Simulation of Li-ion Battery using MATLAB-Simulink for Charging and Discharging

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Abstract. The optimization of batteries has increased in EV and HEV applications out of which Li-ion batteries are widely used for green technology applications as an energy storage system due to its high power and energy density. In electric vehicle applications, drawbacks are observed during charging interval time on the storage system. In such situations, the multi-state charging is considered to be the ideal solution. This paper tells us about the state charging of lithium-ion battery and its criteria of charging/discharging for good battery life using MATLAB Simulink tool. The state-of-charge (SOC), measured and applied for measuring charging/discharging characteristics is an important parameter for defining the performance of a battery. Thus, accurate estimation of SOC is necessary which will protect the battery and prevent its overcharging and discharging. This will also help in improving the life span of the battery. For applications requiring higher efficiency, multi-state charging is applied.

1 Introduction

Batteries are highly applicable in systems having solar energy, EVs, HEVs and other smart-grid systems. Generally, the types of battery include the "Primary Battery (PB)" and the "Secondary Battery (SB)". SB especially Li-ion Battery is highly used and preferred due to its chargeability, high energy ratio and high-power ratio as compared to that of Lead acid and other Nickel Metal Hydride batteries[1]. For predicting performance and optimization of energy disputation, designer take battery behaviour into the account. Thus, information regarding the charging and discharging of the Li-ion battery is an important factor for designing the circuit to attain high power performance and efficiency. Various parameters are associated with behaviour of battery from which the state-of-charge (SOC) of the battery is an important one. The state of charge of the battery is related to the stored charges (Q) and integrated current (I) through the battery. The ratio of Current Capacity to the Nominal Capacity is called the SOC of a battery[2]. As, SOC information of the battery tells you about its charge/discharge control, the correct indication of SOC is important for Hybrid Electric Vehicle Application. In order to determine the SOC, there is no sensor available to measure

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its value. C. Park proposed an algorithm based on Physical measurements in order to determine the SOC which is given by:

$$SOC = 1 - (1 - 1/Q \int_t^0 i(t)dt \ [3]$$ (1)

There were some chemical methods which involved use of Electrolytes like non-sealed Lead Acid batteries where its specific gravity and pH was used to estimate SOC. Voltage method was used which converts battery voltage to SoC with the help of discharge curve of the battery. However, the battery current and temperature affected the voltage of the battery which can be resolved by compensating the voltage by a correction term proportional to the battery current. There was a need of a powerful tool which would help in estimation of SOC in charging discharging and multi-state charging states and that was based on MathWorks called as MATLAB/Simulink. It is a MathWorks assigned software/tool which helps in designing and analysis of a particular element having the base of Python and C Programming Language. It is a simple and handful software having user-friendly toolboxes, libraries, simulation blocks, symbols, arithmetic and logical operation blocks and most important batteries. Battery models included in this software as proposed in the SimPowerSystems libraries. Models built here based on Shepherd equation were not able to distinguish the characterized performance of the battery. Hence, for more accurate results of simulation a better model was needed. For detailed information, a model of Simulink based on Li-ion battery is designed on using the blocks of Simulink libraries. For simplifying the model, the mean value of RC Circuit parameter is taken. L.W. Yao introduced the first Simulink model for a LiFePO4 battery. This model was further validated for experimental results predicting the current and voltage performances and was later on applied on other modules of battery.

Battery technology usage increased due to its high amount of demand in the EV applications. This paper shows the modelling of the SOC of the Lithium-Ion battery with the use of MATLAB-Simulink tool which is measured and applied to evaluate the battery's charge/discharge. The multiple charging and battery life optimization designed circuits were applied to ensure high power and efficiency of the battery having the introduction of multi-state currents[4].

The residing of the paper is arranged in the following manner: Literature is presented in the second section. The third section of this paper includes the Methodology and procedure of the estimation of the battery. The next session includes the Results/ Outcomes of the simulation and the way they are interpreted. The last section highlights the Conclusion and the Future Works of this simulation.

