

Advanced Parameter Measurement of Energy Storage Systems for Smart Grids application

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Abstract— The smart grid approach is envisioned to take advantage of all available modern technologies in transforming the current power system to provide benefits to all stakeholders first of all in the fields of efficient energy utilization and of wide integration of renewable sources. Energy storage systems, especially those based on batteries, could help to solve some issues that stem from the use of renewable energy, in terms of stabilizing the intermittent energy production, power quality and power peak mitigation. With the integration of energy storage systems into the smart grids, their accurate modeling becomes a necessity, in order to gain a robust real-time control on the network, from a point of view of stability and energy stock forecasting. With an accurate and efficient battery model it can be predict and optimize battery performance especially under practical runtime usage such as Battery Management Systems (BMS). This paper proposes a method of parameters estimation using Matlab/Simulink parameter estimation tool for the premonition battery models. It is shown that this model, composed of a controlled voltage source in series with a resistance, can accurately represent four types of battery chemistries. The model is validated by superimposing the results with the experimental measurement's discharge curves.

I. INTRODUCTION

There are basically three types of battery models reported in the literature, specifically: experimental, electrochemical and electric circuit-based. Experimental and electrochemical models are not well suited to represent cell dynamics for the purpose of state-of-charge (SOC) estimations of battery packs. However, electric circuit-based models can be useful to represent electrical characteristics of batteries. The most simple electric model consists of an ideal voltage source in series with an internal resistance [1]. This model, however, does not take into account the battery SOC. Another model is based on an open circuit voltage in series with resistance and parallel RC circuits with the so-called Warburg impedance [2]. The identification of all the parameters of this model is based on a rather complicated technique called impedance spectroscopy [3]. Shepherd developed an equation to describe the electrochemical behavior of a battery directly in terms of terminal voltage, open circuit voltage, internal resistance, discharge current and state-of-charge [4], and this model is applied for discharge as well as for charge.

Many stakeholders of electric systems are heavily investing possibilities and opportunities to upgrade their antiquated delivery, pricing, and service networks performing investments in new management approaches based on smart grid and smart metring concepts [1-8]. In this framework the devices in the grid use a continuously updated price plan to create demand plans that can be aggregated and used to plan energy production. In order to achieve this result, the traditional way of electricity distribution should be able to change using smart microgrid, a small-scale and local power distribution and storage system. Moreover, to ensure energy efficient operation of a microgrid, the variable output from a local renewable energy source must be optimally balanced with loading and energy storage. This give a greater and greater importance to energy storage system also accounting the fact that of renewable energy sources are becoming wide in many countries as a result of active government policies. So different research groups are exploring the possibility to build up hybrid energy systems that include solar, micro-wind and battery storage energy system balancing energy production and controlled to avoid lack of energy supply and failure of the operation of the main grid [10-17]. All the adopted control strategies, in order to obtain reliable results, should base their analysis on a sound model of the adopted storage system. For this aim this paper presents and discuss a method to determine the model parameters from the experimental discharge curves of the battery. The discharge curves are obtained by simulation and validated with the experimental discharge curves.

II. ELECTROCHEMICAL REMARKS

A rechargeable battery is composed of one or more electrochemical cells that convert stored chemical energy into electrical energy during a discharge process or convert electrical energy into chemical energy during a charge

process [5], [19]. An electrochemical cell is a chemical device for generating or storing electric energy. It consists of a positive electrode and a negative electrode, separated by electrolyte (Fig. 1). The electrolyte is capable of conducting ions between the two electrodes, but is itself an electronic insulator. The positive and negative electrodes are immersed in the electrolyte and the reacting substances usually are stored within the electrodes, sometimes also in the electrolyte. The chemical reactions associated with the energy conversion take place at the two electrodes. During discharge (Fig. 1a), the negative electrode contains the substance that is oxidized (i.e. releases electrons), while the positive electrode contains the oxidizing substance that is reduced (i.e. accepts electrons). Those electrons pass through the external load, thereby doing useful work. When the battery is charged, this reaction is reversed and a corresponding amount of energy from an external source has to be supplied to the cell (Fig. 1b) [5], [19].

