An Estimation Method of State of Charge and Lifetime for Lead-Acid Batteries in Smart Grid Scenario

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***Abstract*—This work presents mathematical model of batteries AGM lead acid type that form part of a photovoltaic generating system. The proposed model allows estimation of the voltage of the battery and the state of charge with the objective of designing a controller to create greater duration, efficiency and autonomy of the system. Additionally, we present a mathematical model to estimate the useful life of the battery degraded due to corrosion, cycle, and the state of charge that permits evaluation of the loss of storage capacity in a general distribution scenario. Finally, experimental results and simulations obtained from the monitoring of a bank of batteries in a photovoltaic system are analyzed to validate the proposed model of state of charge. Furthermore, we will present the results of the evaluation of the useful life of the battery in two case studies in the framework of smart grid considering the functioning of a photovoltaic generator under different configurations.**

***Index Terms*—Battery AGM Lead-Acid, State of Charge, Battery Voltage, Degradación, Photovoltaic System, Smart Grid.**

I. Introduction

TODAY the study of smart grids is of great importance because of the problems which exist concerning the generation of power due to the lack of fossil fuels, the low energy efficiency environmental pollution among others [1]. These problems have motivated the generation of electrical energy through renewable sources such as solar energy, eolic energy, biomass, wave energy among others, that together constitute generating sources distributed in smart grids. It should result in these generating systems are formed in modules which convert the energy from the primary source into electrical energy. The photovoltaic systems, in particular, are made of: a) solar panels, b) charge controllers, c) investor or conditioner of power through electrical convertors, and d) the stage of energy conditioning of which the last is the major concern because it reduces the useful life of the battery. Taking this into account, the present investigation is focused on the study of the storage system of the photovoltaic system configured from a bank of AGM batteries, lead acid type, which supplies the required demand for the charge [1].

The control of the elements of an smart grid is highly important and requires continuous supervision of all the components, especially the batteries [2]. To have adequate control of the batteries indispensable it is necessary to understand the behavior of the principal variables, in such a way that it is possible to establish the algorithms of the charge and discharge to take the best advantage of the energy available. Therefore, this document proposes a simulation model that estimates the value of the principal variables such as: the voltage in the terminals, the state of charge (SOC), the depth of discharge (DOD), and a model to determine the degradation of this kind of batteries. With this data we can establish of the criteria of a control design adequate for the storage state in this way achieve longer useful life of the batteries of the photovoltaic system.

This work studied different methods and model to estimate battery state of charge and degradation. Between the following are highlighted: estimation by extended Kalman filter [3], by composed basic circuits RC [4], by measure of open circuit voltage [3], by measure circuits of internal impedance [5], stress model to determine lifetime [6] and by the current

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integral method which it is taken as basis for the development of this work.

This document is organized in the following way. In Section II we present the proposed model to estimate the state of charge of the battery and the model of degradation. Then, in Section III the state of charge model is validated with experimental results and the results are shown of the simulation of the model of degradation. Finally, in Section IV we present the conclusions and the future work of development.

II. Proposed Model To Estimate The Soc And Degradation Model

A. Model for the estimation of the SOC

There is a great variety of proposed models to determine the principal characteristics of the different battery technologies, principally of the lead acid type [1], [7] and ion-lithium [8], [9], among the models that are highlighted: Model of Thevenin, single layer and double layer [3], [1], Copetti and Chenlo model [10], models of third and fourth order [11], [12] and models focused on circuital direct current [7], [13], [4].

Because of the complexity of the interpretive models, this research proposes a theoretical model to characterize the battery AGM type lead-acid [2], [14], as shown in Fig. 1. The model is formed for a source of volts $V_{oc}(t)$ which represents the voltage of the open circuit of the battery and the internal resistance R_{int}. This model is selected because it allows for rapid characterization of the battery, because it only requires the basic parameters such as nominal values obtained from the data sheet.

