Internship Report

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Study and analysis of Li-ion battery and modelling the temperature effects as per Indian climatic conditions

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Abstract

It is evident that temperature variations inside a battery may significantly affect its performance, life, and reliability. In an effort to gain a better understanding of the heat generation in Lithium-ion batteries, a simple model was constructed in order to predict the thermal behavior of a battery pack. The Lithium-ion battery presents in this paper is Lithium Iron Phosphate ($LiFePO4$). The results show that the model can be viewed as an acceptable approximation for the variation of the ambient temperature at a continuous charge current from data provided by the manufacturer.

1. INTRODUCTION

1.1. Background

Electric and hybrid vehicle may present the most promising solution for pollution problems caused by the emission of conventional internal combustion engine. These technologies will highly depend on battery packs. The role of battery as the power source in electric drive vehicle is important. Due to the high energy density, Lithium-ion batteries have gained much attention as a viable candidate to increase vehicle range and performance of electric drive vehicle application. However, there is a variety of thermal limitations for Lithium-ion battery. Most common thermal issues related to Lithium-ion batteries are capacity/power fade, self-discharge, thermal runaway, pack electrical imbalance and cold temperature performance. The battery positive electrode and electrolyte chemistry is said to have an impact of capacity/power fading. Batteries also generate heat during charge and discharge due to enthalpy changes, electrochemical polarization and resistive heating inside the cell. Temperature variation inside the batteries can lead to uneven temperature distribution which creates uneven charge/discharge behavior within the pack. Worst cases, thermal runaway may occur in a cell when heat is not properly controlled and possible to cause fire and explosion. For these reasons, the need for battery thermal management is vital for electric and hybrid vehicles in order to keep the vehicle at its optimum performance. This paper provides an introduction on the theory and objectives of battery thermal management.

1.2. The Lithium-Ion Cell

1.2.1. Background

It was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium batteries followed in the 1980s but the endeavor failed because of instabilities in the metallic lithium used as anode material. Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest specific energy per weight. Rechargeable batteries with lithium metal on the anode (negative electrodes) could provide extraordinarily high energy densities. The inherent instability of lithium metal, especially during charging, shifted research to a non-metallic solution using *lithium ions*. Although lower in specific energy than lithium-metal, Li-ion is safe, provided cell manufacturers and battery packers follow safety measures in keeping voltage and currents to secure levels. In 1991, Sony commercialized the first Li-ion battery, and today this chemistry has become the most promising and fastest growing on the market.

In 2009, roughly 38 percent of all batteries by revenue were Li-ion. Li-ion is a low-maintenance battery, an advantage many other chemistries cannot claim. The battery has no memory and does not need exercising to keep in shape. Self-discharge is less than half compared to nickel-based systems. This makes Li-ion well suited for fuel gauge

applications. The nominal cell voltage of 3.6V can power cell phones and digital cameras directly, offering simplifications and cost reductions over multi-cell designs. The drawback has been the high price, but this leveling out, especially in the consumer market.
Advantages:

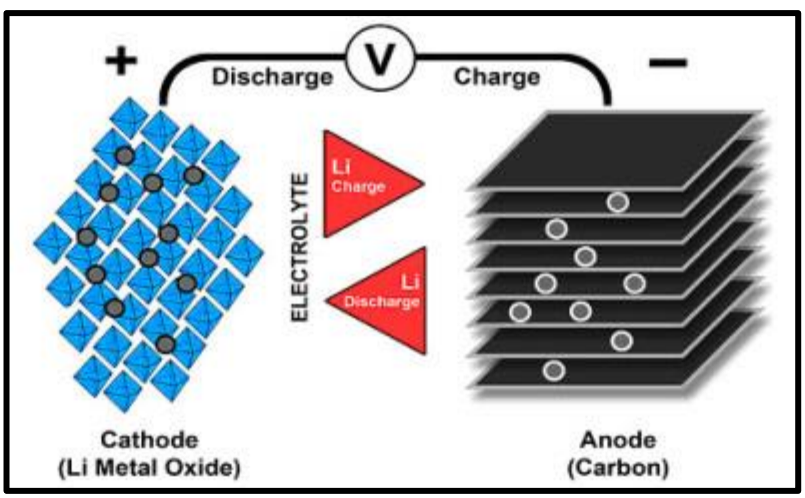
- High specific energy and high load capabilities with Power Cells
- Long cycle and extend shelf-life; maintenance-free
- High capacity, low internal resistance, good coulombic efficiency
- Simple charge algorithm and reasonably short charge times
- Low self-discharge (less than half that of NiCd and NiMH)