A. Current Flow and Polarization

The current in the battery arises from the transfer of electrons from one electrode to the other. When there is no current flow through a cell, the difference between the potentials of the positive and negative electrodes gives an Open-Circuit Voltage (OCV, E_0) of the cell. When current flows, however, mass transport is required to bring the reacting substances to the electrode surface or carry them away. As a result, the voltage under current flow is different from the OCV and the difference comprises: (i) an overvoltage at the electrodes caused by electrochemical reactions and concentration deviations on account of transport phenomena and (ii) ohmic voltage drops caused by the electronic as well as the ionic current flows in the conducting parts including the electrolyte, current-collectors and active masses [5], [19].

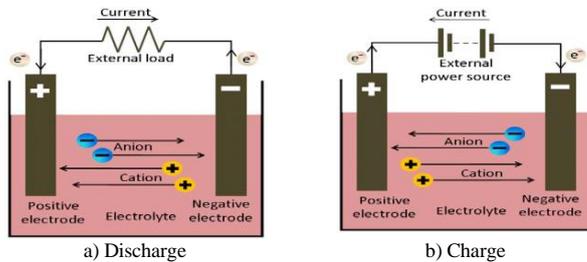


Fig.1 Schematic representation of the operation of electrochemical cell

The sum of both, called polarization, is responsible for a decreased cell voltage (V_{dis}) during discharge and an increased cell voltage (V_{ch}) on charge as shown below with

$$V_{batt} = \begin{cases} V_{dis} & \text{when } i < 0 \\ V_{ch} & \text{when } i > 0 \end{cases} \quad (1)$$

$$V_{dis} = E_0 - V_{op+} - V_{op-} - i \cdot R \quad (2)$$

$$V_{ch} = E_0 + V_{op+} + V_{op-} + i \cdot R \quad (3)$$

where V_{op+} and V_{op-} are the over-voltages at the positive and negative electrodes, respectively, and R stands for the polarization resistance. Due to the polarization effects, the battery voltage under current flow may differ substantially from the OCV depending on the state-of-charge of the battery. These two polarization terms are important components for battery model development.

B. Other Factors Affecting Battery Models

Other important factors affecting battery performance and models include: battery capacity (Q), state-of-charge (SoC), rate of charge and discharge, temperature, and age **Error! Reference source not found..** The battery capacity represents the maximum amount of energy that can be extracted from the battery under certain conditions, and it is determined by the mass of active material contained in the battery. The SoC is defined as the fraction of the full capacity that is available for further discharge. The OCV of a battery is normally a function of the SoC due to the polarization impact, which is a factor that must be considered in battery modeling. The charging/discharging rates affect the rated battery capacity. According to the Peukert's equation, if the battery is being discharged very quickly, then the amount of energy that can be extracted from the battery is reduced [5], [19], **Error! Reference source not found..** The age and history of a battery have impacts on the capacity of a battery. Even when following manufacturers' Depth of Discharge (DOD) specifications, the battery capacity only stays at the rated capacity for a limited number of charge/discharge cycles. If the battery has been taken below its maximum DOD during its usage, battery capacity may be prematurely reduced. The temperature of a battery also affects the energy that can be extracted from the battery. At higher temperatures, the battery capacity is usually higher than that at lower temperatures. But, intentionally elevating battery temperature is not an effective method to increase battery capacity as this also decreases battery lifetime. All these issues lead to the needing to approach the problem of effective modeling storage systems for energy systems with parameter definitions that cannot be static (that is performed once at initial conditions nor basing on manufacturer data sheet) but continuous re-estimation and updating of model parameters. In this framework, this paper proposes a procedure that allows a continuous updating of model parameters that could even performed taking information from charge and discharge that apply during normal battery operations.

