Modeling of Charging Station Batteries for Electric Vehicles

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Abstract

Charging station batteries which are widely used in stand-alone solar system for charging electric vehicles (EVs) are easily damaged by overcharging or by deep discharging. The design of a control system however requires a good understanding of the dynamic behaviour of such batteries and mainly the voltage issue. In this paper, we mainly focused on lead-acid battery as one of the powerful charging batteries. A mathematical model of this type of batteries is investigated. The expression of voltage discharging is given according to discharging time of the battery, discharging current, and other electrical parameters. The parameters of the model are extracted from battery datasheets and using some fitting techniques. The same model of the battery terminal voltage is also used to describe charging processes battery. For this case only the parameters of the battery model are changed. The proposed model is simulated with Matlab/Simulink and the obtained results are compared with experimental results recorded from charging and discharging process using a SW280-YUASA battery. The obtained results and performed comparison show the effectiveness of the proposed model.

Keywords

electric vehicles, lead-acid batteries, basic fitting, modelling, experimentations

1. INTRODUCTION

Electric vehicles (EVs) are promising green transports, and are an important means to solve energy and environmental problems. Charging stations provide power supply for electric vehicles; so, the deployment of a complete infrastructure with sophistic equipments is quite important for the development and promotion of EVs. However, charging process takes several hours and batteries should be efficiently used since the propulsion of these EV depend on their energy storage capacity [Ruzmetov et al., 2013].

EVs are charged by either plugging into electric outlets or by means of on-board electricity generation. There are two main places where the batteries of EVs can be recharged: either on a car park, corporate or public, or at home. With this last recharging solution, a system named Home to Vehicle (H2V) is designed to recharge the EV battery using renewable energy as illustrated by the Figure 1. H2V system can recharge an EV with direct current from the photovoltaic systems storage using a lead-acid battery. Conversely, the system can supply the electricity from the EV back to the household (V2H). In addition, the system can efficiently distribute electricity, including power generated by residential photovoltaic systems (solar panels), to the EV and to the home through the coordination of an energy management system. The study of H2V system requires adequate models for the main components. This paper will mainly focus on the modeling of lead-acid batteries. These batteries have high availability and they are the least expensive storage batteries for any application, while still providing reasonable performance and life characteristics. Due their robustness and stability, lead-acids batteries are commonly used in photovoltaic systems [Cherif et al., 2002].

In fact, the battery state information enables optimal control over the process of charging or discharging the battery, reduces the risk of overcharge and deep charging. Also, it allows extending the battery life and to manage the battery to reach its optimal usage. Many parameters such as the state of charge (SOC), time of charging/discharging, should be taking into account during charging and discharging phases. For this reason, we address in this paper the voltage modeling of

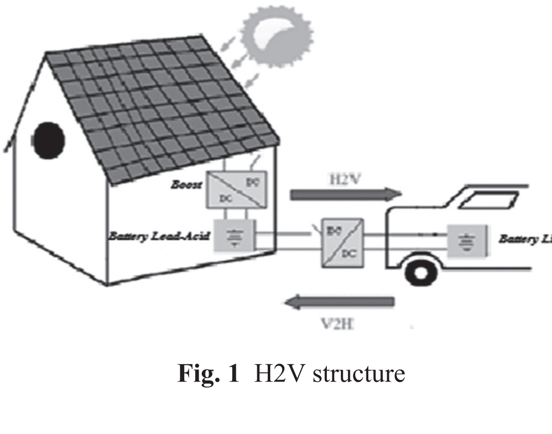

Fig. 1 H2V structure

lead-acid batteries. The proposed model describes the profile of battery voltage considering time and electrical parameters. This relation can be found using the process of constructing a curve gave by manufacturer data or experimental data, and then a mathematical function is deduced, by curve-fitting approach.
The remainder of the paper is structured as follows. Section 2 is devoted to a state-of-the-art of the batteries modelling. Section 3 introduces the developed model and explains the adopted methodology as well as the battery parameters. Simulation results are given in section 4. Experimental results with used procedure for extracting model parameters from tests are given in section 5. A comparison study of obtained simulation and experimental results is reported in this section. Last section concludes the paper.

2. BATTERIES MODELING

In the literature the battery behaviour has been largely represented by many models with varying degrees of complexity. In fact, several research works proposed some battery models which capturing battery behaviour for specifics purpose, from the battery design and performance estimation to the circuit simulation. According to these researches, the battery models can be classified into three categories:
The electrochemical model can be used to optimize the physical design aspects of batteries. It characterizes the fundamental mechanisms of power generation and relates battery design electric parameters with chemical parameters information [Achaibou at al, 2012]. However, this type of models is complex and requires a system of coupled time-varying spatial partial differential equations [Chekired et al., 2011].
The second category is mathematical models which are mostly too abstract to embody any practical meaning but still useful to system designers [Jackey, 2007]. They adopt empirical equations or methods like stochastic approaches to predict system level behaviour, such as battery runtime, efficiency, or capacity.
The third category is electric models [Barsali and Ceraolo, 2002]. These models lie between electrochemical and mathematical models. They are electrical equivalent models using a combination of voltage sources, resistors, and capacitors for co-design and co-simulation with other electrical circuits and systems.

