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Vehicle Characterization for Smart Charging and V2G strategies

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Abstract

TECNALIA has become a key active player in technology development for electric vehicles (EVs), in the fields of materials, mechanics, power electronics and smartgrids. In order to contribute to the development of the technologies dealing with the new paradigm that integrates EV within the grid, where large EV fleets are connected to the grid and can even take part in the electricity markets, TECNALIA has deepen into the definition of the information needed in order to define the charging sequence of EVs. This paper explains the characterization of those elements, related to the vehicle and the user, which could influence on the definition of the optimal charging sequence of EVs. Modelling the behaviour of the vehicle charging system leads to the possibility of establishing charging sequences that minimize the energy spent per charging cycle. This information has been included in a communication protocol developed by TECNALIA and implemented in the EV-ON platform, which purpose is the development of smart charging and Vehicle to Grid (V2G) algorithms.

Keywords — Smart charging, Vehicle to grid, State of Charge estimation, Charging system characterization

1 Introduction

Nowadays, it seems that electric vehicles (EVs) could be a cost effective solution to mitigate some of the problems associated to road transport. Factors such as the increasing oil price and the elevated ecological footprint of internal combustion engines (ICEs) have acted as catalyst in the process of raising the interest of politicians and vehicle manufacturers in EVs.

Nevertheless, the market share of EVs is by now clearly below 1‰. However, in the medium term it is supposed to be a significant portion of the transportation fleet, with a broad forecasting range between about 2% and 20%.

One of the reasons of the short time to market of EV deployment is the lack of need of specific grid infrastructure. Present recharge systems usually operate using classical battery charging algorithms, i.e. charge as fast as possible without taking into account any other consideration. However, as EV penetration increases up to a significant level, and taking into account the homogeneity of the pattern of use of vehicles, this would give rise to new demand peaks that would make the operation of the electrical system more difficult. So, now it is the moment to design EV recharging infrastructures in a way not just to avoid harming grid operation, but even trying to improve it. By means of a smart management of the distributed storage within EVs, it could be possible to adapt the charging profile of the EVs according to grid requirements. Furthermore, it could be possible that EVs would supply services to the grid in certain moments, what is called V2G.

The common characteristic of smart charging and V2G strategies is the intelligent entity that decides the optimal power exchange between each EV and the grid in each moment. The optimization could pursue a huge variety of objectives, such as participating as a regulating element, adapting the power flow to the renewable energy generation, flattening the system load curve or taking advantage of variable energy market prices.

2 Vehicle and user requirements characterization

Anyway, in order to find the optimal power exchange for each EV it is compulsory to know a wide variety of inputs. Depending on the definition of the algorithm the information inputs and their level of detail are different. But an input set is needed in all algorithm implementations: the information describing both the user requirements and the vehicle characteristics.

In simplest charging systems there is no intelligence in the charging points, and the vehicle takes as much power as defined by its internal charging mode of operation, just taking into account the battery voltage. On the other hand, smart algorithms would try to optimize the power flow taking into account specificities of each EV and its user, so they need to deeply know their characteristics. The vehicle controller is the system that would gather all that information so as to be provided to the higher level entity, the scheduler, in charge of calculating the optimal power flow sequence. Figure 1 illustrates the vehicle controller data model.

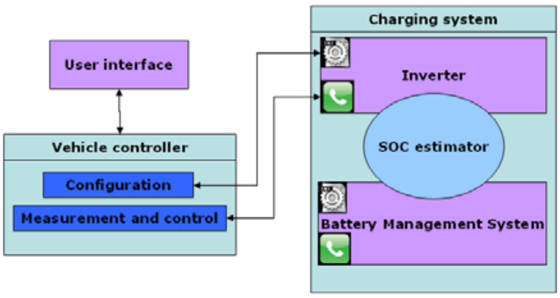

Figure 1. Vehicle controller data model

User requirements affecting each charging process are related to a collection of expected or possible retrieval times associated to minimum required SOC (State of Charge) values. When the user drops off the vehicle he must be able to introduce into the vehicle controller the expected time of retrieval, and the minimum vehicle autonomy required for next trip. Moreover, in case of eventual vehicle retrievals, the user would want to define different values of autonomy. These values of autonomy would be introduced as SOC, energy or distance values (applying an average fuel economy).

