Lithium-ion Battery Safety Tests monitored by LabVIEW and Comsol software for electrical and mechanical characteristics.

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This paper presents a unique cheaper battery safety test bench for electrical and mechanical performance evaluation of lithium-ion batteries where mechanical performance is tested using software and electrical characteristic is tested using hardware. In this work, simulation of mechanical performance of lithium-ion battery such as thermal modelling test at various temperature has been carried out using Comsol software, where battery voltage and temperature are monitored as a control input during a drive cycle and state of charge of the battery on the positive (65-80%) and a negative electrode (14-29%) is monitored and triggered as a control output. A hardware test bench has been developed to execute various electrical tests for evaluating battery performance during a discharge cycle. These electrical tests have been carried out on the LabVIEW software to obtain real-time data and display the battery related information such as voltage and current curves. Further, a battery safety test like external short circuit test has been performed and also for improving the battery efficiency capacitors are connected parallelly with varied load condition. Overall, in this exploration, a newly evolved, accurate, affordable battery testing and monitoring system has been developed.

Keywords: LabVIEW Software, Comsol Software, Battery Safety test, Electrical Test, Mechanical Test

1. INTRODUCTION

From the last few decades, the lithium-ion battery has gained so much attention due to its miscellaneous advantage in the energy storage area because of high capacity, high energy or high power, long cyclability, low memory effect, and low environmental effect¹. In general, the batteries in today's world are not only for portable electronics but it also moves towards a large scale electricity storage on smart grids, the automotive industry in terms of electric vehicles (EVs)², aerospace engineering, communication, back-up, and many more³. Hence, battery technology usage increases rapidly in a wide area for future prospects². So, we focused on lithium-ion batteries but we all know that these are very dangerous and complicated for experiment purpose⁴. So for making these batteries more reliable and safe, the battery test is performed for determining the battery characteristics⁵.

In this paper, we present two types of battery characterization techniques i.e. mechanical and electrical characterization. Mechanical characterization techniques have obtained through Multiphysics Software. In this simulation, experimental data was

used to design a Multiphysics based theoretical model for optimizing the battery drive cycle performances⁶. This model setup includes some physical, thermal and electrical properties and then optimized the mechanical results such as polarization test, thermal test (local temperature), drive current and voltage of the battery during the drive cycle⁷. Hence, we propose a computational technique to diagnose the battery characteristics directly through software without any environmental degradation⁸.

Further, electrical characterization techniques have been analyzed on the data acquisition software i.e. LabVIEW by providing interfacing between hardware and software system⁹. Initially, a hardware prototype for testing a lithium-ion coin cell battery has been designed with the help of a simple electronic circuit. This hardware prototype was interlinked with data acquisition software through NI-6001 DAQ card¹⁰. DAQ card provides a basic function for voltage measurement and transferred hardware data to the real-time LabVIEW software for data analysis. The aim of these experiments is to optimize the current and voltage passed within the circuit during discharge condition and also for performing other safety tests.

Further, this paper is demonstrated as follows. Section 2 describes the model formulation of the lithium-ion battery and also explains the experimental setup in brief. In section 3, mechanical and electrical results are presented with the help of different software. Hence, the paper is summarized with the conclusion in section 5.

2. MODEL GEOMETRY AND FORMULATION

2.1 Lithium-ion battery model formulation

Computational analysis has been performed for this 1D model geometry. In this simulation study, we optimized the battery behavior for an electric vehicle in which we focused on three critical components i.e. specific drive cycle of the vehicle, temperature, and voltage of the battery¹¹. These all three parameters have been monitored and act as an input to the control unit. This monitoring unit helps to demonstrate the state of charge (SOC) of the battery and also decides the battery charging (full) and discharging (empty) condition.

Firstly, the lithium-ion battery model has been formulated on the COMSOL software¹². In this battery, lithium manganese oxide (LiMn_2O_4) is used as a positive electrode and graphite as a negative electrode. These both electrodes were separated with the help of separator (microporous polypropylene sheet Celgard 2400) and filled with liquid electrolyte (LiPF_6 EC:DMC-1:1 ratio) for the movement of ions during charging and discharging process. Furthermore, the outside layer of both positive and negative electrodes was connected with the current collector (CC) made up of aluminum and copper material.

In this formulation, firstly, we focused on the thermal characterization of the material, it has been analyzed by utilizing a heat transfer in the solid interface over a 1D geometry. In 1D geometry, a flat prismatic battery has been taken and allows heat transportation only in one direction. There were two conditions in the prismatic battery for characterized the thermal behavior i.e. thermal insulation and convective heat flux condition. Initially, we set the thermal insulation in the leftmost boundary of the battery which also represents the center of the battery. Similarly, heat flux condition is set in

the rightmost boundary which represents the heating surface of the battery. For air cooled the battery, the heat transfer coefficient is also applied roughly on the boundaries of the battery i.e. $10 \text{ W/(m}^2\text{.K)}$. There are some other parameters discussed in Table. I for thermal characterization techniques of the 1D battery model.

TABLE. I Thermal Properties For 1d Battery Model

Parameters	LiMn ₂ O ₄	Graphite	LiPF ₆	Aluminum CC	Copper CC
Thermal Conductivity(W(m.k))	3.4	1	0.15	400	238
Young Modulus (Pa)	4.9×10^9	4.1×10^9	-	110×10^9	70×10^9
Density (Kg/m ³)	3600	2260	940	8960	2700
Heat Capacity(J/Kg.k)	2500	881	1046	385	900

Additionally, a current load has analyzed for driving an electric vehicle. Hence, we imported a drive cycle data which contains C-rate vs time for this lithium-ion battery model. This drive cycle data may vary up to 20C, and 1C equal to 12A.

2.2 Lithium-ion battery model parameters

The model assembly has certain other parameters, which have been taken from research papers and parameters for designing a coin cell such as electrode thickness, the total thickness of the cell and many more are taken from a research laboratory. These are the operational parameters for simulation analysis. However, these can be changed according to the requirement of simulation analysis. These were the maximum number of parameters that identified theoretically in the lithium-ion battery model and further, other parameters were demonstrated in Table. II Moreover, the stoichiometry of both positive and negative electrode transfer coefficient and the electrolyte charge transfer coefficient have been taken as a known parameter from the literature. These physical properties are explained and optimized according to the simulation analysis. In the next section, the simulation results will be investigated and calculated.

TABLE. II Measured And Identified Parameters For The Lithium-Ion Battery Model
Simulation

Parameter	Units	Value	Description
E _{cell}	V	3.9	Cell Potential
L _{tot}	m	1.42×10^{-4}	Cell total Thickness

eps _{l_sep}	-	0.4	Porosity of separator
T _{initial}	K	328	Initial Temperature
T _{final}	K	395	Final Temperature
Maximum electrode SOC	SOC _{max}	0.79	Operational SOC
Minimum electrode SOC	SOC _{min}	0.02	Operational SOC
Q _B	A·h	12	Battery Capacity
N _{layers}	-	25	No. of cell layers
kT _{batt}	$L_{batt}/(L_{pos}/kT_{pos}+L_{neg}/kT_{neg}+L_{pos_cc}/kT_{pos_cc}+L_{neg_cc}/kT_{neg_cc}+L_{sep}/kT_{sep})$	0.87451 W/(m·K)	Battery thermal conductivity
Rho _{batt}	$(\rho_{pos} \cdot L_{pos} + \rho_{neg} \cdot L_{neg} + \rho_{pos_cc} \cdot L_{pos_cc} + \rho_{neg_cc} \cdot L_{neg_cc} + \rho_{sep} \cdot L_{sep})/L_{batt}$	2189.3 kg/m ³	Battery density
Cp _{batt}	$(Cp_{pos} \cdot L_{pos} + Cp_{neg} \cdot L_{neg} + Cp_{pos_cc} \cdot L_{pos_cc} + Cp_{neg_cc} \cdot L_{neg_cc} + Cp_{sep} \cdot L_{sep})/L_{batt}$	1391.8 J/(kg·K)	Battery heat capacity
C	-	1	C-rate factor

3. OVERVIEW OF EXPERIMENT

For an electrical characterization of coin cell lithium-ion battery, we have to prepare a simple electronic circuit in which Li-ion battery bank has connected for optimizing the discharge curves with the help of commercial software i.e. LabVIEW.

3.1 Materials and equipment

For these experiments, we have six coin-cell batteries (max 3.5V) which are fabricated in a research laboratory, variable resistance (0-500 ohm), motor as a load, capacitors, three switches, wires, a protoboard, a digital multimeter, a personal computer connected with National Instrument 6001 DAQ card and commercial software LabVIEW with updated version¹¹.

3.2 Experiment setup

In this hardware, three electrical tests were performed for optimization of different types of discharge curves. figure. 1 represents a schematic circuit diagram of the hardware prototype in which, we demonstrate a circuit according to the test. Therefore, there were three working conditions in this hardware, firstly when switch SW1, SW4 is closed for monitoring the potential drop across the battery terminal as well as current passes across the resistor is measured through DAQ card channels with respect to time. In the second condition, Switch SW1, SW2 is closed for analyzing a short circuit current across the resistor through an analog input channel 2. Lastly, Switch SW1, SW3, SW4 are closed for monitoring the battery characteristics, when the capacitor bank is connected parallel across the circuit.

Fig. 1 Circuit for Hardware Prototype

When the voltage signal passes across the variable resistor terminals, then data has been recorded by two different input channels of the NI-6001 DAQ card ¹³ and further this device make connection to the PC for automatic data acquisition¹⁴.

Fig. 2 Demonstrates the discharge curve on the LabVIEW Front Panel

We use LabVIEW software for data acquisition which helps to optimize the real-time physical data across various load conditions¹⁴. There are different in-built functions in this software such as logic components, graphics, a mathematical function, and many data acquisition icons which helps to perform automated measurements¹⁵. For writing a program we have two different panels on this software, one is a front panel which helps as an interface between the hardware and the PC¹⁶. It also helps for modifying the experimental condition and introduce virtual information across the panel i.e. it is called a virtual instrument (VI). The front panel helps to introduce the parameters of the hardware circuit such as voltage, current, resistor, experiment time and a number of channels used for recording the data. The second panel is used for designing a block diagram and also provide a proper platform for writing a program by using various icons and connectors. Figure. 2 demonstrates the discharge curve on a LabVIEW front panel.

Fig. 3 Block Diagram of VI front panel

In figure. 3, we represent a block diagram for this VI front panel. This panel controls the sequence of execution and also use the LabVIEW sequence structure. Firstly, we

acquire the data points at the desired voltage channel and then we have to construct a time vector by using a loop structure at the desired rate. Lastly, before plotting a graph we have to separate the data array into two different vectors i.e. potential drop measured across the resistor and voltage signal. Figure. 4 represents a hardware prototype made up by 2032-coin cell Lithium-ion battery which was fabricated in a research laboratory.

Fig. 4 Hardware Prototype for Electrical Characterization

Hence, both the theoretical model and hardware prototype setup have certain parameters which can change according to the requirements. Furthermore, in this paper, the experimental and simulation setup has been used to optimize the battery characteristics¹⁷.

4. RESULT AND DISCUSSION

During battery characterization, the following tests have been performed to optimize the behavior of the Li-ion battery. All simulation results were analyzed at different boundary condition. Hence, all results were explained further with brief descriptions.

4.1 Mechanical Characterization

In this characterization, we have designed a coin cell battery in which a heat source generator used to raise the temperature (30°C- 80°C) of the battery through the separator. In this model, the convective heat flux boundary condition was set using homogenized thermal material properties across the battery. Initially, the temperature was at a constant rate then it starts increasing slowly. Figure. 5 represents the surface temperature at the positive electrode CC during the drive cycle. In this result, the surface temperature accumulated the heat inside the cell which could lead the thermal runaway in a long time. If there would be a small variation in the temperature between surface and center then hot spots were reflected on the cell.

Fig. 5 Coin-Cell Surface Temperature

In figure. 6, plot represents the increase in temperature during the drive cycle. In this, the temperature of the battery on the surface as well as in the center of the coin cell had increased simultaneously otherwise it would lead to destroying the battery surface.

Fig. 6 Temperature of the Battery During Drive Cycle

During this thermal modeling, polarization characteristics of the coin cell battery have optimized because it gives an indication of internal resistance and it also explains the battery lifetime phenomenon. If there would be large polarization takes place across the battery than it reduces the battery life as well as cause heat generation. Hence, battery polarization should always be small. Figure. 7 represents the total polarization of the battery during the drive cycle.

Fig. 7 Total Polarization During Drive Cycle

After this thermal characterization, we have to analyze the battery charging characterization. Initially, the cell voltage varies between 3.6V to 2.5V due to the open circuit voltage. But after a certain time when the drive cycle starts at certain C-rate then the potential of the positive electrode in the lithium-ion battery varies slightly more the negative electrode of the battery¹⁸. Figure.8 (a) represents a Cell voltage during the drive cycle.

Fig. 8 (a) Cell Voltage during Drive Cycle

Fig. 8 (b) Drive Cycle Current on Load

Figure. 8 (b) represents the Drive Cycle Current on load. Battery voltage should always be in a limited range. Hence, we always operate a battery within a specified voltage span (4.2V to 3.3V) due to the battery safety concern.

4.2 Electrical Characterization

In this characterization, two types of test have been performed for monitoring the electrical performance of the battery bank i.e. short circuit test and battery bank connected parallel with a capacitor bank for improving the battery efficiency.

Short circuit test has been performed because it can be a major issue for real-time application because it provides high discharge current, a sudden drop in voltage and causes excess overheating. Figure.9 represents a short circuit test waveform, During this test, we monitored a sudden increase in current (500mA) across the resistor terminal of the battery. The resistor used in this test was very small i.e. 1.6 ohm and the potential drop across it was 0.9V. As there was a sudden sweep in voltage drop occurs across the battery due to a short circuit test.

Fig. 9 Short Circuit Test Waveform

Now, we monitored a current and voltage waveform during normal condition. In this circuit, the load was connected to a battery bank to optimize the discharge characteristics of the battery bank. During this test, the current across the resistor terminal is increased up to 80mA and then stable at 20mA. Similarly, a potential drop across the 24Ω resistor is 0.5V and battery bank potential is 7.4V. Figure. 10 represents the current and voltage waveform without capacitor bank.

Fig. 10 Current And Voltage Waveform Without Capacitor Bank

Further, the three capacitors of 220 microfarads were connected parallel to form a capacitor bank and this capacitor bank was also connected parallel with a battery bank to improve the battery efficiency. During this test, we monitored a sudden rise in current across the resistor i.e. 148mA as we see in the figure. 11 current and voltage waveform with the capacitor bank.

Fig. 11 Current And Voltage Waveform With Capacitor Bank

Hence, we optimized that as we connect a capacitor across the battery, then it provides high accelerating current across the circuit and then it becomes stable at 25mA. The voltage monitored across the battery bank was the same at 7.4V. So, It has been analyzed that the increase in current across the load would be delivered by a capacitor bank.

5. CONCLUSION

In this paper, theoretical and hardware simulation were successfully performed using Multiphysics COMSOL and LabVIEW software. We have performed two types of simulation for obtaining a mechanical and electrical characterization of a lithium-ion battery. In mechanical characterization, we optimized that Li-ion battery behavior during the drive cycle has good capacity and it has superior thermal behavior properties. Similarly, in electrical characterization test, we obtained a good electrical behavior of the Li-ion battery bank.

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