Modeling and Simulation of Standalone Photovoltaic Charging Stations for Electric Vehicles

R. Mkahl, A. Nait-Sidi-Moh, M. Wack

Abstract—Batteries of electric vehicles (BEV) are becoming more attractive with the advancement of new battery technologies and promotion of electric vehicles. BEV batteries are recharged on board vehicles using either the grid (G2V for Grid to Vehicle) or renewable energies in a stand-alone application (H2V for Home to Vehicle). This paper deals with the modeling, sizing and control of a photovoltaic stand-alone application that can charge the BEV at home. The modeling approach and developed mathematical models describing the system components are detailed. Simulation and experimental results are presented and commented.

Keywords—Electric vehicles, photovoltaic energy, lead-acid batteries, charging process, modeling, simulation, experimental tests.

I. INTRODUCTION

ELECTRIC vehicles (EVs) are green transports, and they are good means to solve transport and environmental problems. The environmental benefits of EVs increase with the produced electricity from green sources such as (wind, solar, small scale hydroelectricity). Green sources are also a good solution and alternative enabling to avoid the problem of reliability and safety which can be encountered when grid power is used to charge EVs [1]. Charging stations provide power supply for EVs; so, the deployment of complete infrastructures with sophisticated equipments is indispensable for promoting EVs. However, EV charging processes take much more time than charging processes using fuel car [2], and batteries should be efficiently used since the propulsion of EVs depend on their energy storage capacity [3], [23].

EVs can be charged by either plugging into electrical outlets or by means of on-board electricity generation. There are two main places where the batteries of EVs can be charged: either on a car park, corporate or public, or at home. With this last charging solution, a system H2V is designed to charge BEVs using green sources such as photovoltaic systems as illustrated in Fig. 1. In a H2V system, EV can be charged with direct current from photovoltaic panels (PV) or with current from a Lead-Acid battery installed at home (see Fig. 1). Conversely, the system can provide the electric energy from the EV to the household when this is needed (V2H). The study of these charging/discharging processes H2V and V2H

II. ENERGY STORAGE SOURCES

This paper focuses on the modeling and sizing of EV charging stations using solar energy. More precisely, we address a PV panel mathematical model whose parameters are extracted from PV tests. We address also the voltage modeling of lead-acid battery we use in our system H2V. In fact, the battery state information allows optimal control for battery charging/discharging process, reduces the risk of overcharge and deep charging. In addition, it is possible to extend the battery life and reach its optimal usage. To do so, we focus on the modeling of the lead-acid battery voltage by developing a mathematical model enabling to reach these objectives.

The proposed model describes the profile of battery voltage considering time and electrical parameters. These parameters can be found using manufacturer data or experimental tests. Afterward, a mathematical model is deduced using a curve-fitting approach. Many parameters such as the state of charge (SOC), time of charging and discharging, current of charging and discharging should be taken into account during charging and discharging processes.

The remainder of the paper is structured as follows. Section II introduces the energy storage sources. Section III presents the adopted modeling approach. PV and Lead-Acid battery modeling as well as DC/DC converter topologies are presented in this section. Section IV concerns the system sizing. The obtained results and a comparison study of simulation results with datasheet and experimental results are given in Section V. Last section concludes the paper and gives some future directions of this work.

Fig. 1 EV charging/discharging: H2V2H structure

Energy storage system includes different storage technologies, electrochemical technology (battery), electrical
technology (supercapacitor), and mechanical technology (a flywheel) as detailed in [4]. To compare the energy storage sources many parameters can be considered. Among these parameters we underline energy density, power density, cycle life performance, cost, environmental impact [5]. Fig. 2 illustrates the Ragone diagram of different energy storages.

This diagram shows that supercapacitors (Scaps) have a very high power density but a very low energy density. The batteries have a low power density and high energy density. The batteries are "reversible" generators; they can store electrical energy in chemical form and return it at any time when it is needed. The nature of electric vehicles is governed primarily by the characteristics of the used batteries. The weight and volume of batteries are usually a decisive factor. A BEV must satisfy certain conditions: a good specific power for high accelerations, good specific energy synonymous with good battery life, stable voltage generating regular performances, a long lifetime and low maintenance and recyclable [6].