III. THE BATTERY MODEL

The Fig. 2 shows a typical discharge characteristic, for a Nickel-Metal-Hydrid cell.

The adopted discharge model is similar to the Shepherd model but some terms are added. In fact, the adopted mathematical model for battery voltage is:

$$V_{batt} = E_0 - K \cdot \frac{Q}{Q-it} \cdot it - R \cdot i + A \cdot \exp(-B \cdot it) - K \frac{Q}{Q-it} \cdot i^* \quad (4)$$

where

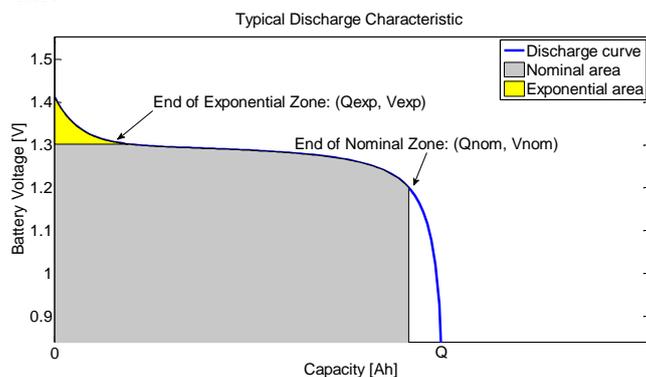


Fig.2 Typical discharge curve

V_{batt} = battery voltage (V)
 E_0 = battery constant voltage (V)
 K = polarisation constant (V/Ah) or polarization resistance (Ω)
 Q = battery capacity (Ah)
 $it = \int i \cdot dt$ = actual battery charge (Ah)
 A = exponential zone amplitude (V)
 B = exponential zone time constant inverse (Ah^{-1})
 R = internal resistance (Ω)
 i = battery current (A)
 i^* = filtered current (A)

where $K \frac{Q}{Q-it} \cdot it$ is the polarization

voltage that includes the terms V_{op+} and V_{op-} of (2) and (3) expressed in such way to better represent the OCV behavior; $A \cdot \exp(-B \cdot it)$ is an exponential term added to represent more accurately the voltage dynamics when the current varies and to take into account the OCV as a function of SoC; $R_{pol} = K \frac{Q}{Q-it}$ represent an additional polarization resistance that with the adoption of a filtered current i^* is able to reproduce an experimentally found voltage slow dynamic behavior for a current step response.

The proposed model is based on specific assumptions and has limitations: 1. The internal resistance is supposed constant during the charge and discharge cycles and doesn't vary with the amplitude of the current. 2. The model's parameters are deduced from the discharge characteristics and assumed to be the same for charging. 3. The capacity of the battery doesn't change with the amplitude of the current (No Peukert effect). 4. The temperature doesn't affect the model's behaviour. 5. The Self-Discharge of the battery is not represented. 6. The battery has no memory effect.

The method to identify the model parameters of the battery proposed in [20] and **Error! Reference source not found.** is based on the evaluation of the "Typical Discharge Characteristics" on the manufacturer datasheet of the battery and it does not require experimental tests on the battery. It has been experimental verified that such an approach, as it is simple and fast, is also of poor accuracy and it can lead to big deviations in battery behavior estimation, especially in dynamic conditions. In fact, the "Typical Discharge Characteristics" on the manufacturer datasheet of the battery are, in most cases, not characteristics of the specific battery but at most average values deducted for entire batteries stock. For this reason they can lead to a forecasting of battery behavior very different from the actual response. Moreover, some typical quantities of the battery, and thus some parameters of its model, vary with battery life, usage and conditions: a discharge curve experimentally taken at the beginning of the battery life could not represent the actual discharge curve of a battery with a certain number of charge-discharge cycles. A continuous estimation and updating of the parameters is necessary to obtain reliable results over time. As it was previously said, in this paper the proposed approach to the identification of battery model parameters is based on the experimental evaluation of the discharge curve of the battery and on an optimization procedure for the parameter assessment. The presented results in the following refer to discharge at the nominal current (typically equal to 20 % of the battery capacity) but the methods can be extended also to different currents with minor changes. An important feature of the proposed model is the simplicity with which the dynamic model parameters are extracted. In fact, it is not necessary to take experimental measures on the battery in order to extract the parameters. Only three points on the experimental's discharge curve, in steady state, are required to obtain the parameters. It is possible to extract the fully charged voltage (V_{full}), the end of the exponential zone (Q_{exp} , V_{exp}), the end of the nominal zone (Q_{nom} , V_{nom}) (when the voltage starts to drops abruptly) and the maximum capacity (Q). Also, the internal resistance (R) is generally given. With these three points, it is possible to solve, using equation 1, the following set of equations. Note that the manufacturer curve is obtained at constant current (generally equal to 0.2C). For the fully charged voltage, the extracted charge is 0 ($it = 0$) and the filtered current (i^*) is 0 because the current step has just started:

$$V_{full} = E_0 - R \cdot i + A \quad (5)$$

For the end of the exponential zone, the factor B can be approximated to $3/Q_{exp}$ since the energy of the exponential term is almost 0 (5 %) after 3 time constants. The filtered current (i^*) is equal to "i" because the current is in steady state:

$$V_{exp} = E_0 - K \cdot \frac{Q}{Q - Q_{exp}} \cdot (Q_{exp} + i) - R \cdot i + A \exp\left(\frac{-3}{Q_{exp}} \cdot Q_{exp}\right) \quad (6)$$

The nominal zone voltage is given by:

$$V_{nom} = E_0 - K \cdot \frac{Q}{Q - Q_{nom}} \cdot (Q_{nom} + i) - R \cdot i + A \exp\left(\frac{-3}{Q_{exp}} \cdot Q_{nom}\right) \quad (7)$$

Finally, the time constant of the filtered current (i^*) is not given by the manufacturer datasheet. Only experimental test can provide this information. However, experimental data have shown a time constant of about 30 secs for the four batteries types.

IV. AUTOMATED MEASUREMENT STATION

In order to characterize the battery and take experimental data for model parameter identification and model validation, an Automated Measurement Station (AMS) has been set up. It is based on a four quadrant power supply, numerically controlled through IEEE 488 bus, and a PXI platform. Its block scheme is shown in Figure 4. It includes a module for data acquisition and one module for waveform generation. The data acquisition module has 8 synchronous analog inputs and ± 10 V input range, 16 bits resolution and 500 kHz maximum sampling rate per channel. The generation module has one analog output at 16 bits, ± 12 V output range, 100 MHz maximum generation frequency and a memory of 256 MB. Through the generation

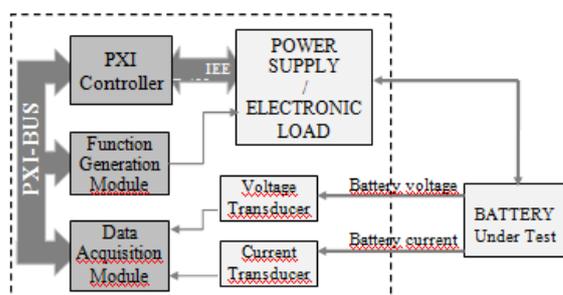


Fig.4 Block scheme of the realized Automated Measurement Station

module, the desired waveforms are generated and then amplified. The utilized power supply is the Kepco BOP 20-20M, with output ranges of $\pm 20 V_{peak}$ for voltage and $\pm 20 A_{peak}$ for current; the frequency bandwidth is in the range of DC-50 kHz. It can operate in the four quadrants of the Voltage/Current plane, therefore it can be used as a supply and as an electronic load, that is, to charge and to discharge the battery. Moreover, thanks to its wide output frequency range, it can be used both in static and dynamic charge/discharge conditions. As voltage transducer a resistive voltage divider has been used, while as current transducer a current shunt (Lem Norma Triax Shunt) with input range of $\pm 30 A_{RMS}$ and resistance of 10 m Ω has been used. Measurement software has been developed in LabView, a graphical programming environment, measuring instruments oriented.

