

An Improved dynamic battery model suitable for photovoltaic applications

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Abstract. Modeling of batteries used in photovoltaic applications has been a real issue for many research groups due to its complex electrochemical and electrical behavior. In this paper, we propose an improvement of the Battery model by identification of all parameters in order to estimate the different areas of Battery's output voltage in real conditions for PV systems. For this purpose, we also performed both static and dynamic simulation. Comparison with real measurement has shown good agreement with the simulation.

Keywords- PVs; battery; modeling; state of charge; parameters identification.

I. INTRODUCTION

Batteries for energy storage are considered as one of the major problem and a weak point in many systems including battery bank such as standalone photovoltaic systems [1]. A deep comprehension of their internal as well as their external interaction has been for a long time a real issue for many research groups. In photovoltaic applications, the battery is subjected to random dynamic working resulting from continuous change in irradiation and temperature. The operation of the battery in unwanted zones such as the overcharge zone, saturation zone, over discharge zone and an exhaustion zone can considerably accelerate the decrease of its life time or leading to their early destruction. The best working regime where the battery is assumed to be safe is the charge/discharge zones. However, keeping the battery in the aforementioned zones involves the knowledge of its actual state of charge (SOC). On the other hand, the electrochemical reactions' complexity and the dependency on working temperature and working zones, let's look to the battery as a very complex system. In this paper, we attempt to introduce a dynamic model for lead acid battery included in a photovoltaic system. The enhancement of a previous work done by Dany and Copetti [1] [2] is proposed. The enhancement focused on the automatic extraction of the whole parameters existing in the battery model.

II. BATTERY MODEL

Based on electric approach illustrated in Figure 1, the battery is represented by an open-circuit voltage V_{oc} resulting of the stored energy from the electrochemical reactions, and an internal resistance R_b due to its voltage drop.

The output terminals voltage of the battery V_{bat} varies according to a specific working area, state of charge SOC and depend strongly on the temperature. Therefore, the relationship of the battery output voltage can be written as a complex function of temperature and state of charge: $V_{bat}=f(T, SOC)$. According to figure 1, V_{bat} is given by:

$$V_{bat} = V_{oc} \pm I.R_b \quad (1)$$

Where I_{bat} is the drawn current from or to the battery. $I>0$ during charge and $I<0$ during discharge.

$$\begin{cases} V_{oc} = f(SOC) \\ R_b = f(I, SOC, T) \end{cases} \quad (2)$$

The battery's resistance is mainly due to the electrical resistance, physical construction and electrochemical resistance. They are commonly grouped under the concept of internal resistance. The internal resistance also varies depending on the temperature and state of charge of the battery [3].

The practice tests allow obtaining a realistic relationship of the battery internal resistance applies to the charge and the discharge Mode. The expression (3) describes the evolution of internal resistance according to the current, temperature and state of charge [1] [3].

$$R_b = \left(\frac{P_1}{1+I(t)^{P_2}} + \frac{P_3}{(1-SOC(t))^{P_4}} + P_5 \right) (1 - \alpha_T(T-T_{ref})) \quad (3)$$

A. State of charge

The state of charge is an indicator of the charge stored in the battery, as a percentage expressing the battery's state of charge. This indicator varies in the range $0 < SOC < 1$. Equations (4-6) describe the evolution of this indicator. It's obtained by calculating the sum of incoming and outgoing amperes from and to the battery relative to its instantaneous capacity