Disadvantages:

- Requires protection circuit to prevent thermal runaway if stressed
- Degrades at high temperature and when stored at high voltage
- No rapid charge possible at freezing temperatures (<0°C, <32°F)
- Transportation regulations required when shipping in larger quantities

1.2.3. Working

Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. (The anode of a discharging battery is negative and the cathode positive). The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. When the cell charges and discharges, ions shuttle between cathode (positive electrode) and anode (negative electrode). On discharge, the anode undergoes oxidation, or loss of electrons, and the cathode sees a reduction, or a gain of electrons. Charging reverses the movement.



1.3. The Lithium-ion Battery Model

1.3.1. Charging and Discharging Equations

In order to study the equations and properties of Lithium-Ion battery, a generic Lithium-ion battery model was used in MATLAB-Simulink and the same was used for further simulations.
For the lithium-ion battery type, the model uses the following equations:

- Discharge Model (i* > 0)

$$f_1(it, i*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

- Charge Model (i* < 0)

$$f_2(it, i*, i) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

In the equations:

- E_0 is the constant voltage, in V.
- K is the polarization constant, in V/Ah, or polarization resistance, in Ohms.
- $i*$ is the low-frequency current dynamics, in A.
- i is the battery current, in A.
- it is the extracted capacity, in Ah.
- Q is the maximum battery capacity, in Ah.
- A is the exponential voltage, in V.
- B is the exponential capacity, in Ah^{-1}.

1.3.2. The OCV-SOC Relation

The OCV of a battery cell denotes the potential difference between the positive electrode and the negative electrode when no current flows and the electrode potentials are at equilibrium.
The soc represents the ratio of the remaining capacity of the battery after a period of use or long-term suspension to its nominal capacity, it is nominal stated as the following equation:

$SOC(t) = SOC(t_0) - \frac{1}{C_N}\int_{t_0}^{t} \eta i(\tau) d\tau$

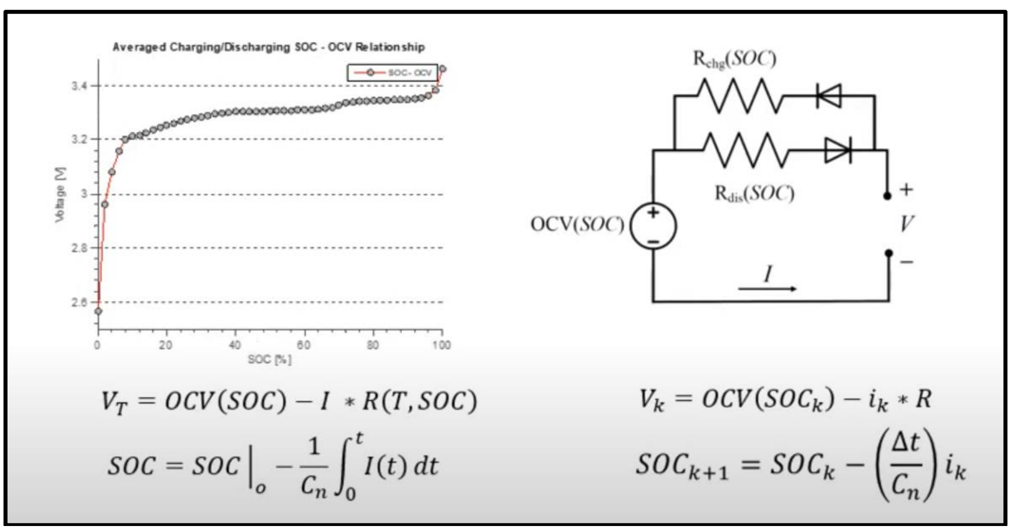
Where SOC (t_0) and $SOC(t)$ denote the initial and current value of SOC, respectively. C_N is the nominal capacity of the battery, i represents the current, $i > 0$ stands for discharge. η indicate charge and discharge efficiency of the battery. Eq. (1) can be converted to discrete format as follows:

$SOC_k = SOC_{k-1} - \frac{\eta T_s}{C_N} I_{k-1}$

In order to obtain the OCV-SOC relationship experimentally, first if you begin with a fully discharged battery and start charging it with very low c-rate, we obtain the open circuit voltage U_{OCV}, then ones we reach a fully charge state at 100% we start discharge the cell with the same low C-rate, we will see that the discharge curve is different from the charge curve, which mean that, for the same SOC level, the value OCVs cannot be the same during charging and discharging because of the hysteresis characteristic.

