Development of Real-Time Battery Models for HIL testing of Battery Management Systems (BMS)

Maplesoft
Engineering
Solutions

The explosion in the use of electronic devices, electrified vehicles and decentralized power utilities (e.g. smart grids) has driven demand for rechargeable batteries, creating a thriving and growing market. Current projections indicate that the global market for rechargeable batteries will be approximately $60 billion in 2015, growing at around 9% per year. This has led many of the major electronics companies to enter the market, with offerings targeting a range of applications: from small and light-weight for hand-held devices to batteries the size of shipping containers for utilities. It has also led to a significant increase in research investment into battery technologies to address many of the technical challenges facing this industry, ranging from increasing specific energy (the amount of charge a cell can hold per kg weight) to thermal stability, battery life extension, and final disposal of spent materials at the end of a battery's life (Battery, 2015).

In this paper, we will focus on one area of development in the context of a project recently carried out by Maplesoft and its partner, ControlWorks Inc, of South Korea. Specifically, we will cover the development of a Hardware-in-the-Loop (HIL) testing system for the Battery Management Systems (BMS) used in one of our client's larger electrical energy storage products, targeting the Smart Grid and UPS markets.

Maplesoft's role in this project was to develop a high-fidelity battery pack model capable of being executed on a real-time platform. This has since been integrated into a turn-key BMS testing system, developed by ControlWorks.

The paper is structured in four parts:

- A description of the client's requirements for the project
- A discussion of the current state-of-the-art tools for modeling battery cells and how this is implemented in the MapleSim™ Battery Library
- A detailed description of the modeling approach used for this particular project
- How the battery stack model was integrated into the BMS testing system from ControlWorks.

Project Requirements

The client involved in this project is a major consumer electronics producer that also offers a wide range of solutions for industrial applications including electrical Energy Storage Systems (ESS). Essentially, these are stacks of a large number of battery cells that are typically used for off-grid power supplies in residential and commercial applications, such as uninterruptable power supplies, renewable-energy systems and remote telecom systems.

Because they are made up of numerous cells, the client's ESS products are highly scalable, ranging from 1kWh residential back-up systems to 1MW for utilities solutions.

As the systems get larger, monitoring and controlling them becomes increasingly complex. Issues such as charging and discharging the cell array in a way that minimizes charge times while maximizing energy efficiency and battery life must be considered when developing Battery Management Systems (BMS) for these products.

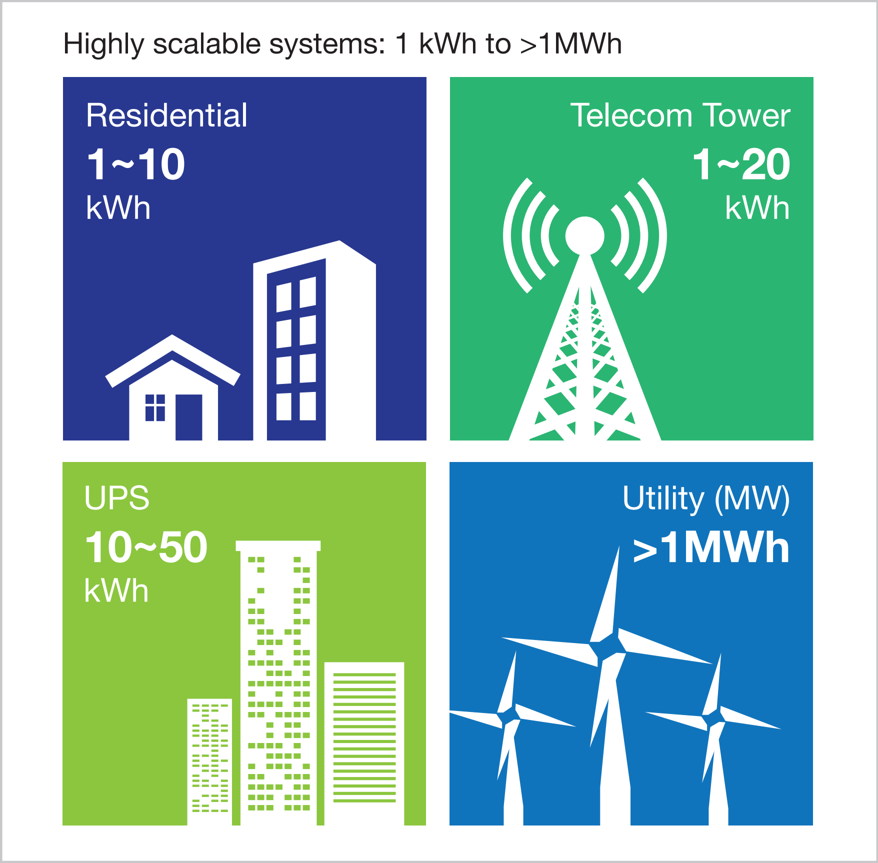


Figure 1: Typical range of applications for Energy Storage Systems

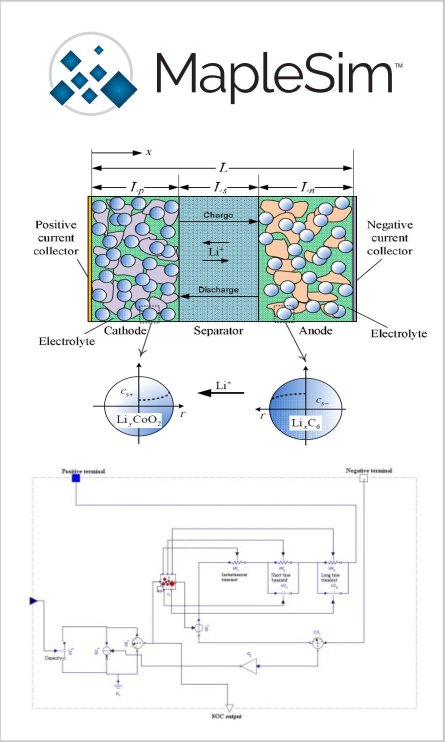


Figure 2: Typical BMS testing systems with real batteries are expensive and potentially dangerous. Replacing the real battery with a virtual battery reduces costs and risk

In particular, testing the BMS poses major challenges: they are costly to put together, faults in the BMS design can cause catastrophic damage to very costly test units, and often it may not be possible to test for all scenarios, like charge balancing across the cells. All this can lead to excessive uncertainty around the test results.