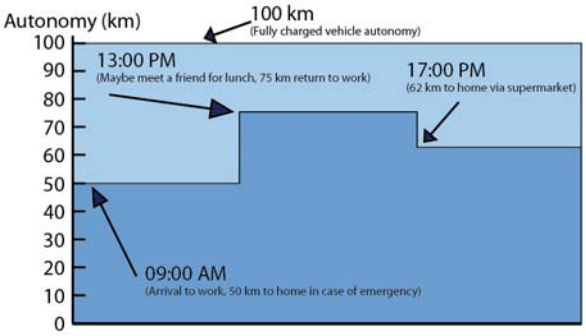

Figure 2. Example of use pattern of an office worker

In fact, user requirements respond to an idealization of the pattern of use of the vehicle by the user, applying an offset due to the margin of confidence settled by the user. On the one hand, conservative users will require the autonomy to be as high as possible after they drop off the car and, on the other hand, some users will accept to limit their mobility range in favor of paying a lower price for energy. This last group of users will be, of course, more attracted by smart charging and V2G methods, being the focus of this kind of approach. Anyway, it is crucial to remark that there is a convergence time between user requirements and the capabilities of the system, which depends on the sizing of the charging system.

The charging system is the controllable power electronics equipment that governs the power flow between the AC charging station connected to the grid and the batteries. Depending on its sizing it is able to manage a maximum value of current. This maximum current defines, together with the nominal voltage, the maximum power allowed to be exchanged with the grid. Typically the charging system is an inverter, which could have the ability of functioning in a bidirectional way. In some vehicles the same inverter is also used to feed the AC motor(s), so, in this case, the power exchange capability with the grid is usually bigger, due to the high power demand of the motors.

Inverters do not present a constant efficiency conversion rate. Basically, it can be assumed to be a function of the current, usually higher than 80%

and increasing with current. The control interface of inverters is usually implemented through software protocols that just allow certain values of AC current, n_I, to be set, so the efficiency can be represented as a set of pairs related to allowed AC current setpoints, as the AC voltage will be imposed by the grid.

$$[P_{DC}]_{n\_Ix1} = [\eta_{INV}]_{1x\,n\_I} * [I_{AC}]_{n\_Ix1} * [V_{AC}]_{1x1} \quad (1)$$

where n_I is the number of AC current values.

This reference set of points must be known by the vehicle controller in order to calculate the total efficiency of the charging system. But, in order to estimate this set of values, there are two possible options: to represent the inverter by its electrical model or to get real data based on measurements. Taking into account that the efficiency of the inverter is not only related to the power electronic components, but it has to do also with, for instance, the consumption of its control system, the empirical option would be the best and more accurate one. The measurements to be performed would be related to a finite collection of AC currents.

There is also another set of input data that has to be taken into account, and is related to the batteries themselves. For each battery, the charging and discharging efficiency is different and depends mainly on the SOC and the DC power. For a given battery technology and internal structure, the variation effect is more obvious in the charging step, where it can be stated that higher power values tend to be more inefficient. This characteristic shows also a strong dependency on other factors, such as the temperature and aging that needs to be considered in order to estimate the system efficiency. The expected efficiency is crucial in order to plan the optimal charging sequence for the EV and it has to be known by the scheduler in advance.

For each aging value, the battery efficiency will be represented in function of the DC power from/to the inverter, P_{DC}, the SOC and the battery temperature, trough a tri-dimensional matrix, as the aging is considered to be constant during each charging sequence. As in the case of the inverter, the elements in the matrix can either be measured or calculated.

But the major problem to be resolved so as to gather efficiency data is not the data gathering itself, but the SOC estimation that is one of the variables of the calculation [1][2]. SOC can not be measured directly, and its value should be provided by the Battery Management System (BMS). The BMS is responsible for the protection of the battery and has the ability to limit the power or even interrupt the charge and the discharge in case of overcharge or underdischarge respectively. The strategies followed to control this capability are closely linked to the SOC value. In small systems where the battery does not have BMS, the inverter has to play this protection role.