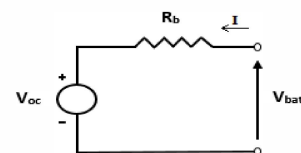


Figure 1. Equivalent circuit for the battery

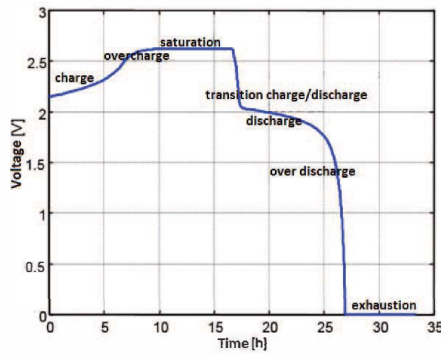


Figure2. Working zones of the battery

$$SOC(t) = \frac{1}{C(t)} \int_{-\infty}^t \eta_c(t) I(t) dt \tag{4}$$

$$C(t) = \frac{C_{nominal} \cdot C_{tcoef}}{1 + A_{cap} \left(\frac{|I(t)|}{I_{nominal}} \right)^{B_{cap}}} (1 + \alpha_c \Delta T + \beta_c \Delta T^2) \tag{5}$$

$$I_{nominal} = \frac{C_{nominal}}{n} \tag{6}$$

Where $C(t)$ the instantaneous capacity, η_c is the Coulomb efficiency and $I(t)$ is the current passing through the battery. $C_{nominal}$ is the nominal capacity (at n hours), C_{tcoef} , A_{cap} and B_{cap} are model parameters, ΔT is the temperature variation from the reference value of $25^\circ C$, $I_{nominal}$ is the nominal current for n hours. This value is commonly taken for 10h. α and β are the temperature coefficients [1].

B. Level of energy

The level of energy (LOE) is an indicator used to show the energy stored in the battery in an instantaneous manner. Expression (7) describes the behavior of LOE. It's obtained by calculating the sum of incoming and outgoing amperes from the battery relative to its maximal instantaneous capacity C_n .

C_n is the maximal instantaneous capacity obtained from equation (5), with battery current equal to zero and maximal temperature value ranging from $-40^\circ C$, $40^\circ C$ as given in equation (8) [2].

$$LOE(t) = \frac{1}{C_n} \int_{-\infty}^t \eta_c(t) I(t) dt \tag{7}$$

$$C_n = \max(C) \Big|_{\substack{I = 0 \\ T = [-40,40]}} \tag{8}$$

C. Working zones

Figure 2 shows the different working areas of evolution of the battery voltage. At first, from 0h to 16h, the battery is charged. In this processes the battery passes through three zones namely: charge, overcharge, and saturation. While from 16h to 27h the battery is discharged according to the following areas: discharge zone, overdischarge zone and exhaustion zone respectively. The transition voltage charge/discharge is a voltage drop due to internal resistance [4].

1) Charge zone: In this zone, the battery accepts energy from the charge source, which increases its state of charge. This area is the best in terms of extending the duration of battery life. The expression (9) describes the evolution of battery voltage in this area. Coulomb efficiency η_c during charging mode depends strongly on the charging rate, its value is close to 100% for low charge currents and a weak state of charge. However, it then deteriorates upon approaching a fully-charged state. Expression (10) reveals this relationship [5]:

$$V_c = (V_{boc} + K_{boc} SOC(t)) + \frac{I(t)}{C_{10}} \left(\frac{P_{1c}}{1 + I(t)^{P_{2c}}} + \frac{P_{3c}}{(1 - SOC(t))^{P_{4c}}} + P_{5c} \right) (1 - \alpha_{rc} \Delta T(t)) \tag{9}$$

$$\eta_c = 1 - \exp \left[\frac{a_{cmt}}{\left(\frac{I(t)}{I_{10}} + b_{cmt} \right)} (SOC(t) - 1) \right] \tag{10}$$

2) Overcharge zone: When the battery reaches the gassing voltage level V_g , it can start to saturate and the charging current starts to decrease. Therefore the battery begins to reduce the charge acceptance due to the effect of gassing electrolyte. This effect appears when the charge is close to its maximum charge (95%) [2]. Some battery models consider this value of battery capacity as a constant included in the equations governing the overcharge zone [1]. V_g is the voltage when the battery starts to liberates hydrogen gas. This area is dangerous for the battery in terms of battery life duration as a result of hydrogen liberation to the atmosphere.