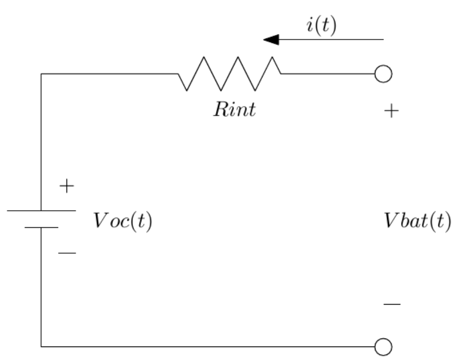

Fig. 1. Circuital Diagram of the Theoretical Model

This model neglects the effect of the ambient temperature having a constant value of 25°C around the components of the battery, and is considered uniquely the stage of charge and discharge [15]. To determine the $SOC(t)$, we use the most common method of the integration of the current [3], [16], but this model is considered to have parameters expressed in $[Wh]$ [15], which makes it necessary to relate the voltage $Voc(t)$ with the current $i(t)$, therefore the equation of the $SOC(t)$ is expressed thus:

$$SOC(t) = SOCo + \frac{1}{SOCm}\int_0^t \frac{i(\tau)\cdot Voc(\tau)}{3600}d\tau \tag{1}$$

where: $SOCo$ is the initial state of charge of the battery [%] and $SOCm$ is the maximum energy of the battery $[Wh]$, which is obtained by the multiplication of the capacity of the battery and the nominal voltage [8]: $SOCm[Wh] = Vnom[V]\cdot Cnom[Ah]$.

To determine the voltage of the open circuit $Voc(t)$ take into account two stages: charge and discharge of the battery, where the constants expressed in the equations have taken [15].

a) Stage of Charge: For this stage the expression is:

$$Voc(t) = (2 + 0.148\cdot\beta)ns \quad , \quad \beta = \frac{SOC}{SOCm} \tag{2}$$

where: ns is the number of the cells of the battery and SOC is the state of energy of the battery $[Wh]$.

b) Stage of Discharge: The voltage of the open circuit is given as:

$$Voc(t) = (1.926 + 0.124\cdot\beta)ns \tag{3}$$

For its part, the proposed model has a unique expression of independent internal resistance to the stage where the battery finds itself [15].

$$Rint = \frac{\left(0.7 + \left(\frac{0.1}{|SOCo-0.2|}\right)\right)}{SOCm}\cdot ns \tag{4}$$

The value is constant and depends on parameters of the battery and its desired characteristics ($SOCo$ and $SOCm$).

With the earlier variables, the voltage of the battery is determined $Vbat(t)$ that is expressed by the equation (5).

$$Vbat(t) = Voc(t) + Rint\cdot i(t) \tag{5}$$

Furthermore, the depth of the discharge, $DOD(t)$, represents the quantity of the energy extracted from the battery and is determined from the $SOC(t)$ [3], like this: $DOD(t) = 1 - SOC(t)$.

B. Model of degradation by performance of amp-hours

The performance model of amp-hours (Ah-throughput) is based on the supposition that the cycle of charge/discharge to determined amp-hours has an impact on the useful life of the battery which depends on the conditions in which the cycle is made. Put another way, it assumes the normal conditions in which a battery can make all the cycles established by the manufacturer reaching a performance in amp-hours (Ah) specific until the end of the battery's useful life. However, the change of the functioning conditions can result in a virtual increase or decrease of the cycle of function. In this form the useful life of the battery is measured as the number of functioning cycles under different conditions which permit the expected performance of amp-hours under normal conditions [6], [17], [18].

The most significant factors which can determine the functioning of the cycle are: a) corrosion of the electrodes that can cause a reduction of conductivity, b) cycled low levels of SOC, c) long periods without a complete charge that can cause sulfation and loss of capacity. In addition to these factors, the model considers the voltage of the battery, the definite state of charge in equation 1.

From the voltage, current and SOC of a cycle of the battery the parameters of the degradation and corrosion can be determined, this uses the model to determine remaining storage capacity (C_R) that is defined as:

$$C_R(t) = C_R(0) - C_{corr}(t) - C_{deg}(t) \tag{6}$$

where: $C_R(0)$ is the initial storage capacity, C_{corr} is the loss of capacity caused by corrosion, and C_{deg} is the loss of capacity caused by degradation. We remember that the end of the useful battery life occurs when the storage capacity falls below 80% of the nominal level, that is to say when $C_R = 0.8$.