Batteries currently used in electric vehicles are: Lead-Acid (LA) battery, Lithium-Ion (Li-Ion) battery, Nickel Metal Hydride [7], Nickel Cadmium battery [6], and Zink-Air. Lithium-Ion battery is the main hope for electric vehicles [8]. It holds a higher voltage per element, good volume and mass performance, and a very high specific energy compared to other types of batteries. It is worth noting that the specific systems of stationary electricity storage are very different from the specific systems of embedded systems for which energies and unit powers are weak. In stationary systems, the amount of energy and the total power available then become largely predominant. Lead-Acid batteries have high availability and they are the least expensive storage batteries for any application, while still providing reasonable performance and life characteristics. They are widely used like the stationary electricity storage in PV systems as given in [9].

III. MODELING OF THE SYSTEM COMPONENTS

In this section, we focus on the modeling of the main components of charging station. To do so, we present PV and Lead-Acid battery models and DC/DC converter topologies.

A. PV Modeling

Several studies are developed about the mathematical modeling of the PV cell. A model of the photovoltaic cell with double diode is developed in [10]. This model consists of a current source representing the light flux, in parallel with two diodes. The diode represents the cell behavior in darkness. Tow resistances, shunt and series resistance are added to present internal losses. The current-voltage (I-V) equation can be simplified by considering the shunt resistance as infinity [11]. Another work has been proposed to simplify the PV cell by using single-model PV cell with one diode [12]. Like this last research work, we use a single-model PV cell in order to formalize the PV solar cell. The equivalent electrical circuit is presented in Fig. 3.

The equation of PV module which expresses the characteristic current–voltage (I-V) of PV module is given as follow [13]:

\[
I_{pv}(V) = I_{pv}(0) - I_s \left( \frac{V + I_s R_{sh}}{n} \right) \left( \frac{V + I_s R_{sh}}{n} + R_{sh} I_s n \right) - \left( \frac{I_s + I_f R_{sh}}{n} \right)
\]

where:
- \( I_{pv}(0) \): reverse saturation current;
- \( I_s \): current of PV module;
- \( V \): voltage of PV module;
- \( R_{sh} \): series resistance of PV module;
- \( R_{sh} \): shunt resistance of PV module;
- \( I_f \): photovoltaic current;
- \( I_0 \): reverse saturation current;
- \( n \): diode ideality factor (1 for an ideal diode);
- \( n_p \): cells in parallel;
- \( n_m \): cells in series;
- \( T \): terminal temperature (25°C).

Generally, unless otherwise specified by the manufacturer, PV module consists of thirty six cells in series (\( n_m = 36 \) cells) and \( n_p = 1 \) cell. The PWX500-12V module is chosen for this study. The parameters \( I_0, R_{sh}, R_{sh} \) of this module are not given in the data sheet, so we have determined it by using the functions 'fittype' and 'fit' of Matlab. The parametric identification is considered by using current-voltage (I-V) characteristic curve of the module extracted from experimental data. The PV panel parameters are reported in the Table I.

<table>
<thead>
<tr>
<th>PV parameters</th>
<th>Digital values</th>
</tr>
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<tbody>
<tr>
<td>( R_{sh} )</td>
<td>0.2297 Ω</td>
</tr>
<tr>
<td>( R_{sh} )</td>
<td>60.78 Ω</td>
</tr>
<tr>
<td>( I_0 )</td>
<td>3.886e-009 A</td>
</tr>
</tbody>
</table>

B. Lead-Acid Battery Modeling

1. Voltage Modeling

In the literature the battery behavior has been described by many models. In fact, several research works proposed some
battery models which describing battery behavior 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: this model is used to optimize
the physical design aspects of batteries, to characterize the
fundamental mechanisms of power generation and lay electric
parameters of the battery with chemical parameters [14].
Shepherd model which can be considered as the best battery
model for using for the hybrid vehicle analysis is one example
of electrochemical model [15].

The mathematical model is the second category. This model
is mostly too abstract to embody any practical meaning but it
is useful to system designers [16]. Ciemat model is one
example of a mathematical model. This model consists of an
ideal voltage in series with resistance, the electromotive force
and resistance which are expressed according to the battery
SOC as detailed in [17].

The third category is electric model. This last lies between
electrochemical and mathematical model. Electric model
consists of voltage source in series with a resistance which is
not function of battery SOC [18].