Expressions (11-15) give equation governing this area:

$$V_g(t) = [A_{gas} + B_{gas} \ln \left(1 + \frac{I(t)}{C_{10}} \right)] (1 - \alpha_{gas} \Delta T(t)) \tag{11}$$

$$V_{ec}(t) = [A_{fonse} + B_{fonse} \ln \left(1 + \frac{I(t)}{C_{10}} \right)] (1 - \alpha_{fc} \Delta T(t)) \tag{12}$$

$$V_{sc}(t) = V_g(t) + (V_{ec}(t) - V_g(t)) \left[1 - \exp \left(\frac{-(LOE(t)C_n - SOC_{V_g}(t)C(t))}{I(t)\tau(t)} \right) \right] \tag{13}$$

$$\tau(t) = \frac{A_{\tau sc}}{1 + B_{\tau sc} \left(\frac{I(t)}{C_{10}} \right)^{C_{\tau sc}}} \tag{14}$$

$$SOC_{V_g} = SOC |_{V_c = V_g} \tag{15}$$

V_{sc} is the overcharge voltage, $\tau(t)$ is a time factor for the overcharge phenomenon, SOC_{V_g} is the state of charge of the battery corresponding to the beginning of electrolyte gassing and V_{ec} is the voltage of saturation zone.

3) Saturation zone: In this zone, the battery cannot accept more energy. At this point, the battery voltage reaches its maximum; its value depends on the charging current of the battery as given by equation (12). Also, this area markedly affects battery health then the charge source must be disconnected immediately.

4) Discharge zone: In this area, the battery provides the energy to the load. It's the best working zone in terms of extending the battery life time, when $V_{bat} > 0.9V_N$, with V_N is

the nominal voltage of the battery. The evolution of the voltage in this area is determined by Equation (16).

$$V_{dc} = (V_{bode} - K_{bode}(1 - SOC(t))) \cdot \frac{|I(t)|}{C_{10}} \left(\frac{P_{1dc}}{1 + |I(t)|^{P_{2dc}}} + \frac{P_{3dc}}{SOC(t)^{P_{4dc}}} + P_{5dc} \right) (1 - \alpha_{rdc} \Delta T(t)) \quad (16)$$

5) Overdischarge zone: In this zone, the battery is nearly empty, when $0.7V_N \leq V_{bat} \leq 0.9V_N$ the voltage decreases rapidly as indicated in equation (16). This area is considered as dangerous area for the battery. The load must be disconnected in this area.

6) Exhaustion zone: It's the very dangerous area for the battery. It can damage the battery, when $V_{bat} < 0.7V_N$. A voltage remainder can appear, but no energy stored in the battery [2].

7) Transition voltage: A difference of voltage appear in transition from the charge to the discharge and vice versa. In the start with a constant current discharge, the initial drop was caused by the internal resistance of the battery [4].

$$V_c|_{I=0} \neq V_{dc}|_{I=0} \quad (17)$$

In order to avoid the discontinuity appearing at this point, a linear expression voltage has been proposed in transition area, When $I_{bat} < |I_\delta|$, with I_δ is a current sufficiently small. The equation (18) shows the linear evolution in this zone [2].

$$V_{cdc} = \frac{V_c|_{I_\delta} - V_{dc}|_{I_\delta}}{2I_\delta} I + \frac{V_c|_{I_\delta} + V_{dc}|_{I_\delta}}{2} \quad (18)$$

Table 1 shows the different limits of the battery voltages.