V. EXPERIMENTAL RESULTS

In this section results regarding experimental characterization of a battery, identification of its model parameters and model validation in dynamic conditions are presented. They refer to a lead-acid 12 V, 44 Ah battery, but the procedure remains valid also for the other types of analyzed batteries, i.e. NiMH, Li-Ion, NiCd. Moreover, in order to prove its effectiveness, the obtained results have been compared with those obtained by simplified method for parameter identification proposed in [20] and **Error! Reference source not found.**. The simplified procedure is applied to the experimental discharge curve unlike what was done in [20] and **Error! Reference source not found.** where reference was made to the discharge curve reported in the manufacturer datasheet so better results are expected.

The applied simplified procedure proposed in [20] and **Error! Reference source not found.**, and here modified, consists in the following steps:

1. Assigning a value for internal resistance R , evaluating it from an experimental test;
2. Evaluating values for $Q, V_{full}, V_{exp}, Q_{exp}, V_{nom}, Q_{nom}$ from experimental discharge curve and extracting from them B, A ;
3. Calculating the values of the two remaining parameters, E_0 and K , from other two points of the experimental discharge curve in the nominal zone.

In the following two subsections the results obtained from tests in static and dynamic conditions are presented.

A. Experimental Validation in Static Conditions

The battery under test has been completely discharged at constant current of 8.8 A, that is a current equal to 20 % of battery capacity (44 Ah). According to Peukert effect ([5], [19], **Error! Reference source not found.**), the

extracted charge is lower than the rated capacity: it results equal to 27.4 Ah, which corresponds to a time for complete discharge equal to 11209 seconds.

The simplified procedure and the proposed identification procedure have been applied to the measured discharge curve. The obtained values of the model parameters are reported in Table I.

With the values of model parameters reported in Table I, the deviations between model outputs and experimental data have been evaluated. Figure 5 shows the measured discharge curve and the model output, where parameters are those obtained with the simplified procedure; Figure 6 shows the relative deviation.

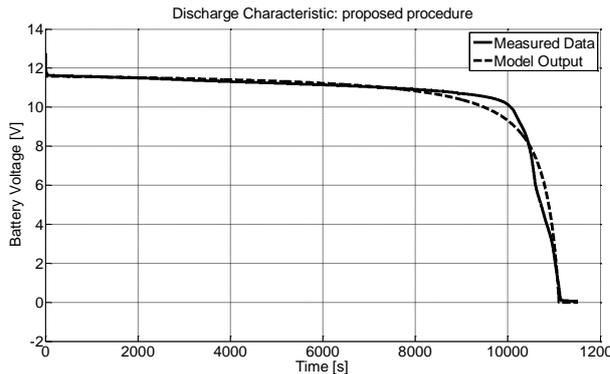


Fig.5 Measured discharge curve and model output with parameters from extracting parameter procedure

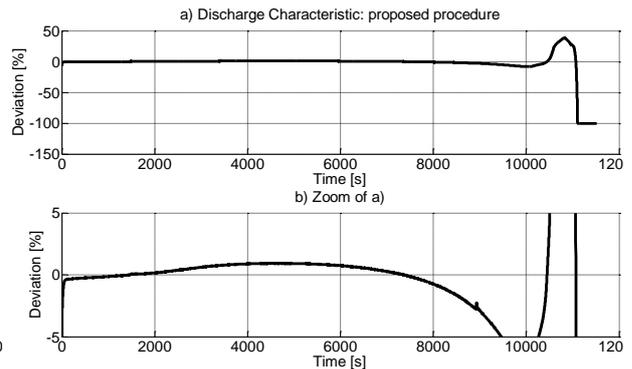


Fig.6 Relative deviation among measured data and model output

Q [Ah]	27.40
E_0 [V]	12.70
R [m Ω]	50.00
K [Ω]-[V/Ah]	0.085
τ [s]	30.00
B [s ⁻¹]	15.73
A [V]	0.52

Table I: Obtained Values of Model Parameters

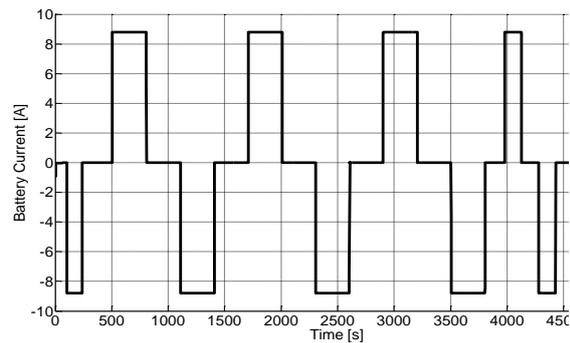


Fig.7 Current pattern used for test in dynamic conditions

B. Experimental Validation in Dynamic Conditions

In order to validate the proposed procedure, the battery has been subject to a test in dynamic conditions. A current pattern such as that in Figure 7 has been used: the period is variable from 20 minutes to 10 minutes, while the value is 8.8 A (i.e. a charge current) for a quarter of period, zero for a quarter of period, -8.8 A (i.e. a discharge current) for a quarter of period and then zero for the last quarter of period. The period has been chosen as variable in order to test battery at variable input situations.

The maximum deviation is lower than 4 % and the root mean squared deviation is about 1.5 %.

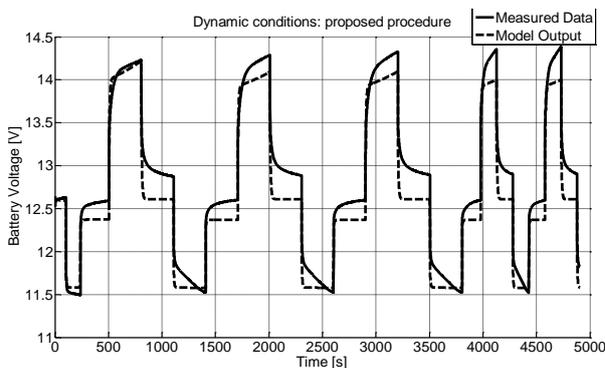


Fig.8 Test in dynamic conditions: measured battery voltage

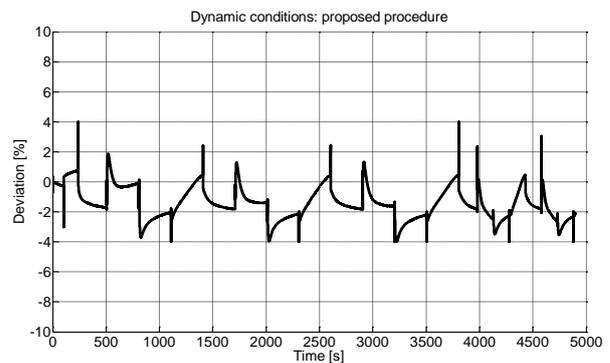


Fig. 9 Test in dynamic conditions: relative deviation among measured

and model output

data and model output

VI CONCLUSIONS

In this paper a technique for optimization of the extraction of model parameters for energy storage systems in Smart Grids, based on experimental data, has been presented. The method could help in performing an accurate modeling of storage system, in order to gain a robust real-time control on the network, from a point of view of stability and energy stock assuring. Apart from many techniques present in literature, the proposed method is based on an experimental data and it could be applied to continuous re-estimation and updating of model parameters. In this framework, this paper proposes a procedure that allows a continuous updating of model parameters, even taking information from charge and discharge that apply during normal battery operations, to obtain reliable results over time. The performance of the battery model has been validated in dynamic conditions and compared with techniques present in literature showing a better accuracy.

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