The scheduler has to know the DC power limit imposed by the BMS, for each possible value of AC current, I_{AC}. This limit depends on the SOC and the battery temperature.

3 Smart charging and V2G algorithms

These are the main charging characteristics that should be taken into account by the scheduler, in order to envisage a complete charging sequence for a particular EV. The optimization done by the scheduler must also consider the objective SOC required by the user. As it is inferred by the explanations given before, depending on the sequence of AC current values ordered by the inverter, the necessary energy for reaching a required SOC value is variable. With the proposed characterization, it is expected to represent accurately the charging system behavior so that the scheduler can know which are all the feasible charging sequences that lead to the required SOC. This is one of the main conditions that smart charging or V2G algorithm must accomplish. Then, the algorithm must select the optimum charging sequence according to other factors, as explained below.

Strategies can be completely different, depending also on the kind of entity in charge of the scheduling (the distribution utility, an energy aggregator, the system operator or even the final user) and could aim to either minimize the energy purchased, the aging effect, the cost of the recharge…

TECNALIA aims at the development of high level smart charging and V2G algorithms. One of the input datasets of these algorithms, presented in this document, corresponds to the vehicle and user requirements characterization. The other data sources are the following:

- **User actuations**: The EV user decides the connection or disconnection of the EV to the grid. Apart from this basic functionality, some additional possibilities should be implemented, such as the choice of the kind of charging process to be executed.
- **Energy trading**: Energy price, dynamic tariffs and power or energy limitations are variables that should be considered to define the charging process. This framework would be defined according to the contractual conditions signed between each user and the energy supplier. This information would also contain the conditions about the price of energy purchase for the scheduler, which would be directly bought in the energy market, if the scheduler is a qualified buyer, or through a trader. The variety of options here is very wide and depends directly on the regulation scheme for energy trading and on EV special tariffs.
- **System operator**: A charging control system for a fleet of EVs should be able to schedule the energy exchange between the grid and each EV based just in energy trading parameters. Anyway, a substantially big fleet of EVs could represent a good opportunity to provide grid support services to the grid operator. The distributed storage system of the EVs connected in charging stations could provide high value services such as load leveling, peak shaving, voltage compensation or spinning reserve among others. Anyway, all these approaches nowadays are a pipe dream, but in the medium term, as EV penetration increases, they could be a cost efficient alternative so as to optimize the management of the distribution grid. The provision of these services by EVs should be regulated, as it happens for other kind of energy generators.
- **Aggregation**: Charge scheduling could be realized for each EV taking into account also the actual scheduling conditions of a set of EVs. In that case, an aggregator would be the entity in charge of interfacing the system operator and/or the energy trader and also coordinating the charge management of the set of EVs.
- **Billing system**: In the most general case, a smart meter must be installed for each charging point, so that all the energy exchanges between each EV and the grid are registered. This information is used for billing purposes.
- **Power quality measurement**: This information could optionally be managed so as to verify the correct following of each EV charging system of the charging sequence dictated by the scheduler and to check that EV inverter works under the conditions defined by the legal framework.

4 EV-ON Platform

TECNALIA has developed the EV-ON platform with the aim of being a platform orientated to the design, development and validation of smart charging and V2G algorithms. The platform implements a flexible intelligent charging point and the charging system of a vehicle.

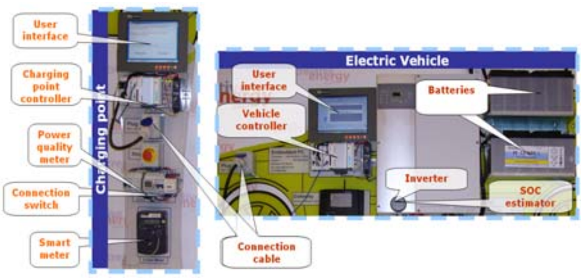

Figure 3. EV-ON Platform

Both systems have been implemented using commercial hardware that could fulfill the broad functional requirements imposed by the multipurpose platform.

