HIL Development and Validation of Lithium-Ion Battery Packs

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Abstract

A Battery Test Facility (BTF) has been constructed at United States Environmental Protection Agency (EPA) to test various automotive battery packs for HEV, PHEV, and EV vehicles. Battery pack tests were performed in the BTF using a battery cycler, testing controllers, battery pack cooler, and a temperature controlled chamber. For e-machine testing and HEV power pack component testing, a variety of different battery packs are needed to power these devices to simulate in-vehicle conditions. For in-house e-machine testing and development, it is cost prohibitive to purchase a variety of battery packs, and also very time-consuming to interpret the battery management systems, CAN signals, and other interfaces for different vehicle manufacturers. Therefore, there is a need to accurately emulate battery pack voltage, power, current, State of Charge (SOC), etc. for testing e-machines as well as performing real-time HIL (Hardware-In-Loop) vehicle simulations by having the ability to instantly select a cell chemistry along with battery pack configuration such as cell capacity, number of cells in series/parallel, coolant type, etc.

This paper presents lithium-ion battery pack HIL development and validation integrated into the EPA Battery Test Facility. The battery pack HIL model consists of lithium-ion cell chemistries, thermal characteristics, battery management system (BMS), and power limit controls. The HIL model of lithium-ion battery pack was validated by simultaneously running a real lithium-ion battery pack with Nissan Leaf EV and GM Volt Range Extended Vehicle power profiles to the battery cycler in the BTF. The emulated battery voltages, currents, SOC, and battery pack temperatures are in excellent agreement with battery pack test data on FTP UDDS, highway (HWFET) and US06 drive schedules.

Introduction

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) [1,2,3] tool has been developed to model vehicle performance, fuel economy, green house gas emissions and battery pack performance for light-duty conventional and hybrid electric vehicles. The ALPHA model can be used as a support tool for future greenhouse emissions regulations or as an in-house research tool to evaluate the efficiency of new advanced technologies. The light-duty Hybrid Electric Vehicle (HEV) model in ALPHA is built upon the heavy-duty Greenhouse Gas Emissions Model (GEM) [4] certification tool. GEM and ALPHA share a set of base plant models and controls common to heavy-duty and light-duty applications. ALPHA adds models for the traction motor, generator, battery, regenerative braking, and supervisory control allowing it to be used for light-duty HEV and EV applications.

In Hybrid Electric Vehicle (HEV), and Plug-in Hybrid Electric Vehicle (PHEV) applications, an accurate estimation and emulation of battery voltage, current, SOC, and pack temperature is of foremost importance to precisely estimate EV driving ranges, and to optimize electric machine and engine power coupling, etc. A signification cost reduction can be achieved by properly sizing battery packs since the battery packs are among the costliest of drivetrain components in the various HEV, PHEV, and EV architectures.

Details regarding the development and validation of a two-time constant equivalent circuit lithium-ion battery cell model, a lumped capacitance battery thermal model, and battery management system (BMS) controls were presented [1]. A lithium-ion automotive battery pack model was used to validate 2010 Toyota Prius power-split hybrid and 2011 Hyundai Sonata P2 parallel hybrid vehicles [3]. A demonstration of maneuver-based Battery-In-Loop (BIL) testing at the EPA Battery Test Facility (BTF) [5] was presented by comparing power commanded to a battery cycler and measured power of a real battery pack.

Lithium-ion manganese-based and iron-phosphate based cell chemistries, thermal and BMS control strategies are implemented in a Hardware-In-Loop (HIL) environment. The HIL model was validated by simultaneously simulating an actual battery pack. The emulated battery pack voltage, current, pack temperature and SOC are compared with those of the actual battery pack. The HIL emulation and actual battery pack test data are in excellent agreement. The real-time emulated battery power can be used to estimate in-house electric machine test beds, heavy-duty hybrid vehicle power pack tests, etc. after correlating actual pack test data and HIL simulations.

The BIL [5] requires an actual battery pack to measure battery pack voltage, current, etc. In this study, battery pack voltage, currents, SOC and pack temperature can be emulated by integrated battery cell model, a thermal model and BMS controls by instantly configuring chemistry along with battery pack configuration such as cell capacity, number of cells in series/parallel, coolant type, etc.

Battery Pack Model

The Battery Pack Model in ALPHA consists of a two-time constant equivalent circuit cell model, a battery thermal model, and battery management system controls (BMS). Accurate SOC and discharge and charge power limits are required to precisely estimate available traction motor power and torque.

Equivalent Circuit Cell Model

A two-time constant equivalent circuit model [6, 7] was applied to calculate terminal voltages of a lithium-ion polymer cell, and battery pack voltages were calculated by multiplying the number of cells in series within the battery pack.

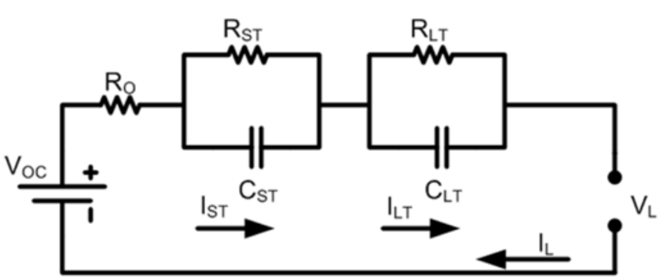

Figure 1. Battery Equivalent Circuit Cell Model

In Figure 1, the Voc is open circuit voltage of a battery cell, R_O is an ohmic resistance of a battery cell, and is dependent on SOC and cell/pack temperatures. R_{ST} and C_{ST} are resistances and capacitances of electro-magnetic short time double layer effects respectively. R_{LT} and C_{LT} are resistances and capacitances of electro-chemical long time mass transport effects respectively. I_L is battery cell load current, and discharge current is positive while a negative current is in charging mode.

Battery cell terminal voltage, V_L, can be calculated by using a typical RC circuit equation (1).

$$V_L = V_{OC} + I_L * R_O + \int (I_L - I_{ST})/C_{ST}\, dt + \int (I_L - I_{LT})/C_{LT}\, dt \tag{1}$$

where $I_{ST} = V_{ST}/R_{ST}$ and $I_{LT} = V_{LT}/R_{LT}$.

Equation (1) was implemented by using Matlab/Simulink block diagrams [4].

Battery pack voltage, V_{Batt}, was calculated by using the following equation.

$$V_{Batt} = V_L * N_{series}/N_{parallel} \tag{2}$$

where N_{series} is the total numbers of cells in series connection and $N_{parallel}$ is the number of modules in parallel connection.

Battery pack voltages, V_{Batt}, and Battery pack currents, I_L, were obtained during battery HIL development and validation processes from BMS CAN communications.

Battery Thermal Model

The lumped capacitance battery thermal model [9] in ALPHA was developed to feed battery pack temperature information to the battery voltage block, battery power limit control block, and BMS control strategies.

The battery pack temperature was calculated by using the energy balance between battery heat generation, Q_{ees_gen}, and heat loss, $Q_{ees\_cooling}$, while taking into consideration the thermal mass of the battery pack and the cooling agent.

$$T_{ees} = \int_0^t \frac{(Q_{ees\_gen} - Q_{ees\_cooling})}{m_{ees} C_{p,ees}} dt + T_0 \tag{7}$$

where m_{ees} is the mass of battery pack electric energy storage system, T_0 is the initial pack temperature, and $C_{p,ees}$ is battery heat capacity [8].

The battery heat generation, Q_{ees_gen}, is calculated by

$$Q_{ees\_gen} = I_L * R_{Batt}{}^2 + (1 - \text{charge efficiency}) * I_L * V_{Batt} \tag{8}$$

The battery pack resistance, R_{Batt}, is obtained by

$$R_{Batt} = (R_O + R_{ST} * I_{ST}/I_L + R_{LT} * I_{LT}/I_L) * N_{series}/N_{parall} \tag{9}$$

where R_O is the battery cell discharging or charging resistance. The cell resistance, R_O, is estimated by using a 2-dimensional discharging look-up table when battery current is positive, and by using the charging resistance for negative battery current.

The battery heat loss, $Q_{ees\_cooling}$, is calculated by

$$Q_{ees\_cooling} = (h\, A_s + kt)(T_{ees} - T_{coolant}) \tag{10}$$

where $T_{coolant}$ is battery pack inlet coolant temperature which, depending on pack configuration, can be the temperature of ambient air, cabin-conditioned air or liquid water coolant. A_s is the battery surface area for convection heat transfer and t is the thickness of the battery pack for heat transfer via conduction.

Lithium-Ion Battery HIL Development

Data-driven hybrid approach modeling is practical when estimating sophisticated electro-chemistry battery pack voltage, current and temperature by combining physics based equations and look-up table based cell test data. As shown in Figure 1, the open circuit voltage (OCV), and cell resistances are required, and therefore they are implemented by using 2-dimensional Matlab/Simulink lookup tables.

As shown in Figure 2, averaged OCV values of iron-phosphate based and manganese based lithium-iron cells are implemented by using two lookup tables due to different cell chemistries. The OCV from a lithium iron-phosphate cell is relatively flat. The averaged OCV values are implemented even though the charging side OCV cell voltage is about 0.1V higher than that of the discharging side OCV cell voltage.

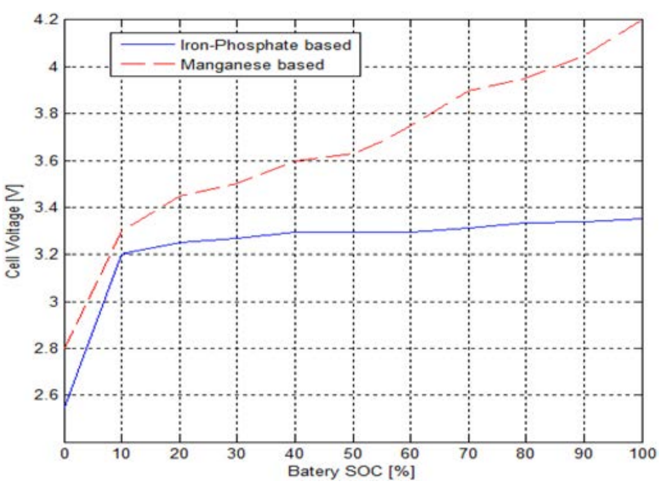

Figure 2. Typical Open Circuit Voltage (OCV) of Lithium-Ion Battery Cells

The discharge and charge power limits are constrained to not over-discharge or over-charge battery cells at the given SOC level. Maximum current slew rates, maximum discharging and charging current limits are also required to protect battery cells.

The averaged values of discharging and charging power limits are implemented by using 2-dimensional lookup tables respectively. In Figure 3, charging power limits are presented by negative numbers while positive values are used for discharging power limits.

As shown in Figure 4, discharging power limits are increased at optimum battery pack temperature areas such as 30°C at the same SOC level. The discharging power limits are also increased at a higher SOC level at the same battery pack temperature. On the other hand, the charging power limits are decreased at a higher SOC level not to over-charge battery cells when the SOC approaches 100%.

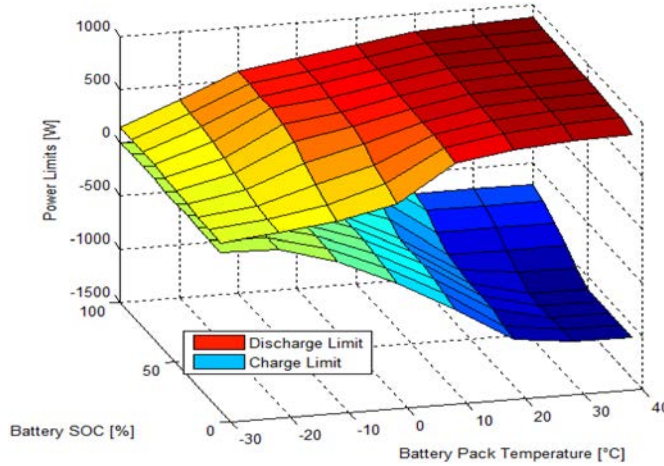

Figure 3. Averaged Discharge and Charge Power Limit Surfaces of a Lithium Iron-Phosphate Battery Cell

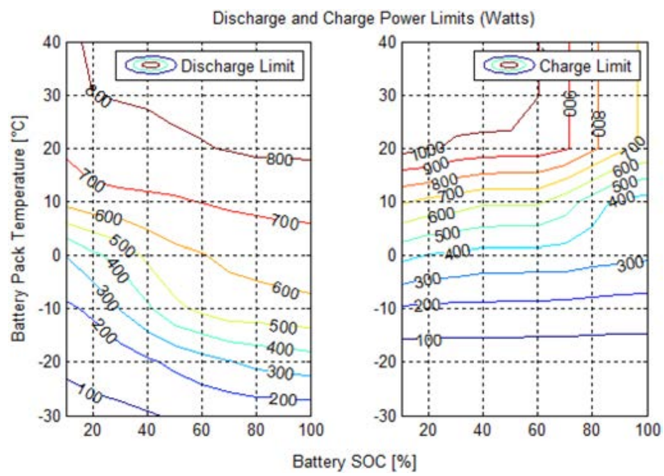

Figure 4. Averaged Discharge and Charge Power Limit Contour Plots of a Lithium Iron-Phosphate Battery Cell

As shown in Figure 5, charging internal resistances are much higher than discharging internal resistance at the very low battery pack temperatures from −40°C to −10°C. The discharging and charging resistances are similar as pack temperatures approach 20 °C.

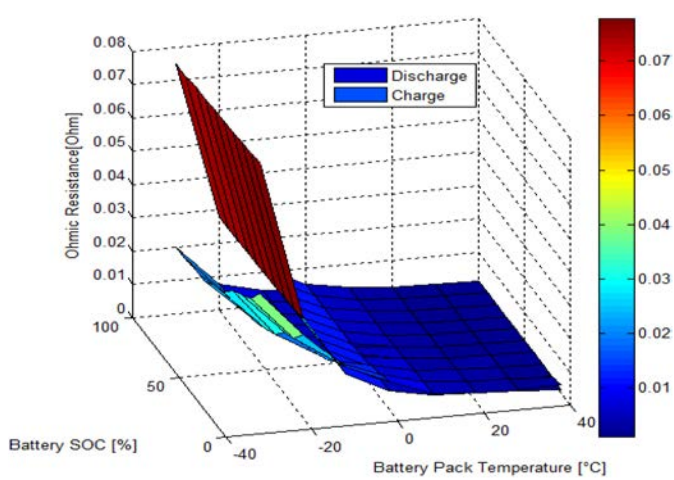

Figure 5. Averaged Discharge and Charge Resistance Surfaces of Lithium-Ion Battery Cells

Lithium-Ion Battery HIL and BIL Settings

As shown in Figure 6, the battery HIL system consists of a battery cycler, test automation system, lithium-ion battery model and vehicle model, and a liquid battery cooler. An actual battery pack is needed to validate battery HIL emulations by simultaneously comparing battery pack test data and HIL outputs. Any sufficient DC power supply can be used as a battery cycler although an Aerovironment AV-900 battery cycler was used in this particular study. A 22.8 kWh 60Ah A123 EV/PHEV energy battery pack was used to validate the HIL emulated battery pack voltage, current, SOC and pack temperature while cycling Nissan Leaf and GM Volt battery power profiles during UDDS, highway and US06 drive cycles. A liquid battery cooler was also used to simulate in-vehicle battery pack temperatures by controlling coolant flow rates and coolant temperature.

Figure 6. EPA NVFEL Battery Test Facility Hardware-In-Loop (HIL)

As shown in Table 1, a 22.8 kWh 60Ah A123 energy battery pack was used to measure battery pack performance by cycling Nissan Leaf and GM Volt power profiles. The power profiles were obtained from 2012 Nissan Leaf EV and 2012 GM Volt EREV (Extended Range EV) ANL (Argonne National Laboratory) dynamometer test data [9, 10].

Table 1. Battery Pack Specifications of A123, Nissan Leaf and GM Volt

Battery Pack	A123 EV/PHEV Energy Pack	Nissan Leaf EV Pack	GM Volt EREV Pack
Cell nominal Voltage (V)	3.3	3.8	3.7
Pack Capacity	60 Ah, 22.8 kWh	66.2 Ah, 24 kWh	45 Ah, 16.5 kWh
Total Number of Cells	357	192	288
Pack Configuration	119 x 1S3P	96 x 2S2P	96 x 1S3P
Cell Manufacturer	A123 - Iron-phosphate technology	AESC – nickel-manganese spinel lithium-ion chemistry	LG Chem – lithium-manganese spinel cells
Pack Cooling	Liquid Cooling	Passive Cooling	Liquid Cooling
Pack Weight (kg)	288	294	198

Battery pack test data such as voltage, current, SOC and temperature were collected using an AVL Lynx test automation system in this particular study.

An in-house EPA lithium-ion battery cell model, thermal model and BMS controls [1] were implemented in the HIL vehicle simulation environment to emulate battery pack performance. Nissan Leaf EV and Toyota Prius PHEV vehicle models will be developed in the near future in addition to EPA's existing 2010 Toyota Prius HEV and 2011 Hyundai Sonata P2 parallel hybrid models [3].

Figure7. A 22.8 kWh A123 Energy Battery Pack at EPA NVFEL Battery Test Facility

Battery pack voltage, current, power, SOC and pack temperature were collected using the built-in BMS CAN in the A123 battery pack as shown in Figure 7. Initial SOC of a real battery pack and HIL model were synchronized based on BMS CAN communication to emulate proper battery voltages and currents from the beginning stages of testing.

HIL (Hardware-In-Loop) Simulation

The BTF battery HIL simulation platform consists of the ALPHA vehicle model, a hybrid/EV e-machine, a battery pack emulator, and a vehicle system controller. The battery pack and HIL battery emulated voltage, current and SOC are displayed as shown in the Figure 8.

Figure 8. Battery Test Facility HIL Test Automation System

For HIL emulation, the ALPHA vehicle model can be used to estimate a demanded battery power for the battery cycler. For the validation, ANL battery power profiles were used to request a demanded battery power to an AV-900 battery cycler.

Open circuit voltage (Voc) and ohmic resistance (R_O) of a battery cell as shown in Figure 1 were implemented by using averaged values of test data. They are dependent upon SOC (State of Charge) and cell temperatures. Look-up table based discharge and charge power limits were also implemented as a function of SOC and cell temperature. Those look-up table data (Voc, Ro, discharge and charge power limits) were obtained from public information/the cell manufacturers when the battery pack support contract were purchased. For an iron-phosphate based lithium-ion cell technology, charging open circuit cell voltage is usually about 0.1V higher than that of discharging cell open circuit voltage at the same SOC level. Due to cell to cell SOC variations, cell voltage differences were observed to be about 0.015V even in the same discharging or charging event. During rapid charging of the A123 pack from 20% SOC to 85% SOC, cell to cell temperature difference also varied from 1.5 to 4°C due to uneven cell coolant flow, coolant temperature variations, etc. Therefore, averaged values of charging and discharging open circuit voltage at a given SOC were used in this study.

DOE (Design of Experiment) based experiments were performed to optimize the pre-calibrated values [1] of short and long time resistances (RST and RLT) and capacitances (CST and CLT) shown in Figure 1 by minimizing the objective function of RMS (Root Mean Square) voltage differences over complete drive cycles. The DOE based calibration is not necessary if short and long time resistance and capacitance values of test data are available.

Using Nissan Leaf EV UDDS drive cycle power profiles, 395.2V of the emulated RMS pack voltage was within 0.1% of the measured 395V RMS pack voltage test data. Overall, the emulated pack voltage and battery power shown in Figure 9 were in excellent agreement with those of the actual A123 battery pack test data.

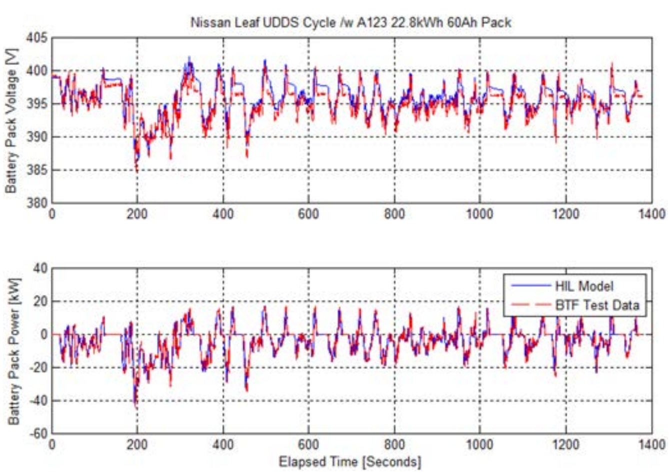

Figure 9. Battery Pack Voltage of Nissan Leaf Emulation during UDDS Cycle

As shown in Figure 10, the emulated battery SOC were also in excellent agreement with the real battery pack test data. The final SOC of the real battery pack was 79% while emulated SOC was 79.3%. The battery SOC in the real battery pack was updated by 0.5% increments due to the BMS SOC resolution. The emulated and tested RMS currents from the UDDS cycle shown in Figure 10 are 23.85A and 23.82A respectively. The pack temperatures between an emulated and a real battery pack were within 0.5 °C degrees. The Pack temperature of the real battery pack remained a near constant 24.5°C during entire UDDS cycle. The pack temperature of the real battery pack was slowly updated in 0.5°C increments through the BMS CAN.

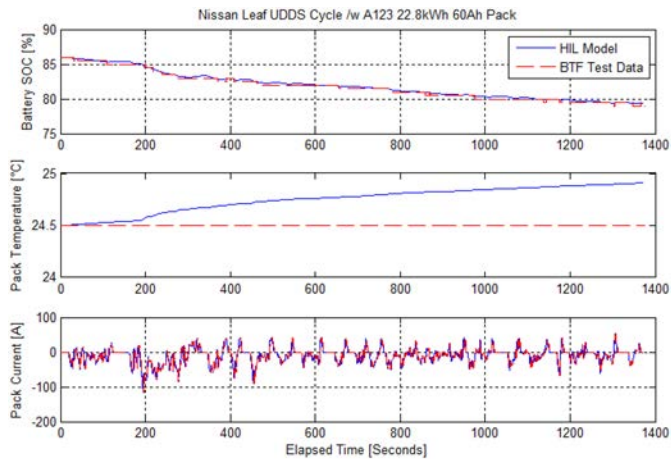

Figure 10. Battery Pack SOC and temperature of Nissan Leaf Pack Emulation during UDDS Cycle

The HIL simulated battery pack voltages shown in Figure 11 are in good agreement with the pack voltage of the actual A123 battery pack test data when cycling ANL power profiles during the highway drive (HWFET) cycle. The 389.7V emulated RMS pack voltage is within 0.2% of the 390.3V RMS pack voltage test data.

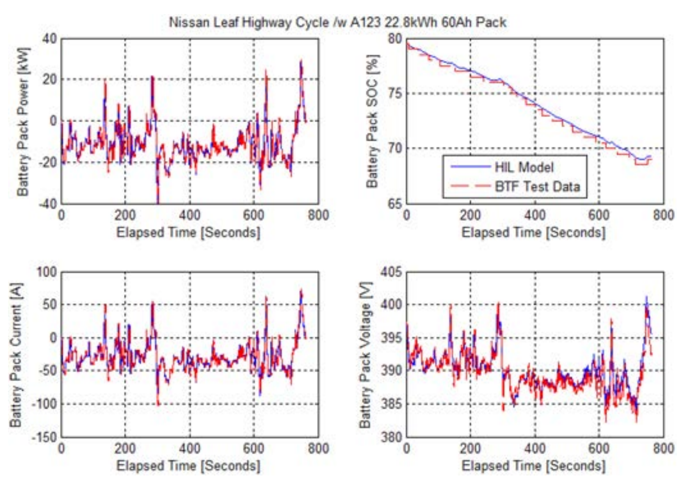

Figure 11. Battery voltage, Current and SOC of Nissan Leaf Pack Emulation during Highway Drive Cycle

The final SOC of the real battery pack was reduced about 10.5% from an initial 79.5% SOC during the highway driving cycle. The final SOC and HIL simulated SOC were almost identical. The approximately 36A RMS current during the highway drive cycle was much higher than the 24A RMS current from the UDDS drive cycle when emulating the Nissan Leaf EV pack.

The 384.4V emulated RMS pack voltage was within 0.2% ranges of the 383.7V RMS pack voltage test data.

The final SOC of the real battery pack was reduced approximately 12% from the initial 62.5% SOC over the US06 driving cycle. The final SOC and HIL simulated SOC differences were 0.2%. The approximately 71A RMS current of the aggressive US06 drive cycle was much higher than the 36A RMS current of the highway drive cycle. Only 1.5% SOC usage window differences were found between the highway cycle and the US06 cycle due to the large capacity of the 60Ah energy battery pack used and emulated in this study. The SOC usage differences would be much larger if using a smaller capacity battery pack such as an HEV battery power pack with 5.5Ah or 6Ah capacity. Overall, the HIL simulated battery pack voltages shown in Figure 12 were in excellent agreement with the pack voltage test data from the actual A123 battery pack even cycling through the very aggressive US06 power profiles.

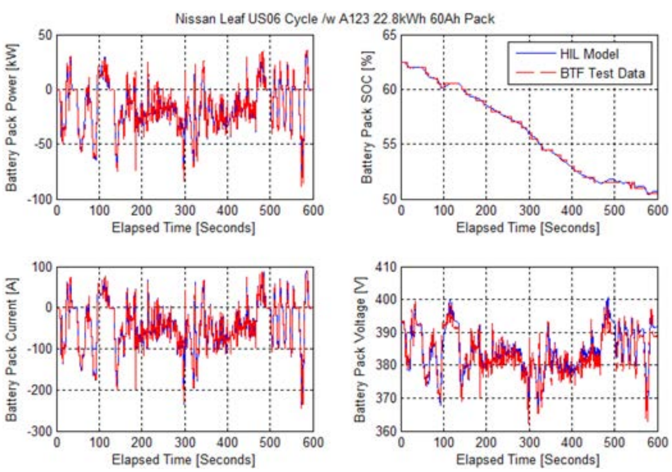

Figure 12. Battery voltage, Current and SOC of Nissan Leaf Pack Emulation during US06 Drive Cycle

After validating the model using the Nissan Leaf EV power profile with the 22.8kWh 60Ah A123 energy pack, the same short and long time resistance and capacitance look-up table values were used without any further calibation while cycling GM Volt ANL power profiles.

Upon cycling GM Volt ANL UDDS cycle power profiles to the A123 energy pack, the emulated 395.5V RMS pack voltage was within 0.1% of the 395.4V RMS pack voltage test data. Overall, the emulated pack voltage and battery power shown in Figure 13 were in outstanding agreement with those of the real A123 battery pack test data.

As shown in Figure 14, the emulated battery SOC was in excellent agreement with the real battery pack test data. The final SOC of the real battery pack and HIL SOC appear exactly identical at 77.5% since BMS SOC was updated in 0.5% increments. The final SOC was reduced by 7% from the initial 84.5% SOC during the UDDS drive cycle. The final SOC was also reduced by 7% from the larger 24kWh 66.2Ah Nissan EV pack UDDS power cycling. The 294 kg Nissan Leaf EV pack is significantly heavier and has higher capacity than the 198kg, 16.5kWh 45Ah GM EREV pack.