TABLE 1. BATTERY WORKING ZONE CONDITION

Battery voltage	Working zone		Zone conditions	
V_{sc}	Saturation zone	$I > 0$	$V_{bat} = V_{ec}$	$\eta_c \approx 0$ $0 < \eta_c < 1$
	Overcharge zone		$V_g \leq V_{bat} \leq V_{ec}$	
V_c	Charge zone		$V_{bat} < V_g$	
V_{cdc}	Changing from charge to discharge or from discharge to charge	$I \approx 0$	$V_{dc} \leq V_{bat} \leq V_c$	
V_{dc}	Discharge zone	$I < 0$	$V_{bat} > 0.9V_N$	$\eta_c \approx 1$
	Overdischarg		$0.7V_N \leq V_{bat} \leq 0.9V_N$	
	Exhaustion		$V_{bat} < 0.7V_N$	

III. BATTERY STATE OF HEALTH

Regarding electrochemical effects such as liberation of H₂O, internal variation and several other factors, the capacity of the battery decreases and the self-discharge current appears along time, which limits its lifetime. Based on practice tests and measurements, a realistic approximation is obtained for modeling the state of battery health in long time term. This indicator is called state of health SOH. This indicator takes into account the phenomena that may affects the battery lifetime such as temperature and unwanted working areas, which reduce the capacity of the battery and increases the self-discharge current over time. Therefore two additional factors

health for working temperature η_T and working zone η_{wz} has been introduced as expressed in equation (19). We note that when SOH is near to 1, the battery is in a perfect state while for battery fully damaged the SOH is near to 0 [2].

$$SOH(t) = 1 - \int_{-\infty}^t (\eta_T + \eta_{wz}) dt \quad (19)$$

Where η_T and η_{wz} are the temperature and working zones factor respectively. Experience shows that whenever a temperature rise of 10°C, the battery health decreases by half. The equation (20) shows the evolution of temperature health factor, where T_{ref} equals to 10°C and α_T and β_T are temperature coefficient [2]. The working zones health factors is obtained a rule of thumb. In Table 2 is shown different values of factor health according to working zones.

$$\eta_T = \alpha_T |T - T_{ref}| + \beta_T \quad (20)$$

TABLE 2. EXPERIMENTAL VALUE OF WORKING ZONE FACTOR HEALTH

Working zone	$\eta_{wz} (s^{-1})$
Saturation and exhaustion zone	5.5×10^{-6}
Overcharge and overdischarge zone	5.5×10^{-7}
Charge and discharge zone	2.7×10^{-7}

With the aging of the battery its capacity decreases according to its state of health. Equation (21) describes the coefficient of capacity reduction η_{C10} .

$$\eta_{C10} = 0.75SOH + 0.25 \quad (21)$$

Then the equation of the capacity becomes:

$$C(t) = \frac{C_{nominal} \cdot C_{coef} \cdot \eta_{C10}}{1 + A_{cap} \left(\frac{|I(t)|}{I_{nominal}} \right)^{B_{cap}}} (1 + \alpha_c \Delta T + \beta_c \Delta T^2) \quad (22)$$

The self-discharge current also depends on state of health. Therefore a coefficient of self-discharge has been defined as given in equation (23).

$$\eta_q = 0.01 - 0.009 \cdot SOH \quad (23)$$

$$I_{adc}(t) = \eta_q \frac{Q(t)}{24h} \Delta \quad (24)$$

IV. STATIC SIMULATION

The simulation of the lead-acid battery model is done under Matlab/Simulink environment. The simulation data are summarized in table 3. We provide for all battery's output the variation according to the temperature. where $T = 10^\circ 20^\circ 30^\circ 40^\circ 50^\circ$. The results are given in the Figures 3 to 6.

After the simulation for constant current, we note that whenever the temperature increase the battery's output voltage decrease considerably as it is shown in figure 4, also for the state of charge and the level of energy in figures 5 and 6. The temperature is an effective factor in evolution of battery 'output.

