Short Circuit Analysis of 72Ah Li-Ion Battery Storage with Four Battery Management Designs

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Abstract

This paper presents the simulated study of 72Ah battery bank, where the possible causes of faults are analyzed due to varying temp. conditions from 22º Celsius to 59º Celsius (71.6º F to 138.2º F), charging conditions, which can lead to short-circuit, potentially causing electrical shock, fire hazard, personal injury, property damage etc. Each cell is 3.7 V, 6.66 Wh, 1800 mA. The system comprises of 400 cells in 40 parallel arrays with 10 cells in each array and four battery management system (BMS) designs were used in the simulation. The short-circuit study has been divided into two fault categories. First one due to faults inside the design of battery management system (BMS) alone in which nine faults are studied where the simulation was run for 20 hours (72000 seconds) of simulation time for each of the nine faults, that is 180 hrs or 648000 seconds of simulation time. The second fault cause is attributed due to mixed faults which comprises faults due to batteries in battery bank and due to faulty BMS which resulted in improper charging of the cells. Eleven faults are found in the second case, where again, the simulation was run for 20 hours (72000 seconds) of simulation time for each of the eleven faults, that is 220 hrs or 792000 seconds. In total, the simulation study is of 1440 000 seconds or 400 hrs or 16.666 days. The data leading to this study and conclusions has also been uploaded.
Short Circuit Analysis of 72Ah Li-Ion Battery Storage with Four Battery Management Designs

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Abstract—This paper presents the simulated study of 72Ah battery bank, where the possible causes of faults are analyzed due to varying temp. conditions from 22º Celsius to 59º Celsius (71.6º F to 138.2º F), charging conditions, which can lead to short-circuit, potentially causing electrical shock, fire hazard, personal injury, property damage etc. Each cell is 3.7 V, 6.66 Wh, 1800 mA. The system comprises of 400 cells in 40 parallel arrays with 10 cells in each array and four battery management system (BMS) designs were used in the simulation. The short-circuit study has been divided into two fault categories. First one due to faults inside the design of battery management system (BMS) and in which nine faults are studied where the simulation was run for 20 hours (72000 seconds) of simulation time for each of the nine faults, that is 180 hrs or 648000 seconds of simulation time. The second fault cause is attributed due to mixed faults which comprises faults due to batteries in battery bank and due to faulty BMS which resulted in improper charging of the cells. Eleven faults are found in the second case, where again, the simulation was run for 20 hours (72000 seconds) of simulation time for each of the eleven faults, that is 220 hrs or 792000 seconds. In total, the simulation study is of 1440000 seconds or 400 hrs or 16666 days. The data leading to this study and conclusions has also been uploaded.

Index Terms—Lithium Cobalt Oxide, Lithium Nickel Cobalt Aluminium, Lithium nickel manganese cobalt oxide, NMC, NCA, LMO, LFP, LCO, Lithium Iron Phosphate, short circuit, fault current, fault diagnosis

I. INTRODUCTION

Lithium(1s²2s¹) is a combustible metal and various battery chemistries are made using an intercalated lithium compound with positive electrode as either Lithium nickel manganese cobalt oxide (LiNiMnCoO₂) or Lithium Nickel Cobalt Aluminium Oxide (LiNiCoAlO₂) or Lithium Manganese Oxide (LiMn₂O₄) or Lithium Iron Phosphate (LiFePO₄), Lithium Cobalt Oxide (LiCoO₂), thus, known as NMC, NCA, LMO, LFP, LCO respectively [3]. The Li-ion batteries, thus, are highly inflammable due to its inherent metal, lithium and electrolyte (non-flammable electrolytes such as aqueous, ceramic solid, polymer, ionic, may be used in future.)

Not only due to inherit chemical composition, like other batteries chemistry, not all cells are created equal. The individual cells in a battery always have somewhat different capacities due to manufacturing variances, assembly variances, and thus, different State of Charge (SoC). With time, all individual cells age at slightly different rates, which gets even more complicated after every charge-discharge cycle.

