BATTERY MODELING – THE FUTURE OF SIZING CALCULATIONS?

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Abstract

IEEE battery sizing has its roots in a paper by E.A. Hoxie, published in 1954. The principles of that paper were adapted to a standards document for lead-acid batteries with IEEE Std 485, first published in 1978. A nickel-cadmium version based on the same principles, IEEE Std 1115, followed in 1992. While these documents have stood the test of time, their origins from before the days of personal computing are clear. Even though most manufacturers have adapted these standards to computer sizing programs, there remain shortcomings for certain applications, such as those with numerous load steps, very long discharge times, or continuously variable loads. As new technologies such as lithium-ion (Li-ion) are being promoted for standby applications, it is worth considering whether it is time to adopt an alternative approach.

This paper describes the use of battery modeling as an alternative to traditional sizing techniques, specifically relating to Li-ion technology. The versatility of such an approach is undeniable, but questions remain. Manufacturers may have different levels of sophistication in their models, and validation could be an issue. Nevertheless, modeling represents an attractive option for battery sizing, raising the question whether IEEE sizing standards may at some point become obsolete.

Introduction

Several decades ago, there were as many sizing methods as there were battery companies. That started to change when the IEEE Battery Working Group (as it was called back then) adopted a modified version of the method published by E.A. Hoxie in 1954[1]. That work eventually led to the publication of the first version IEEE Std 485 for lead-acid batteries in 1978, followed by IEEE Std 1106 for nickel-cadmium batteries in 1992. Both standards have been updated over the years, with the latest versions being IEEE Std 485-2010[2] and IEEE Std 1115-2014[3]. In both cases the underlying calculation method has remained unchanged through the successive revisions.

Hoxie Explained

Both IEEE documents contain a mathematical explanation of the modified Hoxie method. The method can be applied to both constant-current or constant-power loads. (Loads that are not constant-power are generally resistive, with load current decreasing as battery voltage drops. However, resistive loads are conservatively treated as constant-current, with the current value based on the nominal battery voltage.)

Simply stated, a duty cycle with varying loads is broken down into what are called Sections. The Sections all start at the beginning of the duty cycle and expand stepwise to take in one additional load step per Section, so Section 1 contains the first load step, Section 2 contains the first two load steps, and so on. Each Section is then broken down into Periods. The first Period is the initial load step, extended to the end of the Section. The second Period starts at the second load step, and considers the change in current (which is negative if the second load is lower than the first), extended to the end of the Section. Each period is therefore a single load change for a certain time. Battery sizing factors are used to calculate a battery capacity for each Period in the Section, with those capacities being added together to give the Section size. This concept is illustrated in Figure 1 for a simple two-load duty cycle.

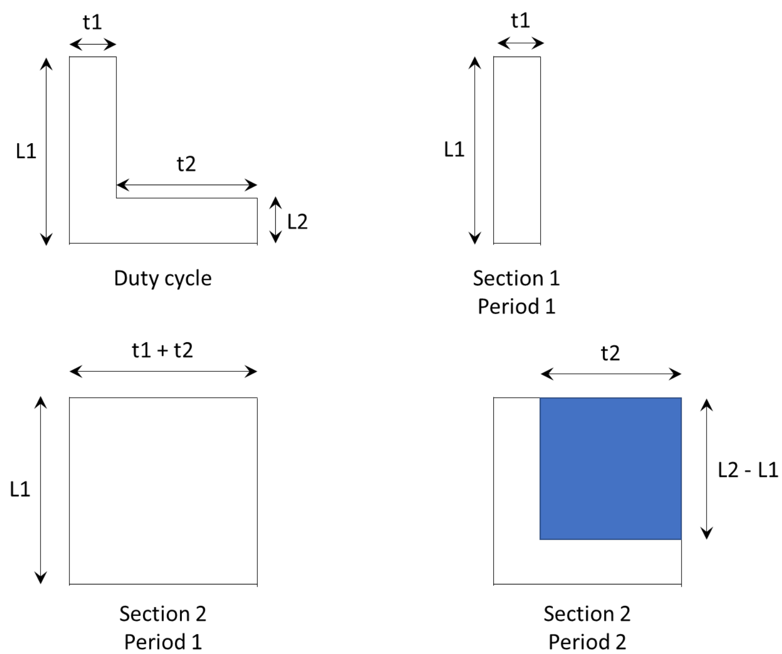


Figure 1. Modified Hoxie treatment of two-load duty cycle

In the second Section, the second Period yields a negative battery capacity (since L2 minus L1 is negative), and when that value (shaded area) is subtracted from the Period 1 capacity, the remaining, unshaded area is the original duty cycle. In this way, a complex duty cycle can be broken down into a series of discrete loads for which capacity calculation is simple.