Table 3 static simulation data

Nominal capacity	Charging current	Discharging current
$C_{nominal} = 100 \text{ Ah}$	$I = +10 \text{ A}$	$I = -10 \text{ A}$

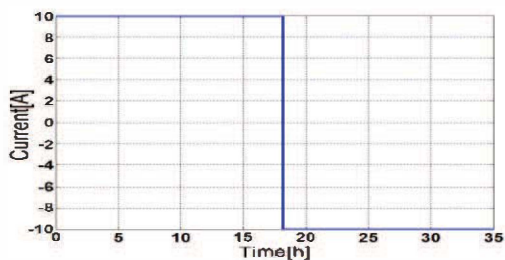


Figure 3 Current for charge and discharge

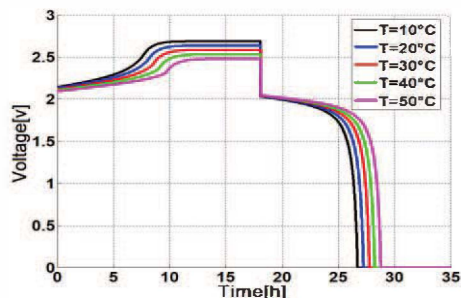


Figure 4 variation of voltage as functions Temperature

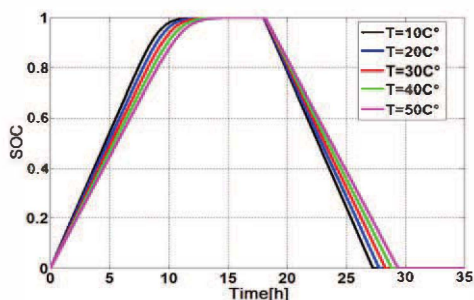


Figure 5 variation of SOC as functions Temperature

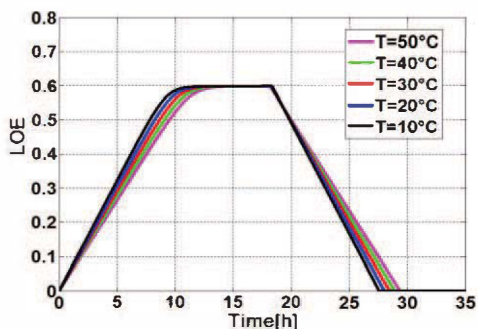


Figure 6 variation of LOE as functions Temperature

V. BATTERY CONNECTED TO A PV MODULES AND LOAD

In the PV systems, the battery is an important part for energy storage. In case of lack of radiation the battery

provides the energy to the load, and behaves as a load when there is power generated by PV modules. Therefore we propose an integration of this dynamic model of the battery in the PV system in order to validate it in dynamic mode. We note here that the battery is working without regulation of its output voltage to allow the PV generator sweeping all the allowed working zones [6].

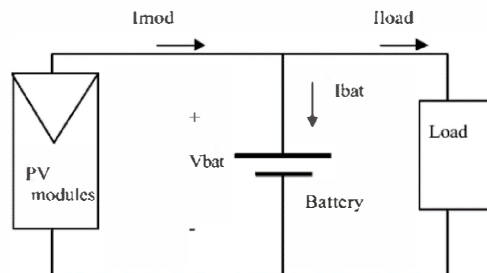


Figure 7 Standalone basic PV system

In order to validate the model in dynamic mode, real measurements have been used for a lead-acid battery with the following characteristics in standard test condition (Table 4). The current provided by PV module is shown in figure 8.

TABLE 4 PV MODULES AND BATTERY CHARACTERISTICS

PV module characteristics		Battery's nominal parameter
$V_{oc} = 21.8 \text{ V}$	$I_{mpp} = 7.67 \text{ A}$	$V_{bat} = 12 \text{ V}$
$I_{sc} = 8.17 \text{ A}$	$P_{mpp} = 175 \text{ W}$	$C_{10} = 110 \text{ Ah}$
$V_{mpp} = 17.7 \text{ V}$		

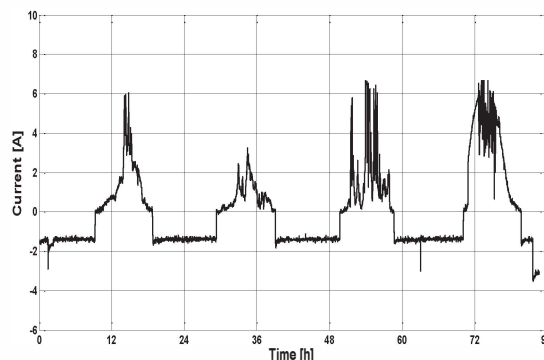


Figure 8 Battery current provided by PV modules

VI. IDENTIFICATION OF PARAMETERS

In order to validate the model, we used Levenberg-Maquart [7] algorithm for parameters extraction. The parameters' values given in Table 5 have been taken as initial values for identification algorithm [7].

The new parameters obtained which gives the best matching between measured and simulated results are given in Table 6. In figure 9 it is shown the the measured versus simulated battery's output voltage. According the extracted parameters, the estimated SOC is shown in figure 10.

TABLE 5 NOMINAL VALUES FOR MODEL PARAMETER

$C_{\text{nominal}}=110 \text{ Ah}$	$P_{1\text{dc}}=4 \text{ Vah}$	$P_{1\text{c}}=6 \text{ Vah}$	$A_{\text{fonse}}=2.45\text{V}$
$n=10 \text{ h}$	$P_{2\text{dc}}=1.3$	$P_{2\text{c}}=0.86$	$B_{\text{fonse}}=2.011\text{Vh}$
$C_{\text{tcoef}}=1.67$	$P_{3\text{dc}}=0.27 \text{ V h}$	$P_{3\text{c}}=0.48 \text{ VAh}$	$A_{\text{tsc}}=17.3 \text{ h}$
$\alpha_{\text{c}}=0.005^\circ \text{ C}^{-1}$	$P_{4\text{dc}}=1.5$	$P_{4\text{c}}=1.2$	$B_{\text{tsc}}=852 \text{ h}$
$\beta_{\text{c}}=0^\circ \text{ C}^{-1}$	$P_{5\text{dc}}=0.02 \text{ Vh}$	$P_{5\text{c}}=0.036\text{Vh}$	$C_{\text{tsc}}=1.67$
$A_{\text{cap}}=0.67$	$a_{\text{cmd}}=20.73$	$A_{\text{gas}}=2.24 \text{ V}$	$\alpha_{\text{rdc}}=0.007^\circ \text{ C}^{-1}$
$B_{\text{cap}}=0.9$	$b_{\text{cmd}}=0.55$	$B_{\text{gas}}=1.970 \text{ Vh}$	$\alpha_{\text{rc}}=0.025^\circ \text{ C}^{-1}$
$V_{\text{bodc}}=2.085 \text{ V}$	$V_{\text{boc}}=2\text{V}$	$\alpha_{\text{gas}}=0.002^\circ \text{ C}^{-1}$	
$K_{\text{bodc}}=0.12 \text{ V}$	$K_{\text{boc}}=0.16 \text{ V}$	$\alpha_{\text{fc}}=0.002^\circ \text{ C}^{-1}$	