An attractive solution to these early-stage BMS testing challenges is to use virtual batteries – mathematical models of the battery cells that are capable of displaying the same dynamic behavior as the real ones. Maplesoft has been actively developing such mathematical models for several years. Not only are they proven to be highly accurate, they are computationally efficient and able to achieve the execution performance required to deliver real-time performance for batteries containing hundreds of cells on real-time platforms.

It is for this reason that our client selected Maplesoft Engineering Solutions to develop the virtual battery for implementation on a turn-key BMS test system, developed by Maplesoft's partner, ControlWorks, Inc. of South Korea.

Maplesoft's role in the project was to deliver a battery model capable of being configured to represent a stack of up to 144 cells that can be connected in any combination of parallel and series networks. Fault modes were also required, such as individual cells shorting or opening, along with variations in charge capacity from cell to cell, and degradation of capacity over the life of the cells.

Approaches to developing high-fidelity battery models

Before delving into the project in detail, let's take a look at the current state-of-the-art for modeling battery cells and how these approaches are implemented in the MapleSim Battery Library.

There are two main approaches to battery modeling. The first is to use equivalent electrical circuits that reflect charge capacity and internal resistance through the use of standard electrical components to represent these properties. These equivalent-circuit models are conceptually simple and computationally light, while capable of capturing many of the non-linear behaviors within the cell. However, their scope of operation is somewhat limited and it is not easy to map the components of the model to the physical aspects of the real cell.

At the opposite extreme, electrochemistry-based battery models – those that include the details of the underlying physics in the reaction between the electrodes and electrolytes – have been shown to be highly accurate predictors of the overall charge/discharge characteristics of a cell. This physical behavior can be represented by a system of well-documented partial differential equations (PDE), such as those developed by Newman. However, solving these PDEs can only be achieved through the use of computationally intensive techniques such as finite-element (FE) and computational fluid dynamics (CFD) methods. These approaches make them unsuitable for system-level modeling since they can

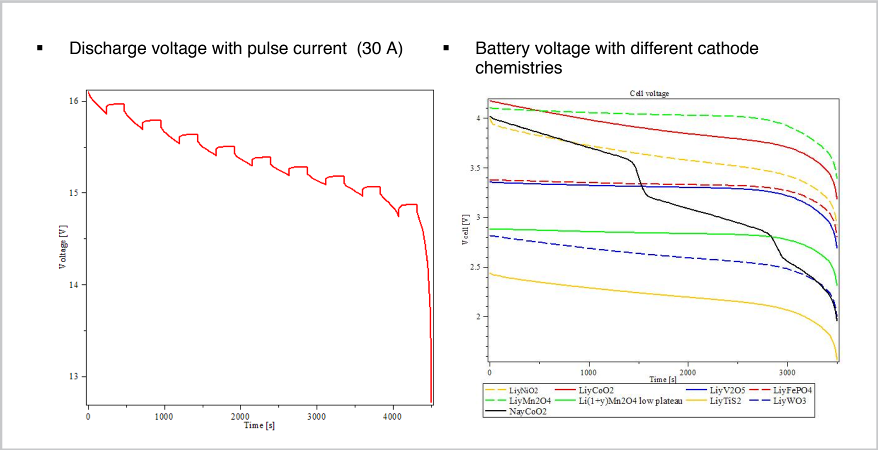

- Discharge voltage with pulse current (30 A)
- Battery voltage with different cathode chemistries

Figure 3: Typical simulated charge/discharge results from the MapleSim Battery Library for various cell chemistries

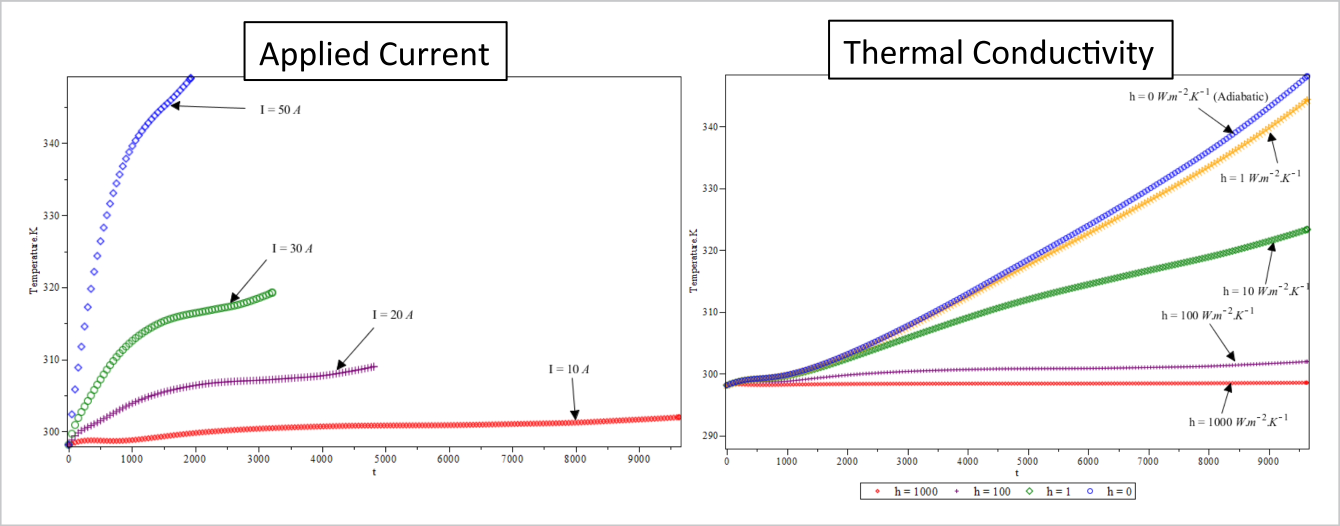


Figure 4: Thermal Effect on Cell Properties

take hours to compute the behavior over a few seconds. Certainly, this makes it impossible for the real-time applications required for this project.

However, in the last few years a new technique has been developed. This compromise approach provides real-time performance while almost completely maintaining the accuracy of the full physics models. This uses a rigorous PDE discretization technique to simplify the model to a set of ordinary differential equations (ODE) that can be readily solved by system-level tools like MapleSim. Furthermore, through the many advanced model optimization techniques employed in MapleSim, the resulting model code is very fast and capable of running in real-time (Dao, 2011).

Using these physics-based models, it is possible to implement battery models that predict charge/discharge rates, state of charge (SoC), heat generation and state of health (SoH) through a wide range of loading cycles within complex, multi-domain system models. This approach provides the performance needed for system-level studies, with minimal loss in model fidelity.

Furthermore, the underlying foundation for model formulation and integration in MapleSim is based on the conservation of energy. Therefore, where there are inherent inefficiencies in the model, lost energy is computed as well as the effective (or "useful") energy. This means that the user can consider a certain proportion of the energy lost through heat (very close to 100% in applications like this). This makes these models very useful for performing thermal studies in order to, for example, determine component sizes for cooling systems required to control battery temperature.

This is critically important when battery State of Health (SoH) must be considered. As we will see later, the operating temperature of each cell has a very significant effect on the degradation of its performance. If not carefully controlled, this can lead to reduced operational life of the battery or, in extreme cases, destruction through thermal runaway.

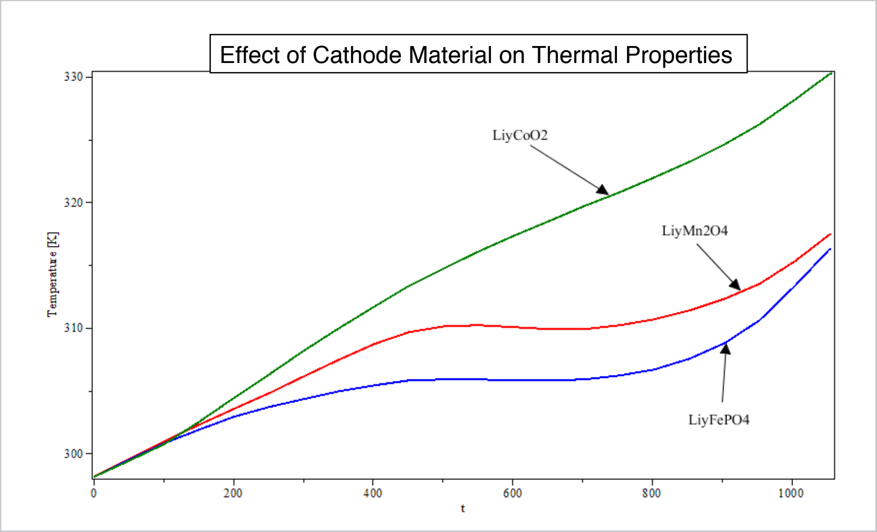


Figure 5: Effect of cathode material on thermal properties of cell

Thermal runaway is a common problem in many battery-powered systems. It arises due to unforeseen loading cycles driving the current to a point where the cooling system cannot dissipate the lost energy quickly enough, or the cooling system is somehow compromised so the battery heats up. As the battery heats, its efficiency decreases, causing even more energy loss. Left unchecked, this vicious cycle can cause the battery temperature to increase to dangerous levels, leading to failure or, in extreme cases, fire or explosion.

Using MapleSim with the MapleSim Battery Library, it is possible to replicate these scenarios to understand the underlying causes and develop strategies for addressing or avoiding them.

Modeling State of Health (SoH)

Within the MapleSim Battery Library, SoH or capacity fading – during both storage and cycling - is incorporated in both the electrochemical and equivalent circuit models. Studies have shown that the primary cause of capacity fade in the cell is the growth of the Solid Electrolyte Interface (SEI) film between the electrodes and electrolyte. This is caused by the chemical reaction between the two, very similar to corrosion. When the battery is new, the reaction is quite vigorous and an initial SEI forms, slowing down the reaction and protecting the electrode surfaces during battery operation.

However, as the battery ages, the SEI slowly thickens in a predictable manner, gradually reducing battery capacity and increasing internal resistance throughout its operational life.

- Thermal run-away model for Li-ion pack:

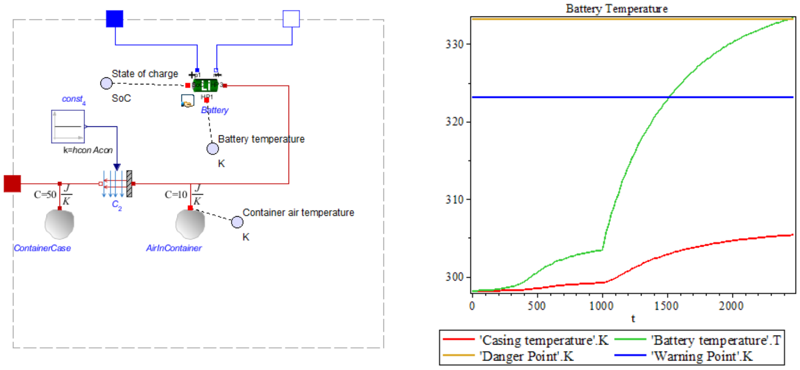


Figure 6: Simulation of thermal runaway using the Li-Ion model from the MapleSim Battery Library

Thickness of the SEI film:

$$d\delta/dt = JM/\rho A$$

Li⁺ flux due to the SEI film formation on the anode during charge:

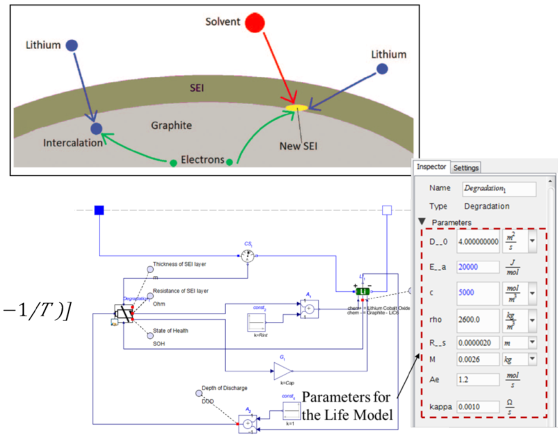
$$J = kA(c - Js/AD)$$

Temperature dependence of diffusion coefficient:

$$D = D_{ref}\,[E_a/R\,(1/T_{ref} - 1/T)]$$

Resistance of SEI film:

$$R_{film} = R_{film,0} + \frac{\delta}{\kappa_s}$$



Name Degradation$_1$
Type Degradation
Parameters

D__0	4.000000000	m²/s
E__a	20000	J/mol
c	5000	mol/m³
rho	2600.0	kg/m³
R__s	0.0000020	m
M	0.0026	kg
Ae	1.2	mol/s
kappa	0.0010	Ω/s

Figure 7: Life model (SEI formation on the anode during charge), and implementation in MapleSim

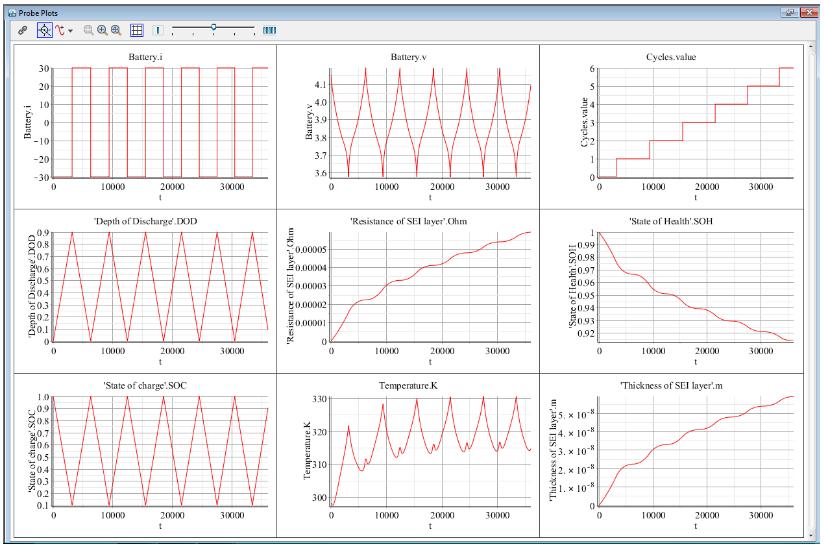


Figure 8: Results from Li-Ion simulation, showing effect of SEI on cell degradation

The formation of the SEI is dependent on several factors, such as the number and depth of charge/discharge cycles, as well as applied current, time in storage, and temperature. These can vary considerably depending on the electrode/electrolyte chemistries used.

In order to factor SoH into the battery models, these properties are implemented in the battery library as parameters and look-up tables, depending on the chemistries selected.

Figure 8 shows an example model that implements SoH data for a Lithium-Ion battery, showing the effect on charge capacity, internal resistance and temperature.

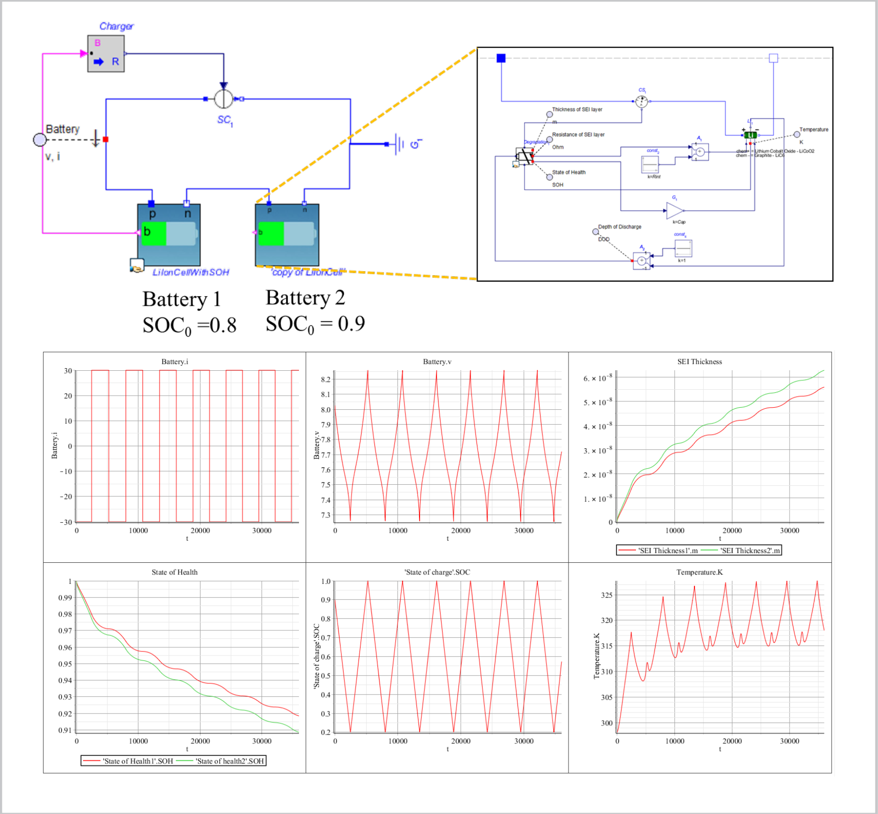


Figure 9: MapleSim model showing the effect of imbalanced charging on two cells

Cell-charge Variance and Charge Balancing

A common problem with batteries with large numbers of cells is that all cells are not created equal. A slight variance in the cell make-up during manufacture can accelerate the degradation of a cell that may have a slightly higher rate of SEI growth than others in the stack. If all the cells are treated the same by the BMS and receive the same charge/discharge demand (current in and out), the depth of discharge (DOD) in one cell may be, say, 80% while in another it is closer to 90%. This will cause the SEI growth rate to increase faster in the more deeply discharged cell.

As seen in Figure 9, this will increase the likelihood of that cell failing either through complete loss of charge capacity or, more disturbingly, through overheating. This is why it is critically important for the BMS to monitor the state of health of each cell and control the current into and out of them in order to balance the charge across all the cells.

Development of cell-pack models for real-time applications

For the purpose of this project, the key requirements for the battery model were:

- Up to 144 Li-Ion polymer cells for testing the BMS of our client's ESS products
- Ease of configuration for different requirements (parallel/series networks)
- Several sensors per cell: current, voltage, SoC, SoH
- Implementation of chemistry variations due to manufacturing tolerances
- Fault-insertion on each cell: open-circuit, shorting
- Capability to run in real-time (target execution-time budget of 1 ms)

The real-time requirement was the biggest challenge for this project. While the MapleSim physics models are fast, they are not as scalable as the equivalent-circuit model. Therefore, it was decided to use the EC models and include some customized elements from the physics models for this purpose.

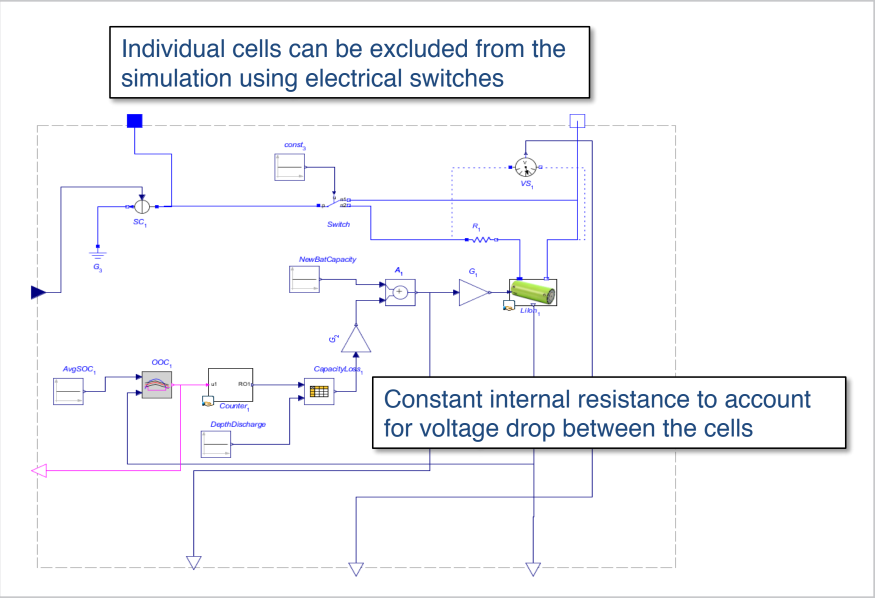
Model Structure

In the case of Energy Storage Systems, each ESS battery is made of several “stacks” that, in turn, contain several cells. The MapleSim model follows this structure.

Each cell is a shared, fully parameterized subsystem, using the customized equivalent-circuit model described earlier. Additionally, each cell can be switched to open circuit using logical parameters.

The stack model is made of 18 cell subsystems connected either in parallel or series, depending on the requirement. Input signals are provided for charge balancing from the BMS. Output signals are provided back to the BMS to monitor the condition of the stack: Supply voltage, SoC and SoH.

Finally, the full ESS is made of several stacks with IO signals fed to and from the BMS.



Individual cells can be excluded from the simulation using electrical switches

Constant internal resistance to account for voltage drop between the cells

Figure 10: Cell model with internal switching

- Inputs:
  - Active balancing current determined by battery BMS
  - Applied current
- Outputs:
  - Stack voltage
  - Stack SOC
  - Stack SOH

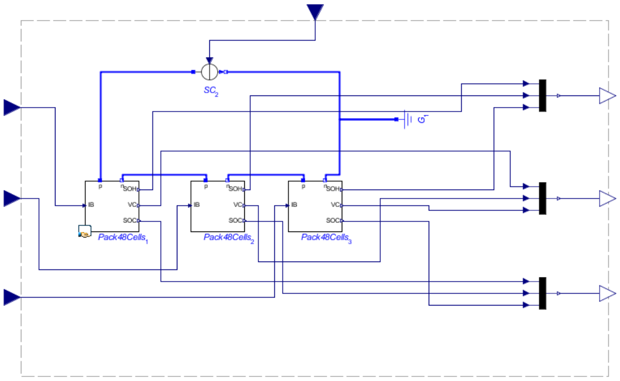


Figure 11: Cell stack model

> The MapleSim™ model of the Li-Ion battery was selected because of its proven ability to provide equivalent-circuit or, where necessary, electro-chemical physics-based models and still achieve real-time performance. The code-generation and compilation tools are very easy to use making the integration of the model into the HIL system very fast and cost effective. That, plus the excellent development support we have received from Maplesoft’s Engineering Solutions team, has made this a very smooth project.
>
> ***Kenny Lee, PhD**, Director of Research Center of Automotive Electronics, ControlWorks Inc., www.control-works.co.kr*

Model Calibration and Validation

As outlined in the paper "Simplification and Order Reduction of Lithium-Ion Battery Model Based on Porous-Electrode Theory (Thanh-Son Doa, 2011)," much of the accuracy of the model is dependent on experimentally derived parameters determined from charge/discharge test results. Added to this, the variation in performance due to manufacturing variations needed to be included in order to test the charge-balancing capability of the BMS. Instead of testing every cell, a smaller batch was tested, from which the average cell response could be determined as well as the statistical distribution of the variants. These were used to implement the manufacturing variability into the cell stack.

The average cell response was determined using the parameter-estimation tool supplied with the MapleSim Battery Library. This uses optimization techniques to determine the values of cell-response parameters that provide the closest "fit" to the experimental results. This response was then validated against response data from other cells to ensure the resulting model is a very close estimation.

The State of Health behavior was implemented as a look-up table based on experimental results. The model determines the capacity and internal resistance based on the number of charge/discharge cycles and depth of discharge (DOD) from the lookup.

This approach was tested with various charge/discharge cycles. Fig 13 shows the results from one such test.

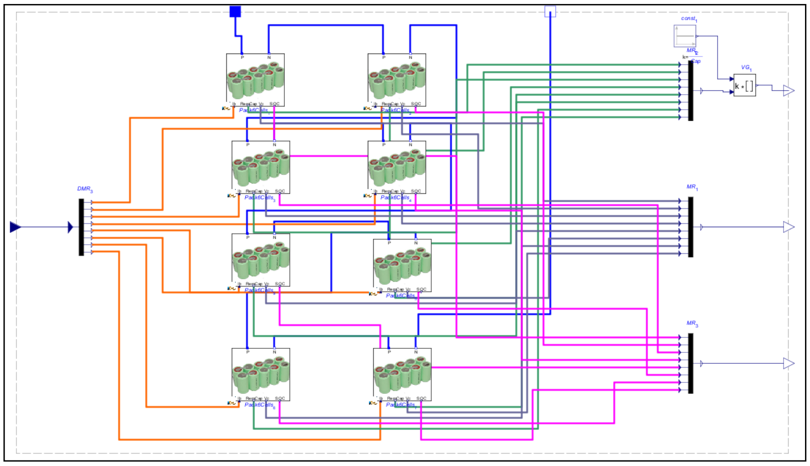


Figure 12: ESS Battery model

Introduction to the MapleSim Battery Library

The MapleSim Battery Library allows you to incorporate physics-based predictive models of battery cells into your multidomain system-level models.

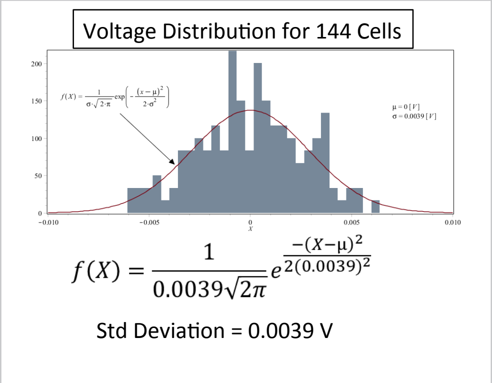
- Save time and avoid problems by taking battery behavior into account early in your design process.
- Understand the loading effect on the battery as it undergoes many different duty cycles and how the battery will behave as part of the greater system.
- Gain a better understanding of the heat flow in the battery, how rising temperature and age affects efficiency, and what critical factors could cause thermal runaway.
- Adjust your designs to optimize performance and reduce the risk of undesirable effects.

To learn more, visit:
www.maplesoft.com/batterylibrary

As mentioned earlier, the variation of cell behavior was implemented through the use of random variants, generated from the statistical distribution determined from the charge/discharge results from testing 48 cells. This was applied to all 144 cells and then compared with the real test results. In figure 14 we see that the maximum variance of the voltage from the experimental data was 14mV, while from the simulation it was 13mV: acceptable for the purpose of this project.