The goal 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 characteristics of the battery depend on its
SOC, charging/discharging current and charging/discharging
time. As given in [19], the SOC of the battery is defined by:

\[ \text{soc} = \text{soc}_0 - \frac{1}{C_u} \int i(t) dt \] (2)

where: SOC\(_0\): initial state of charging percentage; C\(_u\): battery
capacity in Ampere-hours; i(t): battery current.

In the H2V concept the Lead-Acid battery YUASA SW280
was used, the nominal voltage is 12V and the capacity C\(_u\) is
7,6 Ah, for n = 20. The effect of temperature on discharging
curves is not given by the datasheets, so the modeling is done
at a temperature of 20°C.

As exposed in [20], datasheets give the relationship
between E (open circuit voltage) and SOC (State of Charge).
For the battery YUASA SW280 this relationship is linear as
illustrated in Fig. 4. A mathematical equation of SOC
according to E is established using a linear approximation

\[ V(t) = At^3 + Bt^2 + Ct + D \] (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.

2. Identification of Parameters A, B, C, D

Using basic fitting technique, the parameters A, B and C are
given as polynomial functions of 7\(^{th}\) 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:

\[ \begin{pmatrix} \frac{a}{b} \frac{b}{c} \end{pmatrix} = M \begin{pmatrix} V \end{pmatrix} \] (4)

where the vector V is given by:

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

The matrix M is given by Least Square Fitting as detailed in
[21].

The parameter D represents the starting voltage (voltage at
the beginning of charging/discharging). Experimentally, the
expression of this parameter is given by:

\[ D = E \pm dv \] (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:

\[ dv = RI \]  

(6)

R corresponds to the battery resistance which 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 find \( dv = E - V_0 \). For several values of \( dv \), using (6), we calculate the resistance values for each corresponding values of \( dv \), and then we find the relationship between R and I using interpolation method. This calculation is detailed in [21].

C. DC/DC Charger Topologies

Solar energy is converted to electric energy by the PV panels. Electric energy is used for recharging Lead-Acid batteries via DC/DC Boost converter (see Fig. 5(a)). Boost converter is controlled by maximum power point tracking algorithm (MPPT) for obtaining always the PV maximum power at PV panel output.

In addition, a Buck-Boost (current-bidirectional converter) is used for charging embedded Li-Ion battery into the EV from home energy (H2V). This converter can be used also for charging Lead-Acid batteries from vehicle battery (V2H) when it is needed. Fig. 5 (b) corresponds to a DC-DC current-bidirectional converter.

\[ \text{Fig. 5 DC-DC charger topologies} \]

A. Ev Sizing

The power demand is due to speed variations, tire friction dissipation, aerodynamics dissipation, and mass elevation. This power demand can be expressed as in [22] by:

\[ P = V \left( C \cdot M g \cos(\alpha) + M g \sin(\alpha) + \frac{M \cdot dV}{dt} + \frac{1}{2} \rho S C_r V^2 \right) \]  

(7)

where V: vehicle speed; M = 1000 (kg): vehicle mass; \( \alpha = 0 \) (radians): road angle with a horizontal line; g = 9.81M·s\(^{-2}\): acceleration of gravity; \( C_r = 0.01 \): friction coefficients; \( C_x = 0.30 \): aerodynamic coefficients; \( \rho = 1.225 \) (km. m\(^3\)): air density; S = 2.5(m\(^2\)): front surface area.

\[ \text{Fig. 6 Combined recharging cycle} \]

\[ \text{Fig. 7 NEDC driving cycle} \]

So the vehicle energy demand equals to 17kWh. This amount of energy needs to be embedded and stored in the Li-Ion batteries pack. For testing vehicles, driving cycles have been normalized. European light-duty vehicles have to face the New European Driving Cycle (NEDC). The NEDC consists of 4 repeated urban cycles (ECE-15) and an Extra-Urban driving cycle. Fig. 7 shows the NEDC driving cycle with the speed and the power demand of the small car.