When battery capacities have been calculated for all the Sections, the largest value becomes the uncorrected battery size. In IEEE Std 485, that uncorrected size is adjusted for the minimum expected battery temperature, a design margin (to account for load growth and/or less-than-optimum conditions), and an aging factor (to allow for reduced capacity at the end of battery life). The main difference in IEEE Std 1115 is that the adjustment for temperature is made in the calculation for each Period.

Limitations of the IEEE Method

While the IEEE sizing method is effective for the types of load profile found in generating stations and utility substations, it has several limitations:

- It is cumbersome for duty cycles with numerous load steps
- There is no consideration for temperature changes during the duty cycle, including
    - Ambient temperature changes during prolonged duty cycles
    - I^2R heating effects
- There is no provision for operation at partial states of charge (other than through the design margin)
- There is no accommodation for ramping loads
- There is no consideration (yet) for new technologies

An Alternative Approach

Battery modeling represents an alternative to such stepwise sizing methods. Equivalent-circuit models of varying levels of sophistication have long been used to describe battery behavior. For example, a Thevenin battery model is shown in Figure 2.

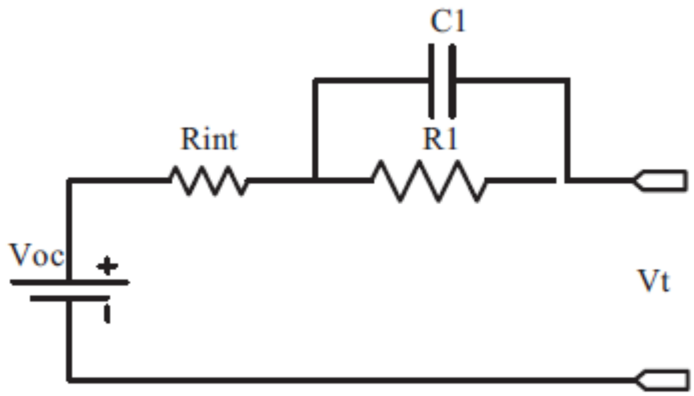


Figure 2. Typical Thevenin battery model

The issue with such equivalent-circuit models is that they are static, whereas the parameters used to represent a battery vary dynamically during charging and discharging. Modeling platforms such as Matlab-Simulink provide the capability to incorporate this dynamic behavior, with the potential to generate sophisticated treatments of electrical and thermal battery characteristics. Non-aqueous Li-ion technology lends itself particularly well to such characterization, and advanced models have been developed with these capabilities, even allowing the assessment of the level of battery aging associated with a duty cycle. (While such models in theory could be developed for traditional lead-acid and Ni-Cd technologies, the added complexity of side reactions associated with water makes this much more difficult, and the author is not aware of any similar models for those technologies.)

One such model is shown in Figure 3. Inputs are shown on the left side, and include battery architecture (series cells and parallel strings), and initial conditions such as state of charge, battery and ambient temperatures, and battery age in capacity and resistance. The resistance in this case is the average internal resistance of each cell, with a separate allowance being made for connection resistances. In the great majority of cases, reduction in capacity and increase in resistance are closely linked, so a fixed relationship between the two can be used. These age parameters allow the assessment of battery performance at any stage of life, thus eliminating the need for the IEEE aging factor.

Inside the model, each input is handled by a specific mathematical function that defines the way in which that parameter changes one of more of the values in the underlying cell model. In constructing the Matlab-Simulink model, each of these functions must be tested and validated in various combinations to ensure accuracy.

