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PRESENTATION OF MODELS OF VALVE-REGULATED LEAD-ACID BATTERIES AND MODEL SIMULATION COMPARED TO THE ACTUAL BATTERY BAHAVIOUR

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Abstract: In this paper, the electrochemical reactions inside the VRLA (Valve Regulated Lead-Acid) lead battery are described and their influence on the battery's dynamics is shown. There are a large number of battery models that describe the behaviour and dynamics of the battery. The most favourable for energy analysis are electrical models where the response of the battery in the circuit is simulated exclusively using standard electrical components. Four electric models of the VRLA battery are presented, of which the hybrid electric model is the best for application. State-of-charge-SOC is the most important battery parameters for management and monitoring in a microgrid. Simulation of the charging of the hybrid electric model and a comparison with the actual charging characteristics of the VRLA battery are presented. All simulations and tests are performed out in the Matlab environment.

Keywords: VRLA battery, battery SOC, open-circuit voltage, hybrid electric model, microgrid

INTRODUCTION

DC power supply systems are used to power the most demanding consumers that require uninterrupted voltage even in the event of a network or auxiliary generator power failure. Continuity of power supply is achieved by actively relying on a backup energy source. Therefore, the most suitable is an electrochemical battery, which, in the event of a network outage or an unacceptable deviation in voltage, takes over the power supply of connected consumers.

An electrochemical battery is a component that converts chemical energy into electrical energy and vice versa using an electrochemical reaction. Electrochemical reactions within a cell are essential for analysing battery operation, and this paper will present the chemical process during battery charging and discharging. The basic division of battery models is into electrochemical, mathematical and electrical models, and their mutual difference lies in the way their internal processes are represented. Electrical models are more favorable for energy analysis and some of them, as well as their characteristics, will be presented in the following chapters.

Battery parameter estimation methods are very important because some parameters cannot be measured at the external battery terminals. Since battery dynamics are modelled as a nonlinear system, various techniques are applied, from simple to complex (e.g. recursive techniques using Kalman filters), to develop estimators that will track battery parameters.

1. PROCESSES INSIDE THE BATTERY CELL

An electrochemical battery is a component that converts chemical energy into electrical energy through an electrochemical reaction and vice versa.

Depending on the charging capacity, we distinguish between primary and secondary electrochemical batteries. Primary batteries are non-rechargeable and usually have the ability to achieve higher stored energy and power density, while secondary batteries have the ability to be recharged. Secondary batteries are the most suitable choice for stationary uninterruptible power supply systems, they are used to store electrical energy in a DC microgrid. The most commonly used type of secondary battery in telecommunications is lead-acid batteries, namely sealed, valve-regulated, lead-acid batteries (VRLA).

A VRLA battery (hereinafter referred to as the battery) is completely sealed, with the exception of a valve that serves to release gases in emergency charging conditions. The term battery is used to refer to a combination of several basic electrochemical devices called cells, connected in series or parallel, depending on the required capacity or voltage. A battery can also

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consist of a single cell, which is common in low-power consumers, such as electronic devices [1].
The electrochemical cell shown in Figure 1 consists of three main parts [3]:

1. Anode – the negative electrode, donates electrons to the external circuit and oxidizes during the electrochemical reaction during discharge.
2. Cathode – the positive electrode, accepts electrons from the external circuit and reduces during the electrochemical reaction during discharge.
3. Electrolyte – usually a liquid, such as water or other solutions with dissolved salts, acids, or bases. It is an ionic conductor, and allows charge to be transferred between the anode and cathode within the cell. The electrolyte must not be electrically conductive, which would cause an internal short circuit in the cell [2].