1.3.3. Coulomb Counting Method:

The coulomb counting method, also known as ampere hour counting and current integration, is the most common technique for calculating the SOC. This method employs battery current readings mathematically integrated over the usage period to calculate SOC values where SOC(k) is the initial SOC, Cn is the rated capacity, I_k is the battery current. The coulomb counting method then calculates the remaining capacity simply by accumulating the charge transferred in or out of the battery. The accuracy of this method resorts primarily to a precise measurement of the battery current and accurate estimation of the initial SOC. With a pre-known capacity, which might be memorized or initially estimated by the operating conditions, the SOC of a battery can be calculated by integrating the charging and discharging currents over the operating periods.



1.3.4. The temperature effects equations

For the lithium-ion battery type, the impact of temperature on the model parameters is represented by these equations:

- Discharge Model (i* > 0)

$$f_1(it, i*, i, T, T_a) = E_0(T) - K(T) \cdot \frac{Q(T_a)}{Q(T_a) - it} \cdot (i * + it) + A \cdot \exp(-B \cdot it) - C \cdot it$$

$$V_{batt}(T) = f_1(it, i*, i, T, T_a) - R(T) \cdot i$$

- Charge Model (i* < 0)

$$f_1(it, i*, i, T, T_a) = E_0(T) - K(T) \cdot \frac{Q(T_a)}{it + 0.1 \cdot Q(T_a)} \cdot i * - K(T) \cdot \frac{Q(T_a)}{Q(T_a) - it} \cdot it + A \cdot \exp(-B \cdot it) - C \cdot it$$

$$V_{batt}(T) = f_1(it, i*, i, T, T_a) - R(T) \cdot i,$$

with

$$E_0(T) = E_0|_{T_{ref}} + \frac{\partial E}{\partial T}(T - T_{ref})$$

$$K(T) = K|_{T_{ref}} \cdot \exp\left(\alpha\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

$$Q(T_a) = Q|_{T_a} + \frac{\Delta Q}{\Delta T} \cdot (T_a - T_{ref})$$

$$R(T) = R|_{T_{ref}} \cdot \exp\left(\beta\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right),$$

where:

- T_{ref} is the nominal ambient temperature, in K.
- T is the cell or internal temperature, in K.
- T_a is ambient temperature, in K.
- E/T is the reversible voltage temperature coefficient, in V/K.
- α is the Arrhenius rate constant for the polarization resistance.
- β is the Arrhenius rate constant for the internal resistance.
- $\Delta Q/\Delta T$ is the maximum capacity temperature coefficient, in Ah/K.
- C is the nominal discharge curve slope, in V/Ah. For lithium-ion batteries with less pronounced discharge curves (such as lithium iron phosphate batteries), this parameter is set to zero.

- The cell or internal temperature, T, at any given time, t, is expressed as:

$$T(t) = L^{-1}\left(\frac{P_{loss}R_{th} + T_a}{1 + s \cdot t_c}\right),$$

where:

- R_{th} is thermal resistance, cell to ambient (°C/W).
- t_c is thermal time constant, cell to ambient (s).
- P_{loss} is the overall heat generated (W) during the charge or discharge process and is given by

$$P_{loss} = (E_0(T) - V_{batt}(T)) \cdot i + \frac{\partial E}{\partial T} \cdot i \cdot T.$$

1.3.5. Limitations and Assumptions

Limitations:

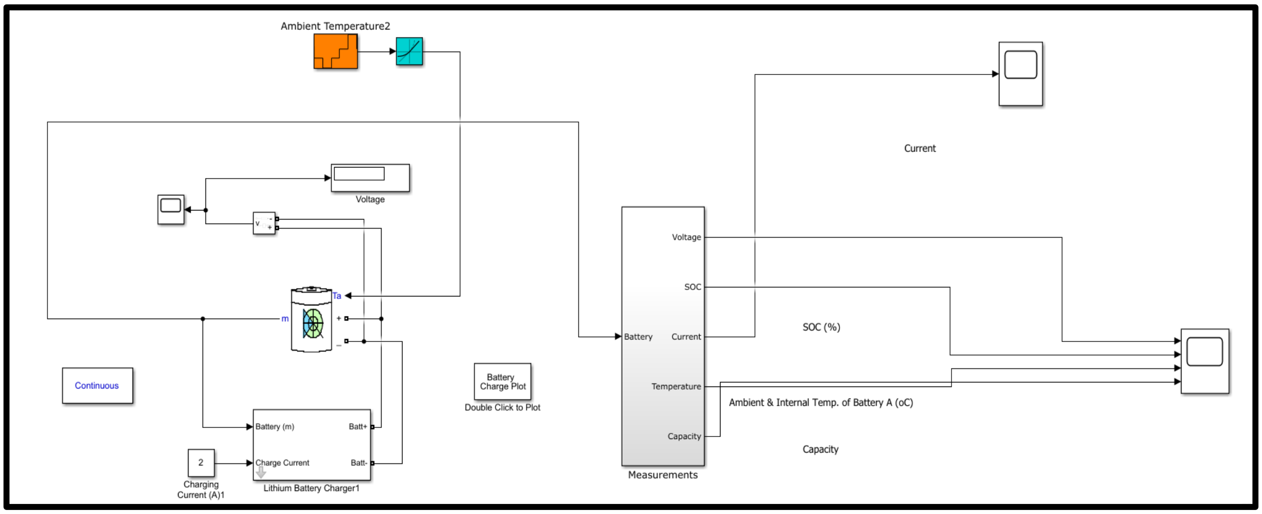
- The minimum no-load battery voltage is 0 V and the maximum battery voltage is equal to 2 × E_0.
- The minimum capacity of the battery is 0 Ah and the maximum capacity is Q_{max}.

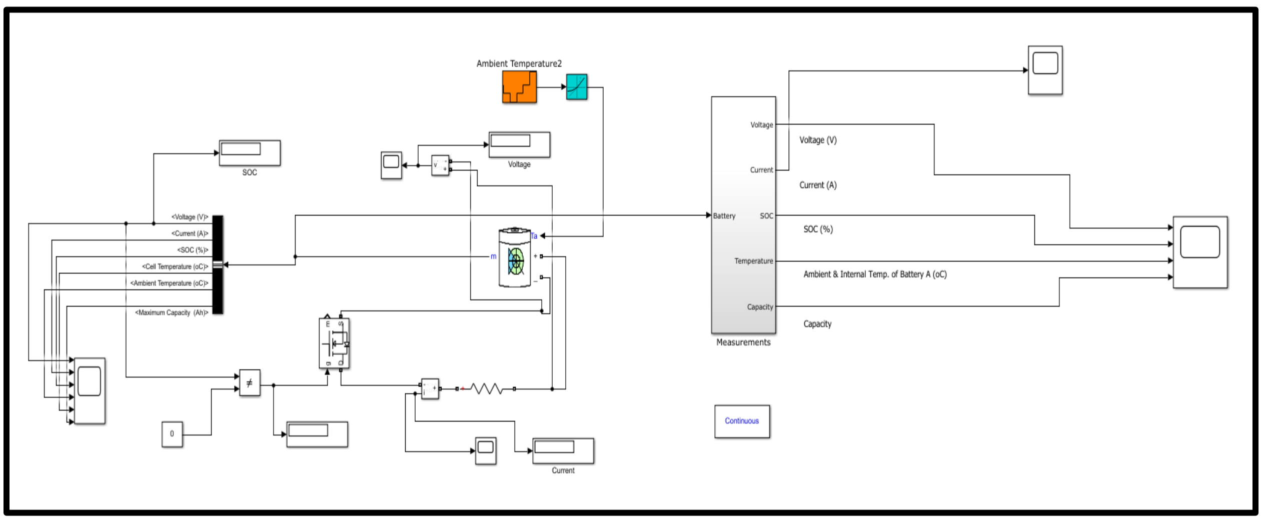
Assumptions

- The internal resistance is assumed to be constant during the charge and discharge cycles and does not vary with the amplitude of the current.
- The parameters of the model are derived from the discharge characteristics. The discharging and charging characteristics are assumed to be the same.
- The capacity of the battery does not change with the amplitude of the current.
- The self-discharge of the battery is not represented. It can be represented by adding a large resistance in parallel with the battery terminals.
- The battery has no memory effect.