TABLE 6 EXTRACTED PARAMETER VALUES BY LEVENBERG–MARQUARDT ALGORITHM

$C_{\text{nominal}}=109.0443 \text{ Ah}$	$P_{1\text{dc}}=9.5044 \text{ Vah}$	$P_{1\text{c}}=6.0809 \text{ VAh}$	$A_{\text{fonse}}=2.2126\text{V}$
$n=10 \text{ h}$	$P_{2\text{dc}}=4.9361$	$P_{2\text{c}}=1.6701$	$B_{\text{fonse}}=2.4264 \text{ Vh}$
$C_{\text{tcoef}}=0.5361$	$P_{3\text{dc}}=0.9311 \text{ V h}$	$P_{3\text{c}}=0.3375 \text{ VAh}$	$A_{\text{tsc}}=18.2031 \text{ h}$
$\alpha_{\text{c}}=0.1320 \text{ }^\circ\text{C}^{-1}$	$P_{4\text{dc}}=0.037$	$P_{4\text{c}}=0.9853$	$B_{\text{tsc}}=990.6910 \text{ h}$
$\beta_{\text{c}}=0 \text{ }^\circ\text{C}^{-1}$	$P_{5\text{dc}}=1.8837 \text{ Vh}$	$P_{5\text{c}}=1.7838\text{Vh}$	$C_{\text{tsc}}=0.0825$
$A_{\text{cap}}=0.3031$	$a_{\text{cmd}}=29.9987$	$A_{\text{gas}}=2.1860 \text{ V}$	$\alpha_{\text{rdc}}=0.0167^\circ \text{ C}^{-1}$
$B_{\text{cap}}=0.5027$	$b_{\text{cmd}}=0.0021$	$B_{\text{gas}}=1.7342 \text{ Vh}$	$\alpha_{\text{rc}}=0.01^\circ \text{ C}^{-1}$
$V_{\text{bodc}}=2.1612 \text{ V}$	$V_{\text{boc}}=1.9016 \text{ V}$	$\alpha_{\text{gas}}=0.0034^\circ \text{ C}^{-1}$	
$K_{\text{bodc}}=0.2190 \text{ V}$	$K_{\text{boc}}=0.16 \text{ V}$	$\alpha_{\text{fc}}=0.003^\circ \text{ C}^{-1}$	

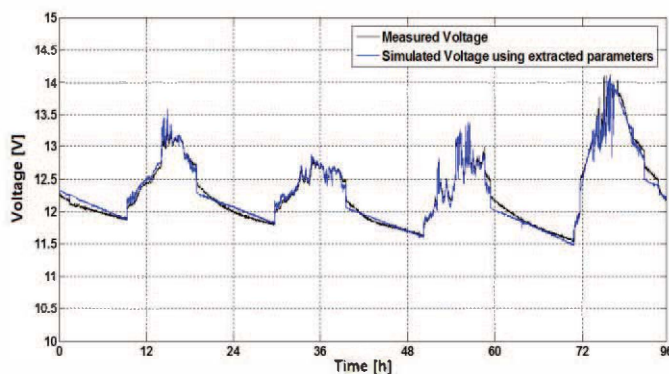


Figure 9 measured vs simulated voltage with extracted parameters

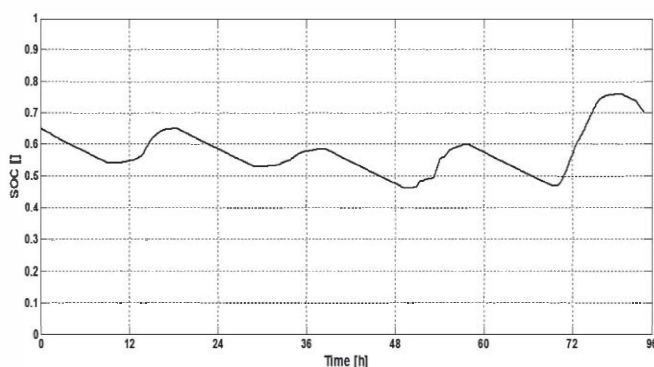


Figure 10 SOC estimated with extracted parameters

VII. CONCLUSION

In this paper we proposed a dynamic model of lead acid battery which can predict its behavior in real conditions of

work. The model's parameters extraction conducted with Levenberg–Maquart algorithm has given the best matching between the prediction model and real measurements.

The proposed model gives a useful tool to manage the state of charge and the prediction of the working voltage so that unwanted working zones can be avoided with an appropriate electronic charge regulator. Also, this model is appropriate for many applications involving energy storage using lead-acid batteries such as electric or hybrid cars.

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