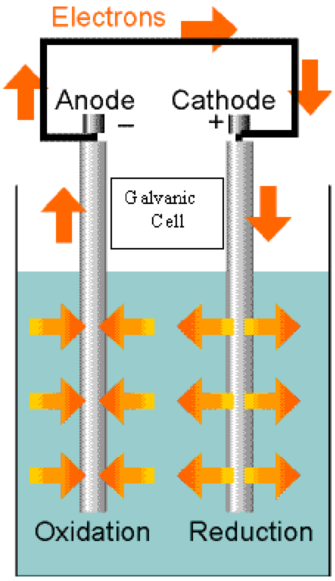

Figure 1: Electrochemical battery cell

A commercial battery with a nominal voltage of 12 V consists of six electrochemical cells, an example of one is shown in Figure 1. For a complete analysis of the battery operation, it is necessary to know the internal electrochemical reactions of the cell. During battery discharge, lead ions (Pb+) reach the negative electrode, react with sulfuric acid (H2SO4) to form a layer of lead sulfate (PbSO4) on the same electrode. A similar process of lead sulfate formation occurs on the positive electrode, where additional water molecules are formed. During battery charging, the described process occurs in the reverse way, i.e., lead sulfate decomposes into lead (Pb) on the negative electrode and lead dioxide (PbO2) on the positive electrode. The complete electrochemical reactions of charge/discharge, which are shown in detail in Figure 2, can be expressed as [2], [4]:

- Positive electrode:

$$PbO_2 + H_2SO_4 + 2H^+ + 2e^- <=> PbSO_4 + 2H_2O \quad (1)$$

- Negative electrode:

$$Pb + H_2SO_4^- <=> PbSO_4 + 2H^+ + 2e^- \quad (2)$$

- Overall reaction:

$$Pb + PbO_2 + 2H_2SO_4^- <=> 2PbSO_4 + 2H_2O \quad (3)$$

This type of battery does not lose electrolyte water, which is why they are called "maintenance-free". Charging outside the specified voltage range can still cause a small amount of hydrogen to be released through the exhaust valve. The effect is much more pronounced at high battery charging, as the combined effect of the battery's open-circuit voltage (V_OC or OCV) and polarization can cause a significant increase in the total voltage. After a certain voltage threshold, the rate of hydrogen and oxygen production increases, which can pose a safety threat. If such charging conditions are maintained for a long time, premature loss of battery capacity will occur [2].

Sensitivity to elevated ambient temperatures results in permanent loss of capacity depending on the temperature and its duration. The harmful effects of elevated ambient temperatures can be mitigated in sealed lead-acid batteries by temperature regulation of the rectifier voltage. Since it is not realistic to ensure that unwanted operating modes in which the battery releases hydrogen do not occur, it is necessary to provide the minimum necessary ventilation (natural ventilation is usually sufficient). For the same reason, it is necessary to keep the battery away from devices that overheat or spark [5], [6].

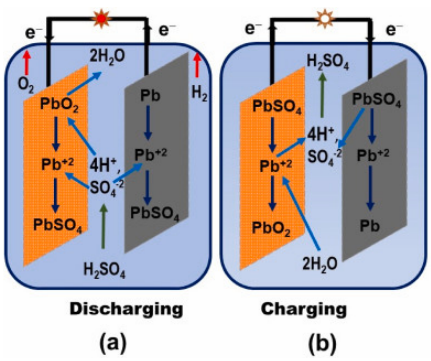

Figure 2: Electrochemical reactions inside a battery cell [7]

The voltage of a battery cell is a reflection of its internal electrochemical reactions, and consists of the open circuit voltage V_{OC}, which is a function of the cell's state of charge, and the voltage drop associated with the current operating environment. When the battery is not in operation, i.e., when it is idle, V_{OC} is linearly related to SOC in the range of 5% to 100% SOC, while nonlinearity exists only in the range of 0% to 5% SOC [6].

By connecting the cell to an external circuit, electrical energy causes chain reactions within it, which correspond to the magnitude of the current. The mass movements of the ions change the internal structure of the electrodes and convert chemical energy into electrical energy and vice versa. A part of the converted chemical energy is lost as heat by the flow of current through the resistances, which creates an instantaneous internal voltage drop in the cell. The voltage drop can be divided into two parts: the dynamic voltage drop caused by electrochemical reactions and concentration variations, and the instantaneous voltage drop caused by the resistances of the conductive parts and electrolyte [8].

The total voltage drop present at the terminals of a battery cell consists of three basic components: V_OC which is a function of SOC, instantaneous voltage drop caused by internal resistances, and dynamic voltage drop resulting from cell diffusion. The basic principle in battery modeling is derived from the aforementioned definition of total voltage drop [8].

2. BATTERY MODELS

Battery models are divided into: electrochemical, mathematical and electrical models. Electrochemical models were developed for detailed simulations of the internal reactions of a battery cell, the calculation procedure for specific parameters is complex due to the use of complex numerical algorithms, which requires a long simulation time. Mathematical models are created in an abstract way, where the parameters of the battery cells are displayed through charging and discharging curves, which are used for calculations in mathematical functions. The parameters that can be obtained from this model are the battery life and capacity, however, for determining important properties of the battery cell such as the state of health, they are not precise and give larger errors. The error in the results of mathematical models is 5%- 20% [7], [10]. The most suitable for energy analysis are electrical models, which are based on the fact that the battery response in the circuit is simulated exclusively using standard electrical components, such as voltage and current sources, resistors, capacitive and inductive elements [2], [8], [11]. The accuracy of electrical models is between electrochemical and mathematical models (1% - 5% error). There are a large number of electric battery models, and each of them has good and bad properties. There are three main groups of electrical models: Thevenin models, impedance models and models based on cumulative battery SOC monitoring (Runtime-Based-R-B).

2.1. Thevenin electrical model

Thevenin electrical model in its basic form, shown in Figure 3, includes a series resistance (R_serial) and a parallel RC circuit (R_transient and C_transient) to predict the battery response to a transient load for a given SOC, assuming that V_OC (SOC) is constant. It does not perform a cumulative calculation of battery charge.

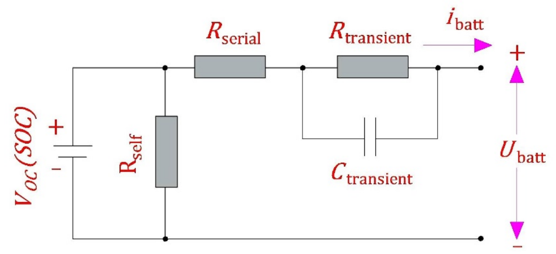

Figure 3: Thevenin electrical model

Thevenin electrical model, using a variable capacitance instead of V_{OC} (SOC), creates a nonlinear relationship between V_{OC} and battery SOC, which requires more complexity in calculating V_{OC}, but allows for obtaining battery life with an error of 5% (0,4 V voltage error) at constant charge and discharge current. R_self presents self-discharging of the battery and has a large value. This electrical model can also be used with a larger number of parallel RC circuits, which creates great complexity in calculating V_{OC} at a given SOC and ambient temperature. From the above, we can conclude that no Thevenin model can predict battery life accurately and simply [10], [12].

2.2. Impedance electrical model

Impedance electrical models (Figure 4) use electrochemical impedance spectroscopy to obtain an equivalent impedance model in the frequency domain, and it is necessary to adjust the results with complex procedures. Impedance models only work at a certain SOC and temperature and cannot predict the DC response and battery life [13].

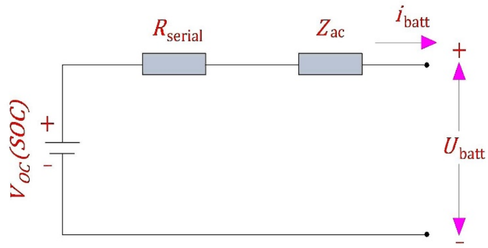

Figure 4: Impedance electrical model

Electrochemical impedance spectroscopy is a method for estimating SOC. The internal impedance of a battery is calculated by applying a small current signal with different frequencies to the battery and measuring the corresponding voltage using EIS equipment. This method is time-consuming to perform and is suitable for analysis when the battery is not in operation. Internal resistance testing is a method that applies short-term loads to the battery and determines the internal resistance of the battery based on measuring the changes in voltage and current. Since the internal resistance increases with time, due to chemical decomposition of the active material, and also due to the decrease in SOC, this approach is unreliable due to the dependence of battery parameters on SOC and temperature [14]. Z_ac is internal impedance of a battery obtained using electrochemical impedance spectroscopy method.

2.3. R-B electrical model

R-B electrical models (Figure 5) use complex circuit, are based on accumulated SOC monitoring, and are only accurate for constant charge and discharge currents. They cannot accurately predict battery life and DC voltage response for varying load currents [9].

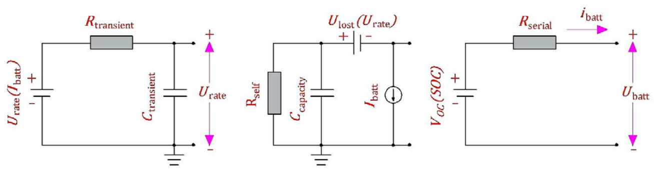

Figure 5: R-B electrical model

2.4. Hybrid electrical model

The hybrid electric model (Figure 6) is a electric model that includes the best characteristics of each above mentioned model. The capacity C_capacity and the current source are taken from the R-B electrical model, and define the capacity, SOC and discharging time of the battery. The properties of the Thevenin electric model in the hybrid model are determined by the transient response, and the properties of the impedance model by the AC response [8].

The useful capacity of a battery is the total energy obtained from the battery when it is discharged from a charged state to the discharge voltage limit. The capacity decreases with increasing the number of battery discharge cycles, increasing the load current, longer storage periods resulting in battery self-discharge, and decreasing ambient temperature. The useful capacity of a battery can be modeled with a full-capacity capacitor $C_{capacity}$, a self-discharge resistor R_{self}, and an equivalent series resistor (the sum of R_{serial}, R_{fast} and R_{slow}). The full-capacity capacitor $C_{capacity}$ represents the total energy stored in the battery and can be calculated as follows:

$$C_{capacity} = 3600 \cdot K_{nom} \cdot k_1 \cdot k_2$$

where are: K_{nom} (Ah) nominal capacity of the battery, k_1 coefficient showing the dependence of battery capacity on the number of charge/discharge cycles and k_2 coefficient showing the dependence of battery capacity on ambient temperature.

The voltage V_{SOC} across $C_{capacity}$ according to expression (4) can take a value between 0 V and 1 V, which corresponds to an SOC of 0% to 100%. The self-discharge resistor R_{self} describes the energy lost due to self-discharge when the battery is stored for a long time and is dependent on the SOC, temperature and number of charge and discharge cycles.

When we load a battery, which is in a stationary state, with a step current and record the voltage at its terminals, we will obtain a voltage-time dependence, where the time response can be divided into two parts: the instantaneous voltage drop, which depends on and is modeled by the series resistor R_{serial}, and the voltage drop that is modeled by a serial connection of multiple parallel RC circuits (researchers have shown that two parallel RC circuits form an optimum between accuracy and model complexity) [15].

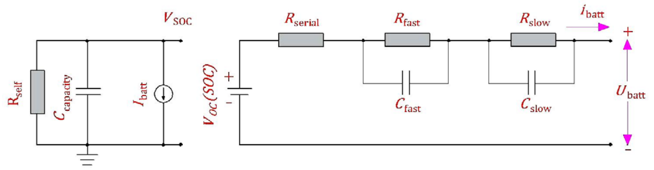

Figure 6: Hybrid electrical model

The hybrid electric model is a third-order model, the states chosen are: voltage V_SOC on C_capacity, voltage on the fast RC circuit V_fast and voltage on the slow RC circuit V_slow. Also, the input of the system is the battery current I_batt, and the output of the system is the battery voltage U_batt. The hybrid electrical model in the time-continuous domain can be represented by the following matrix expression:

$$\begin{bmatrix} \dot{V}_{SOC} \\ \dot{V}_{fast} \\ \dot{V}_{slow} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \dfrac{-1}{R_{fast} \cdot C_{fast}} & 0 \\ 0 & 0 & \dfrac{-1}{R_{slow} \cdot C_{slow}} \end{bmatrix} \cdot \begin{bmatrix} V_{SOC} \\ V_{fast} \\ V_{slow} \end{bmatrix} + \begin{bmatrix} \dfrac{-1}{C_{capacity}} \\ \dfrac{1}{C_{fast}} \\ \dfrac{1}{C_{slow}} \end{bmatrix} \cdot I_{batt}$$

The discrete-time hybrid electrical mode with sampling time T can be represented as follows:

$$\begin{bmatrix} V_{SOC}(k+1) \\ V_{fast}(k+1) \\ V_{slow}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1-\dfrac{T}{R_{fast} \cdot C_{fast}} & 0 \\ 0 & 0 & 1-\dfrac{T}{R_{slow} \cdot C_{slow}} \end{bmatrix} \cdot \begin{bmatrix} V_{SOC}(k) \\ V_{fast}(k) \\ V_{slow}(k) \end{bmatrix} + \begin{bmatrix} \dfrac{-T}{C_{capacity}} \\ \dfrac{T}{C_{fast}} \\ \dfrac{T}{C_{slow}} \end{bmatrix} \cdot I_{batt}(k)$$

The output from the system, i.e. the voltage on the battery in the discrete-time domain, is defined by the expression:

$$U_{batt}(k) = (k) - V_{fast}(k) - V_{slow}(k) - R_{serial} \cdot I_{bat}(k)$$

The dependence of the battery V_OC on the state of charge of the battery in a non-linear relationship, however, due to the ease of use of the hybrid electric model, this dependence will be linearized and can be represented by the expression as follows:

$$V_{OC} = \alpha \cdot V_{SOC} + b$$

where a and b are the battery open-circuit voltage parameters. Using the above linearized model (8) can affect the deviation of the model from the actual battery voltage values during charging and discharging. The deviation of the model occurs at the end of charging and discharging and the above error is taken into account in the model.

3. COMPARISON OF SIMULATION RESULTS OF THE HYBRID ELECTRICAL MODEL AND EXPERIMENTAL TESTS

Figure 7 shows VRLA battery with a nominal voltage of 12 V and nominal capacity 155 Ah which was used for experimental tests. This type of battery was chosen because it is most commonly used as a backup power supply at telecommunication base stations of the company JP Hrvatske Telekomunikacije d.d. Mostar.

Figure 7: VRLA battery 12 V, 155 Ah

3.1. Experimental results

Experimental setup consist of VRLA battery pack with a nominal voltage of 48 V (four VRLA batteries with a nominal voltage of 12 V connected in series), battery monitoring, DC 48 V charger, DC 48 V discharger and computer for data acquisition. The tests were performed by discharging with a current of 15 A and charging with a current of 14 A for one hour, after which the battery pack was left in a resting state for 20 minutes. These periods of discharging/charging and dormant were repeated until the battery pack was completely discharged, or charged. For the termination of charging and discharging, the manufacturer's data for the lower discharge voltage limit (43,20 V) and the upper charge voltage limit (54,50 V) of this type of battery were used. Discharging and charging of the battery stack are shown on figures 8 and 9. The battery monitoring measured the voltage of battery stack U_batt, the battery current I_batt, the temperature of battery terminal T_batt and the voltage of each 12 V battery. After the tests, using the discharge and charge curves of the battery pack, the battery parameters (R_serial, R_fast, R_slow, C_fast and C_slow) of the hybrid electric battery model are calculated for both types of tests (discharge and charge).

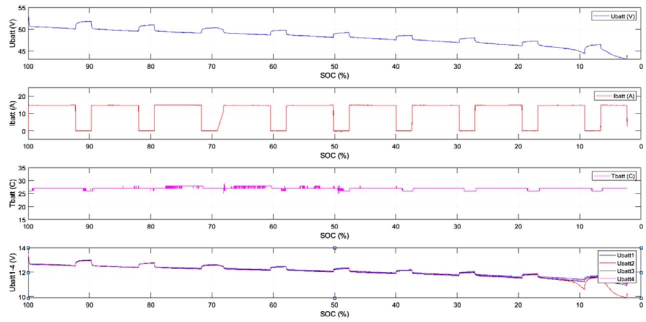

Figure 8: Discharging of VRLA battery stack

3.2. Model simulation

After the conducted previous tests, using the discharge and charge curves of the battery stack, the battery parameters (R_serial, R_fast, R_slow, C_fast and C_slow) of the hybrid electric battery model will be calculated for both types of tests (discharge and charge). The identification obtained values of the battery parameters, i.e. their mean values are as follows: R_serial=139,50 mΩ, R_fast=80,60 mΩ, R_slow=46,50 mΩ, C_fast=3400 F and C_slow=89145 F. Also, the parameters obtained from the manufacturer's data sheets for this type of battery are: C_capacity=129600 F,R_self=42600 Ω,a=7,70 V and b=44,20 V.

The previous battery parameters will be used in the hybrid battery model implemented in the Matlab/Simulink environment (Figure 10).

