



November 20, 2005

Attempting clairvoyance with battery performance

By Gabriel A. Rincón-Mora, Senior Member, IEEE, and Min Chen, Student Member, IEEE, The Georgia Tech Analog & Power IC Design Laboratory

The light-weight, long-lasting, high-performance attributes of cellular phones and laptop computers, among other equally impressive portable devices currently in the marketplace, are responsible for igniting the overwhelming growth of the battery-powered electronics industry. The demand for smaller and longer lasting solutions, in fact, is only increasing, and key to this success is the battery, which can range from single-use alkaline and zinc-air to rechargeable nickel-cadmium, nickel-metal hydride, lithium-ion, and lithium-polymer technologies. Unfortunately, however, advancements in circuit and system integration have outpaced energy and power density improvements in the battery. Consequently, as batteries conform to the size constraints of portable applications, capacity and output power are necessarily compromised.

Degradation in battery performance over time not only affects functionality but also operational life, proving inadequate the traditional assumption that the battery is an ideal voltage source. Including the effects of the battery on state-of-the-art systems during the design phase is therefore of increasing importance for optimal life and performance. The problem is securing a suitable Cadence-compatible model.

Battery Models

State-of-the-art electrical models for batteries are either Thevenin-, impedance-, or runtime-based. Thevenin- and impedance-based models, shown in Figures 1(a)-(b), assume both open-circuit voltage and capacity or state-of-charge (SOC) are constant and approximate loading and ac/transient effects with an impedance network of passive devices for transient response and/or curve-fitting impedance blocks (for example, Z_{AC}) derived from electrochemical-impedance spectroscopy experiments for ac response. Both these models concentrate on either transient or ac response, but neither considers temperature, lifetime limits, or steady-state open-circuit voltage variations (that is, DC effects). Reported runtime-based models (Figure 1(c)), on the other hand, predict operational life and steady-state variations of the open-circuit voltage, but at the cost of complexity and therefore increased simulation time, which is why an impedance matching network for predicting transient and/or ac response is usually forfeited, yet this is exactly what is needed to fully comprehend the degrading characteristics of the battery.

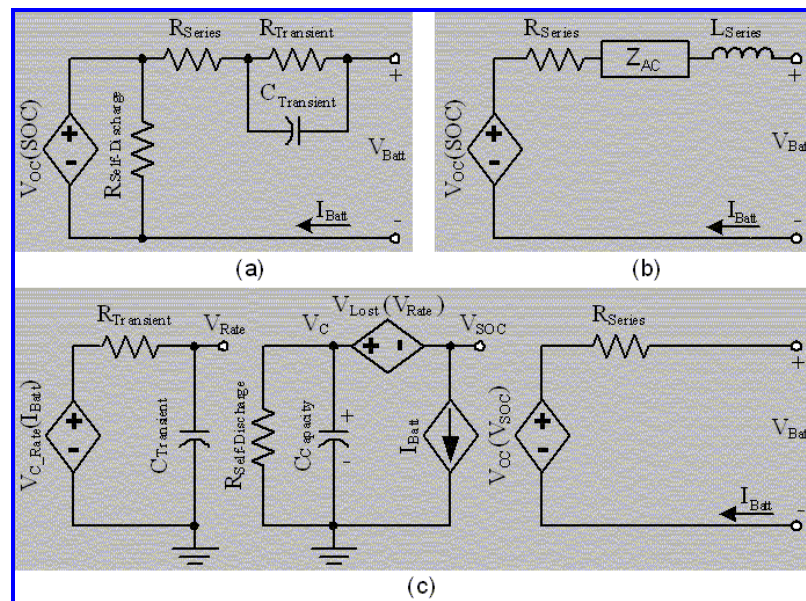


Figure 1. (a) Thevenin-, (b) impedance-, and (c) runtime-based electrical battery models.

Simplifying the battery model...

The basic requirements of the model are to predict lifetime and steady-state (or DC), ac, and transient response performance, in other words, combine the attributes of Thevenin-, impedance-, and runtime-based models, but in a more compact and electrically meaningful fashion, more like the one presented in Figure 2 [1]. The proposed model is separated in two, lifetime and voltage-current (I-V). The former is a simplified version of the runtime-based model and the latter a straightforward expansion of the Thevenin-based scheme.