Below is the definition of the analytical expression of the degradation by corrosion.

$$C_{corr}(t) = C_{corr,limit} \frac{\Delta W(t)}{\Delta W_l} \tag{7}$$

where: $C_{corr,limit} = 0.16C_d$ y $\Delta W_l = 365 \cdot 24 \cdot k_s L_{80\%}$

$$\Delta W(t) = \begin{cases} \left[k_s \cdot \left(\frac{\Delta W(t-1)}{k_s}\right)^{\frac{1}{0.6}} + \Delta t\right]^{0.6} & \text{si} \quad U < 1.74 \\ \Delta W(t-1) + k_s \cdot \Delta t & \text{si} \quad U \geq 1.74 \end{cases}$$

$$U = \begin{cases} U(0) - gH + \rho_c \frac{I_b}{C_N} + 0.5 \frac{\rho_c M_c I_b F}{C_N (C_c - F)} & \text{si} \quad I_b > 0 \\ U(0) - gH + \rho_d \frac{I_b}{C_N} + 0.5 \frac{\rho_d M_d I_b H}{C_N (C_d - H)} & \text{si} \quad I_b \leq 0 \end{cases}$$

where F is normalized SOC and H is the normalized DOD.

Below is the definition of the analytical expression of the degradation by cycle.

$$C_{deg}(t) = C_{deg,limit} \exp\left(-c_{Z_N}\left[1 - \frac{Z_N(t)}{1.6 Z_{IEC}}\right]\right) \tag{8}$$

where: $C_{deg,limit} = 0.8C_d$ and $Z_N(t)$ is the number of cycles experienced until time t and is defined as:

$$Z_N(t) = \frac{1}{C_N} \sum_{\tau=0}^{t} I_Z(\tau) \cdot \Delta t \tag{9}$$

where: $I_Z = |I_b|$ for $I_b \leq 0$ and $I_Z = 0$ for $I_b > 0$.

In Table I are defined the variables and parameters used in the model of degradation, however the sources [6], [17], [18], [19] will direct you to a better understanding.

TABLE I
ACID-LEAD BATTERY PARAMETERS AND VARIABLES

Parameter	**Description**	**Value**
k_s	Corrosion rate	0.0435
$L_{80\%}$	Estimated lifetime in years	12
$U(0)$	open circuit voltage	2 V
g	Variation coeff. of U with SOC	0.054 V
ρ_c, ρ_d	Internal Resistance	0.43609, 0.37885
I_b	Battery current	[A]
C_N	Capacidad Norminal	205 Ah
M_c, M_d	Variation coeff. of resistance with SOC	0.36488, 0.28957
C_c, C_d	Normalized Capacity	1.001, 1.642
Z_{IEC}	IEC Number of Cycles	1200
C_{Z_N}	Degradation coeff.	5

The subindexes c and d refer to battery charge and discharge.

III. DISCUSSION OF RESULTS

The proposed model is implemented in the tool Simulink of Matlab® through arithmetic blocks as illustrated in Fig. 2. Each subsystem of the diagram contains its respective implementation from the mathematical model.

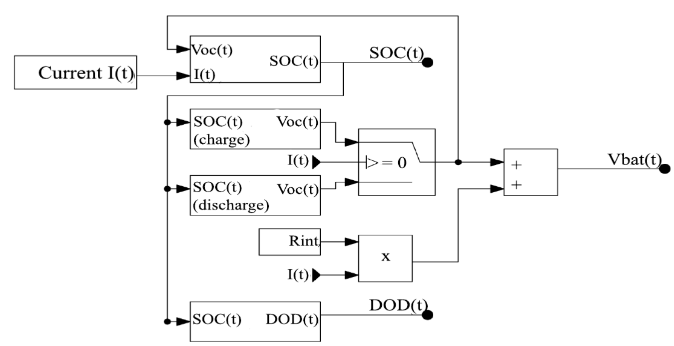

Fig. 2. Diagram of the block model of the state of charge battery

Below we present the results of the simulation and experiments of two case studies. For the evidence of the model to take into account a battery of lead-acid type of reference $MT122050$ [20], the most relevant specifications are presented in Table II.

Therefore the parameters required for the model are: $ns = 6$, $Vn = 12V$ y $Cn = 205Ah$.

1 $Case$: We present a configuration of charge-discharge where the state of charge ($SOC(t)$) has a variation between 100% and 20%, the current of charge-discharge (Fig. 3), is taken from the variation of a photovoltaic system connected to a charge that has approximately a current consumption $i(t) = 10A$ for a period of approximately of eight hours. These

TABLE II
STUDY BATTERY $MT122050$

Parameter	Value
Nominal Voltage	12 V
Nominal Capacity	205 Ah
Temperature	25 °C
Max. Charge Current	60 A
Max Discharge Current	1500 A

current values are entered into the proposed model jointly with an initial state of charge $SOCo = 0.96$, to validate the model. The results of $Vbat(t)$ and $SOC(t)$ are presented in Fig. 4 and Fig. 5 respectively.

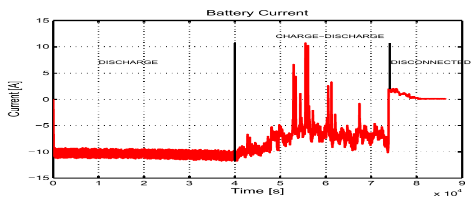

Fig. 3. Current Charge-Discharge of the First Case Study

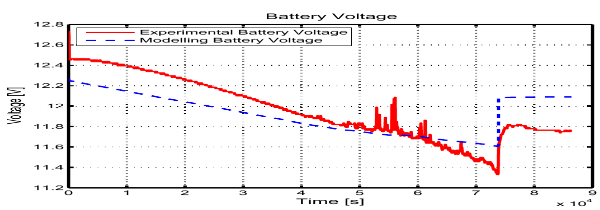

Fig. 4. Battery Voltage from the First Case Study

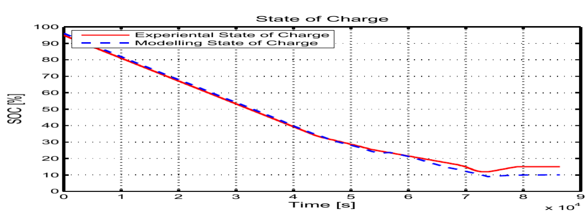

Fig. 5. State of Charge in the First Case Study

2 *Case* : In this case study the configuration of charge and discharge is between 100% and 70% for $SOC(t)$ with an initial state of charge $SOCo = 0.97$. In this case the system is submitted to a discharge $i(t)$ of $10A$ for two hours, a recharge with energy from the panels for four hours and finally two additional hours of discharge at $10A$; this gives results for the profile of current for the battery in Fig. 6. The results of the simulation and experiments are shown in Fig. 7 and Fig. 8.