2. Basic Charging and Discharging Model of Lithium-ion Battery

A basic model of charging and discharging of a Lithium-ion battery was made in MATLAB-Simulink to study the voltage, current and capacity characteristics of the battery while charging and discharging. For the charging and discharging models, a 3.6V 3.6Ah ($LiNiO_2$) battery was used for simulation. The Lithium-Battery charger block of Simulink was used as a charger in the simulation. This charger is based on constant current/constant voltage (CC/CV) method.



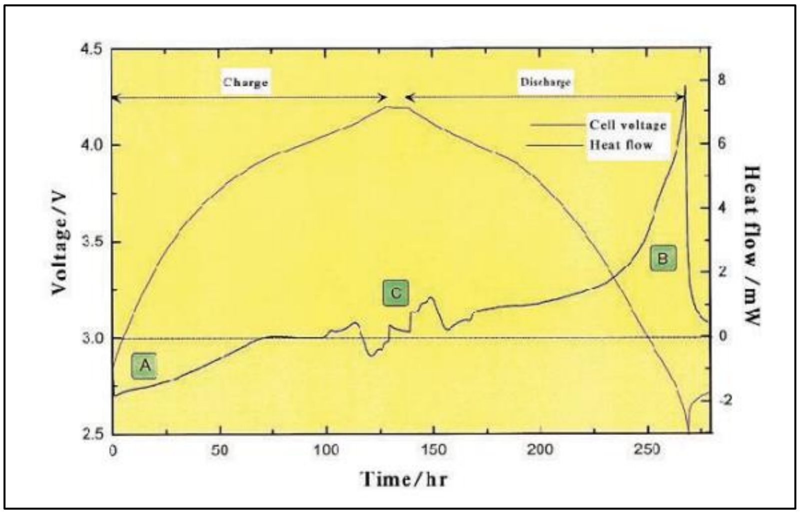


2.1.The Temperature Effects

2.1.1. Overview

Prevention of excessive temperature rise in Lithium chemistry cell packs has always been a major design issue. Most Lithium-Ion (Li-Ion) cells must not be charged above 45°C or discharged above 60°C. These limits can be pushed a bit higher, but at the expense of cycle life. In the worst case, if cell temperatures get too high, Thermal Runaway may occur, resulting in battery failure or even a cell fire. Prevention of excessive temperature rise in Lithium chemistry cell packs has always been a major design issue. Most Lithium-Ion (Li-Ion) cells must not be charged above 45°C or discharged above 60°C. These limits can be pushed a bit higher, but at the expense of cycle life. In the worst case, if cell temperatures get too high, venting may occur, resulting in battery failure or even a cell fire.

2.1.2. The Chemistry



The chemical reaction that takes place during charging of Lithium chemistry cell is endothermic (the reaction absorbs heat). The discharge reaction is exothermic and produces heat. This plot above shows a charge cycle followed by a discharge cycle of a single Li-Ion cell and details the heat flow into and out of the cell during this process. Note that the initial section of the plot, labelled "A", shows the endothermic nature of the charge chemical reaction. Note that the endothermic nature of the charge chemical reaction is weak in comparison to other heat sources.

The discharge section labelled "B" is exothermic, but near the end of discharge, the heat produced increases rapidly, indicating a rapid increase in cell impedance near the end of cell capacity (note that constant current charge and discharge was used). This is compounded by the fact that many times, the load on a battery is constant-power in nature. As the battery voltage decreases near the end of its capacity, the current must increase to maintain constant power.

2.2. Temperature variation based on Indian climatic conditions

In order to make actual business sense of the Li-ion technology, the Li-ion batteries have to sustain the normal life cycle requirements and withstand wide span of storage temperatures that the conventional vehicles have been good at and still ensure good life. EVs have so far been a nascent market for South-East Asian regions and India in particular. The Indian ambient conditions range from less than -5°C to greater than 50°C with relative humidity up to 100% in most of the coastal areas where there is very high vehicular density. Hence it is reasonable to state that the batteries have to consistently withstand high temperatures with high humidity and still satisfy their calendar life requirements. It is very realistic that the vehicles would be subject to a parking soak of temperatures exceeding 45°C during the summer months. This leads to a challenging task of thermal and battery management to maintain battery life under these soaking conditions. The options of passive (when vehicle off) thermal management system and storage strategy is critical to ensure adequate battery life. For example, Chevrolet Volt from General Motors has a Lithium-ion Battery pack which is actively managed thermally. This means, the Volt can actively cool and heat using 50-50 glycol/water mix and AC refrigerant by using them intelligently. Though this approach ensures life of the Battery pack, it adds system cost and complexity.

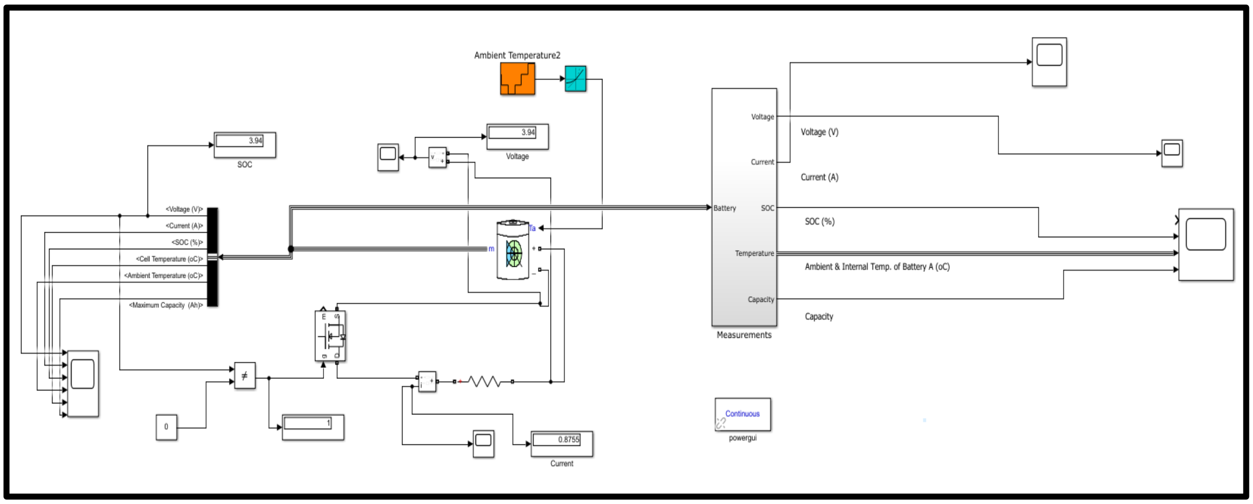
2.2.1. Temperature effect on battery in extreme cold conditions

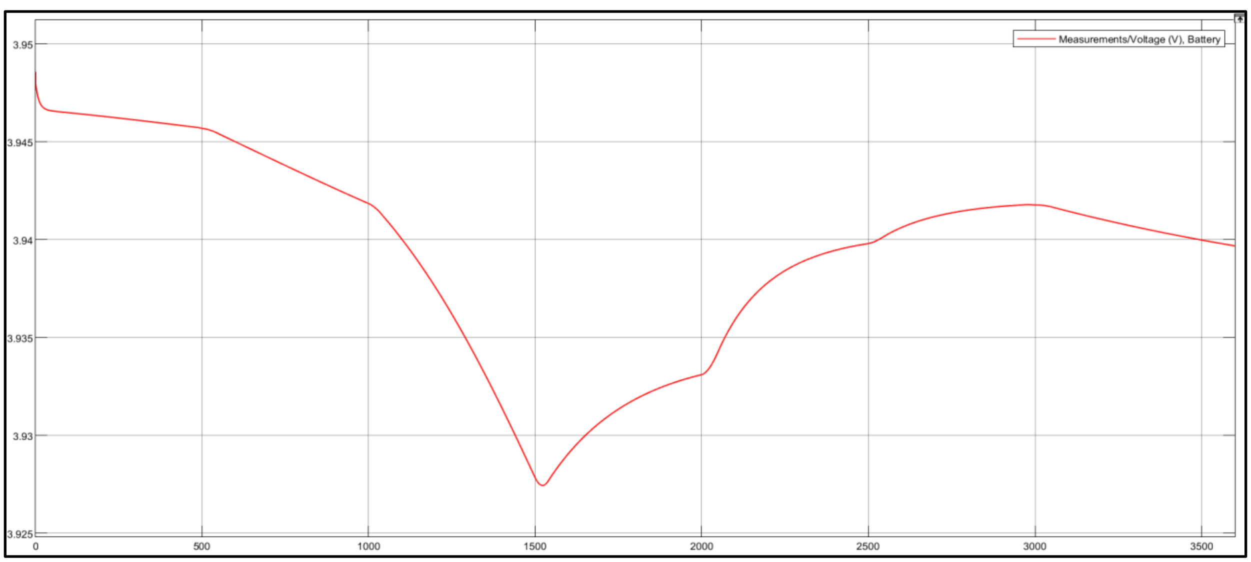
In recent years, the thermal management of Li-ion batteries has been the focus of a number of studies as it is a crucial consideration to get them operated at optimum conditions. While both cooling and heating are equally critical, the emphasis of recent studies were mainly towards high temperature applications with noticeably less attention to their operation in low temperature climate conditions (i.e., particularly for stationary applications). This calls into question on issues relating to the effect of low temperature operation on the performance of Li-ion batteries: for instance, reduced energy and power densities of the batteries. It is noteworthy that the Li-ion batteries operate at the same temperature range of human's tolerable range; however, both the high and low temperatures can greatly reduce their performances while overheating can lead to safety issues such as thermal runaway and explosions.

