd. 1965. Design of Primary and Secondary Cells: II. An Equation Describing Battery DischargeJ. Electrochem. Soc. 112(7): 657-664.

[7] H.L.Monegon, Engineering design handbook for standalone PV systems, report no. M108, Monegon Ltd, Gaithersburg, MD, 1981, pp 29-39.

[8] Jensimiriam E, Seenichamy P & Ambalavanan S. 2013. Prediction of lead-acid battery performance parameter: a neural network approach. Bulletin of Electrical Engineering and Informatics. 2(1): 65-74.

[9] Mauracher P, Karden E. 1997. Dynamic modelling of lead-acid batteries using impédance spectroscopy for parameter identification. Journal of Power Source.67: 69-84.

[10] Sunori S, K. & Juneja P. K. 2015. ANN Controller Design for Lime Kiln Process. Bulletin of Electrical Engineering and Informatics. 4(4):304-313.

[11] Hannan E, Deistler M. 1988. The statistical theory of linear systems. Wiley series in probability and mathematical statistics. John Wiley & Sons.

[12] Hemian Lucas Norbert. Wiegman. 1999. Battery state estimation and control for power buffering applications. PhD thesis, The University of Wisconsin-Madison. 216.

[13] Mclntyre M, Burg T, Dawson D, B Xian. 2006.Adaptive state of charge Estimator for Battery. Proceedings of the 2006 American Control Conférence Minneapolis. Minnesota, USA. 14-16.

[14] Ghosh S, Maka S. 2009. A NARX modeling-based approach for evaluation of insulin sensitivity. Biomedical Signal Processing and Control. 4(1): 49-56.

[15] Ghosh S. Maka S. 2011. Genetic algorithm based NARX model identification for evaluation of insulin sensitivity. Applied Soft Computing. 11(1): 221-226.

[16] Nader Jamali Soufi Amlashi, Amin Shahsavari, Alireza Vahidifar, Mehrzad Nasirian. 2015. Nonlinear System Identification of Laboratory Heat Exchanger Using Artificial Neural Network Model. International Journal of Electrical and Computer Engineering. 3(1).