B. Sizing of PV Panels

Data of PV sizing are given in Table II. Characteristics and sizing PV panels are reported in Tables III and IV. PV panels are supposed to be installed on the roof and have a good orientation for capturing a maximum solar radiation.

\[ \text{Fig. 8 Combined solar panel efficiency} \]
**TABLE II**

<table>
<thead>
<tr>
<th>Device</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power of receiver</td>
<td>4704 W</td>
</tr>
<tr>
<td>Usage time</td>
<td>6 h</td>
</tr>
<tr>
<td>Factor Corrector</td>
<td>1.3</td>
</tr>
<tr>
<td>Radiation</td>
<td>5 k Wh/m².j</td>
</tr>
</tbody>
</table>

**TABLE III**

**CHARACTERISTICS OF SOLAR PANEL PWX500-12V**

<table>
<thead>
<tr>
<th>PWX500-12V Characteristics</th>
<th>Digital values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power max</td>
<td>50 W</td>
</tr>
<tr>
<td>Optimal current</td>
<td>2.9 A</td>
</tr>
<tr>
<td>Optimal voltage</td>
<td>17.2 V</td>
</tr>
<tr>
<td>Short circuit cure</td>
<td>3.2 A</td>
</tr>
<tr>
<td>Open circuit volt</td>
<td>21.6 V</td>
</tr>
</tbody>
</table>

**TABLE IV**

**SIZING OF SOLAR PANEL PWX500-12V**

<table>
<thead>
<tr>
<th>PWX500-12V Sizing</th>
<th>Digital values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PV panels</td>
<td>148</td>
</tr>
<tr>
<td>Surface of PV</td>
<td>70 m²</td>
</tr>
<tr>
<td>Power max</td>
<td>7.4 kWc</td>
</tr>
<tr>
<td>Weight</td>
<td>1361 kg</td>
</tr>
</tbody>
</table>

**C. Sizing of Lead-Acid Battery**

As underlined previously we use of YUASA SW280 Lead-Acid battery as the embedded battery at home. Its characteristics are reported in Table V, and sizing results are presented in Table VI.

**TABLE V**

**CHARACTERISTICS OF LEAD-ACID BATTERIES YUASA SW280**

<table>
<thead>
<tr>
<th>YUASA SW280 Characteristics</th>
<th>Digital values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>Volume</td>
<td>151x65x99 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>2.7 kg</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>7.6 Ah</td>
</tr>
<tr>
<td>Energy/Volume</td>
<td>93 Wh/l</td>
</tr>
<tr>
<td>Energy/Weight</td>
<td>30 Wh/Kg</td>
</tr>
<tr>
<td>Internal resistance of charged battery</td>
<td>15 Ω</td>
</tr>
<tr>
<td>Maximum discharge current in minute</td>
<td>50 A</td>
</tr>
</tbody>
</table>

**TABLE VI**

**SIZING OF LEAD-ACID BATTERIES**

<table>
<thead>
<tr>
<th>YUASA SW280 Sizing</th>
<th>Digital values</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° in series</td>
<td>4</td>
</tr>
<tr>
<td>N° in parallel</td>
<td>78</td>
</tr>
<tr>
<td>Pack voltage</td>
<td>48 V</td>
</tr>
<tr>
<td>Pack capacity</td>
<td>588 Ah</td>
</tr>
<tr>
<td>Pack mass</td>
<td>842.4 kg</td>
</tr>
</tbody>
</table>

**V. SIMULATION AND EXPERIMENTAL RESULTS**

The simulation platform of PV system consists of PV panels, Lead-Acid batteries, Boost converter and MPPT P&Q as illustrated in Fig. 8. Hereafter, we present simulation results of PV model and we report a benchmarking with datasheets and experimental results.

**A. PV Simulation Results**

I-V characteristics of a PWX500-12V module are simulated according to (1). The simulation results are compared with datasheets for several levels of the radiation. Fig. 9 shows the superposition of the characteristic curves of PV panels I = f(V) with a cell temperature = 25°C and solar radiation at 5 levels: 1000W/m², 800W/m², 600W/m², 500W/m², 400W/m².

**Fig. 8 PV system controlled by MPPT algorithm**

**Fig. 9 Comparison of simulation results with datasheets for several levels of radiation and at cell temperature of 25°C**

Fig. 9 shows that the simulation results match with those of the datasheet. After comparing the simulation results with the datasheet, we compared the simulation results with experimental results of current-voltage (I-V) characteristics and power-voltage (P-V) characteristics. The used materials for experimental tests are PWX500-12V module, variable load, current sensor, voltage sensor, contact thermometer, and light meter as illustrated in Fig. 10. The aim of these tests is to determine the I-V, P-V curves of the PV panel and find the PV panel electric parameters from the I-V curve.