The hardware mainly consists of the following components:

Electric Vehicle:

- Controller: Industrial embebbed PC (Beckhoff CX 1030) with Windows XP Embedded OS.
- Inverter: Xantrex SW4024. Standard battery inverter controllable by means of Xan BUS proprietary protocol (accessed by the vehicle controller through a gateway to standard Modbus protocol).

- Batteries: Standard vented Pb batteries.
- SOC estimator: Xantrex DC-LINK PRO. As the batteries have no BMS and the inverter does not provide an accurate SOC estimation, an external estimator is used.
- User interface: Axiomtek PANEL 6100-O/P 10.4". Industrial TFT LCD Monitor with touch screen.
- Plug: SCAME (Libera series for EVs).

As the purpose of the platform is not the testing of real EV charging systems, a simple standard battery management system has been used. Functionally, it represents the same characteristics of an EV charging system, with the benefit of the usage of a bidirectional controllable inverter.

Charging point:

- Controller: Industrial embebbed PC (Beckhoff CX 1030) with Windows XP Embedded OS and additional IO module for connection switch control.
- Smart meter: 5CTM-E2C-423200UB with IEC 60870-102 communication protocol from ZIV.
- Power quality meter: CVM MINI-HAR-ITF-RS485-C2 Power analyzer with Modbus RTU communication protocol from Circutor.
- User interface: Axiomtek PANEL 6100-O/P 10.4". Industrial TFT LCD Monitor with touch screen.
- Plug: SCAME (Libera series for EVs).

TECNALIA has fully developed the EV-ON platform software. A new protocol orientated to support algorithm development platform has been developed and implemented in Java. This protocol includes the modeling of user requirements and the vehicle characterization presented in this article.

The software module structure is shown in Figure 4. Both in the vehicle and the charging point controller there is a main software thread, the *Manager*, which coordinates and provides communication among the rest of the modules. Driver modules provide the ability to communicate with the different proprietary hardware equipment. Their interface with the manager has been developed so that the exchanged messages represent the standard classes defined by the modeling stage. This structure has been implemented so that the software customization to adapt different hardware equipment involves uniquely driver development.

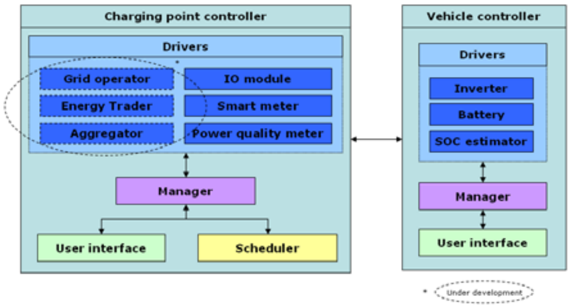

Figure 4. Software modules

The *User interface* modules in both vehicle and charging post provide different abilities, such as introducing user requirements, visualizing instant and historic values of measurements, starting and stopping the charging process, or selecting the scheduled algorithm.

In the vehicle controller the following modules have been developed:

- **Battery driver**: The Pb battery used has no BMS, so the functionality of this module is just to get the battery efficiency characteristic from the respective configuration file.
- **Inverter driver:** This module configures the inverter parameters, sets the inverter in both charge or sell to grid modes of operation, sends the scheduled AC current setpoints to the inverter and acquires power measurements both in the DC and AC inverter buses. Also reads the internal configuration file where available AC current setpoints and inverter efficiency is defined. The inverter used just implements classical 2 or 3 step charging sequences (bulk, absorption and float). In order to manage the inverter as required by the smart charging procedure, where the scheduler is the entity which decides the current to be set up in each moment, this inverter is always managed in bulk mode. In this mode, the inverter current flow is limited by an AC current parameter when battery

voltage is lower than the threshold defined by a concrete voltage level, which is, in fact in this case, a current setpoint. With this usage the inverter is the equipment that implements the BMS functionality of limiting DC power, and its driver is responsible for reading the correspondent configuration file.