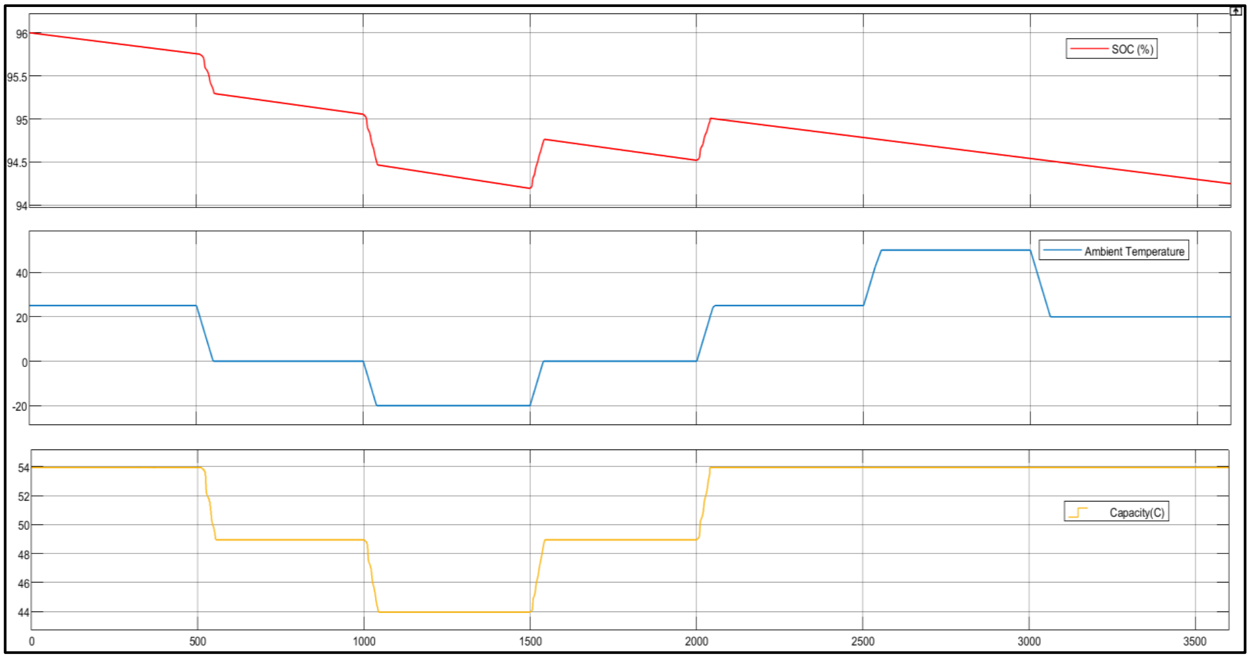
As reported by Gering, the limitations of the Li-ion batteries can be put into two categories of intrinsic and operational limitations. The intrinsic limitations are due to unavoidable materials-related constraints that are irrespective to the battery usage condition. Examples of the intrinsic limitations include transport characteristics of the electrolyte, charge transfer rates within the electrode materials, and others. Meanwhile, the operational limitations are related to how actively a cell is being cycled under specified state of charge (SOC) and temperature. Hence, it is known that the challenges faced by the Li-ion batteries at low temperature conditions are clearly related to the operational limitations. Previous research studies have shown that rapid charging of the Li-ion batteries at sub-zero temperatures can potentially harm the batteries and lead to their degradation. For example, the capacity of the Li-ion batteries is greatly reduced as much as 95% when operated at -10 °C rather than at 20 °C. This drop in the capacity is unacceptable in many applications when the Li-ion battery storage system fails to meet the load demand due to aging behaviour associated with their operation at extreme cold conditions. It was suggested that such occurrence of performance loss at cold conditions is caused by a significant rise of internal resistance that tends to increase the cell's internal temperature (warming the cell) and potentially degrade the Li-ion in the long run. Hence, among the efforts suggested to improve the Li-ion's performance are advanced thermal behaviour study, upgraded electrode materials, improved charging/discharging arrangement and comprehensive battery's thermal management.