2 Literature Review

2.1 Classification of Li-ion batteries

The table given below consists of various types of Li-ion based batteries. All batteries have different performance and they are selected according to the application. In this table we have mentioned various parameters which are important to analyze the performance and efficiency of battery.

Table 1. Classification of Li-ion Batteries

PROPERTIES	*LiCoO2*	*LiMnO4*	*LiNiMnCoO2(NCM or NMC)*	*LiFePO4*	*LiNiCoALO2(NCA)*	*LI4TI5O12*
Anode	Graphite	Graphite	Graphite (sometimes Si and Li4Ti5o12 added)	Graphite	Graphite	Nano-structured Li4Ti5O12
Cathode	Lithium cobalt oxide	Lithium manganese oxide	Lithium nickel manganese cobalt oxide	Lithium iron phosphate	Lithium nickel cobalt aluminum oxide	Lithium nickel manganese cobalt oxide
Electrolyte	Blend of lithium salts	Blend of lithium salts	Blend of lithium salts	Blend of lithium salts	Blend of lithium salts	Blend of lithium salts
Cell internal resistance	High	Low	Low	Low	High	Low
Thermal stability	Low	High	High	High	Low	Highest
Voltage	3.6v	3.7v	3.6 to 3.7v nominal	3.2to 3.3v nominal	3.6v nominal	2.4v nominal
Energy density	150 to 200Wh/kg	100 to 150 Wh/kg	150 to 220Wh/kg	90 to 120Wh/kg	200 to 260 Wh/kg, sometimes even 300 Wh/kg	70 to 80 Wh/kg
Charge rate	0.7 to 1c	0.7 to 1c, maximum 3c to 4.2c	0.7c to 1c, 4.2v to 4.3v maximum	1c typical	0.7c fast charge possible with some cells	1c typical 5c maximum
Discharge rate	1c	1c, 10c possible with some	1c, 2c possible with some cells	1c, 25c possible with some	1c	10c possible, 30c for 5 second pulse

		cells and 30c pulse output		cells and 40c pulse output		
Discharge level	2.5v	2.5v	2.5v	2.5v	3v	1.8v
Cycle life	500 to 1000	300 to 700	1000 to 2000	1000 to 2000	500	3000 to 7000
Thermal runaway temperature	150c	250c	210c	270c	150c	High
Rating						
Energy density	4	3	4	2	4	2
Power density	2	3	3	4	3	3
Safety	2	3	3	4	2	4
Lifespan	2	2	3	4	3	4
Performance	3	2	3	3	3	4
Cost	3	3	3	3	2	1
Overall	16	16	19	20	17	18

2.2 How to increase the battery life?

The use of battery outside or beyond its limits decreases its life therefore to increase the battery life BMS plays an important role because all the limits are handled by BMS. For example, charging discharging, usage temp and various other parameters.
Therefore, by following ways we can increase the battery life :
Active balancing and Cell switching: these two things are controlled by BMS therefore proper and efficient code and circuit should be made for the battery pack.
Through optimized partial charging: Batteries have a limited lifespan because of degradation. This can be reduced by using optimized partial charging methods. Nowadays many electrical devices come with this feature. Due to limited lifespan, it becomes a costly method for the customer to fully replace the battery unit. To reduce this degradation, we can have an optimized partial charging method. In the optimized charging, method the battery is charged to a certain point and also discharges the battery up to certain limits. in this method we also have another method in which we charge according to the usage of the battery for example if a person is traveling only 50km a day then the battery can only be charged up to 75 to 80% and when he or she has to travel longer distance then only he can have fully charged battery it can also call as next day prediction. This all happens with the help of

intelligent BMS of the battery. This method increases battery life and battery performance [6].

Avoid charging to 100%*:* - we should always avoid charging to 100% or fully charge the battery. When we charge the battery to 100% it will create higher float voltage in the battery and will damage as well as decrease the performance. If someone want always a fully charged battery then he or she should take a battery in which battery works on the lower float voltage such as li-ion phosphate cells. They usually work on lower float voltage than the more similar li-ion batteries. Sometimes if there is no stopping method after 100% then overcharging occurs and this will accelerate the aging process of the batteries.

Limiting battery temperature: - when we limit the working temp of the battery it increases the battery life and battery performance. For example, we should not charge the battery in cold temp also we should not discharge the battery at high temperatures. The temperature of the battery has to be at a particular temperature. The charging below 0 degrees Celsius will generate metal plating. And this metal plating is observed at the anode which will slowly generate internal short and result in producing heat. All this will make it difficult to handle and unstable. In many recent devices, there is a provision of stopping of charging and discharging when reached to the particular temperature.

Avoid the high charge and discharge rate: having large charging and the discharging rate will generate more heat into the battery and will reduce the lifecycle and efficiency of the battery. A higher current rate is directly related to a higher stress rate in batteries.

Avoiding deep discharging: - disking deeply will damage the battery soon or permanently. As mentioned earlier deep discharging will create metal plating and it will result in a short circuit. This makes the battery hard to handle and there may be a chance of explosion. Many BMS are made according to it in which discharging stops at a particular point.

Selecting the proper charge termination method: - in this we selected charge rate or a charger in which we require minimum termination of the current charge. Which will extent the battery life by avoiding 100% charge of the battery? For example, termination or stopping the cycle when current drops up to c/5. This is also similar or same to decreasing the float voltage to 4.1 V. in both cases the battery is not charged to 100% which is good for battery life.

2.3 Degradation of Li-ion battery

Li-ion batteries have become more popular than the other batteries available in markets for various applications like power storage in-grids, electric vehicles and even in space missions, this is mainly because of its high power and considerably high life compared to others. Due to lot of research going on in li-ion sector and its high demand, manufacturing cost of li-ion battery is decreasing. It is very important for us to study the degradation of li-ion battery.

2.3.1 Battery degradation is classified into following models:

2.3.1.1 Theoretical method:
a.   The main focus of theoretical degradation model is on loss of li-ions and also different active materials.
b.   The model also comes up with explanation of different degradation mechanism and how the condition of battery affects it.

c.   It is quite difficult to directly co-relate charging and discharging with the molecular level process occurring in battery cell because of lack of study in field of molecular level degradation process.

2.3.1.2 Empirical method

a.   Compared to theoretical, empirical method is considered to be convenient for storage planning and operational study.

b.   Empirical methods are limited by fundamental experimental data, therefore sometimes a model designed or particular application may not be applicable to others.

c.   These types of methods have satisfactory accuracy.

2.3.2 Types of Ageing

2.3.2.1 **Calendar ageing: -**Calendar ageing is referred to battery degradation overtime; the rate of this process is affected by Temperature and the State of Charge, calendar ageing can be expressed as a function of temperature (T), SoC(S) and time (t).

2.3.2.2 **Cycle ageing: -**There is some life lost every time the battery goes from charging to discharging, this is called as Cycle ageing. Cycle ageing is related to depth of discharge, average SoC of that cycle and average cell temperature (Tc)[7].

2.4 How to slow down battery ageing:

- Do not use of battery in high ambient temperature environment and also avoid exposure to direct sunlight.
- Keeping battery inactive/discharged for long amount of time should be avoided, if such situation arises make sure to charge battery in between even if it is not required.
- Do not charge the battery very frequently (keep a habit of charging the battery only after soc drops below 25%).
- If the operation is critical replace battery after SOH drops below 90% otherwise after 50%.

3 Methodology

3.1 Steps for Charging Circuit:

Insert Simscape Electrical from the Add on (this will be included in library it has components like battery, mosfet, RLC unit etc.) Add Li-ion battery from the Library also add a DC voltage source. (Set voltage and Amp hr.). Insert RLC unit and select its type as RL also set the values of resistance and inductance. Connect positive terminal to RL unit. Insert two mosfets and connect them branch it and connect to another end of RL unit. Add a resistive load and a RC unit set its values. Connect Resistor, RC unit and mosfets in parallel. Insert an ideal switch. (Connect a constant block to it). Set the charging voltage and connect its one end to ideal switch and other to resistor. Add a Bus selector select SOC, current and voltage. Connect it to the battery. Add a 3 Go TO tags to the Bus selector name them SOC, Current and Voltage. Also add tags for mosfet 1 and mosfet 2. Then we have to create a sub system for charging so first add PID controller and PWM Generator and connect them. Use the Mosfet_1 tag connects it to PWD branch that connection and connect to Mosfet_2 tag with a not gate in between. Insert an add operator (change it to +-) and connect it to PID controller. Add

constant block and connect to the – of add block (this is reference current) and set the required value. Use the Current tag and connect it to + of add block. (This is our sob system). Add scope to check outputs; make connections of SOC, current and voltage to scope. Figure 1 shows charging circuit for Li-ion battery.
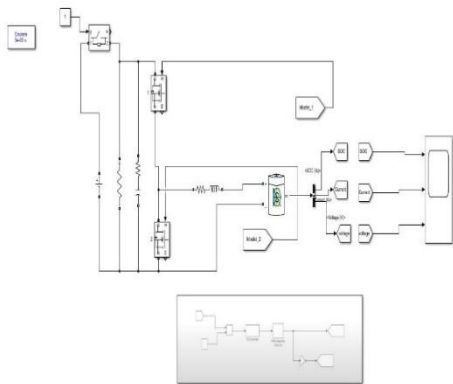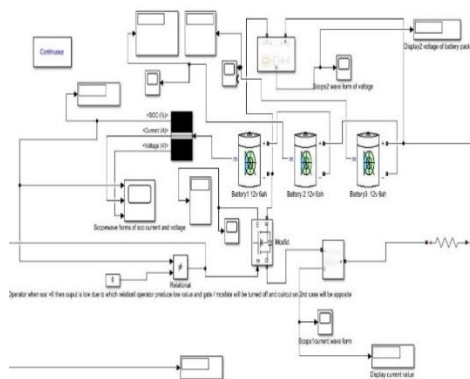

Figure 1 Circuit for charging of Li-ion battery   *Figure 2 Circuit for discharging of Li -ion battery*

3.2 Steps for Discharge circuit:

Add LI-ion Battery from Library. (Insert 3 cells and connect them in series). Change the nominal voltage, rated capacity and state of charge as per your application. Add the load resistance and set the resistance value. Insert mosfet (to control the circuit) and current measurement; complete the connections by joining mosfet current measurement and resistance in series. Add a scope and display and give current measurement as input to them. Further connect mosfet to first battery and the other end of resistance to the third battery. Insert a relational operator to control the mosfet also add a constant bock and set it to 0. Add a Bus selector and connect it to first battery; in bus selector select SOC, Current and Voltage. For displaying waveforms insert a scope. Branch the SOC signal and give it as input to the relational operator (set the relation to 'not equal to'). So, when SOC becomes 0 relation operator gives a low signal. Insert Voltage measurement Connects its two ends to Positive and Negative ends of the battery; further add a scope and display to it. Also add a display for the SOC value. Set the simulation time as per requirement. Figure 2 shows circuit for discharging of Li-ion Battery.

3.3 Steps for circuit having charging till 85% and then discharging till 15%-

Add a continuous power GUI. Add Li-ion battery using library option. Connect it to a Bus Selector. Select SOC (%) element in it and connect it to a GOTO tag branch the connection and add a display to the branched connection. Use the SOC GOTO tag and connect a scope to it. Connect the negative and positive ends of battery to two ideal switches (with initial state 0). Add a DC source voltage connect it to the ideal switches and complete the circuit. Now branch the connection of battery terminals and ideal switches and connect it to two different ideal switches (initial state 0). Add a load resistance in series with switches and complete the circuit. Take a chart, create a two statement blocks in it; statement 1 block (Charge entry: Pulse=1), statement 2 block (Discharge entry: Pulse=0). Give conditions to it; condition 1 – SOC>85, Condition2 – SOC<15. Use a SOC tag use it as input to chart, create GOTO Pulse

tag as output to chart. Now we will design timer circuit. Add a clock and a constant block with a value of 10 connects both to a relation operator (>). Then add second clock and constant block with a value of 200 and connect it to relation operator (<). Connect both relation operators to a product1 block. Add another product block. Connect not gate and product1 to it then create a Discharge tag and connect it to product block. Now take two pulse tags and connect it to ideal switch and ideal switch1 respectively, similarly connect two discharge tags to ideal switch2 and ideal switch3. Figure 3 shows development of circuit having 85% charging rate and 15% discharging rate.

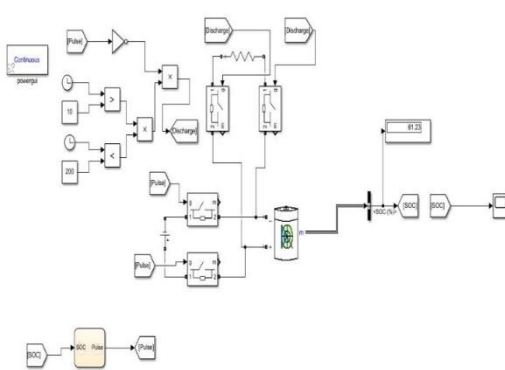### 3.4 Steps for multi-state charging circuit:

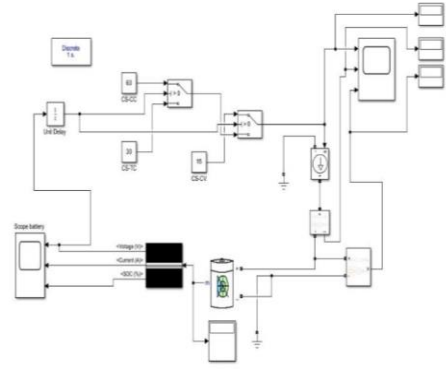***Figure 3*** *Charging 85%- Discharging 15% Circuit*   ***Figure 4*** *Circuit with different C rates*

Insert Li-ion battery from library. Connect the battery to a bus selector and select SOC, Current and Voltage and connect these to a scope. Branch the connection of voltage and connect it to a unit dely. Add a switch block (with > 0 condition) and give output of unit delay to input 2 (condition) of switch block. Add a constant block CS-CC with value 60 and connect it to input 1 of switch block add another constant block CS-TC of value 30 and give it as input 3. Add another switch1 block (> 0 condition) and connect the output of unit delay to input 2 (condition) of switch 1, connect output of switch to input3 of switch1 and add a constant block CS-CV of value 15 and connect it to input 1 of switch1. Add a controlled current source. Also add a standard voltage measurement and current measurement block from the library. Connect the output of switch1 to input of the controlled current source then connect it to scope1 and display. Now connect positive terminal of battery to positive terminal of voltage measurement block then connect the negative terminals to ground. Connect the output of voltage measurement to a scope1 and a display2. Branch the connection of positive terminals of battery and voltage measurement; connect it to negative terminal of current measurement. Connect positive terminal of current source to positive terminal of current measurement. Then connect output of current measurement to scope1 and display1[3]. Figure 4 shows circuit for multi-state charging i.e., with different C rates.
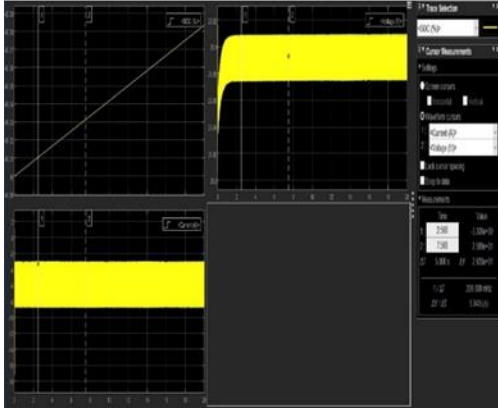
4 Results and Discussion

Figure 5 *Output graph of charging circuit*

Figure 6 *Output graph of discharging circuit*

4.1 Charging Circuit:

The variation of state of charge, current and voltage against time. When we look at the curve of SOC as shown in fig. 5 above we can see that as the time increases, the state of charge also increases and the curve is linear. The current in this case remains constant throughout the entire run. The voltage increases as the time increases to a certain point and then remains constant for the remaining time of the circuit.