- **SOC estimator driver**: The measurement of the SOC estimator given by an external integrating device is gathered.

Another functionality of the vehicle software is the improvement of the empirical characterization of the efficiency of the inverter and the batteries and the DC power limit. The manager module logs the measurements acquired through the inverter and SOC estimator drivers and those measurements are used to update the values of the characteristics, so that the accuracy is maximized.

The specific software modules of the charging point controller are:

- **IO module driver**: Controls the connection switch managed by the charging point, which is closed after the charging sequence is to be started and opened immediately after the user queries the vehicle retrieval through the user interface of the charging point.
- **Smart meter driver**: Receives the energy accumulated in both directions, from the vehicle to the grid and vice versa, for each charging process, tariff type and tariff validity period.
- **Power quality meter driver**: Gets data about power, energy and grid quality in the connection point.
- **Aggregator**: This optional entity would be in charge of coordinating a large fleet of EVs like a unique resource, so it is considered in the middle of the charging points and the grid operator and the energy trader, explained below. Energy aggregators seem to be the most feasible option in the near future to manage massive EV connection to the grid. These aggregators would interface the grid operator and the energy trader with the users, assuming part of the risk of energy market price volatility in exchange for economic profit. Aggregators also could make EV fleet charging act as a classical generation unit or Demand Response (DR) provider.
- **Grid operator**: This module would support the interface with the grid operator, in those schemes where the EV fleet charging scheduling depends on the grid state, as in the case where regulation services are provided by EVs.
- **Energy trader**: Represents the information related to the energy price. Depending on the approach, it could represent a special tariff for EVs, the daily market energy price…
- **Scheduler**: Implements the logic necessary to schedule charging and V2G algorithms, taking into account the information provided by the vehicles and the user, and from the grid operator and energy trader or the aggregator. For basic charging algorithm just the information about the vehicle and the user is needed.

5. SOC estimation

As previously stated, the SOC is one of the most important parameters to be considered in order to optimize the use of the battery energy. This parameter is defined in absolute terms of amperes hour (Ah) or as a percentage of its maximum capacity (%). In addition to this parameter, the voltage profile needs also to be considered in order to know the energy available in the battery.

The main problem encountered so as to give values to the characteristics defined before is that the SOC is not directly measurable. Different methods have been suggested on the literature to estimate the SOC [3] in base of other parameter that can be observed on the battery such as the terminals voltage, current and the temperature. These methods can be divided in two different groups:

- **Coulomb Counting or Book Keeping**: These methods are based on the integration of the current passing through the battery terminals. In order to improve the method's precision, other parameters such as efficiency and temperature need to be considered. Due to the fact that measurements inherently imply a certain level of inaccuracy (noise, offset, gain, etc.), the result tends to diverge from the real SOC value. In order to solve this problem, the calculation must be adjusted periodically by another method. Typically this value is adjusted whenever the fully charged or discharged state is reached. This is the method used by the Xantrex estimator installed in the EV-ON platform.

- **Adaptive Methods**: Under this category a wide number of different methods are considered. They are based on the use of different mechanisms such as fuzzy logic, neural networks or Kalman filters. Most of them use the information provided by different parameters that can be measured on the battery such as voltage, current and temperature. Since they are not based on the integration of a single measure, they provide excellent precision over a wide range of conditions.

In complex scenarios such as the electric vehicle, adaptive methods are preferred over the book keeping ones. They not only provide a better SOC estimation, but they are also able to estimate other parameters such as the output voltage or the SOH (State Of Health, that is, aging). The ability to predict the output voltage based on the SOC and power requirement provided by these methods is needed in order to estimate the global system efficiency.

5.1 Battery Model

TECNALIA has developed a SOC estimation method for ion-lithium batteries that could be used to develop a SOC estimator that would provide the battery characterization data defined in the section 2 of this paper. This method does not take into account the effect of battery temperature in battery efficiency.

In order to develop and implement an adaptive method, a battery model is required. This model not only provides a mechanism to obtain the system equation but also to simulate the battery performance under different scenarios.

Different models have been suggested. For the scope of this work, the Randle [4][5] second order model has been selected.

The battery model (figure 5) is based on two main components. The first one represents the EMF (OCV, Open Circuit Voltage) produced by the electrochemical reaction inside the battery by means of a voltage source dependent of the SOC.

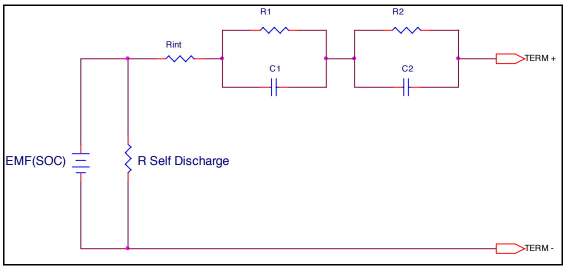

Figure 5. Randle second order model

The second component models the over potential phenomena through a complex impedance. This impedance is represented by one series resistance and two R//C circuits. The series resistance models the ohmic resistance present in the connection between the different parts of the battery. The two R//C circuits represent the voltage transients due to mass transport and double layer diffusion phenomena inside the battery.

One additional resistance can be used in order to model the self discharge phenomena, but for the case of lithium-ion batteries it is generally ignored.

In order to obtain the values of the different components of the model, a characterization process is required. For this purpose TECNALIA has developed a battery characterization system based on the following components:

- Control and Data Acquisition System. It is based on Lab-View™ running in a PC doted of GPIB interface. Over this platform TECNALIA has developed a modular software that automates the battery testing procedures.
- National Instrument cDAQ 9172. This system provides the capability to supervise the battery voltage and current. It also provides the capability to supervise up to 4 temperatures by means of thermistors.
- Delta Elektronika SM15-400 DC Power Supply. It provides the capability to execute different charging cycles under the supervision of the control and data

acquisition system.

- H&H ZS Electronic DC Load. It provides the capability to execute different discharge cycles under the supervision of the control and data acquisition system.
- Climatic Chamber. It allows the battery characterization under different ambient temperatures.

The figure 6 shows a photo of this experimental setup and its schematic diagram.

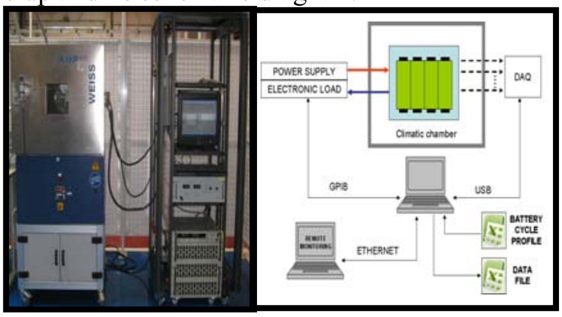

Figure 6. Battery characterization system

Based on this system, a characterization procedure has been implemented. Different charge-discharge cycles are applied to the batteries under test. The information gathered during these test is the base to obtain the following parameters:

- **OCV/SOC relationship**: In order to obtain this relationship, two consecutive charge and discharge pulsed cycles are applied to the battery (figure 7). For each pulse, the battery is let to rest until its voltage reaches a pseudo equilibrium point. In this way, two curves are obtained for the charge and discharge process. The average of these two curves represents the OCV/SOC relationship (figure 8).

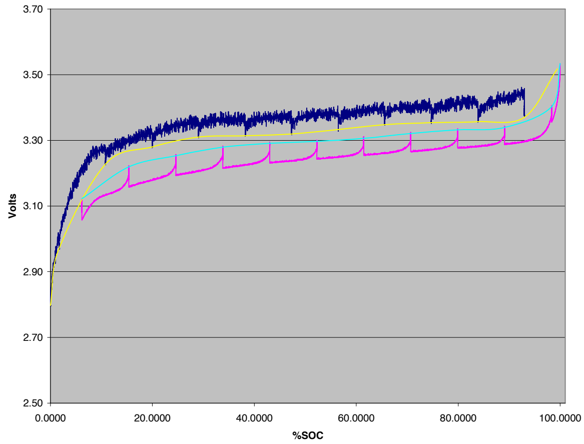

Figure 7. OCV/SOC characterization process

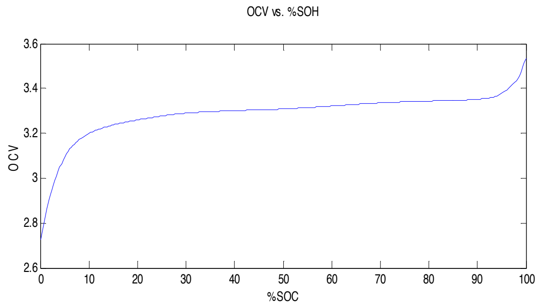

Figure 8. OCV/SOC curve obtained for A123-M1 Battery

- **Rint Value:** The Rint value is obtained from the analysis of the curve described by the voltage when the current is interrupted in each of the pulses. On this point, the voltage describes an initial step that is described by equation 2:

$$\Delta V = R\text{int} * \Delta I \qquad (2)$$

- **Rx//Cx Values**: These values are also obtained form the analysis of the voltage relax curve. In this case only the exponential part of the curve is used. This curve is fit to the equation 2 and the values of the circuit components are obtained from the equations 3 -8.

$$V = V\max - A - B + A \cdot e^{-\tau 1 \cdot t} + B \cdot e^{\tau 2 \cdot t}$$
(3)

For a charge pulse

$$V = V\min + A + B - A \cdot e^{\tau 1 t} - B \cdot e^{\tau 2 \cdot t} \qquad (4)$$

For a discharge pulse

$$R1 = \frac{A}{|I|} \qquad (5)$$

$$C1 = \frac{1}{R1 \cdot \tau 1} \qquad (6)$$

$$R2 = \frac{B}{|I|} \qquad (7)$$

$$C2 = \frac{1}{R2 \cdot \tau 2} \qquad (8)$$

The procedure previously described has been applied to an A123-M1 battery obtaining the results shown in figures 9 to 11.

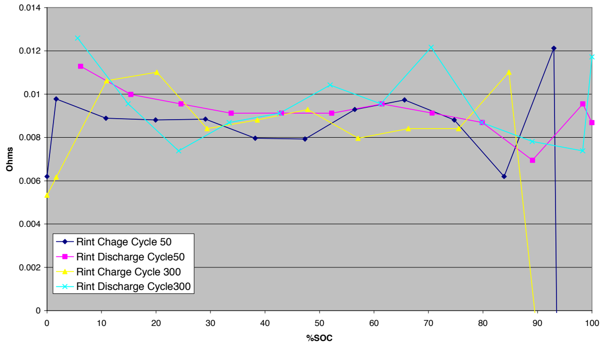

Figure 9. Rint Vs SOC

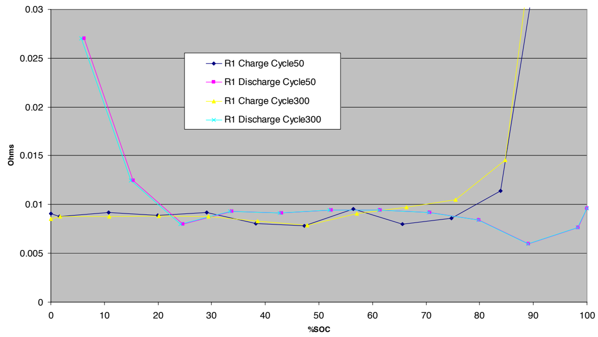

Figure 10. R1 Vs SOC

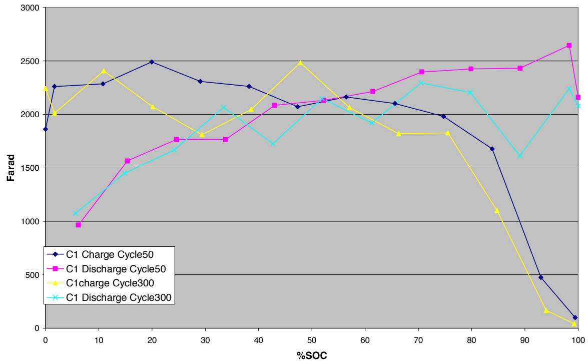

Figure 11. C1 Vs SOC

It can be observed that for a SOC range between 20 and 80% the values of all the components of the model are relatively constant. In most electric vehicle applications the SOC outside this range is not used. Therefore we can assume the average of this range as the component value.

Table 1. Component values used in the model

Parameter	Value
Rint	9,9 mΩ
R1	12,8 mΩ
C1	2001,4 F
R2	311,3 mΩ
C2	57401 F

Based on these values, two models have been implemented in Matlab/Simulink™. The first one (figure 12) simulates a single cell and the second one (figure 13) represents a complete battery system with a configuration of the xSyP type (where x represents the number of series connected cells and y the number of parallel connected cells).

These two models represent a useful tool to evaluate the change on the SOC of the battery under a defined usage profile.

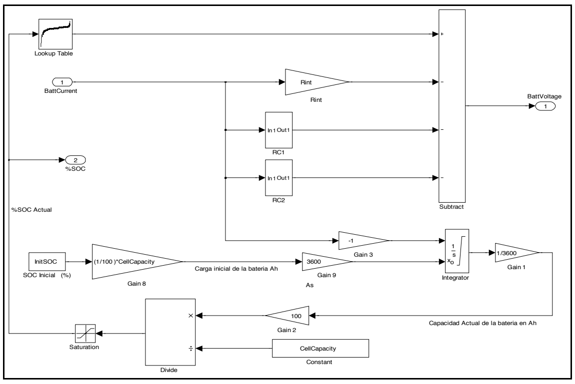

Figure 12. Simulink Single Cell Model

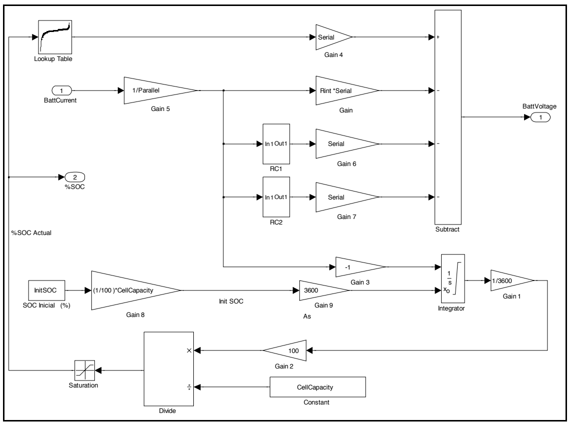

Figure 13. Simulink xSyP Battery Model

6 Conclusions

The EV is bound to play a key role in the electric grid of the future. Its contribution as a huge distributed energy storage resource will provide the flexibility needed to come to a more efficient energy model. This goal will only be possible by the development of smart charging capabilities that cope with the two sides of this question:

- The electric vehicle as an individual item.
- The global electric scenario.

On the one hand, the requirements of the individual users must be fulfilled while optimizing the efficiency and cost of the charging procedures. On the other hand, the total number of EVs should be intelligently managed in order to make efficient use of generation, transmission and distribution infrastructures.

The charging system characterization is crucial so as to achieve that the entity in charge of defining the optimal charging sequence for each EV can realize the scheduling taking into account the different efficiency of each feasible charging sequence. The key issue, in this case, is the battery efficiency estimation. Precise methods must be developed for the evaluation of the SOC, which is needed for the efficiency calculation. TECNALIA has developed a SOC estimation method for ion-lithium batteries, which has been implemented in two Matlab/Simulink™ models.

In addition, and based on these considerations, TECNALIA has defined a characteristic model which has been implemented on the EV-ON platform. This platform is aimed at the development of highly optimized smart charging and V2G procedures. A first set of solutions has already been proposed. This facility will be the core for future works in this area, which should be driven not only by technical innovation but also by alignment with upcoming regulations for the EVs and the grid.

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