2.2.2. Ambient temperature model

In order to simulate the ambient temperature as per Indian climatic conditions, a model was built in MATLAB-Simulink. 3.6V 48Ah $LiNO_2$ battery model was used for this simulation. A discharge circuit was made to discharge the battery current. The ambient Temperature block was used to give temperature inputs at various levels. Considering the Indian climatic conditions, the temperatures of [25 -20 0 25 50 20] ℃ were given at step timings of [0 500 1000 1500 2000 2500 3000] seconds respectively. A MOSFET switch is used to control the discharge circuit and a resistor of 4.4k ohms is used to discharge the current. From the simulation results we can observe how the different parameters of battery such as Voltage, SOC and Capacity vary with the ambient temperatures.







3. Methodology

The Constant Current-Constant Voltage (CC-CV) method was used to charge the battery in the simulation. There are two charging stages for the CC-CV charging strategy. At the first stage, the battery is charged using a constant current I. When the voltage reaches the switch voltage Vsw, which is a predefined voltage that is very close to the full charge voltage V_{full} , the CV stage starts. The current decreases until the end of charge current IEOC to prevent damage to the battery. The CC charging is more suitable for slow charging with a 0.5 C-rate (C) and a typical charging time of 2 h. However, if the constant charging current is below 0.5 C, the charging time can be increased significantly. The CV mode that normally follows the CC mode can limit the overvoltage stress on the battery cells and can improve the charging capacity while resulting in a longer charging time.

4. Additional Learning

In order to get learn something new and additional along with the internship, Sir suggested me to go through the NPETL course- **“**Pulse width Modulation for Power Electronic Converters” by Dr. G Narayanan, IISc Bangalore. The following topics were covered in the course:

1. Power electronic converters for dc-ac and ac-dc power conversion:

Electronic switches, dc-dc buck and boost converters, H-bridge, multilevel converters – diode clamp, flying capacitor and cascaded-cell converters; voltage source and current source converters; evolution of topologies for dc-ac power conversion from dc-dc converters.

2. Applications of voltage source converters:

Overview of applications of voltage source converter, motor drives, active front-end converters, reactive compensators, active power filters

3. Purpose of pulse width modulation:

Review of Fourier series, fundamental and harmonic voltages; machine model for harmonic voltages; undesirable effects of harmonic voltages – line current distortion, increased losses, pulsating torque in motor drives; control of fundamental voltage; mitigation of harmonics and their adverse effects

4. Pulse width modulation (PWM):

Square wave operation of voltage source inverter, Triangle-comparison based PWM.

5. Analysis of dc link current:

Relation between line-side currents and dc link current; dc link current and inverter state; rms dc current ripple over a carrier cycle; rms current rating of dc capacitors

6. Inverter loss:

Simplifying assumptions in evaluation of inverter loss, dependence of inverter loss on line power factor, influence of PWM techniques on switching loss, design of PWM for low inverter loss.

5. Conclusion

An experimental simulation study relating to Li-ion batteries was conducted based on their operations at different Indian climate conditions. Evidently, the relation between the cell's internal temperature in addition to electrochemical and thermal processes was established based on the temperature rise effect in the Li-ion cells. The finding comes to a good agreement that reduced capacity of the cell is affected by low temperature and high current operations. Although in reality, the thermal analysis is more complex than what is presented here and there is a great scope for improvement and future work in this area of battery heat generation modelling. The Thermal behaviour of the Li-ion cell was analysed for discharging at sub-zero temperatures.

6. Acknowledgement

First and foremost, I am sincerely thankful to Dr. Prasun Mishra for giving his valuable time, guidance, advice, and encouragement throughout the period of this summer internship.

I would also like to thank my seniors for letting me know about this internship opportunity through LinkedIn and sharing valuable knowledge and experience.

A special thanks to Dr. G Narayanan, IISc Bangalore whose NPETL course was taken up by me as suggested by Sir. The course provided immense knowledge to me along with the internship.

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