2.1 Electrochemical Model (Shepherd Model)

The Shepherd model is, in a certain point of view, the best known and most often used battery model for hybrid vehicle analysis. The model describes the electrochemical behaviour of the battery in terms of voltage and current. [Ceraolo, 2000; Zhoua et al., 2008]. It is often used in conjunction with the Peukert equation to obtain battery voltage and state of charge taking into account power draw variations [Zoroofi, 2008].

2.2 Electric Model

The most simple and commonly used model is the electric model which consists of an ideal voltage source in series with an internal resistance [Dürr et al., 2006].

2.3 Ciemat Model

This model depends on two principal elements: internal resistance and voltage source. It depends also on a set of parameters as detailed in [Gergaud, 2002; Geraud et al., 2003].

3. MODELING APPROACH

3.1 Voltage modeling

The purpose of this section is to determine a relationship between the battery voltage and the battery time charging/discharging. This expression takes into account the electrical parameters. During cycles of charging and discharging, the characteristic of the battery depends on its SOC, charging/discharging current and charging/discharging time. As given in [Coleman et al., 2007], the state of charge of the battery SOC is defined by:

$$SOC = SOC_0 - \frac{1}{C_n}\int i(t)d\,t \qquad (1)$$

where:

- SOC_0: Initial state of charging percentage,
- C_n: Battery capacity in Ampere-hours,
- i (t): Current of the battery,

In the H2V concept the lead-acid battery YUASA SW280 was used, the nominal voltage is 12 V and the capacity C_n is 7, 6 Ah, for n = 20. Since the effect of temperature on discharging curves is not given by the manufacturer, the modelling is carried out with a temperature of 20 °C.
As exposed in [Yuasa Battery, 2010], manufacturers give the relationship between E_0 and SOC. For the battery YUASA this relationship is linear as illustrated in Figure 2.
Using a linear approximation technique, a mathematic expression of SOC versus E_0 is established as follows:

$$SOC = 0.78E_0 - 8.93 \qquad (2)$$

Based on the curves showing the evolution of the terminal voltage discharging, we deduce an expression of the voltage discharging battery by an extrapolation of the points which have been raised.

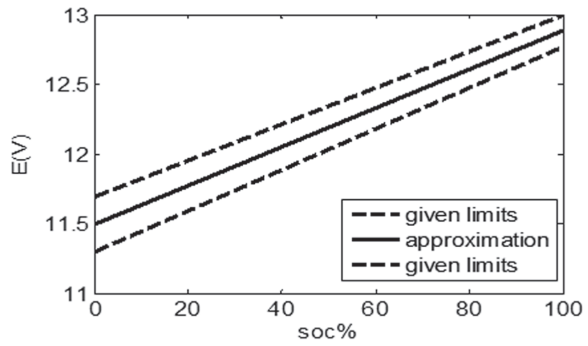

Fig. 2 Variation in the open circuit voltage versus SOC

For charging curve, the datasheet don't give sufficient curves. So, we charge the battery with constant current in order to obtain the curve enabling to describe the relationship between the terminal battery voltages during charging versus the charging time. The battery is charged with constant current I_1 until the battery voltage rose to overcharge voltage. And then it discharges at constant current, until the battery voltage dropped to the deep-discharge protection point. These two steps constitute a testing cycle. We repeat these processes with currents I_2, I_3, I_n. Finally, the obtained curves, from performed tests, describe the variation of the terminal voltage during charging over the time. Based on the test data we deduce an expression of the voltage charging battery by an extrapolation of the point which we have raised.

From the datasheet, we obtain the curves and with applying the method of extrapolation of the curve, we obtain an equation which given as a polynomial of 3rd degree by the equation (3).

$$V(t) = At^3 + Bt^2 + Ct + D \quad (3)$$

Where: A, B, C, and D are the parameters of the battery whose expressions are detailed in the following subsection. It is worth noting that the parameters A, B, and C depend on the battery current. The parameter D depends on the battery current and the open circuit voltage.

3.2 Identification of parameters A, B, C

Using basic fitting technique, the parameters A, B and C are given with polynomials of a 7th degree depending on the battery current I. These parameters can be determined by:

- Case of charging: A= a*e-07; B = b; C = c.
- Case of discharging: A = (4, 63e-13)*a; B = (2,7778e-009)*b; C = 0, 016667*c.

Where a, b and c are given by:

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = M\,V^t \quad (4)$$

where the vector V and the matrix M, are given by:

$$V = [I^7, I^6, I^5, I^4, I^3, I^2, I, 1]$$

$$M = \begin{pmatrix} a_1 & a_2 & a_3 & a_4 & a_5 & a_6 & a_7 & a_8 \\ b_1 & b_2 & b_3 & b_4 & b_5 & b_6 & b_7 & b_8 \\ c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 \end{pmatrix}$$

M is given by Least Square Fitting as follows:

- For charging case, I < 0,

$$M = \begin{pmatrix} -0.304 & -2.279 & -6.997 & -11.37 & -10.51 & -5.478 & -1.472 & -0.154 \\ 1.926e04 & 0.001 & 0.004 & 0.007 & 0.007 & 0.003 & 9.314e-04 & 9.73e-05 \\ -0.311 & -2.329 & -7.155 & -11.638 & -10.763 & -5.613 & -1.508 & -0.157 \end{pmatrix}$$

- For discharging case, I > 0,

$$M = \begin{pmatrix} -0.0031 & 0.122 & -1.618 & 8.158 & -19.49 & 20.97 & -10.61 & 1.891 \\ -3e-004 & 0.022 & -0.515 & 5.071 & -20.24 & 33.39 & -17.86 & 3.265 \\ 3e-07 & -1.6e-05 & 0.0003 & -0.0023 & 0.008 & -0.01 & -0.002 & 5.284e-06 \end{pmatrix}$$

3.3 Identification of the parameter D

The parameter D represents the starting voltage (voltage at the beginning of charging/ discharging). Experimentally, the expression of the parameter D can be expressed as follows:

$$D = E \pm dv \quad (5)$$

Where E is the open circuit voltage, dv is the initial voltage drop at the switching on process in the battery. We use the sign "+" (respectively "-") in the case of the battery charging (resp. discharging). The initial voltage drop at the switching on process in the battery is given by:

$$dv = R.I \quad (6)$$

R, corresponding to the battery resistance, is a function of the current I. Using the technique of basic fitting; we can find the relationship between R and I. We measure the values of the open circuit voltage E and the values of the starting voltage V_0 of the battery, then we compute dv = E - V_0. For several values of dv, using the equation (6), we calculate the resistance values for each corresponding values of dv, and then we find the relationship between R, I using interpolation method.

The resistance R is expressed as a polynomial equation of the 5th degree as in the equation (7).

$$R = P_1 I^5 + P_2 I^4 + P_3 I^3 + P_4 I^2 + P_5 I + P_6 \quad (7)$$

Parameters P_1, P_2, P_3, P_4, P_5, and P_6 are determined by the Least Square Fitting method. The following equation determines the values of each parameter in these two cases:

- For charging case, $I < 0$,

$(P_1\ P_2\ P_3\ P_4\ P_5\ P_6) = (40.968\ 193.12\ 339.77\ 275.94\ 101.68\ 13.759)$

- For discharging case, $I > 0$,

$(P_1\ P_2\ P_3\ P_4\ P_5\ P_6) = (-0.071\ 0.7288\ -2.795\ 4.913\ -3.905\ 1.331)$

4. SIMULATION RESULTS

The work presented in this section is focused on the battery discharging. Once the parameters A, B, C, and D are determined, the voltage is plotted for several current rates on the same graph as the curves of the manufacturer (Figure 3).

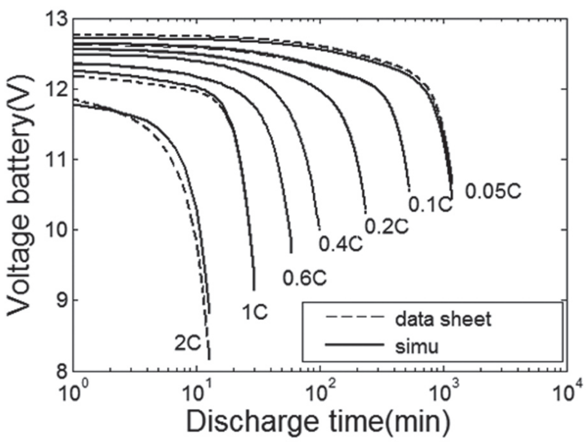

Fig. 3 Comparing the simulation of discharge voltage with the manufacturer data

Based on the obtained results, absolute error and relative error are reported in Table 1.

The parameter C represents the nominal capacity of the battery with C = 7.6 Ah.

The average error represents good model accuracy for each rate of discharging current. For the last rate of discharging current (2 C), see Figure 3, more deviations appear. The simulation curves coincide with the manufacturer (datasheet), which allows concluding that the analytical expression represents well the evolution of the terminal voltage battery YUASA SW280.