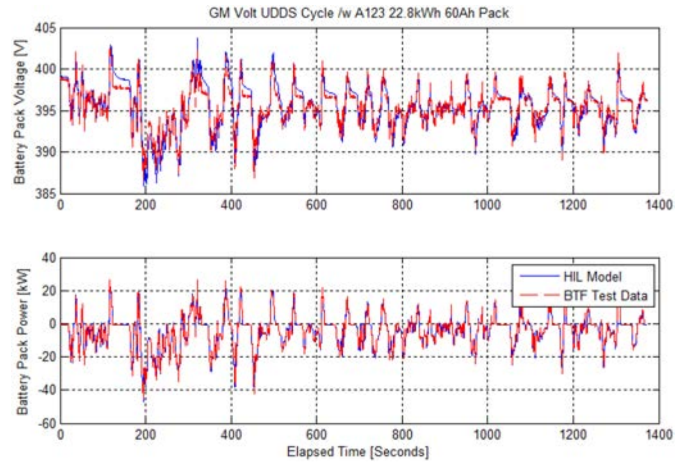

Figure 13. Battery Pack Voltage of GM Volt Pack Emulation during UDDS Cycle

The emulated and tested RMS currents of the UDDS cycle shown in Figure 14 were 26.39A and 26.34A respectively. The RMS current of GM EREV pack was greater than that of Nissan Leaf EV pack since 1715 kg vehicle weight of GM volt EREV is heavier than 1521kg vehicle weight of the Nissan Leaf EV. The pack temperatures of the HIL emulation and the A123 battery pack were approximately 27°C. The pack temperature of the real battery pack was again changed by 0.5°C increments through the slower BMS CAN update.

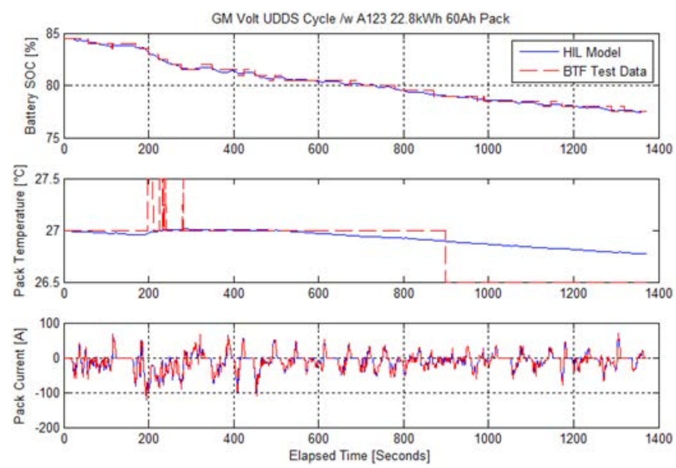

Figure 14. Battery SOC, Pack Voltage of GM Volt Pack Emulation during UDDS Cycle

The HIL simulated battery pack voltages shown in Figure 15 were in good agreement with the pack voltage of the A123 real battery pack test data while cycling ANL power profiles during the highway drive cycle. The emulated RMS pack voltage of 390.0 V was within 0.1% of the 389.9V RMS pack voltage test data.

The final SOC of the real battery pack was reduced about 21.5% from an initial 84.5% when running two highway driving cycles. Therefore, about 10.75% SOC was reduced when running a single highway cycle ANL GM Volt power profile. The 38A RMS current over the highway cycle was again higher than 27A RMS current over the UDDS drive cycle.

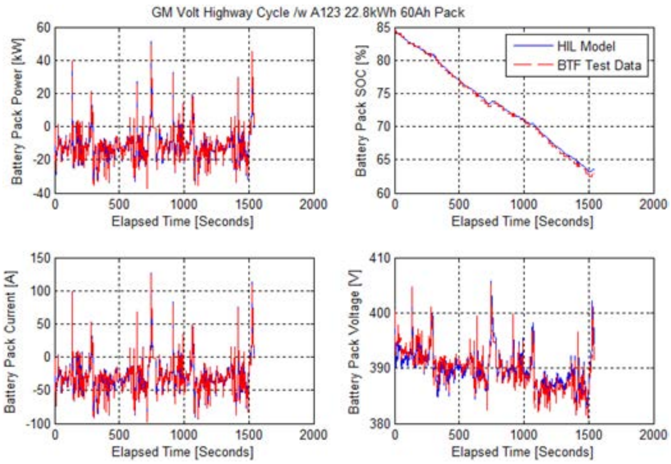

Figure 15. GM Volt Pack Voltage, Current, SOC HIL Simulations in 2 × Highway Drive Cycles

As shown in Figure 16, the final SOC of the real battery pack was reduced about 22.5% from 85.5% of the initial SOC during the two US06 driving cycles. The final SOC and HIL simulated SOC difference is 0.4% when cycling two US06 ANL power profiles. The 75A RMS current of the aggressive US06 drive cycle was much higher than 38A RMS current of highway drive cycle. The HIL emulated RMS pack voltage of 388.7 was within 0.2% ranges of the 389.3V RMS pack voltage test data. Overall, the HIL simulated battery pack voltages and pack test data were in excellent agreement.

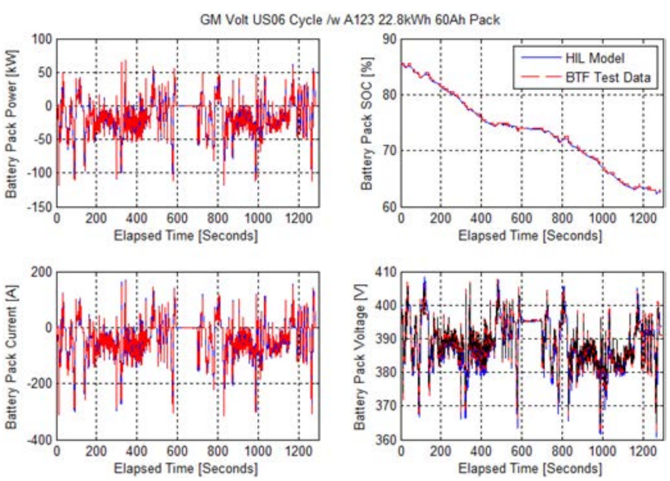

Figure 16. GM Volt Pack Voltage, Current, SOC HIL Simulations in 2 × US06 Drive Cycles

As shown in Table 2, the battery HIL simulated battery pack voltage, current, pack temperature, and SOC of the Nissan Leaf Pack Emulation were excellent agreement with those of the A123 battery pack test data. Without any further calibrations or "tweaking", the HIL simulated and pack test data as shown in Table 3 were in excellent agreement when applying GM Volt EREV ANL power profiles.

The two time constant equivalent circuit battery model can be useful even in new cell development and cost reduction estimation as long as good and reliable values of ohmic resistance, open circuit voltage, short and long time resistance and capacitance and discharge/charge power limits can be identified.

Table 2. Battery pack RMS voltage, RMS current, RMS temperature of Nissan Leaf EV Battery Pack Emulation

Drive Cycle	SOC initial/final [%]	RMS voltage [V]	RMS current [A]	RMS pack temperature [°C]	Test/HIL
UDDS	86/79	395	23.82	24.5	Test
	86/79.3	395.2	23.85	24.93	HIL
Highway	79.5/69	389.7	36.18	24.54	Test
	79.5/69.3	390.3	36.16	24.89	HIL
US06	62.5/50.5	383.7	71.12	25.62	Test
	62.5/50.7	384.4	71.05	25.14	HIL

Table 3. Battery pack RMS voltage, RMS current, RMS temperature of GM Volt EREV Battery Pack Emulation

Drive Cycle	SOC initial/final [%]	RMS voltage [V]	RMS current [A]	RMS pack temperature [°C]	Test/HIL
UDDS	84.5/77.5	395.4	26.34	26.84	Test
	84.5/77.5	395.5	26.39	26.92	HIL
Highway	84.5/63	389.9	37.68	24.19	Test
	84.5/63	390.0	37.7	24.16	HIL
US06	85.5/63	389.3	74.92	28.02	Test
	85.5/62.6	388.7	75.22	27.10	HIL

Summary/Conclusions

A two-time constant equivalent circuit battery cell model along with a lumped capacitance thermal model and BMS control strategies were implemented in the battery pack model of the ALPHA tool. The battery model was used within the NVFEL Battery Test Facility HIL environment to simultaneously run the battery HIL model and a real battery pack to validate the battery model using regulatory drive cycle power profiles. An excellent agreement between the battery HIL and the real A123 battery pack test data was achieved. All of the battery models validated in this work will be placed into the public domain.

In addition to providing additional evidence of the validity and usefulness of equivalent circuit modeling, this result validates the EPA ALPHA model in its approach to modeling the performance of commercially representative EV/PHEV battery packs under duty cycles relevant to light-duty EV/PHEVs and particularly with respect to the chemistry and general pack configuration represented by the 22.8 kWh A123 Energy Pack.

The look-up table based OCV, internal resistances and discharge/charge power limits in the battery pack model can be easily updated from cell manufacturers or from published literature for subsequent lithium-ion battery cell chemistry performance studies and evaluations.

The data-driven battery pack HIL model and tools can be applied to in-house e-machine testing and development, heavy duty hybrid power pack testing, etc. without purchasing a variety of different battery packs.

A significant cost savings and testing time reduction can be achieved by not having to interpret the battery management systems, CAN signals, and other interfaces for different vehicle manufacturers. HIL based fuel economy and greenhouse gas emission estimations are feasible by accurately emulating battery pack voltage, power, current, SOC, etc. for testing e-machines as well as for performing real-time HIL vehicle simulations by having the ability to select a cell chemistry along with a battery pack configuration such as cell capacity, number of cells in series/parallel, coolant type, etc.

The battery HIL model was validated with 2012 Nissan Leaf EV and 2012 GM Volt ANL power profiles for the UDDS, highway and US06 cycles.

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