The Plug-in hybrid electric vehicle as generator and load - Battery modeling

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Abstract—This document presents an initial study on the bidirectional link between hybrid electric vehicles and the electric grid, focusing mainly on the battery issue. Plug-in hybrid electric vehicles can be the compromise between the current fossil fuel problem and the desirable scenario in the light vehicle fleet.

On this context, batteries are the critical element of the system as such they are the main focus of this study. Batteries are not as developed as desired, although recent technology shows promise on locomotion applications.

On a modeling level, batteries are a complex system with several states that requires estimation and are easily influenced by external factors. The chosen model has the ability to represent several phenomena in an intuitive way, on the other hand this model was further improved to better represent these same phenomena. The model in question requires a specific methodology for parameter extraction and consequently an automatic measurement system.

The Kalman filter appear on this thesis as a possible solution for state estimation on batteries.

Plug-in hybrid electric vehicle (PHEV), Vehicle-to-grid (V2G), Battery, Battery Modeling, Model Parameters, Kalman Filter

I. INTRODUCTION

In present times there are growing concerns in transportations and on the electric grid, since both are affected by the growing fuel issues. Hybrid electric vehicles (HEV) and renewable energy sources appear as a way to decrease the oil dependency [1]. However, renewable sources are unpridictable, bringing more complexity to an electric system that does not possess significant means of storage [3] [4].

The common hybrid electric vehicles don’t meet expectations due to underdeveloped battery technology. Plug-in hybrid electric vehicles (PHEV) are the next step ahead and can be the solution for current problems. PHEV’s are characterized by the possibility to recharge its battery from the electric grid and increased electric motor power [1].

The concept vehicle to grid (V2G) appears from the possibility of connection vehicles and the electric system on a bidirectional path. Since batteries are used only 4% of the time for transportation purpposes, they can be used for the remaining time as a means of storage to the grid [3] [4] [5].

The major technological barrier for V2G and PHEV’s are the batteries. Although batteries have existed for a century the actual commercial specifications don’t meet the requiremens for locomotion system. Lithium ion batteries are the most suitable at this moment and its latest breakthrough show promise [12].

On the other hand, battery modeling requires more studies in order to prepare and optimize future systems [16]. As an electrochemical device, the batteries are a complex system, where we can directly measure voltage and current, and where we need to estimate capacity and state of charge (SOC). In addition, the performance of batteries varies with the current and state of charge, as well as external factores like temperature and age [11].

Several approaches are used on battery modeling: physical, abstract and empirical. These several approaches differ on complexity, configuration effort and analytical insight. Electric circuit models are an abstract approach which allows the use of existing tools, the integration on a full electric system, and familiarity for electrical engineers [15] [21].

The common information on battery datasheets isn’t enough for full battery modeling. The electrical circuit models require specific experiments for parameter extraction [15]. On battery tests many problems arises due to the impossibility of measuring the state of charge directly. There is a need to find a methodology for parameter extraction and the required estimation [24] [25].

The Kalman filter is a well known solution for many applications that requires state estimation like global positioning system (GPS). It can be introduced on batteries in order to get a close match between the dynamic model and the experimental results [16] [17] [18].

II. HYBRIDS

The HEV’s and their expansion PHEV’s are an assembly of several major technologies, such as electric and combustion motors, power electronics, and batteries. The development of this kind of vehicle is recent due to the number of technologies involved being in a state of maturation [1].

Common internal combustion engine (ICE) vehicles have only one kind of propulsion system, while hybrids have both conventional and electric. The supposed advantage of HEV’s over common vehicles is the increased efficiency related to the possibility of inertial and breaking energy regeneration [1]. The hybrid electrical vehicles can be classified in different architecture and classes.

The structure of the propulsion system is defined by its architecture.
• **Series**, the internal combustion engine (ICE) mechanical output is first converted into electricity, either charging the battery or propels the wheels via electric motor.

• **Parallel**, both electrical and internal combustion deliver power in parallel to drive the wheels.

• **Series & Parallel**, this configuration incorporates features of both series and parallel.

• **Complex**, this is a more complex configuration due to the possibility of bidirectional power flow on the electric motor.

![Series Diagram](image1)

![Parallel Diagram](image2)

![Series-parallel Diagram](image3)

![Complex Diagram](image4)

Fig. 1. Four common architectures of Hybrid Electric Vehicles [1]

The function and power of the electric motor defines the class.

• **Micro**, vehicles where the electric motor (around 2.5kW and 12V) essentially intervenes on the vehicle’s start.

• **Mild**, the electrical motor can join the propulsion in parallel hybrid architecture, with power around 10-20kW at 100-200V.

• **Full**, the electric motor has typically 50kW (or more) at 200-300V, and is characteristic of series and complex architectures.

Aiming for a future solution, the tendency is to increase the role of electricity, i.e. more power on the electric motor and more capacity on the batteries. PHEV’s are a result of this tendency, being classified as full hybrids with complex architectures and with the possibility to recharge from the grid. The PHEV’s can be a valuable compromise solution while future technologies such as fuel cell still present major problems [1]. In addition, PHEV’s can be a platform where current technology (such as biofuel) can be used, and a platform for developing and advancing technologies for future solutions [2].

On the industry PHEV’s are appearing as concept cars on automotive industry shows, and sometimes by the expansion of the well-known toyota Prius.

The release data of General Motors PHEV is 2010, the so-called Volt is under huge expectation [2].

III. V2G

The vehicle to grid (V2G) as explained before is the concept of bidirectional power flow connection of vehicles and the grid. The viability of this technology depends on the Electrical Drive Vehicles (EDV’s) success. The main idea is using the storage that’s bought for transportation purposes, that in average is underused [3] [4] [5]. For further understanding lets make a fast review of the electric grid and on the needs for V2G.

A. Grid

The electric grid is a complex system that lacks significant storage. The variations of the load must be accompanied closely by the power generation. Since the load varies largely along the day and according to the seasons, with the lack of storage the whole system must be oversized to support maximum load [4] [5]. Also the power markets reflect the lack of storage hence the prices can easily suffer inflation.

Four types of power markets can be defined:

• **Base Load**, the bulk of generation, usually done by power plants with low cost per kWh, such as nuclear.

• **Peak Power**, the generation done on most demanding periods, usually from power plants with the ability of switch off and on fast.

• **Spinning reserves**, the generation working as a backup to preventing unexpected events.

• **Regulation**, the generation responsible for controlling the frequency and the voltage under defined bands.

The several markets differ on dispatch time, availability, price, contract, response, and control. In addition they may differ from country or region, yet the matrix is generally the same [4] [5].

B. The vehicle and v2g

Major requirements:

• Electrical drive vehicle with storage ability, and a system of control and energy measure.

• Bidirectional connection with the grid.

• Possibility of communication with the dispatch.

Plug-in vehicles have almost all the technology for v2g, the extra requirements have low capital-costs [4]. This last subject can be a source of a lot of work and discussion.

On the other hand major limitation on power provided by v2g are [4] [5]:

• Physical connection, typically house outlets are sized for low power and current, usually 2kW.
The battery capacity, the power and energy available depends on the needs of the driver. It can be defined as useful energy for V2G, the energy that the driver does not need. For further studies this is a variable of utmost importance requiring statistical approaches for quantifying it. Since the available power depends on the dispatch time \( t_{\text{disp}} \) and on energy conversion efficiency \( \eta \), it can be defined as:

\[
P_{\text{V2G}} = \frac{E_{\text{available}}}{t_{\text{disp}}} \cdot \eta \tag{1}
\]

Power electronics on a practical application can’t limit the power that V2G can support since the electronic is projected to be superior to the electric motor power.

C. Grid vs V2G

Since the PHEV’s will bring a new load to the grid, if the charge is mainly during the night, the diary load will be flatter. This means the average use of the plants or capacity factor are increased [4] [5] [6]. A flatter load diagram without additional power plants can be possible with V2G [6]. Optimally dispatched vehicles can also generate power (in addition to the night period) in the most demanding times. This can be the impact of a PHEV fleet on the base load and peak power markets.

However, vehicles have the electronics that allow the entrance on the other two markets. On the article [5] are stated as main advantages of V2G generation: the quick response, the low inactivity costs, distributed generation, and low capital costs. The disadvantage consists only on battery costs and longevity. Regulation and spinning reserves are ancillary services mainly paid for the quick response and power availability, characteristics that match with V2G advantages. It’s suggested that as the fleet increases different markets can be occupied to maximize the revenue. First the ancillary services then the peak and base load.