The right side of the model shows the various outputs, such as voltage, state of charge, and battery temperature. This model mimics real battery behavior, including operation of the contactor in the battery management module, which opens in the case of an abusive situation. Also included are outputs for capacity and resistance aging, allowing degradation to be monitored through the duty cycle.

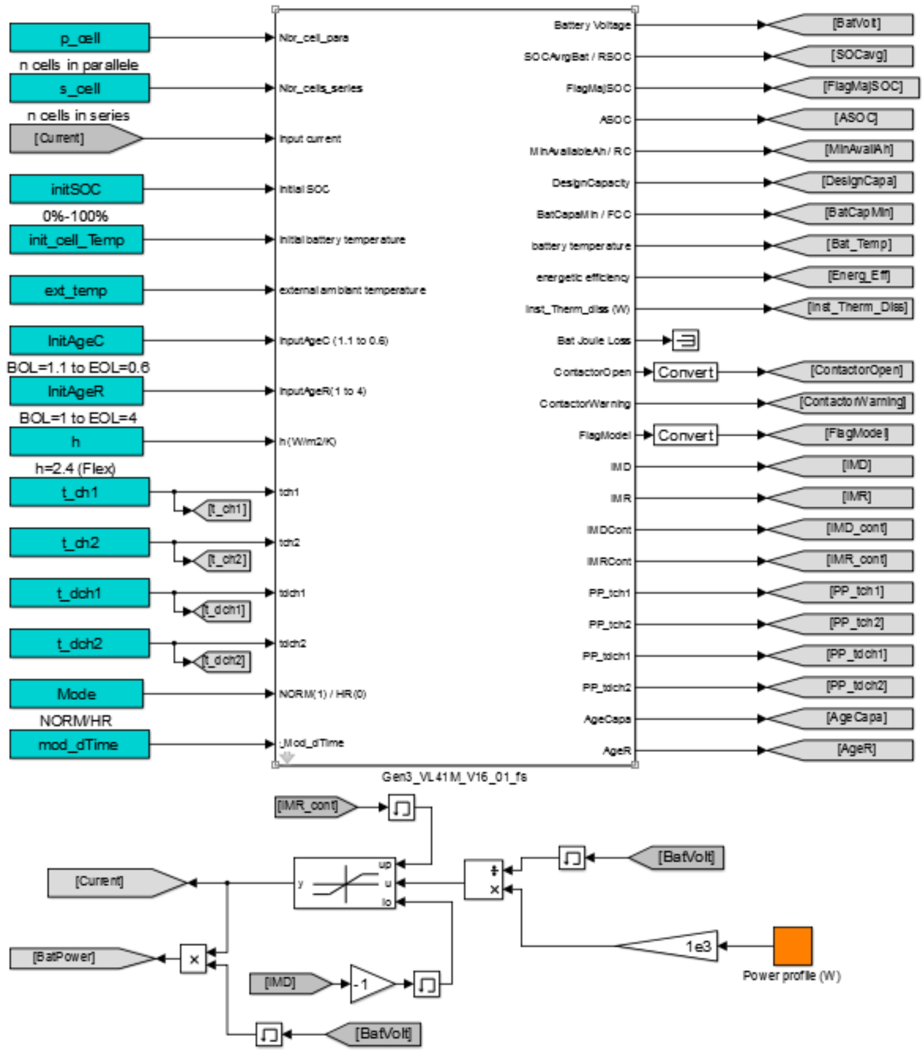
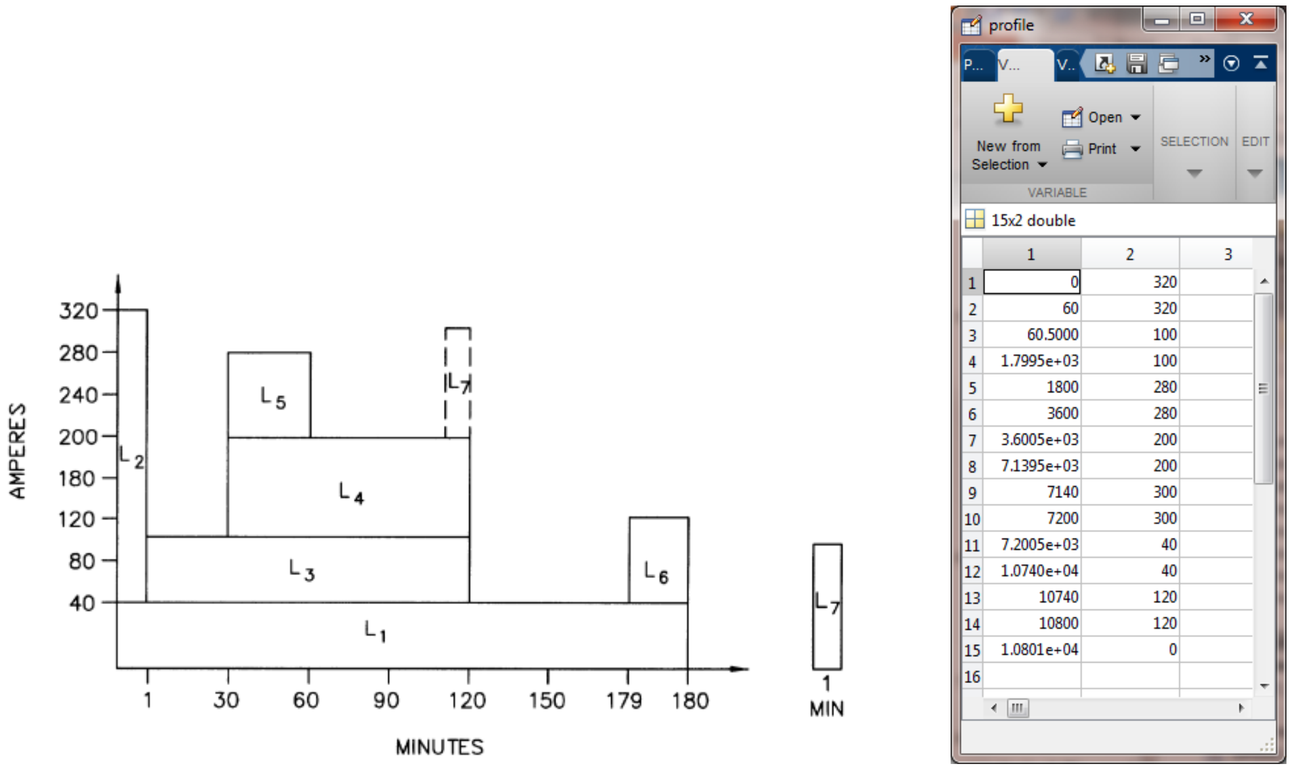