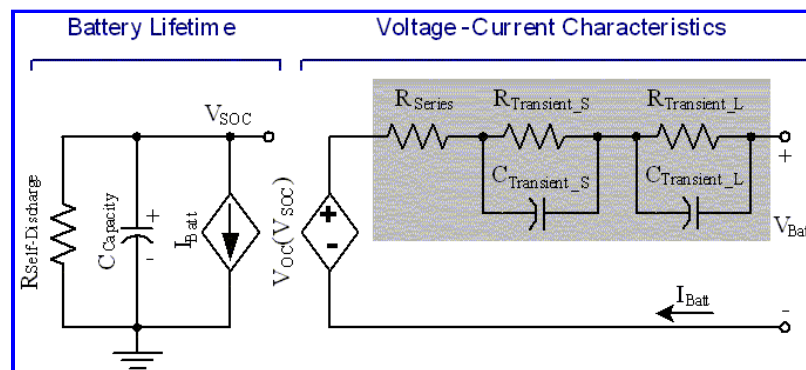


Figure 2. Proposed electrically insightful battery model.

Self-discharge, capacity, and state-of-charge (SOC) determine the operational life of the battery. Load current I_{Batt} , as expected, drains the battery and therefore discharges capacitor C_{Capacity} , which represents capacity – C_{Capacity} is initialized to 1 V when the battery is fully charged. Resistor $R_{\text{Self-Discharge}}$ models the self-discharging effects of unloaded batteries, continually draining the battery. The resulting normalized voltage across the capacitor (V_{SOC}) consequently represents the percentage of energy left in the battery (SOC). Half a volt, for instance, implies the battery is half full. The translation of this to open-circuit voltage is accomplished through dependent voltage source V_{OC} , the nominal function of which is shown in Figure 3(e). For lithium-ion technologies, for example, fully charged and fully drained batteries have open-circuit voltages of 2.7 and 4.2 V, respectively. Other technologies would likewise exhibit a similar translation, but with appropriate voltage values for their respective chemistries.

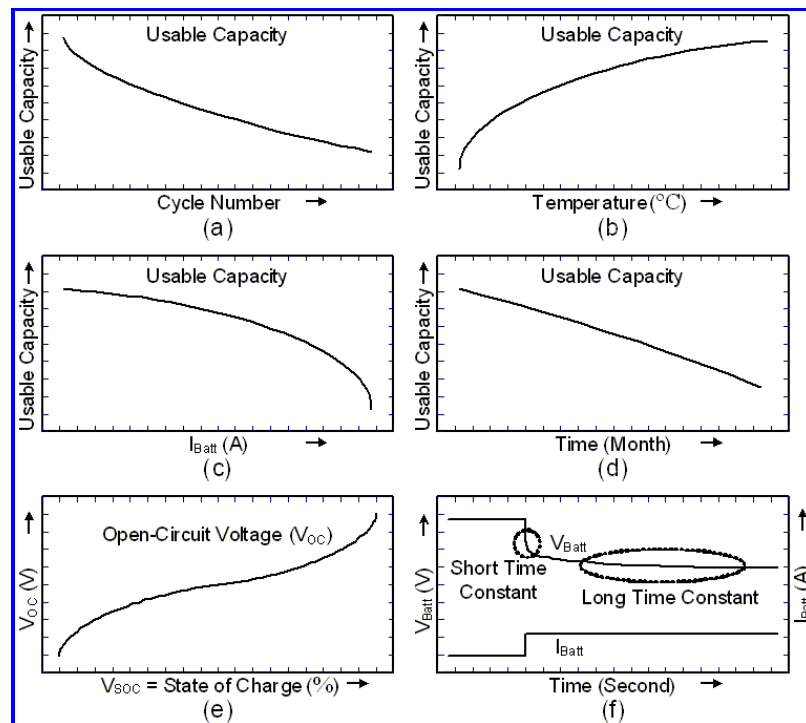


Figure 3. Usable capacity and open-circuit voltage, and their various dependencies on (a) cycle life, (b) temperature, (c) current, (d) shelf-time, (e) SOC, and (f) transient loads.

Understanding the Model Parameters...

As electrically intuitive as the proposed model is, its various components can exhibit significant nonlinearities and interdependencies across temperature, load, and re-charge history (that is, cycle life). Usable capacity, as is often referred, for example, may depend on cycle number, temperature, load current, and shelf-life, depending on the battery chemistry and the process technology used to fabricate it, as illustrated in Figure 3(a)-(d). Normally, usable capacity decreases with recharge cycle, load current, and shelf-life and increases with temperature.