In addition V2G can support large-scale renewable energy by providing storage and ancillary services [5].

D. Ongoing Projects

As the first studies appear, industry is starting to looking at V2G as an opportunity. The company ACpropulsion has several prototypes for V2G and show their work on the web [10]. On the other hand several utilities are announcing test projects [9].

IV. BATTERIES

Currently batteries are the main barrier for the development of many applications and technologies [1] [12] [15].

The microscopic phenomena are next described.

A. Physics

As an electrochemical device a battery converts chemical energy into electrical energy. A battery is a group of cells, which is the base element of an electrochemical device. A cell is composed by an anode, a cathode, and an electrolyte. The chemical processes are complex and the theoretically equations are known, but practical application is impossible [11].

The standart potential of a cell depends on the nature of the active materials on the cell, and the useful capacity depends on the quantity. The practical voltage and capacity are different from the theoretical, since there are several secondary phenomena that introduces losses, and which define electrochemical efficiency. This phenomena are explained next, and are represented in figure 2.

- **Activation** losses, due to the energy necessary to activate the electrochemical reactions;
- **Polarization** losses, due to different concentrations of active materials;
- **Ohmic**, due to internal impedance;

The voltage on a cell may be given by:

\[
E = E_0 - [(\eta_{ct})_a + (\eta_{ct})_c] - [(\eta_{ct})_c + (\eta_{ct})_a] - iR_i = iR \tag{2}
\]

\( E_0 \) = electromotriz force in open circuit
\( i \) = operation current
\( R_i \) = internal resistance
\( \eta_{ct})_a,\eta_{ct})_c \) = polarization due to concentration gradients
\( \eta_{ct})_a,\eta_{ct})_c \) = polarization due to activation, and charge transference.

The tree groups of losses represent several phenomena, however the dominant are the double layer capacity, the charge transfer, the diffusion and the ohmic impedance [11] [20].

In addition, the performance of the battery is also affected by:

- **Voltage level**
- **Current**
- **Temperature**
- **Mode of charge/discharge**
- **Age**

B. Specification to phev and V2G

The desirable specifications for locomotion applications and consequently for V2G are high energy and power density, low cost and maintenance, high cycling or longevity, and specially safety [11] [12]. The most promising technology is based on
lithium ion with iron phosphate as cathode [12]. This cathode allow:

- Good energy and power density
- Flat voltage characteristic
- Cheap cathode
- Safety due to high heat absorption

Many companies like A123Systems (responsible for GM-Volt batteries) are trying to improve the weak characteristics of this cathode [13]. There are several other working on anode improvements [14].

V. MODELATION

The battery modeling is crucial to obtain good management systems or optimize the applications in case, or just to study the impact on other systems. In V2G we need an intuitive, simple and accurate model. These characteristics may be impossible to get in a model if we take in account every factor and phenomena [16].

On the section above the phenomena were described in a microscopic point of view. However a macroscopic model which represent the main characteristics of battery is desirable. A battery has the following characteristics [11]:

- Voltage which results of the contribution of the several cells.
- Current, defined by the external device or connection.
- Capacity, defined by the quantity of active materials on the several cells.
- State of charge, defined by the quantity of active materials in reagent form.
- Impedance, represent the relation between the voltage and current.
- Losses, represent the electrochemical efficiency in energy conversion (chemical to electric).

The main problem on battery modeling is that some variables need to be estimated [24] [25]. From the enumerated only the voltage and the current are directed measured. All the other variables need to be estimated. In addition these variables depends on each other and from external factores like temperature and age [23].

Electrical circuit models are grouped in tree approaches [23].

- Impedance is the approach where the focus is on batteries impedance or dynamics on voltage response to a current pulse, representing it by an equivalent circuit [19].
- Run time based is the approach where the focus is on the voltage evolution over the state of charge on a stationary regime [23].
- Thevenin is an approach that mixes both, voltage evolution and the dynamics [21].

