Battery Types and Electrical Models: A Review

G. Marin-Garcia, G. Vazquez-Guzman, J.M. Sosa and Adolfo R. Lopez
Tecnologico Nacional de Mexico / ITS de Irapuato
36821 Irapuato, Mexico
gerardo.mg.300196@gmail.com, gerardo.vazquez@ieee.org, jmsosa@ieee.org, adolfo.lopez@itesi.edu.mx

P.R. Martinez-Rodriguez and D. Langarica
School of Sciences
UASLP
San Luis Potosi, Mexico
pamartinez@ieee.org, diego.langarica@uaslp.mx

***Abstract*—Batteries performance is an important issue for those systems with an implicated energy storage system where it is important to known three fundamental internal parameters, state of charge (SoC), state of health (SoH) and state of operation (SoF). In order to know these internal states some techniques as adaptive observers are use together with a battery model. In this paper, the main characteristics of the most common and commercial batteries, as well as the most cited batteries models in the literature are studied. Then a comparative analysis making emphasis in its qualities and applications is performed. The main idea of the paper is to provide a wide and fast view of the main characteristics together with the advantages and drawbacks of the batteries and battery models. In future works, this information can be a good reference to design algorithms for parameter identification or internal states estimation.**

I. Introduction

Nowadays, the fossil fuels (oil, gas and coal) are the most used source of energy to generate energy and fit the electricity needs of society, around 65% [1]. The main problem is the generated pollution, that is continuously growing and every day pushing to increase the climate change. However, in the near future the cost to extract these kind of fuels will increase and the natural reserve will not longer be available.

A nearby alternative to ensure a good future is to use renewable energy systems to generate electricity. For example, photovoltaic systems, wind power systems, smart-grids, electric mobility, etc. Moreover, some of these systems use energy storage, so that the big problem is the power capacity, efficiency and charging methods of the batteries [2]. These characteristics of the system are different for each of them, therefore, the proposed study includes a description and comparison regarding the main characteristics of the most common batteries.

Another important issue of the battery based energy storage systems is to measure and predict their behavior by means of simulations of the processes of charge and discharge of the battery. In particular, to estimate its state of charge (SOC), state of health (SOH) and state of function (SOF) [3]-[6]. These states are theoretical measurements and can be performed, for example, using an electrical model together with an Extended Kalman Filter (EKF). Therefore, the accuracy of the algorithm, in this case using EKF, relies on the accuracy of the battery model [7]-[8]. Thats why, it is important to study and review the most commonly used battery models in order to known the most suitable model for a particular application. Then, this paper provides a comprehensive review and analysis of the main types of batteries and electrical models used to estimate the different states of a battery system.

II. Batteries

Batteries are devices capable of storing energy, by means of transformations from chemical to electrical energy, transporting electrons from the cathode to the anode during the discharging process, and vice versa during the charging process. In the literature, there are two main types of batteries named, primary and secondary. In the case of the primary batteries, the chemical degradation during the discharging process is not reversible it means that they can not be recharged. Nevertheless, in the case of the secondary batteries, the chemical degradation during the discharging process is reversible, then, by applying a reverse current to the battery, the materials used to build the battery are capable to retrieve their charging properties [9].

A. Battery structure

A general battery structure is mainly made with an electrochemical cell which is built with materials used for the anode and cathode, where the anode produce oxidation and the cathode produce reduction [9], [10]. The electrodes can be implemented using conductive materials, then, both the anode and cathode terminals of the cells inside the battery are interconnected. Moreover, the electrolyte is a chemical solution where the electrochemical cells are immersed, this substance allows the exchange of electrons between the cells during the chemical reaction. Finally, the separators are sheets of porous and insulating materials that are used to separate the electrodes, anode and cathode, from the cell and between cells, in order to avoid short circuits.

B. Main characteristics of the battery

The main characteristics of a general battery can be described as follow [11]. The quantity of energy is the energy storage capacity produced by the electrochemical reaction which is measured in Wh and is the product of the output voltage and the maximum deliverable current [12]. Additionally, the maximum deliverable current is the amount of Ah that a battery can supply to the load. Another important characteristic is the internal resistance which is a few ohms resistance and

978-1-7281-9953-5/20/$31.00

it is designed in a very careful way by the manufacturer. This is generated by the composition and physical conditions of the separators and the electrolyte. The discharge depth is the percentage of the total battery capacity used in a discharge process. It is superficial if the discharge is less than 20% or deep if the discharge is up to 80% of the nominal capacity, it means that, shorter charge/discharge cycles produce a longer service life. The lifespan is the number of charge-discharge cycles without noticeably negative effects on the operation of the battery [13]. The self-discharge parameter is the slowly lost of the energy stored in the battery. Finally the memory effect is the parameter that measures the maximum battery capacity which can be decreases because of three main reasons: an incomplete charge, stay discharged for a long time or stay unused for a long time.

III. Battery types

Battery types refers to the materials or elements that carry out the electrochemical activity to store energy [12], [13]. In what follows, a brief description of different types of batteries is provided [14].

A. Lead-Acid (Pb-Ac)

This battery is composed of lead dioxide at the anode and a matrix or sponge lead at the cathode. The electrolyte can be liquid (sulfuric acid and distilled water) or a paste or gel with a pressure-regulating valve.

- Advantages: Low cost, tolerate intensive use, is a highly studied technology, high voltage per cell, allows deep discharge, low self-discharge rate ($> 0.1\%$) [15], high efficiency ($75\% - 80\%$) [15] and is recyclable.
- Disadvantages: Heavy weight due to the lead, low power density (30 to 50 Wh/Kg) [15], short lifespan (an average of 500 to 1000 cycles) [15], does not allow fast charging and may require maintenance.
- Important considerations: If the battery fails, must be replaced. The corrosion at the anode (due to charging and increased voltage), sulfuring (due to battery discharge, especially if done entirely) and deep discharges shorten their lifespan (when the maximum battery capacity is less than 80%, its degradation is very fast).
- Applications: Uninterruptible Power Supply Systems (UPS), power management, grid stabilization and starting systems.

B. Nickel-Cadmium (Ni-Cd)

Nickel-Cadmium are batteries composed of a cadmium anode and a nickel hydroxide cathode. The electrolyte is composed of potassium hydroxide. The charging technique for this battery is by constant current [14], since there is no direct relationship between the voltage and the charge level.

- Advantages: It is a well-studied technology, good behavior at different temperatures (-40^oC -60^oC) [16], allow overloads which are dissipated as heat, long life cycle (greater than 3500 cycles, reaching $50,000$ cycles only if is recharged at 10% of the total charge and is used continuously) [15], allows to deliver energy peaks, allows deep discharges, small internal resistance, higher power density ($50 - 75$ Wh/Kg) [15] and it is ideal for series connections.
- Disadvantages: Is is an expensive technology, cadmium is very polluting, deprecated by the use of other types of batteries, considerable self-discharge (10% monthly) [16], low voltage per cell, large memory effect and can be damaged by high temperatures.
- Important considerations: The user must be careful with the handling of battery waste, a control system must be designed for the discharge and recharge processes to guarantee a long life and prohibition or limitation of its use in a legal way [15].
- Applications: Backup and energy storage, portable devices and energy management.

C. Nickel-Metal Hydride (Ni-MH)

This is a battery composed of a nickel hydroxide anode and a metal hydride cathode. It is a modification or improvement of the nickel-cadmium battery. Its main characteristics are as follow:

- Advantages: They have all the advantages of nickel-cadmium, in addition to a higher energy density than those of nickel-cadmium ($60 - 120$ Wh/Kg) [15], the memory effect is eliminated and it is free of cadmium, then is less polluting and penalized.
- Disadvantages: High self-discharge rate ($15\% - 20\%$ per month) [16], does not withstand heavy discharges, low voltage per cell, life time around $300 - 500$ charge cycles [16], longer charge time than nickel-cadmium and less tolerance to forced its operation (overloads or complete discharges).
- Important considerations: The high self-discharge rate can be reduced or “blocked” with a small charge current (floating charge) [17].
- Applications: Backup, energy storage and energy management.

D. Sodium sulfide (Na-S)

This type of battery with a new technology, it has a sulfur anode and a sodium cathode. The electrolyte is a ceramic compound of aluminum oxide used as a separator and as a electrolyte. Its main features are:

- Advantages: Extremely fast response, allows large energy peaks (reaching 600%) [15], long lifespan thanks to liquid electrodes which are not affected by changes in temperature and does not produce noise or vibrations.
- Disadvantages: the cell voltages must be well controlled to avoid undesired effects, very high operating temperature due to the chemical reactions (270^oC -350^oC) [15], internal self-overloads can be generated in the cells by the operation and this can increase the internal resistance, it must not be completely discharged and requires control and protection systems.

- Important considerations: It is a very expensive technology because it is patented by NGK. Some important considerations regarding temperature and use should take in to account for its application.
- Applications: Renewable energy sources and energy management.

E. Lithium ion (Li-ion)

Lithium ion batteries are based on compounds with lithium in both electrodes, generally with graphite in the cathode and with lithium in the anode. The most commercial variety are lithium-cobalt oxide, lithium-cobalt phosphate or lithium-manganese oxide [17]. The charge-discharge process is based on the insertion-disinsertion of lithium ions, thus generating the conversion of chemical to electrical energy.

- Advantages: High energy density (75-125 Wh/Kg) [15], has not memory effect, low self-discharge effect ($> 10\%$) [17] and high voltage per cell (3.3V$-$4.0V) [17] and long lifespan with good charge-discharge techniques.
- Disadvantages: Requires a charging circuit, low current peak capacity, duration of between 2 to 5 years [15] whether or not they are used, rapid degradation of the electrodes if it is completely discharged, susceptible to high temperatures, expensive in comparison with other technologies such as Pb-Ac and they can be damaged by over voltage events.
- Important considerations: Charging is recommended when the charge down to less than 50%, but should not be allowed to fully discharge, a noticeable battery degradation happens in one year with or without use (it is minimal), requires a special charging-discharging techniques per cell in applications where multiple cells are used to ensure the maximum lifespan.
- Applications: The main applications can be, portable devices, automotive industry, renewable energy and energy management.

F. Lithium polymer (Li-Po)

The Li-Po battery is an improvement or modification to the lithium ion battery, but its main characteristic is that the electrolyte is a solid polymer, allowing the creation of tiny batteries, because the solid electrolyte use less space than the liquid electrolyte. Its main characteristics are:

- Advantages: High power density (higher than that of lithium ion, $130-200$ Wh/Kg) [16] thanks to the electrolyte, reduced volume, less weight, no memory effect and low self-discharge rate.
- Disadvantages: This type of battery is expensive due to the electrolyte that reduced conductivity, it has a higher internal resistance (solved with gel electrolytes, but with a lower power density), requires charge control and is still under development.
- Important considerations: The user must be careful with the charging process since it can swell as a sign of damage, in this case the battery must be replaced. Bad operation can cause an explosion, and if it is not used for a long time (more than 3 months), keep them in dry and cool places at medium load but never fully unloaded.
- Applications: Tiny portable devices.

TABLE I
COMPARATIVE TABLE OF THE DIFFERENT TECHNOLOGIES

Parameter / Technology	Pb-Ac	Ni-Cd	Ni-MH	Li-ion	Li-Po
Cell voltage (V * cell)	2 V	1.2 V	1.2 V	3.3 V	3.7 V
Self-discharge (% / month)	$>$ 20%	10%	30%	8%	5%
Lifecycles	500-800	1500-2000	300-500	2000 V	$>$ 1000
Life time (years)	$5-15$	$10-20$	$10-15$	$2-5$	$2-7$
Specific energy (Wh / Kg)	30-40	40-60	30-80	100-250	130-200
Efficiency	50%-92%	70%-90%	66%	80%-95%	90%-95%
Overload tolerance	-	V. Good	Good	V. Bad	V. Bad
Impact robustness	Good	V. Good	Good	V. Bad	V. Bad
High temperature work	Mean	V. Good	Mean	V. Bad	V. Bad

Na-S batteries do not have extended information due to the poor marketing.

IV. Battery modeling

Battery modeling is an empirical or analytical representation that allows to measure or predict theoretical internal parameters such as the State of Charge (SOC), State of Health (SOH), State of Function (SOF), open circuit voltage (OCV), effect of the temperature, effect of the aging, etc.; or physical parameters such as voltage, current, and temperature [3]-[6]. These are useful for the design, control and optimization of Battery Management Systems (BMS) used in portable electronic devices, power backup systems, electric/hybrid cars and renewable energy systems with energy storage.

Battery models can be classified according to the parameters or aim as follow:

A. Electrochemical model

Electrochemical models are based on the dynamics of chemical reactions that occur inside the battery cells. They are the most accurate models because the simulation is at the particle level, but the slowest since they use nonlinear differential equations.

B. Mathematical model

This type of model can be analytical or stochastic; an analytical model uses few equations to describe the behavior of the battery, presenting its behavior as a simpler system (i.e. two-tank model [5]), and the stochastic model is based on discrete time, where great precision is preserved, but it is slower and more difficult than the analytical model (i.e. Markov chain [5]).

C. Ageing model

It is based on three main parameters: the internal resistance of the battery, the loss of energy and the self-discharge. Where the main objective is to model the phenomenon of aging of the battery in the present and future.

D. Thermal model

It is based on the history of storage and operating temperature, factors that impair the performance, life time and safety of the battery. It allows knowing and predicting the behavior and operation of the battery in certain temperature conditions [18], [19].

E. Electric model

These models are based on describing the behavior of the battery based on passive electrical components and power supplies, where some of these models use non-linear elements. These types of models are the balance between precision and calculation speed, being one of the most used in terms of time-benefit compared to the previous ones [20]-[22].

Due to the aforementioned, the electric or equivalent circuit models will be studied in depth in this paper, since it is the most widely used due to its quick and simple simulation and acceptable high precision in real time, as well as being the ideal for making connections to networks or electrical and electronic circuits.

V. Electric battery models

In what follows, some of the most commonly used models for batteries are presented where the importance or function of each element is shown, with this knowledge it is possible to propose improvements by adding elements to expand the response and precision in the prediction, based on the desire effect to be simulated.

A. Internal resistance model

This is the simplest model, it describes the relationship between the voltage drop with the corresponding operating current. It consists of a voltage source representing the open circuit voltage (OCV), in series with a resistor that simulates the internal resistance of the battery, as shown in Fig. 1 (a) [19]-[31].

The analysis of this model starts considering the required power resulting from the product of the terminal voltage U_t and the battery current I.

$$P = U_t \cdot I \tag{1}$$

where U_t is calculated as:

$$U_t = U_{OC} - IR_e \tag{2}$$

The U_{OC} is determined by the SOC, that can be calculated by the following equation:

$$SOC = \frac{Ah_{max} - Ah_{used}(\eta_{Coulomb})}{Ah_{max}} \tag{3}$$

where,

$$Ah_{used} = \int_0^t \begin{matrix} Ah, & for\ Ah > 0\ , discharge, \\ (\eta_C \cdot Ah)\mathrm{d}t & for\ Ah < 0\ , charge. \end{matrix} \tag{4}$$

The efficiency of Coulomb (η_C) is the real charge in the battery, by the consideration of losses (it can be for materials or temperature) and behavior at the battery during charge (for example the dissipation of over energy or charge in every cell). The limits in (4) describes the direction of current, if it is discharged, the Ah will be greater than 0, on the contrary, during the charge this value is smaller than 0.

Therefore the battery model can be completed by obtaining the current and solving for R_e:

$$I = \frac{U_{OC} - \sqrt{U_{OC}^2 - 4R_eP}}{2R_e} \tag{5}$$

$$R_e = P - (I \cdot U_{OC}) \tag{6}$$

Some important characteristics are as follow:

- Application: It is used to evaluate the behavior of the battery in a stable DC state and operating in the ohmic zone of the battery. In addition, it allows to represent and measure quickly and easily, but not totally accurately, the state of charge (SOC), power (P) and state of health (SOH) of the battery.
- Limitations: The voltage changes induced by the load changes are very perceptive and the internal resistance does not change with the current.
- Considerations: The parameters vary according with the SOC, temperature and current direction.
- Required parameters or tests: Capacity tests [23], open circuit voltage tests [23] and internal resistance tests [23].

B. RC model

This model is, in part, based on the internal resistance model previously described, the voltage source is replaced by a high impedance capacitor that represents the electrochemical storage (C_b), a small capacitor value that represents the transient effects of the battery (C_c) with its respective resistance (R_c), the internal resistance that has the same purpose as the previous model (R_e), and the resistance of the terminals (R_t), as shown in Fig. 1 (b) [23], [32].

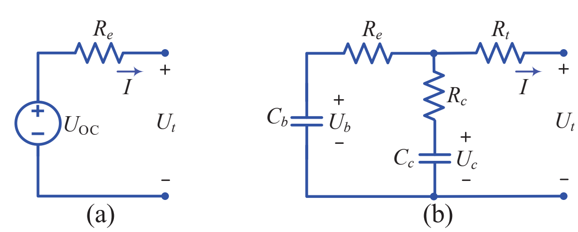

Fig. 1. Electric battery models, (a) Internal resistance model and (b) RC model.

The equations that represent the states and parameters of this model are the following:

$$\begin{vmatrix} \dot{U}_b \\ \dot{U}_c \end{vmatrix} = \begin{vmatrix} \frac{-1}{C_b(R_e+R_c)} & \frac{1}{C_b(R_e+R_c)} \\ \frac{1}{C_c(R_e+R_c)} & \frac{-1}{C_c(R_e+R_c)} \end{vmatrix} \begin{vmatrix} U_b \\ U_c \end{vmatrix} + \begin{vmatrix} \frac{-R_c}{C_b(R_e+R_c)} \\ \frac{-R_e}{C_c(R_e+R_c)} \end{vmatrix} \begin{vmatrix} I \end{vmatrix} \tag{7}$$

$$\begin{vmatrix}U_t\end{vmatrix} = \begin{vmatrix}\frac{R_c}{R_e+R_c} & \frac{R_e}{R_e+R_c}\end{vmatrix}\begin{vmatrix}U_b \\ U_c\end{vmatrix} + \begin{vmatrix}-R_t & \frac{-R_eR_c}{R_e+R_c}\end{vmatrix}\begin{vmatrix}I\end{vmatrix} \quad (8)$$

Some of the most important characteristics are described as follow:

- Application: Useful for performing an electrochemical analysis by means of an electrical circuit, having the advantages of both (precision and speed), especially for transient effects such as instantaneous current.
- Limitations: It is a bit studied and used model, in comparison with the next ones, in particular the Thevenin model.
- Considerations: The parameters vary depending on the SOC and the temperature.
- Required parameters or tests: Through a test of OCV, there is an analysis of successive discharge by current pulses, where the OCV represent the SOC, in the interval of 100% and 0% of battery capacity, which can be calculated as in [32].

C. Thevenin model

The thevenin model is also called One Time Constant model (OTC), this model is based on the internal resistance model, adding the dynamic behavior of the battery produced by the capacitive effects of the cells and the load transfer. This allows predicting the battery voltage in transient response and in dynamic conditions which are represented by the capacitor C_p and the polarization which is modeled by the resistance R_p, as shown in Fig. 2 (a) [28]-[31].

The principal advantage of this model is that the transient response can be simulated based on the pairs of RC circuits in parallel. For the Fig. 2 (a), it is possible to measure the immediate response (in seconds); adding another RC pair the medium term (minutes) and with a third RC pair the long term (hours) [30].

The equations that represent the circuit in Fig. 2 (a) are:

$$U_t = U_{OC} - U_p - IR_e \quad (9)$$

$$\dot{U}_p = -\frac{U_p}{R_pC_p} + \frac{I}{C_p} \quad (10)$$

Regarding the main characteristics of this model, they can be summarized as follows [33]-[35]:

- Application: Designed for electric vehicles, allowing the analysis of voltage variations at different loads and the transient response for charging and discharging process.
- Limitations: The main characteristic and improvement of this model is based on the response of the capacitor C_p, its value must be selected carefully. The use of a wrong value will provoke a mistake in the simulation results or incorrect immediate transient response.
- Considerations: It is affected by SOC and temperature. The values of the elements must be accurate to guarantee a correct prediction.
- Required parameters or tests: A hybrid power pulse characterization test (HPPC) [33] [36], where the voltage and current drop is measured, which is performed during a certain SOC value. It is possible to carry out the method of least squares [37], which allows estimations to be made online and offline.

D. PNGV model

Designed by the Partnership for a New Generation of Vehicles development and cooperation program, with Ford, Daimler and GM participating. This model is based on the Thévenin equivalent model, the main difference is that another capacitor in series has been added to produce the voltage variations in the charging process, causing a greater precision of the electrical model. The voltage source represents the open circuit voltage U_{OC}, the internal resistance of the battery (R_e), the polarization resistance (R_p), the capacitor representing the transient response (C_p) and the capacitor that produces the open circuit voltage variations (C_b), as shown in Fig. 2 (b) [35]-[39].

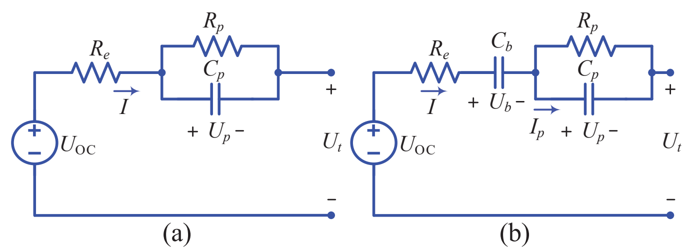

Fig. 2. Electric battery models, (a) Thevenin model and (b) PNGV model.

The system is define by the equations:

$$\dot{U}_b = U_{OC} - \frac{1}{C_b}\left[\int I\mathrm{d}_t\right] - R_eI - R_pI_p \quad (11)$$

$$\dot{U}_p = -\frac{U_p}{R_pC_p} + \frac{I}{C_p} \quad (12)$$

Some interesting details are listed below:

- Application: It is used to obtain a better result than that of internal resistance, since it demonstrates the instantaneous effects of loading and unloading.
- Limitations: Depending on the number of RC circuits, the operation of the battery is better reproduced, but at the same time, it increases the difficulty and simulation.
- Considerations: The value of the SOC, the temperature and the capacitor C_b must be exact, since otherwise the response will vary whit the real behavior.
- Required parameters or tests: A hybrid power pulse characterization test (HPPC) [33] [36], where the voltage and current drop is measured, is performed during a certain SOC value. Using this measure, it is possible to obtain the transient response, whit this and the value of the other elements, it is possible to calculate the C_b capacitance using the time constant RC.

VI. Conclusions

Batteries, have become essential in all portable electronic devices like laptops, cellphones, gadgets, cameras and more. In systems that need a largest storage capacity the utility of a battery technology it depends of the capacity needed, the physical space available and the cost. Balancing benefits, features, and disadvantages for all types of batteries the best is the Li-ion, where a drawback is the relative high cost and the charging system. However, the high power density, the lifespan and the high voltage per cell, make this technology the best for a wide range of applications. In the case of the battery models, the electric equivalent circuit o electric model is the best, specially for its compatibility to interact with other electrical devices under a simulation environment. Finally and according with the analysis, the best equivalent circuit model is the Thevenin model, where the main drawback could be the difficulty to interpret the data and the time for the model proves.

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