Figure 3. Matlab-Simulink model of a lithium-ion battery

Modeling examples

Example 1 – IEEE sample duty cycle

IEEE Std 485-2010 includes a sample duty cycle, shown in Figure 4a. The duty cycle includes a random load (L_7). In the IEEE approach, the capacity required for a random load is calculated separately, and simply added to the largest Section size. Figure 4a shows the random load (dashed outline) at the most critical point in the duty cycle. The modeling approach would require the duty cycle to be run once without the random load, and then for the random load to be added at the most critical point (lowest battery voltage) and the model to be re-run. Leaving the random load as shown, Figure 4b shows how the duty cycle would be expressed in a Matlab variable, with the time shown in column 1 and the current in column 2. (Matlab requires that the time values be monotonically increasing, so each load step occurs over half a second, rather than instantaneously.) For this example, it is assumed that the initial battery temperature is 10°C.

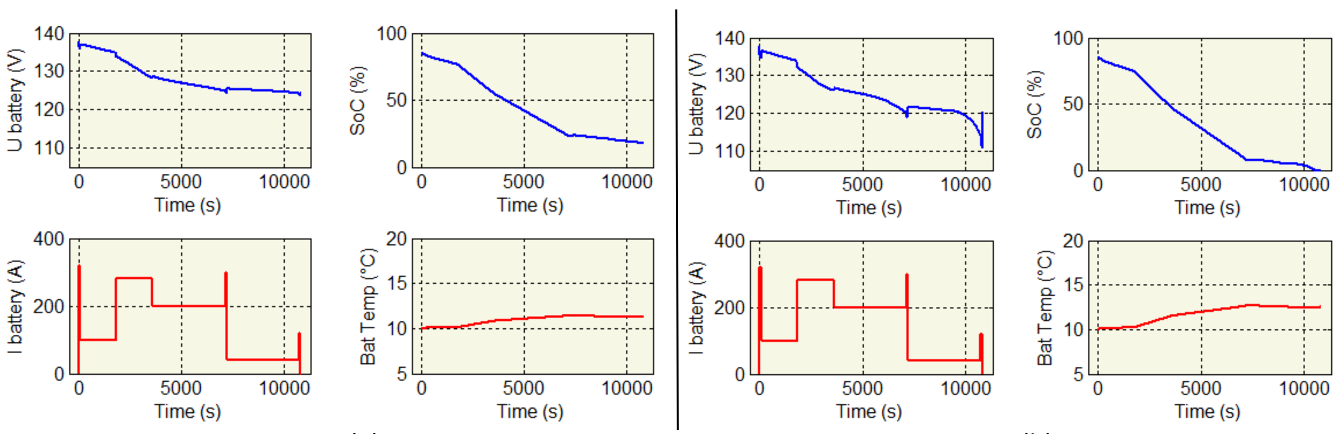


	1	2	3
1	0	320	
2	60	320	
3	60.5000	100	
4	1.7995e+03	100	
5	1800	280	
6	3600	280	
7	3.6005e+03	200	
8	7.1395e+03	200	
9	7140	300	
10	7200	300	
11	7.2005e+03	40	
12	1.0740e+04	40	
13	10740	120	
14	10800	120	
15	1.0801e+04	0	
16			

(a) (b)

Figure 4. Sample duty cycle from IEEE Std 485

Figure 5a shows simulation results for a new battery, while Figure 5b shows results for a battery aged to 80% of rated capacity.



(a) (b)

Figure 5. Simulations of sample duty cycle for (a) new battery and (b) aged battery

The impact of battery aging can be seen in the curves for voltage, state of charge, and temperature.

Example 2 – PJM regulation

This example shows the ability of the battery model to follow an extremely complex duty cycle that would be next to impossible to calculate using the IEEE method. PJM Interconnection is a not-for-profit company that runs the electricity grid in 13 mostly mid-Atlantic states. PJM was an early adopter of energy storage systems to provide fast regulation service (balancing generation and load), and there are now over 300MW of battery-based resources following PJM's RegD (for Dynamic) signal. This signal is energy-neutral and changes every two seconds. A sample day of the RegD signal is shown in Figure 6.

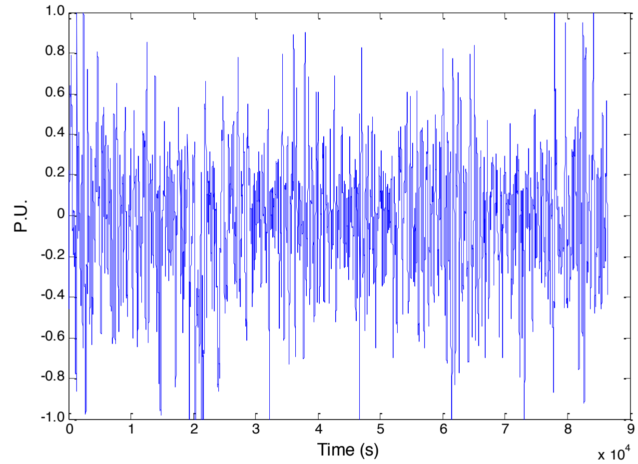


Figure 6. Sample day of PJM RegD signal

Simulation results for a battery following this signal are shown in Figure 7.