A model that can combine several advantages of both approaches is proposed in [23], and it’s represented on figure 3. In this model:

- Battery capacity is represented by a capacitor ($C_{capacity}$ on battery lifetime circuit) where the voltage is normalized to 1V. The full charged capacitor with 1V represents the full charged battery or 100% SOC. The voltage at the capacitor represents the state of charge.
- The current source on the left circuit (lifetime) represents the battery current and it discharges/charges the capacitor as the battery is discharged/charged.
- Selfdischarge is represented by $R_{self-discharge}$, however this phenomena is secondary since it takes months to be significant (Losses around 10% SOC per month) [23].
- The battery’s voltage can stabilize after a rest of several hours or even days [24], this defines open circuit voltage($V_{oc}$). The open circuit voltage is function of the state of charge making the connection between both circuits.
- The dynamics on a battery can be divided as fast and slow. On the models the parameter $R_{series}$ represents the fast dynamics and the RC ladders the slow dynamics (mainly due to diffusion process) [20] [24].
- The Losses are represented by the losses on the resistors $R_{series}$, $R_{transient}$.

VI. PARAMETERS EXTRACTION

A. Methodology

The model requires specific experimental tests for parameter extraction which can follow a proposed methodology by [25]. This methodology consists on analyzing the voltage response to an pulse of current, over several operating points (SOC,current). On this tests influences of temperature are ignored, however they can be contabilized in the model based on datasheets.

A typical voltage response is represented in 4. Considering the proposed model with just one RC ladderl, electrical circuit equations are:

$$U_{bat} - U_{oc} - U_{R} - U_{C} = 0 \quad (3)$$

$$\tau_{D} \frac{\Delta U_{c}}{\Delta t} + U_{D} - I_{bat}.R_{D} = 0 \quad (4)$$

The voltage response follow the next equation:

$$u_{bat}(t) = I_{bat}.R_{series} + R_{D}.I_{bat}(1 - e^{(-\frac{t}{\tau_{D}})}) \quad (5)$$
The parameters $R_{\text{series}}$, $R_D$ and $C_D$ can be extracted by data fitting the experimental and theoretical responses, equation 5. The fast dynamics gives $R_{\text{series}}$, and the slow gives $R_D$ and $C_D$, since $\tau_D = R_D C_D$.

The parameter $V_{oc}$ can be rapidly estimated by two different methods [24], [25]. On this work its assumed only the first order of variation on the dynamics, which means the rest period to test the batteries consists on several minutes.

B. Automatic system

Since there is no direct way to measure state of charge, there is a need to test the battery from fully charged to fully discharged. If the test is under constant current, the electrochemical efficiency may be constant. Under these facts state of charge will vary linearly with time.

This methodology to extract parameters and to determine soc, requires an automatic system with the possibility to read voltage, current, and control of the interruption of charge/discharge.

The schematic of this system is presented on figure 5.

![Schematic of the test system](image)

The test system was built using current and voltage sources and sensors, a data acquisition board which allows communication with Matlab, a switch which consists on a IGBT controled by an auxiliar system (receives a signal from the board).

C. Measuring

The test battery is a VRLA (Valve Regulated Leak Acid) which has advantages over the common Leak acid, namely increased resistance to temperature, mechanical stresses, and safety on overcharge. This battery consists on isolating the electrolyte on a gel or separators.

The discharges applied to several resistances in parallel. The variations of current near the average value dont exceed 10% of it.

The battery is considered discharged based on datasheets 10.5V for 2A and 9.5V for 6A.

Battery is considered charged after the current reaches 20% of C, in this case 0.4A. On leak acid batteries, the internal resistance is higher compar to the lithium ion and consequently the cycle voltage is reached at lower SOC. This fact doesnt allow the use of a method for Voc estimation proposed by [24].

The rest time between load impulses on batteries are picked based on the first order response, 10minutes to make it simple.

The phenomena of temperature, self discharged and age are considered secondary on battery operation comparing to the influences of state of charge and current on the parameters.

D. Experimental Tests

The several discharge tests are shown on figures 7, 8. The voltage evolution is similar to the results in [24]. The sampling frequency is 20Hz.

The typical slow voltage response is represented on figure 6, the overvoltage varies for low state of charge (under 20%).

![Overvoltages at different SOC](image)

Since the test battery is a leak acid the voltage quickly converges to the float voltage around 70% to 80% state of charge, after this point constant voltage must be applied.

E. Matlab script

The maths required for parameter extraction justify the creation of a dedicated script on Matlab. The schematic is represented on figure 9.

The data is saved on matlab and manipulated on this script. The fast and slow dynamics of the battery can be distinguished by the impedance spectrum. The slow dynamics is assumed to
be less than 1Hz and fast dynamics to be superior than 1Hz. SOC estimation is done by ampere counting on the test.

The data fitting for parameter extraction is done by using the Matlab Curve fitting toolbox, where the .m code was generated and introduced on the script. The script also includes a filter in order to eliminate possible noise on the data.

F. Parameters obtained

The parameters Voc, Rseries, Rd and Cd are represented on the following figures. Voc is linear, which is common for VRLA batteries, the hysteresis (0.8V) between charge/discharge voltage is that of leak acid [11].

The variation of Rseries and Rd due to current is superior to the initially expected. The leak acid batteries got superior internal impedance and more non linear phenomena than lithium ion.

The Cd evolution is the expected intuitively, the less state of charge will derive on a bigger overvoltage.

In the article [21], its proposed a similar model, but with some differences, the parameters are based not on state of charge but on voltage. On figure 12 its presented the Rseries + Rd obtained in [21].

G. Simulation

The chosen model can be improved. The losses on battery capacity with current aren’t considered. A solution can be the introduction of an element that dissipates the same power as the resistors Rseries, Rd, with a variable of correction. The model is the following:

\[ Z = K \frac{i_{k-1}[R_{series_{k-1}} + R_{d_{k-1}}]}{V_{oc_{k-1}} - 1} \]

The variable K is a correction factor. With this model voltage drop losses are equivalent to capacity losses, and 0% SOC can correspond to the cutoff voltage. On the other hand the model above ignores the possibility of rest on batteries. A solution for modeling the effect of rest on the dynamics is the introduction of a capacitor in parallel with \( C_D \). This introduction will decrease the time constants of overvoltages.

To simulate this model there is a need to create a script on matlab, since non linear models don’t work well on the simulink toolbox.

The model is based on the following equations 7,8. On state-model form.
The simulation of a 4A discharge with 2A parameters brings errors, especially at the voltage drop.

**H. Kalman Filter**

Kalman filters can be a solution for an optimal match between a simple model and experiments. In addition, these kind of filters with a good dynamic model can match the experimental results with noise by iteration [16] [17] [18].

The parameters in the model function of SOC and current vary slowly. An extended kalman filter (EKF) can be obtained by assuming the linearization under the operating point.

The kalman filtering algorithm can be divided in two phases, for linear systems is the following [26]:

### Time update equations

\[ \hat{x}_k = A_{k-1} \hat{x}_{k-1} + B_{k-1} u_{k-1} \]  

\[ P_k^- = A_{k-1} P_{k-1}^- A_{k-1}^T + Q \]
Measurement update equations

\[
K_k = P_k^- C_k^T [C_k, P_k^- C_k^T + R]^{-1}
\]

(11)

\[
\hat{x}_k^+ = \hat{x}_k^- + K_k[ z_k - C_k \hat{x}_k^- - D_k \cdot u_k]
\]

(12)

\[
P_k^+ = [I - K_k C_k] \cdot P_k^-
\]

(13)

The matrices according to the proposed model are the following:

\[
[A_k] = \begin{bmatrix}
1 & 0 \\
0 & 1 - \frac{\Delta t}{C D_{k-1} \cdot R D_{k-1}}
\end{bmatrix}
\]

(14)

\[
[B_k] = \frac{\Delta t}{Z}
\]

(15)

\[
[C_k] = \begin{bmatrix}
\frac{\Delta V_{oc} \cdot (soc)}{R_{series}} & 1
\end{bmatrix}
\]

(16)

\[
[D_k] = [R_{series_k}]
\]

(17)

The results of the simulation are presented on the next figures 17, 18.

The initial SOC was set to 200% which converges fast to 90%. The covariance and variances of noise and errors are set empirically.
REFERENCES

[12] Pesaran, Ahmad Battery Choices and Potential Requirements for Plug-In Hybrids, National Renewable Energy Laboratory