4.2 Discharge Circuit:

The figure 6 above shows the variation of SOC current and voltage against time for battery 2 of 12V 6Ah. It is observed that the SOC of this battery decreases as time changes and the voltage and current decrease for the initial time but later remain constant for the entire time period.
This figure also shows the variation of Battery 3 of 12V and 6Ah and channel lining against time. The SOC of the battery as we can see is decreasing with respect to change in time and the voltage and current of the battery are reduced initially but later follow a constant path through the entire time interval. The channel lining is constant
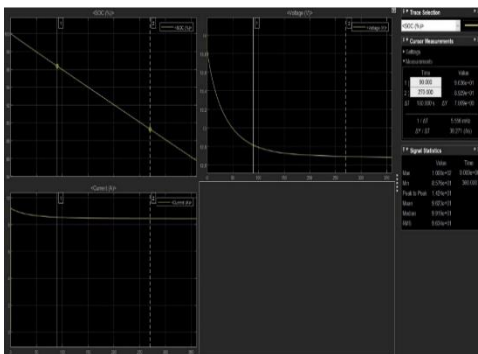

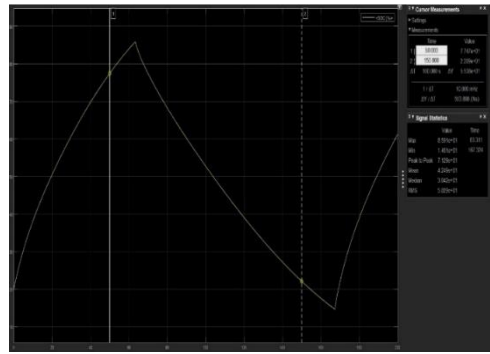**Figure 7** *Variation of Current Voltage and SOC*

Figure 8 *Graph of charge-discharge circuit*

throughout the entire run. Figure 7 shows the individual variation of the SOC, voltage and current of 12V 6Ah Battery where we can that SOC decreasing linearly with the increase in time. The voltage changes from 14V to 13.8V initially i.e., at t=0 and then starts decreasing parabolically till time t=270s and further remains constant till the end. The current in this case rises from 0 to 10A at t=0, then starts decreasing till t= 90s and remains constant throughout the entire time period.

4.3 85% charging – 15% discharging Circuit:

The curve of Figure 8 shows the state of charge of battery where it charging up to 85% and then starts discharging till 15%**.** It is seen that the State of charge is increasing up to 85% at time t = 60s to t=63s and once it reaches the optimum value it starts discharging and this process takes place until it reaches 15%. This point is achieved at time t=165s to 167s and then it again starts charging and thus this cycle is continued for the entire time period/run of the circuit.

5   Conclusion and Future Works

In this paper, a circuit is designed for the SOC of Li-ion battery at different states of charging and is modelled and simulated on MATLAB/Simulink tool. The concept of State of charge is considered and pertained to determine the charging and discharging characteristics of a Li-ion Battery. In order to achieve high efficiency, the multi-state charging is enforced on the battery for filling the capacity of the battery and then it is further evaluated. Along with this, an 8-bit microcontroller is inserted and introduced having a constant voltage of 20V and a current varying from 5A to 60A which manipulates the configured three state current design. Simulating and modelling a circuit having fixed charge and discharge percentage helps in improving the battery life as well as degradation of the battery which is illustrated in the circuit having 85% charge and 15% discharge rate. The results of simulation tell us that, operating on Lithium-ion battery of 12V 6Ah, the time interval of filling is reduced to approximately 30% at a working temperature of 35˚C. Optimizing the current values for CS_TC, CS_CC, CS_CV can be done as a future work.

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