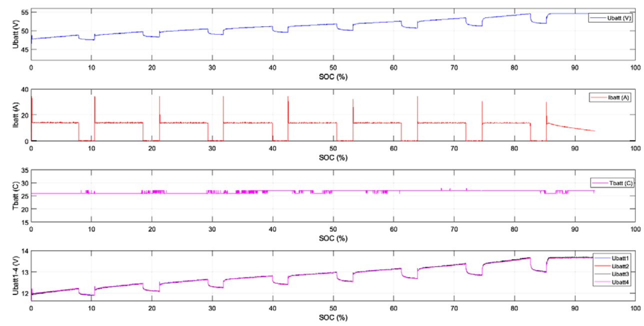

Figure 9: Charging of VRLA battery stack

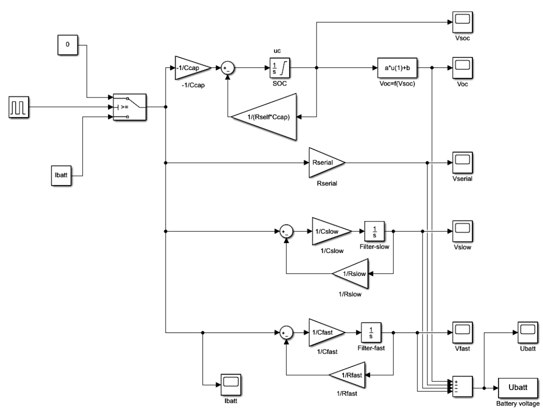

Figure 10: Hybrid electrical model in Matlab/Simulink

In order to verify the validity of the battery model, discharge and charge simulations will be compared with the actual values measured during the tests. If the battery model agrees with the actual state of measurement with maximal 5% error, the hybrid electrical model can be used to present the behaviour of VRLA batteries, control the charging and discharging process, identify and estimate battery parameters.

Simulations of the hybrid electric model were performed in Matlab/Simulink and a comparison of the battery stack voltage obtained from the simulation and measurements during the discharging and charging are shown in figure 11 and 12.

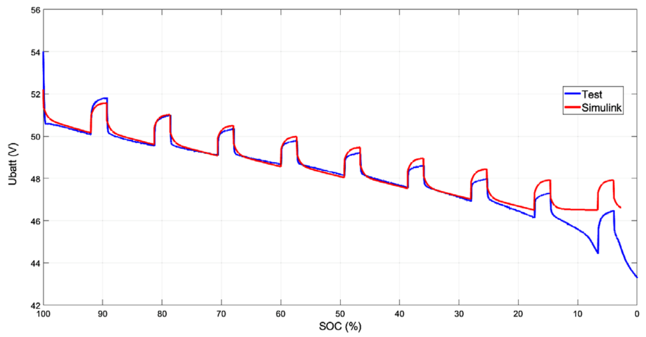

Figure 11: U_{batt} - Comparison of model and discharging of VRLA battery stack

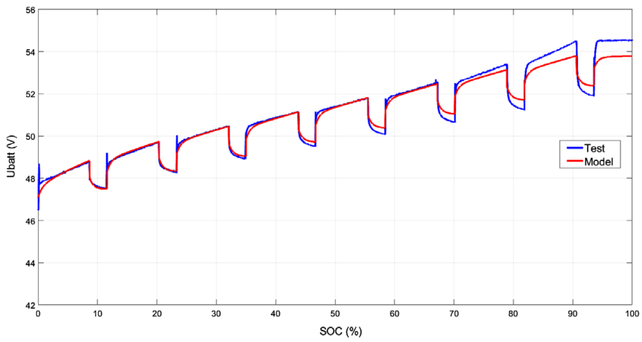

Figure 12: U_{batt} - Comparison of model and charging of VRLA battery stack

Comparison of model simulations and actual battery stack measurement characteristics showed that there is a deviation of the model at the end of charging and discharging and the deviations are less than 5%. Also, it can be concluded that the deviation occurs due to the linearized relationship of the open circuit voltage to the state of charge, whose relationship at the end of charging and discharging is significantly nonlinear. Due to the simplicity of calculations with a linear characteristic, this model error is not large and is taken into account in the hybrid electric model.

4. CONCLUSION

The valve-regulated lead-acid batteries are still the best solution for telecommunication base stations in terms of price and lifetime. This paper presents and describes the electrochemical reactions and dynamics inside the valve-regulated lead-acid batteries. There are a large number of battery models that describe the behaviour and dynamics of this type of the batteries. Also, it was shown that of all the electrical models, the hybrid electrical model best describes the behaviour of valve-regulated lead-acid batteries during discharge and charge tests.

The hybrid electrical model was implemented in the Matlab/Simuling environment. The actual parameters obtained by identifying the battery stack on which the discharging and charging tests were performed. A comparison of the simulations and the actual test characteristics of the battery pack showed that there is a deviation of the model at the end of charging and discharging and the deviations are less than 5%. From the above, it can be concluded that the hybrid electrical model can be used to represent the behaviour of valve-regulated lead-acid batteries.

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