**Fig. 10 Test bench of PV panel**
Fig. 11 Comparison I-V curves of PV model and experimental results

Fig. 12 Comparing P-V curves of PV model and experimental results

Fig. 13 PV module current, voltage and power applying MPPT algorithm

Figs. 11 and 12 show the superposition of the experimental and simulation results for the I-V and P-V characteristic curves respectively. The comparison study of the two results shows a good accuracy of this model.

The MPPT algorithm is applied to obtain the PV maximum power. Fig. 13 shows PV module current, voltage and power applying MPPT algorithm.

**B. Simulation Results of Battery Lead-Acid**

The work presented in this section is focused on the battery model results. Once the parameters A, B, C, and D are determined, the voltage is plotted using (3) for several current rates on the same graph compared with the curves of the datasheets, Fig. 14.

Based on the obtained results, absolute error and relative error are reported in Table VII. The parameter C represents the battery nominal capacity with C = 7.6 Ah.

The average error represents good model accuracy for each rate of discharging current. The simulation curves coincide with datasheets, which allows concluding that the analytical expression represents well the evolution of the terminal voltage battery YUASA SW280.

The comparison of obtained simulation results with experimental measurements for validation of the battery model accuracy is reported. 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. Figs. 15 and 16 show the test bench of battery test. It is worth to note that the performed tests for battery model and PV model are carried out within the laboratory FEMOT-ST/FCLAB in Belfort, a small city in the north east of France. We underline also that the PV tests are done in the first week of November 2011.

**TABLE VII**

<table>
<thead>
<tr>
<th>Discharging current</th>
<th>Absolute error</th>
<th>Relative error</th>
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<tbody>
<tr>
<td>0.05C</td>
<td>0.03</td>
<td>0.44%</td>
</tr>
<tr>
<td>0.1C</td>
<td>0.01</td>
<td>0.1%</td>
</tr>
<tr>
<td>0.2C</td>
<td>0.003</td>
<td>0.03%</td>
</tr>
<tr>
<td>0.4C</td>
<td>8.95×e-4</td>
<td>0.008%</td>
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<tr>
<td>0.6C</td>
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</tr>
<tr>
<td>1C</td>
<td>0.05</td>
<td>0.43%</td>
</tr>
<tr>
<td>2C</td>
<td>0.276</td>
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</tr>
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Fig. 14 Comparing the simulation of discharge voltage with the datasheet (dashed line refers to datasheet)

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Fig. 15 Test bench of charge battery

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The proposed model enables to predict the voltage battery for discharging rate other than those given in datasheet. Fig. 17 shows results of battery discharging for I=3.22A and 2.9A.

In Fig. 17, 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.

Voltage and current of Lead-Acid battery with MPPT algorithm are presented in Fig. 19. We remark that the battery voltage increases until reaching the voltage of full charge and then the current switched off. The pack of batteries is fully charged for nearly 3 hours.

Fig. 20 presents the control performance in terms of current and voltage control. We can observe that the Li-Ion current is tracking its reference allowing a fast Li-Ion batteries charge (the Li-Ion battery is charged until 80% in less than 30min), than the last 20% are charged very slowly according to the Li-Ion battery characteristics (about 5 hours to obtain a full charge (100%)). Fig. 20 (b) corresponds to the Li-Ion SoC (starting from an arbitrary initial condition, 40% in this case).

The combined recharge cycle control is illustrated in Fig. 20 (a) where we can see the first value control corresponding to the current until 80% of SoC and the voltage control from 80% to 100%. Once the SoC is reaching 100%, the Li-Ion recharge is stopped and the control equals to 0 (the value of $i_{Li}$, $i_{Li}(A)$ in Fig. 20 (a), and the value of Alpha in Fig. 20 (c). Alpha is the temperature coefficient of the short-circuit current).
To properly coordinate the operations of all elements of charging/discharging system H2V and V2H, a modeling and sizing of the whole system is required to describe and simulate the behavior of each element. In this paper, we performed a mathematical modeling of charging station for EV using solar energy; model parameters of PV panel and lead-acid battery are identified using fitting methodology. PV and Lead-Acid models are validated experimentally. MPPT control method for obtaining PV maximum power is applied. System sizing is prepared and finally home batteries pack is charged by PV current until reaching full charging voltage. The obtained results show that the batteries Li-Ion can be charged promptly from the current of Lead-Acid batteries using buck/boost converter. In our future work, we will focus on the energy management in both directions H2V and V2H with a particular attention to bring to the battery as mean of energy storage.

VI. CONCLUSION

REFERENCES


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