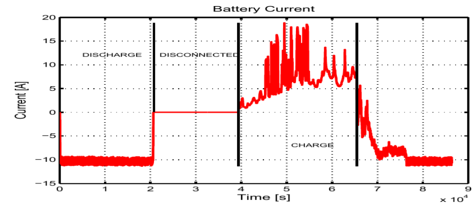

Fig. 6. Current of Charge-Discharge in the Second Case Study

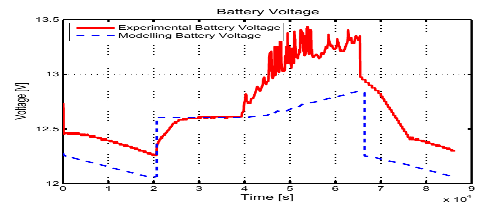

Fig. 7. Voltage of the Battery in the Second Case Study

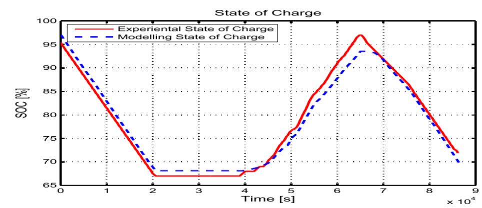

Fig. 8. State of Charge in the Second Case Study

Additionally, we present the evaluation of the useful life of the storage system in the previous cases. The estimation of the useful life is made by calculating the loss of storage capacity implied in each regime of charge-discharge, assuming that these cycles are repeated daily. In the first case, in Fig. 9 it can be seen that after 48 months of functioning the capacity is reduced to under 80% coming to an end of the useful life. In the second case, we can observe in Fig. 10, that the system gets an additional period of 12 months compared to the first coming to an end of the useful life after 60 months of functioning.

These results must principally be the state of charge in the first case the average SOC maintained at 50%, while in the second case the SOC is maintained at approximately 85%, the result is a major degradation for the system in the first case study, since the lead-acid batteries it is recommended to maintain the SOC at high values to avoid sulfation and later corrosion of the electrodes.

Although the model shows very interesting and consistent results according to the literature reviewed. It is possible make improvements such as the inclusion of other variables such as temperature, average state of charge and others working conditions which vary according to the site location of the system. In the same way the model should be tested under the interaction with components based on renewable energy systems, given the interest of the subject and achieve a robust model capable of performing a correct estimation to the different behaviors that can arise.

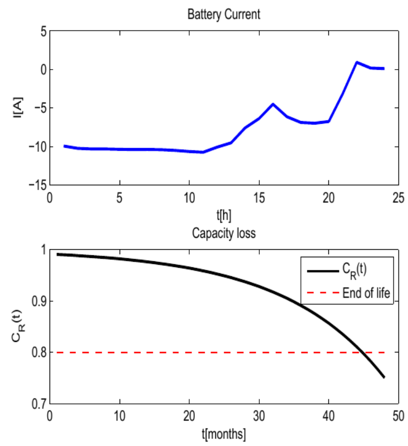

Fig. 9. Loss of Capacity for the First Case Study

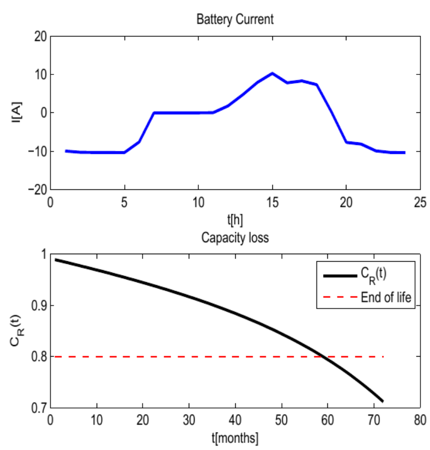

Fig. 10. Loss of Capacity for the Second Case Study

IV. Conclusions and Future Work

The proposed model of AGM type lead-acid batteries for the estimation of SOC needs uniquely named parameters of manufacture to fit the real behavior o the batteries. Furthermore, the model of degradation represents an important tool to evaluate the impact which could have a specific configuration of control of charge-discharge for the battery, in this way it is possible to analyze various case studies in the framework of smart grids and chose the configuration of control which allows the best performance with respect to the use of energy of the battery and its useful life.

The resulting model can be included in a power management system battery for charge/discharge planning in order to maximize its lifetime.

The model is interesting because it is defined by some parameters found in the literature for lead-acid technology, this relatively simple way for the simulation of any battery technology. However, it would be interesting to validate this model by means of experimental results, in several case studies of smart grids.

The simplicity of the model to estimate the useful life allows this to be included in the objective function as a problem of optimizing conditions for the charge-discharge of the energy of the battery, considering the different charges and generators distributed as part of a smart grid. Finally, with the data obtained in this manner from future work, the design of an optimal controller for battery charge will be completed with objective of improving the useful life of the storage system.

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