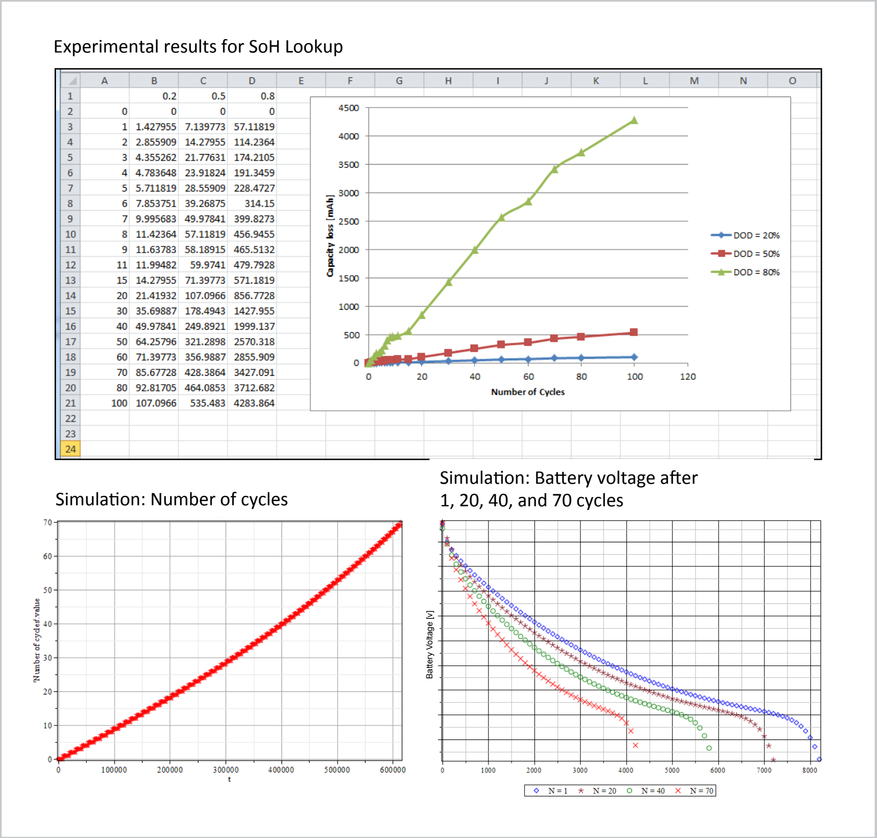
Model-code Generation and Performance Benchmark

Finally, the model was converted to ANSI-C through the MapleSim Connector for Simulink®. This produces an s-Function of the battery model that can be tested for performance and accuracy with a fixed-step solver on a desktop computer in Simulink® before moving it to a real-time platform. The simplest solver was used and the performance bench showed that the average execution time was approximately 20 times


Voltage Distribution for 144 Cells

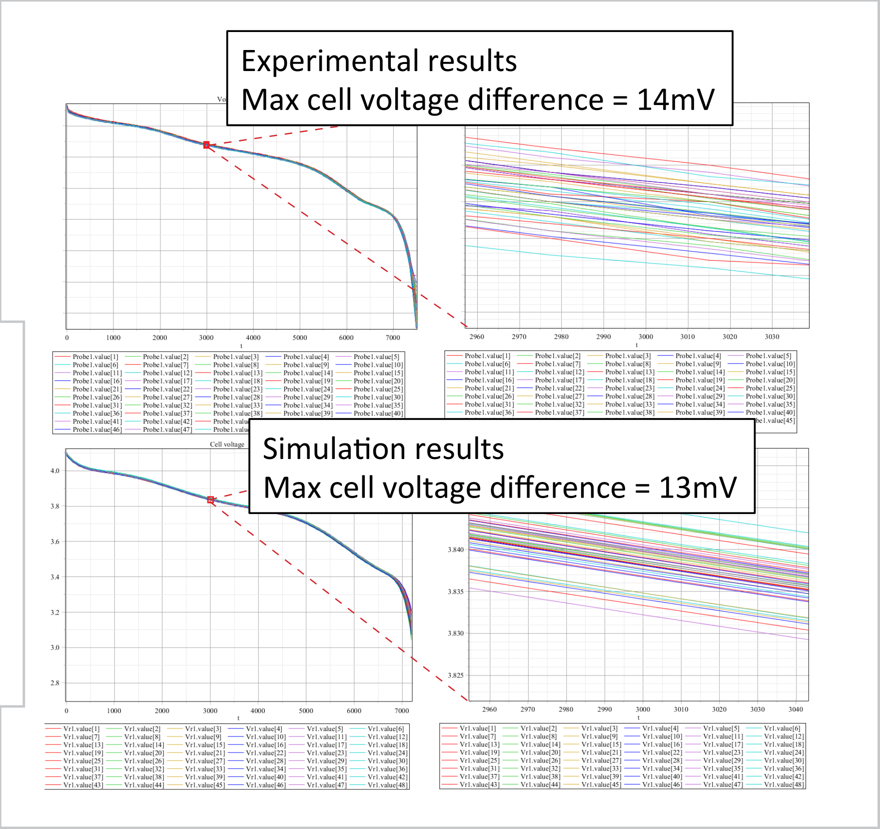
$$f(X) = \frac{1}{0.0039\sqrt{2\pi}} e^{\frac{-(X-\mu)^2}{2(0.0039)^2}}$$

Std Deviation = 0.0039 V


Experimental results for SoH Lookup

	A	B	C	D
1		0.2	0.5	0.8
2	0	0	0	0
3	1	1.427955	7.139773	57.11819
4	2	2.855909	14.27955	114.2364
5	3	4.355262	21.77631	174.2105
6	4	4.783648	23.91824	191.3459
7	5	5.711819	28.55909	228.4727
8	6	7.853751	39.26875	314.15
9	7	9.995683	49.97841	399.8273
10	8	11.42364	57.11819	456.9455
11	9	11.63783	58.18915	465.5132
12	11	11.99482	59.9741	479.7928
13	15	14.27955	71.39773	571.1819
14	20	21.41932	107.0966	856.7728
15	30	35.69887	178.4943	1427.955
16	40	49.97841	249.8921	1999.137
17	50	64.25796	321.2898	2570.318
18	60	71.39773	356.9887	2855.909
19	70	85.67728	428.3864	3427.091
20	80	92.81705	464.0853	3712.682
21	100	107.0966	535.483	4283.864
22				
23				
24				

Figure 13: SoH simulation showing effect on battery voltage


Experimental results
Max cell voltage difference = 14mV

Simulation results
Max cell voltage difference = 13mV

Figure 14: Cell voltage distribution based on results from 48 cells

faster than real-time, occupying 5.5% of the real-time system time budget. This demonstrates that the battery model can easily be scaled up from the current 144 cells, if required.

Integration of cell-pack models into BMS testing system

The resulting model was provided to Control Works for integration into the BMS testing system they were developing for their client.

The schematic of the BMS testing system is shown in figure 16. The battery model is connected to a model of the loading system that applies the charge/discharge current over different duty cycles, with IO signals connecting to the BMS interface.

The final testing station provides the engineer with the ability to configure the battery model (number of cells, series/parallel, etc.) and apply a range of tests to it.

The engineer can also go back to the MapleSim model at any time to make any necessary changes to the model configuration and easily generate the model for use on the real-time platform. In this system, the real-time software is National Instruments' VeriStand™, driving a PXI real-time system. The MapleSim Connector for NI VeriStand Software automates the model integration process, allowing the engineer to produce the real-time model quickly and reliably.

Stack model was converted to Simulink® S-function for real-time simulation

- Total simulation time = 18,000s
- Solver = Euler
- Time-step: 0.001s
- Total execution time: 985s
  on Intel i5 M520 2.4 GHz CPU
- Average execution time = 5.5% of 0.001s

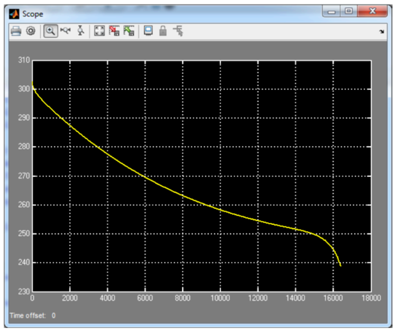


Figure 15: Real-Time Simulation in MATLAB/Simulink®

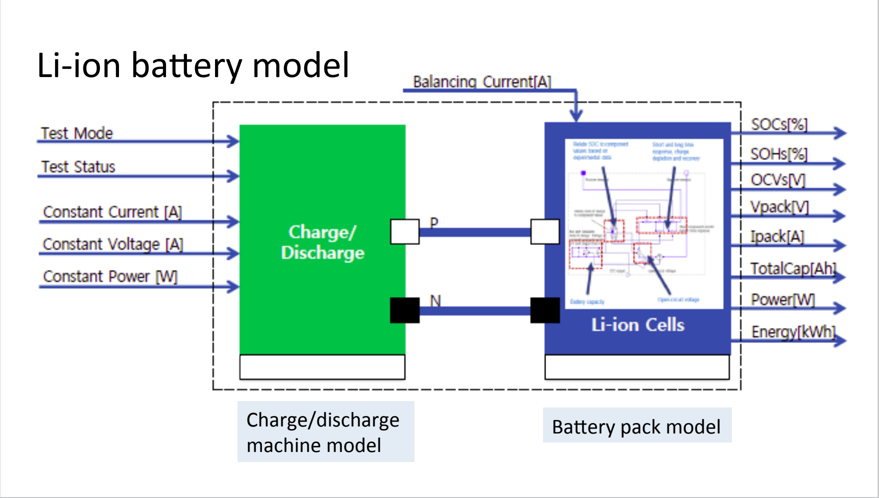


Figure 16: Battery model integration into BMS test system

The ESS BMS Testing System from ControlWorks is a complete turn-key system, integrating the real-time battery models, signal conditioning units, fault-insertion tools, and standard communications protocols (CANbus for automotive, Modbus for industrial applications). Software on the operator system includes NI VeriStand™, NI TestStand™ and MapleSim.

The system allows the engineer to run the BMS through a range of tests on the battery model, including Constant Current (CC) and Constant Voltage (CC/CV) charge/discharge cycles, as well as Constant Power (CP) and Constant Resistance (CR) discharge cycles.

Results are displayed on the operator console through NI VeriStand™ and NI TestStand™.

Summary

For testing ESS Battery Management Systems (BMS), the use of "virtual" batteries is proving to be an effective alternative to the use of real batteries. They allow the engineer to avoid the risks of damage to the batteries - and subsequent costs - while testing and optimizing the BMS design in a close-to-reality loading environment.

Techniques for battery modeling have advanced significantly over the years to the point where physics-based cell models that would have taken hours to solve in a FE or CFD tool can now be implemented in a system model to predict how they would behave under loading from complex multi-domain systems (mechanical, electromechanical, fluids, thermal, etc.).

Maplesoft has developed a deep expertise in the modeling of batteries for use in system-level studies, and that expertise is now available through the MapleSim Battery Library. This provides ready-made physics-based and equivalent-circuit models that deliver the fidelity and performance required for implementation on Hardware-in-the-Loop testing platforms through MapleSim's optimized code generation capability.

It is for this reason that ControlWorks – a real-time testing-systems integrator with a lot of experience in developing BMS test stands – selected the Maplesoft Engineering Solution team as their model-development partner for this project. Our client now has a fully-configurable battery model for testing the BMS for their ESS products, allowing them to develop better products, reduce project risks and get to market faster.

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