5. EXPERIMENTAL RESULTS

A final step in this analytical study is the comparison of obtained simulation results with experimental measurements. Experimentations are carried out under ambient temperature. To perform the experimental tests, some materials are required such as regulated power supply for constant charge current, electronic load to discharge with constant current, acquisition card with voltage probe, PC with Labview and a current sensor.

Table 1 Errors between datasheet and simulation results

Discharging current	Absolute error	Relative error
0.05 C	0.05	0.44 %
0.1 C	0.01	0.1 %
0.2 C	0.003	0.03 %
0.4 C	8.95.e-4	0.008 %
0.6 C	0.006	0.05 %
1 C	0.05	0.43 %
2 C	0.276	2.83 %

The advantage of the proposed model is that it predicts the voltage battery for the discharge rate other than those given in datasheet. Figure 4 shows the results of the discharge battery for I = 3.22 A and 2.9 A.

In Figure 4, we show that the experimental curves match well with those given by the analytical expression. This leads to the conclusion that the analytical expression represents well the evolution of the battery voltage Yuasa SW280. To display the precision of the battery charging voltage model given by the equation (3), the obtained experimental results and simulation results of the equation (3) are compared and shown in Figure 5, and Figure 6.

The accuracy of the simulation model in charging battery case is demonstrated by comparing the simulation results and the measured data. The satisfactory agreement has been found with relative error voltage

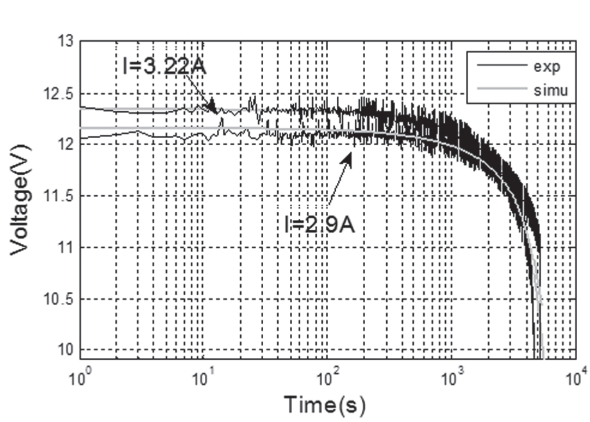

Fig. 4 Comparison of simulation and experimental results of discharging terminal voltage

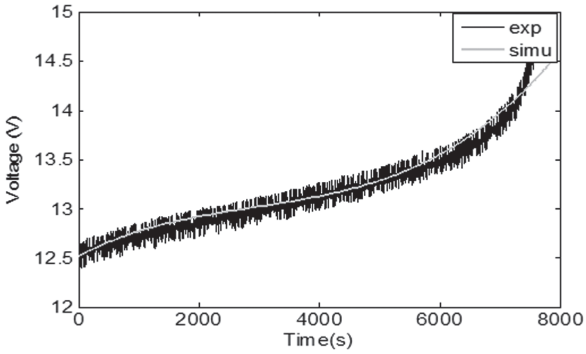

Fig. 5 Comparison of charging terminal voltage simulation and experimental data for I = 1.7 A

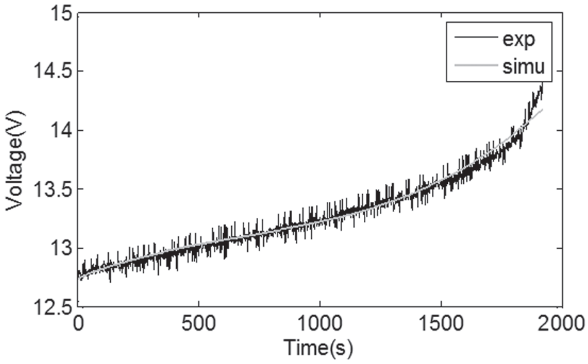

Fig. 6 Comparison of charging terminal voltage simulation and experimental results for I = 0.6 A

Table 2 Errors between experimental and simulation results for the battery charging

Charging current	Absolute error	Relative error
I = 1.7	0.0581	0.44 %
I = 0.6	0.0421	0.32 %

prediction of around [0.32 % - 0.44 %] see Table 2.

6. CONCLUSION

Several modelling approaches of lead-acid batteries exist in the literature. All developed models are more or less complex depending on the desired objectives. Some models allow only simulate the behaviour of the battery under certain conditions. Other physics-based models aim to understand the battery operations. In this paper, we propose a modelling based approach for lead-acid battery charging voltage and discharging. Indeed, the proposed model takes into account the electric parameters of the battery and its charging/discharging time. In this study, only three battery parameters which are open circuit voltage (E), current (I), and time (t), should be known to predict the evolution of the battery voltage. The proposed model predicts the battery voltage for discharging rate current other than those given in datasheet. This model is specific for Yuasa batteries and useful for the energy management system H2V.

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