The usable capacity's dependence on load current and shelf-life, of course, are already modeled by the discharging effects of current-controlled current source I_{Batt} and self-discharge resistor $R_{\text{Self-Discharge}}$ (Figure 2). Even though $R_{\text{Self-Discharge}}$ may be a function of SOC, temperature, and cycle number, a zero-order approximation is often sufficient. Alkaline batteries, for instance, have long shelf-lives and can therefore be modeled with large independent resistor values. C_{Capacity} , on the other hand, is dependent on temperature and, in some cases, cycle number. In the case of lithium-ion batteries, for example, usable capacity is a strong function of temperature and a weak function of cycle life.

The transient response of most batteries normally ascribes to instantaneous and time-delayed voltage drops, as illustrated in Figure 3(f). The instantaneous portion of the response is modeled with a combination of series resistors (R_{Series} , $R_{\text{Transient}_S}$, and $R_{\text{Transient}_L}$ in Figure 2). They are broken in segments so that various time constants can be defined with appropriately sized parallel capacitors ($C_{\text{Transient}_S}$ and $C_{\text{Transient}_L}$). For most lithium-ion and nickel-metal hydride technologies, two time constants are sufficient to keep errors within a few milli-volts, which is why a second-order filter is used in the Thevenin-based portion of the proposed model.

Testing the proposed model...

The parameters of the proposed model were extracted and curve-fitted for an 850 mAh TCL PL-383562 lithium-polymer battery and tested against several periodic, multi-step load profiles, one of which is shown in Figure 4 [1]. The Cadence-simulation results show good correlation against experimental data, with less than 30 mV of instantaneous error voltage and less than 0.5% of runtime error. The proposed electrically descriptive model therefore achieved its objectives of predicting operational life and DC, ac, and transient effects in a circuit-compatible simulating environment.

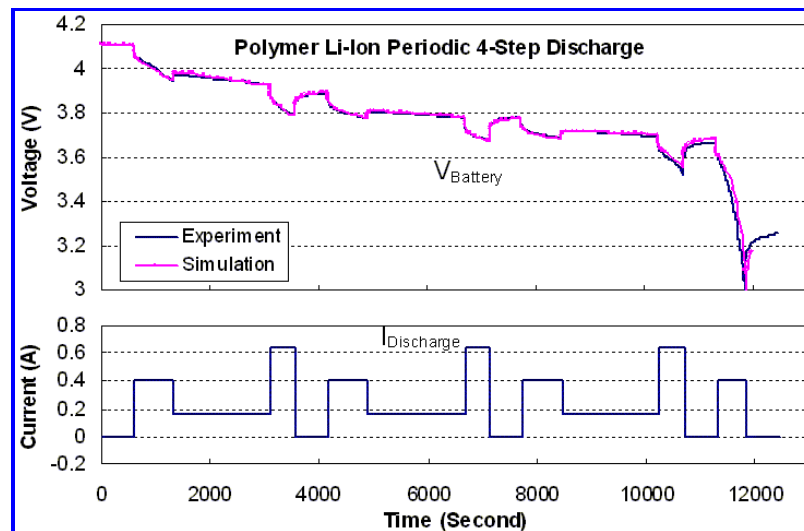


Figure 4. Experimental and simulation results for an 850 mAh TCL PL-383562 lithium-polymer battery and its proposed model under a periodic, multi-step load profile.

The accuracy of the foregoing scheme is dependent on how well the model matches the nonlinearities and interdependencies of its various components and the extent of the effects of process variations on batteries in a mass-production environment. The performance achieved in Figure 4 was the result of several multi-dimensional curve-fitting functions, which were not only labor intensive to extract but also potentially intensive to process, especially with top-level, transistor-based simulations. Approximating and linearizing many of these functions will degrade performance but the acceleration in simulation time may more than make up the difference, which is why linear first-order approximations will be evaluated. Simplifying and applying the proposed model to other power sources such as micro fuel cells is also ongoing.

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech Analog and Power IC Design Laboratory, at gta@ece.gatech.edu. More information about our research can be found at <http://www.rincon-mora.com/research>.

References:

[1] M. Chen and G.A. Rincón-Mora, "An Accurate Electrical Battery Model Capable of Predicting Runtime and I-V Performance," *IEEE Transactions on Energy Conversion*, to be published.



LTC[®] 3780

High Power Buck-Boost



All material on this site Copyright © 2005 [CMP Media LLC](http://www.cmpmedia.com). All rights reserved
[Privacy Statement](#) | [Your California Privacy Rights](#) | [Terms of Service](#)