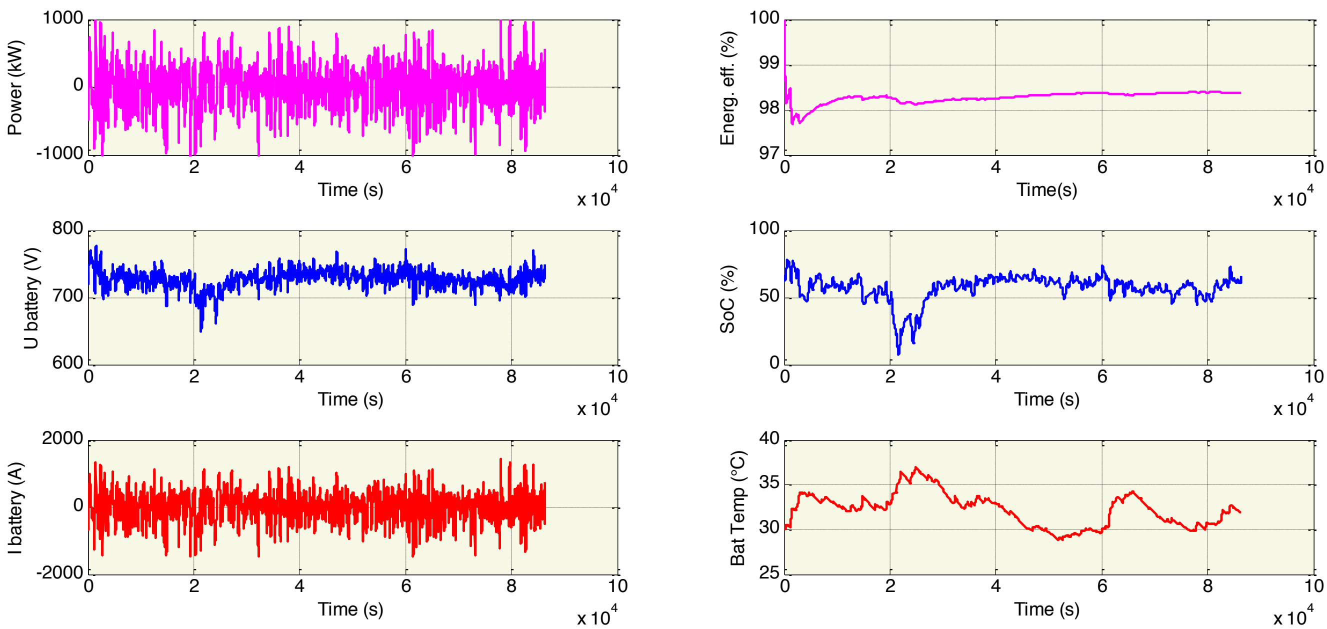


Figure 7. Simulation of PJM RegD sample day

Summary – is modeling a substitute for IEEE sizing?

Clearly, for the Li-ion model detailed above, the answer is an unequivocal 'yes.' Such a model can provide a greater level of precision, for example, regarding the variation in performance at different states of charge, whereas the implicit assumption in the Hoxie model is that performance is always proportional to remaining capacity, regardless of the state of charge. However, there are caveats that must be addressed. First is the issue that not every battery manufacturer has such a model, and many are less sophisticated. If the model cannot address the end-of-life performance of the battery, then post-simulation adjustments must be made. Another complication is that no Li-ion manufacturer (to the author's knowledge) publishes the type of tabular discharge data required for use in IEEE sizing calculations.

The IEEE sizing standards have provided valuable service over the years, giving users a common approach to sizing and allowing an 'apples-to apples' comparison between manufacturers. However, they have their roots in a time before computer-driven modeling was widespread, and the question must be asked whether sizing standards will become irrelevant once robust models are widespread.

Battery users will no doubt have concerns over the use of modeling, and in particular over the question of model validation. They will be expected to trust that the model is accurate, and that may not be a comforting thought to some. Having said that, users are expected to trust the published discharge data tables and curves from lead-acid and nickel-cadmium battery manufacturers, so is trusting a model all that different?

The IEEE Energy Storage and Stationary Battery Committee, which maintains IEEE Stds 485 and 1115, has begun publishing standards relating to new battery technologies, including Li-ion. Sooner or later, the committee will have to determine how to proceed on the subject of sizing these new products.

References

1. Hoxie, E. A., "Some discharge characteristics of lead-acid batteries," AIEE Transactions (Applications and Industry), vol. 73, no. 1, pp. 17–22, Mar. 1954.
2. IEEE Std 485-2010, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications
3. IEEE Std 1115-2014, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications