# Lead/acid batteries for photovoltaic applications. Test results and modelling

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## Abstract

This work presents the results of experiments carried out on lead/acid batteries during charge and discharge processes at different currents and temperatures, selected to a cover a large range of operating conditions, including those encountered in photovoltaic (PV) system applications. The results allow us to verify the relations among the battery external parameters (voltage, current, state-of-charge and temperature), the behaviour of the internal resistance, and to deduce a model that represents the discharge and charge processes, including the overcharge. Finally, normalized equations with respect to the battery capacity are proposed, which allow us to fix the values of parameters and hence the model is valid for any type and size of lead/acid battery.

## Introduction

The storage of energy in batteries is one of the causes of failures and loss of reliability in PV systems in which operation conditions are quite different compared with conventional applications. The availability of a theoretical model fitted to experimental data is important to understand the behaviour of batteries during the life cycles in realistic conditions. It would allow us to determine the way to design the regulation system, the charge and discharge control and to simulate and optimize PV systems with battery voltage.

The simplest equation to represent the relationship between the voltage ($V$) and current ($I$) during charge and discharge is given by:

$$V=V_{oc}\pm RI \quad (1)$$

where $V_{oc}$ is the open-circuit voltage and $R$ the internal resistance, both assumed constant. The current $I$ is positive during charge and negative during discharge.

However, an expression of the current and voltage as a function of the state-of-charge, temperature and internal resistance variations would provide a more realistic description of the processes.

To this end, we carried out a set of experiments with several lead/acid batteries to verify the voltage variations and the behaviour of internal resistance during charge and discharge, at different currents and temperatures.

In the eqn. (1), the internal resistance $R$ is the sum of two components [1]: (i) ohmic (sum of conductors resistances: grid, cell terminals, active material and electrolyte between the plates, in the pores of the separator and in the pores of the plate), and (ii) polarization (which is a function of charge transfer and processes diffusion).

Therefore, $R$ represents the steady-state and dynamic behaviour. Three different procedures were tried to measure this resistance. The complete description of these procedures and their corresponding results are given in a previous article [2].

In this paper, we show the main results and conclusions of the tests and, consequently, the model obtained.

## Tests and results

Charge and discharge tests were realized with an automatic test facility (Digatron BTS 500) that allows current-controlled battery tests. Thermostatic baths with water circulation were used for temperature control. Experiments were conducted on three lead/acid batteries designed for PV solar applications: Fulmen EF2050–$C_{10}$=50 Ah, Varta Vb624–$C_{10}$=120 Ah and ATSA Tudor STTH180–$C_{10}$=180 Ah. The low current rates in the range of $I(C_5)$ to $I(C_{100})$ and temperatures from 5 to 45 °C were considered. During each test the external parameters, i.e., the current and the temperature, were kept constant. The voltage, current and internal battery temperature were periodically recorded. Some of the results obtained are presented in the following Figs.

Figure 1 shows the voltage variation during charge and discharge as a function of the current rates for the Tudor battery at 25 °C. At low currents, the capacity increases during discharge and during charging it guarantees the full re-establishing of the active materials. Moreover, the temperature influences directly the capacity and the final charge voltage, as it can be observed in Figs. 2 and 3; consequently for regulation effects, the voltage should be corrected with both current and temperature.

In addition, specific tests to measure the internal resistance at various states of charge during the charge and discharge processes were realized [2] for the same batteries and conditions of currents and temperatures above. Due to the current rates utilized, the battery behaviour was considered as a sequence of steady states, disregarding the transient effects. The experimental study consideres three measurement procedures: 'current pulse', 'periods-of-rest' and by a 'milliohmmeter', from which we conclude that the overall resistance measured by the 'periods-of-rest' method is the best value to represent the effects of internal resistance on the voltage evolution during charge and discharge. Moreover, the dependence of this resistance on the state-of-charge, temperature, current and capacity can be summarized as follows:

(i) the value of resistance during recharge is greater than in the previous discharge, principally due to overcharge effects (Fig. 4);

(ii) the resistance increases with decreasing temperature; this effect can be represented by a linear function for the temperatures range 5 to 45 °C [3];

(iii) the dependence of the resistance on the current has been verified under slow current rates as is usual in PV applications (Fig. 5), and

(iv) for low battery capacities, the internal resistance increases.

## Model

A simple model is required for simulation purposes, which represents the battery behaviour in charge (including overcharge) and discharge processes, by means of the external parameters voltage, current, state-of-charge and temperature.

Several authors have proposed models for representing the battery operation during these processes. The validity of such models is usually analysed in terms of

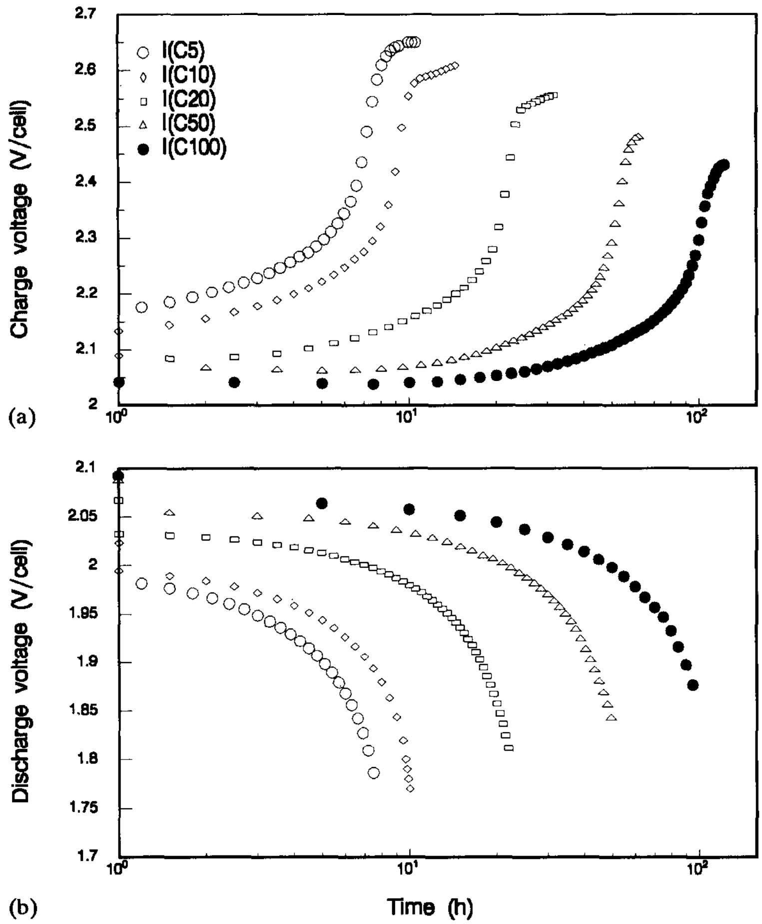


Fig. 1. Voltage vs. time in (a) charge and (b) discharge at various currents and 25 °C for a Tudor battery.

their ability to represent the battery voltage evolution during constant current and constant temperature charge and discharge. Along these lines, we analysed the models proposed by Shepherd [4], Facinelli [5], Menga *et al.* [6] and Mayer and Biscaglia [7], because these models are currently used in PV storage systems simulation. Their agreement with experimental data obtained from these tests were verified. The correct parameter values used in each model were fitted and the results obtained allow us to conclude that these models can adequately reproduce the behaviour of batteries during discharge (the root mean square error, RMSE [8], remains at less than 40 mV/cell in all the models), but they do not represent the charge and overcharge processes (RMSE in the order of 100 mV/cell for all the models) and the temperature variation.

As a result of that, we propose a modified model, based on the Shepherd model, in which equations for internal resistance, capacity, correction for temperature effects in different parameters and an expression for overcharging are included.

The different equations which form the modified model are consequently presented.

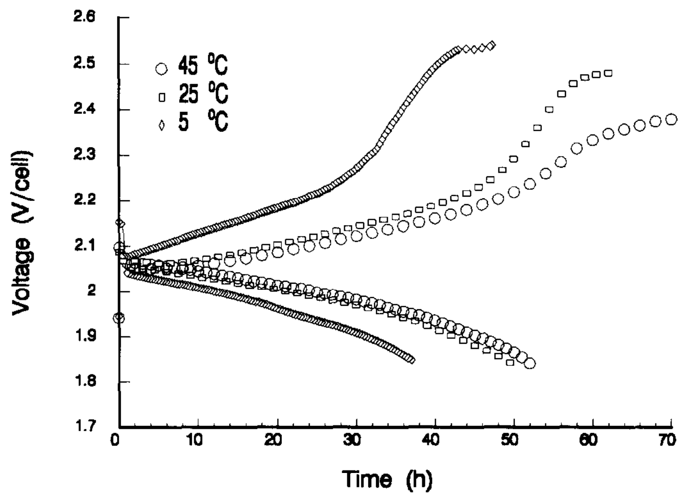


Fig. 2. Effects of temperature at $I(C_{50})$ current for a Tudor battery.

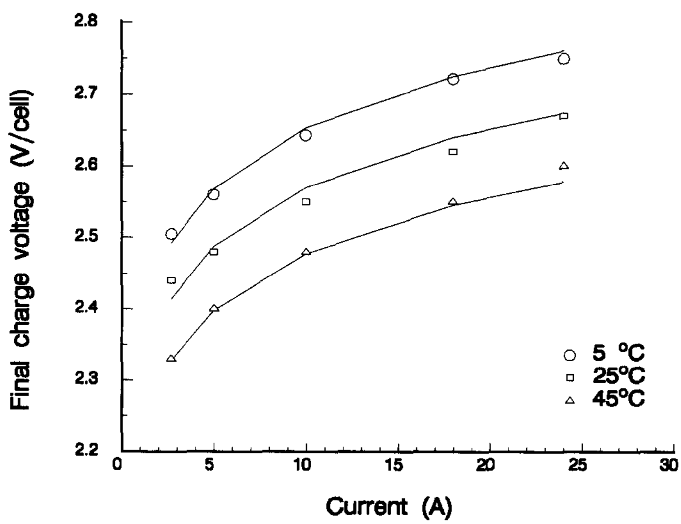


Fig. 3. Final charge voltage vs. temperature at various currents for a VARTA battery.

*Charge and discharge voltage*

For discharging and for charging up to overcharge, the changes in voltage can be written as:

$$V=\left(V_{oc}+K\frac{Q}{C}\right)\pm IR \qquad (2)$$

where the first term represents the equilibrium voltage variation with the state-of-charge, $K$ is an empirical parameter, $Q$ ($=It$) is the charge delivered or supplied at time of interest, $C$ is the battery capacity and $R$ the internal resistance. The values of $C$ and $R$ are given in the following sections.

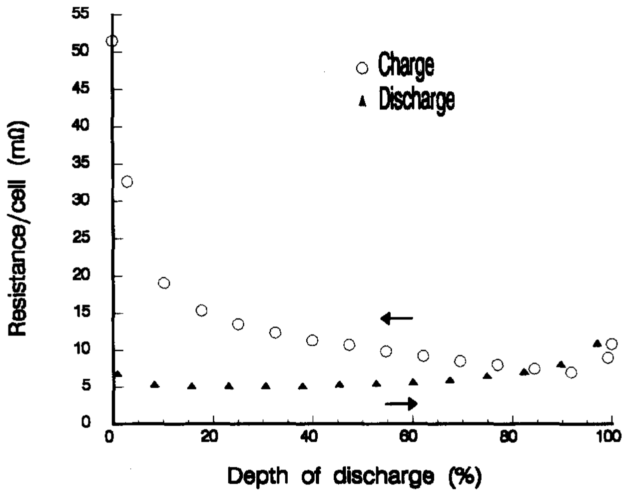


Fig. 4. Overall internal resistance for $I(C_{10})$ current at 25 °C for a VARTA battery during charge and discharge processes.

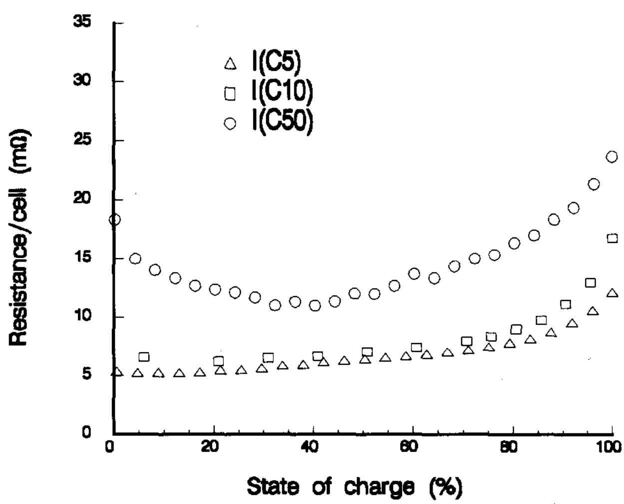


Fig. 5. Overall internal resistance during charge at 45 °C for a Tudor battery.

*Battery capacity equation*

The battery capacity equation was modified from Baikei *et al.* [9] to include the low-current operation and temperature effects; the expression is rewritten as:

$$C = \frac{C_T}{1 + aI^b}(1 + \alpha_c \Delta T + \beta_c \Delta T^2) \quad (3)$$

where $C_T$ is a constant that represents the limit capacity when the discharge current tends to zero, $a$ and $b$ are empirical parameters and $\alpha_c$ and $\beta_c$ are the temperature correction factors. The polynomial term to correct the temperature effects in the capacity allows to obtain a close fit.

*Internal resistance equation*

The specific tests realized made it possible to obtain a relation among the internal resistance and state-of-charge, current and temperature during charge and discharge processes. In the following expression, the overall internal resistance is represented by a sum of series resistances that correspond to different phenomena:

$$R=\left(\frac{P_1}{1+I^{P_2}}+\frac{P_3}{(1-Q/C_T)^{P_4}}+P_5\right)(1-\alpha_r\Delta T) \tag{4}$$

where $P_1$ to $P_5$ and $\alpha_r$ are parameters to be determined and $C_T$ is the maximum capacity according to eqn. (3).

This equation is the same for charge and discharge, but the parameter values differ for the two processes.

*Overcharge phenomenon*

The specific characteristics of PV systems with respect to charge intensity variation with solar radiation and low charge intensity, impose a design of a regulator quite different than those used, for example, with starter batteries or stationary batteries. In order to study the relations about the overcharge process, the tests included charging where gassing occurred and the results demonstrated that the final charge voltage ($V_{ec}$) increases with the current intensity and with decreasing temperature (Fig. 3). These dependences can be represented by an equation as proposed by Graña *et al.* [10] and modified by us to include low current effects:

$$V_{ec}=[A+B\log(1+I)](1-\alpha\Delta T) \tag{5}$$

where $A$, $B$ and $\alpha$ are parameters to be determined. The same argument can be used to write a function for the gassing voltage ($V_g$) with different parameter values.

The overcharge phenomenon (gassing evolution) can be represented by an exponential function, such as:

$$V=V_g+(V_{ec}-V_g)\left(1-\exp\left(-\frac{t-t_g}{\tau}\right)\right) \tag{6}$$

where $t$ is the time, $t_g$ is the time corresponding to $V_g$ and $\tau$ is the time constant of the phenomenon. $\tau$ is inversely proportional to charge current intensity and can be written as the following equation:

$$\tau=\frac{p_1}{(1+p_2I^{p_3})} \tag{7}$$

Therefore, the overall charge process is represented by eqn. (2), up to the start of gassing ($V\leqslant V_g$) and by eqn. (6) for overcharging ($V>V_g$) until a constant final voltage ($V_{ec}$) is reached.

The correct parameter values were fitted for the model from experimental charge and discharge curves for each battery tested using a non-linear regression method (Marquardt algorithm [11]). Table 1 presents the Tudor battery parameters. For the other batteries the parameter values are different. The agreement from this model to actual data for the three batteries measured is shown in Table 2 by means of the root mean square error, RMSE, and the mean bias error, MBE statistical quantities.

Figures 6 and 7 show the fit of the model to Tudor battery data for different conditions.

TABLE 1

Parameters of the model for a Tudor battery

| | | | | | | |
|---|---|---|---|---|---|---|
| (a) Capacity | $C_T=300.5$ | $\alpha_c=0.008$ | $\beta_c=-0.00014$ | $a=0.064$ | $b=0.82$ | |
| (b) Resistance | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $\alpha_r$ |
| Charge | 0.041 | 0.88 | 0.003 | 1.2 | 0.0003 | 0.02 |
| Discharge | 0.022 | 0.78 | 0.002 | 1.25 | 0.0002 | 0.007 |
| (c) Voltage | | | | | | |
| Discharge | $V_{oc}=2.09$ | $K=-0.12$ | | | | |
| Charge | $V_{oc}=1.99$ | $K=0.16$ | | | | |
| Overcharge | $V_{ec}$ | $A=2.3$ | $B=0.12$ | $\alpha=0.0018$ | | |
| | $V_g$ | $A=2.13$ | $B=0.09$ | $\alpha=0.0017$ | | |
| | $\tau$ | $p_1=21.8$ | $p_2=0.22$ | $p_3=1.52$ | | |

TABLE 2

Comparison between values measured and calculated by the model

| V/cell | Tudor | | VARTA | | Fulmen | |
|---|---|---|---|---|---|---|
| | Discharge | Charge | Discharge | Charge | Discharge | Charge |
| MBE | 0 | −0.011 | 0.003 | −0.026 | −0.006 | 0 |
| RMSE | 0.016 | 0.028 | 0.02 | 0.044 | 0.019 | 0.028 |

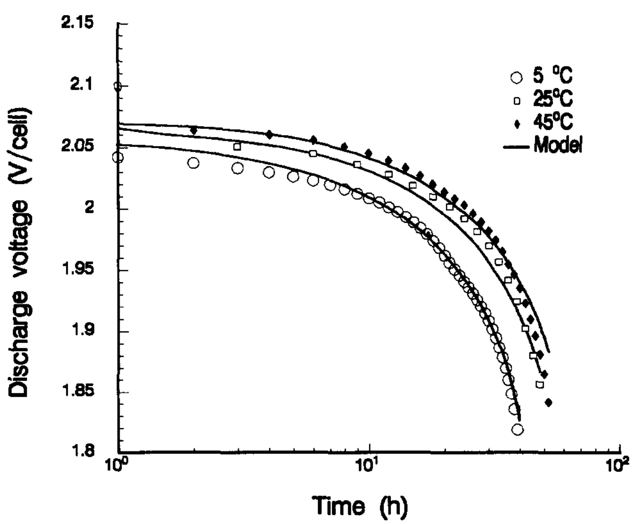


Fig. 6. Modified model for discharge curves.

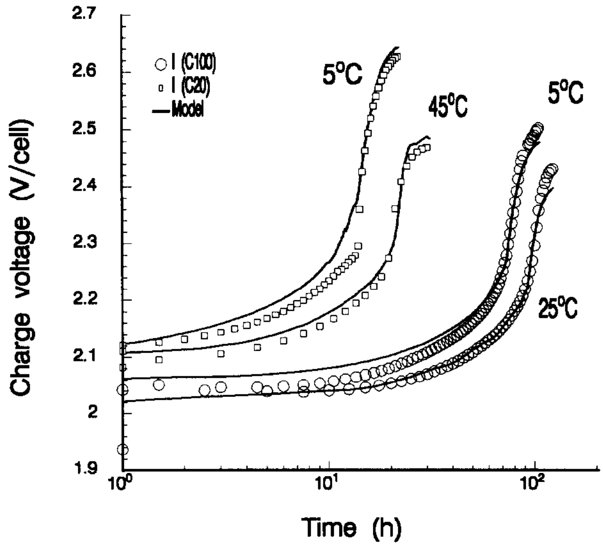


Fig. 7. Modified model for charge and overcharge curves.

As can be seen, the model represents the set of experimental data concerning both processes with a good degree of accuracy (RMSE remains at less than 30 mV per cell for both charge and discharge).

However, in order to decrease the large number of the parameters to be identified, some assumptions can be made such as:

(i) In the capacity model, the constant $C_T$ (maximum capacity) can be estimated by the nominal capacity for 10 or 100 h discharge given by manufactures (about 70% over $C_{10}$ and 10% over $C_{100}$) and, to correct the effect of temperature, a linear function is satisfactory within the temperature range from 5 to 45 °C and $\alpha_c = 0.005$ °C$^{-1}$.

(ii) The parameter $P_5$ in the resistance eqn. (4) represents an ohmic resistance, for example, the cell terminals resistance, and can be neglected due to its small value.

(iii) The temperature factor for correcting the final charge voltage and gassing voltage, $V_{ec}$ and $V_g$, is about 2 mV °C$^{-1}$ per cell.

(iv) The two curves for charge and discharge, for example $I(C_{10})$ and $I(C_{100})$ at two different temperatures, that are usually found in the manufactures data sheet, are sufficient to obtain the parameter values in the above equations.

**Normalized model**

The results show that for each battery capacity the parameter values are different and this is a major inconvenient for PV general simulation purposes, because the particular battery design and capacity characterization requires a detailed testing procedure, often beyond the standard manufactures data sheets, hence likely to be both expensive and time-consuming. Then, despite the lower accuracy, it is desirable to have a normalized model with battery capacity, which would possible to keep constant the value of parameters and, therefore, would be valid for any size of batteries.

In this sense, we propose a normalized model with battery capacity. In order to generalize the equations, the variation of the resistance parameter values with the battery capacity was verified and it was found that this variation conformed with the equation $R_A C_A = R_B C_B$ (the subscripts A and B represent different battery capacities). We consider that this assumption can be applied to different battery manufactures and other factors, such as the ageing of batteries, are negligible. The same argument was used to normalize the overcharge model. The equations were rewritten as functions of $C_{10}$ capacity rated and are presented as follows:

(i) discharge

$$V_d = \left(2.085 - 0.12\frac{Q}{C}\right) - \frac{I}{C_{10}}\left(\frac{4}{1+I^{1.3}} + \frac{0.27}{(1-Q/C_T)^{1.5}} + 0.02\right)(1-0.007\Delta T) \quad (8)$$

$$C = \frac{C_T}{1+0.67\left(\dfrac{I}{I_{10}}\right)^{0.9}} \quad (9)$$

$$C_T = 1.67\ C_{10}(1+0.005\Delta T) \quad (10)$$

(ii) charge until $V \leqslant V_g$

$$V_c = \left(2+0.16\frac{Q}{C}\right) + \frac{I}{C_{10}}\left(\frac{6}{1+I^{0.6}} + \frac{0.48}{(1-Q/C_T)^{1.2}} + 0.036\right)(1-0.025\Delta T) \quad (11)$$

(iii) overcharge to $V > V_g$ (eqn. (6))

$$V_{ec} = \left[2.45 + 2.011\ \ln\left(1+\frac{I}{C_{10}}\right)\right](1-0.002\Delta T) \quad (12)$$

$$V_g = \left[2.24 + 1.97\ \ln\left(1+\frac{I}{C_{10}}\right)\right](1-0.002\Delta T) \quad (13)$$

$$\tau = \frac{17.3}{1+852\left(\dfrac{I}{C_{10}}\right)^{1.67}} \quad (14)$$

Like the preceding analysis presented in Table 2, we verify how this model represents the battery behaviour during the processes for the complete set of data (three batteries, five current rates and three temperatures). Table 3 shows the results obtained by this normalized model.

It can be observed that the average value of RMSE for the three batteries remains at less than 50 and 40 mV/cell for charge and discharge, respectively. We believe these values are reasonable for a model, avoiding the characterization for each individual type of battery.

TABLE 3

Comparison between values measured and calculated by the normalized model

| V/cell | Tudor | | VARTA | | Fulmen | |
|---|---|---|---|---|---|---|
| | Discharge | Charge | Discharge | Charge | Discharge | Charge |
| MBE | 0.03 | 0 | 0.015 | −0.023 | −0.017 | 0.025 |
| RMSE | 0.038 | 0.033 | 0.029 | 0.064 | 0.024 | 0.038 |

## Conclusions

A set of data obtained from tests at different current ($I(C_5)$ to $I(C_{100})$) and temperatures (5 to 45 °C) allows us to write equations that represent the battery behaviour in the charge and discharge processes. These equations include the effects of temperature variations, operation at low currents and operation in overcharge. The correct parameter values for the three batteries tested were fitted and the results obtained show that the model can reproduce adequately the behaviour of the batteries during the operational processes, including overcharge.

The overcharge model is suitable for the design of regulators and PV system control units under current and temperature conditions that will achieve correct battery charging and prevent destruction under prolonged overcharge operation.

Nevertheless, simplifications can be made on the model to decrease the large number of parameters to be identified that will permit the model to be fitted by means of a minimum of experimental data. Moreover, the data for other batteries allow us to rewrite the model equations as a function of the battery capacity and, thus, the values of parameters can be fixed and the model is valid for any size of lead/acid battery. In spite of less accuracy, this normalized model can be used satisfactorily in PV systems simulation programs to represent battery operation.

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