Despite this risk, Li-Ion has high energy density weight (W-hr/kg) and volume (W-hr/L) with 100% Depth of Discharge (DoD), as a result of which all of Li-Ion chemistries are being used in one application or other, namely electric vehicles (EV), power tools, grid energy storage, medical equipments, cell phone, aviation products, trackers, laptop, plug-in hybrid electric vehicle (PHEV).

The commonly used battery management systems (BMS), are based on passive cell balancing, to make sure operation within safe operating area, and these are widely implemented for monitoring and protecting upto 192-series of cells, equal to 355.2VDC. Also, some active cell balancing based BMS are also available but with higher cost.

The theoretical storage capacity of 37V, 72 Ah is made with 400 cells and need a customised BMS. The BMS is the only monitoring method and if it fails, the short-circuit will happen, which will cause fire (Class-D). It is important to note that Li-ion batteries fire cannot be extinguished with water, which is explained as follows:

A. Reaction with Water

In case of short-circuit, the fire caused by Lithium-ion battery cannot be extinguished with water as the reaction is highly exothermic, forming inorganic compound lithium hydroxide (LiOH·(H₂O)ₙ) and highly flammable hydrogen (H₂), which has an enthalpy of 286kJ/mol, that is, energy per molecule [4][5][7]. Thus, it comes under class-D fire, which can be extinguished with dry powder agents like graphite powder (1s²2s²2p⁴), powdered copper (1s²2s²2p⁴), with the rest composition of other gases [6]. Lithium reacts with oxygen (O₂) giving inorganic compound lithium oxide (Li₂O) [7].

B. Reaction with Air

Air consists of 78.08% Nitrogen (1s²2s²2p⁴), 20.95% Oxygen (1s²2s²2p⁴), with the rest composition of other gases [6]. Lithium reacts with oxygen (O₂) giving inorganic compound lithium oxide (Li₂O) [7].
The data which has lead to this study is fully uploaded on [1]. Earlier, the author had carried out this study with battery capacity of 1.5 A (1500 mA), not 1.8 A. So, the manually earlier calculated and tabulated is shown in Table II.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lithium Melting point</td>
<td>180.54 °C or 356.97 °F</td>
</tr>
<tr>
<td>2</td>
<td>Melting point of Electrolyte LiPF₆</td>
<td>200 °C or 392 °F</td>
</tr>
<tr>
<td>3</td>
<td>Heat of fusion (latent)</td>
<td>3.00 kJ/mol</td>
</tr>
<tr>
<td>4</td>
<td>Heat of vaporization</td>
<td>147.1 kJ/mol</td>
</tr>
<tr>
<td>5</td>
<td>1st Endothermic Ionization energy</td>
<td>520.2 kJ/mol</td>
</tr>
<tr>
<td>6</td>
<td>2nd Endothermic Ionization energy</td>
<td>729.8 kJ/mol</td>
</tr>
<tr>
<td>7</td>
<td>Thermal conductivity</td>
<td>84.8 W/m/K</td>
</tr>
</tbody>
</table>

The melting point of Nickel, Manganese are 6-7 times higher than lithium, short-circuit will happen.

The system comprises of 400 cells in 40 parallel arrays with 10 cells in each array and four battery management system (BMS) designs were used in the simulation. Each cell is 3.7 V, 6.66 Wh, 1800 mA. So, the system becomes of 37 V, 72Ah.

The paper is rewritten as the author is making some prototype in which he needs to refer his old analysis for his safe design.

II. SHORT-CIRCUIT CONDITIONS

The various possible ten different faults which can lead to short-circuit areas follows

A. Fault : Battery Management System

Battery Management systems are employed as (i) Discrete Passive Cell Balancer (ii) Discrete Active Cell Balancer (iii) Centralised Active Cell Balancer.

(i) Fault : Discrete Passive Cell Balancer

This is the most widely implemented method - using more than one BMS to monitor large group of cells, and this method has three main drawbacks. The passive cell balancing in itself is an inefficient way of implementing BMS but popular as easily available in the market, with auto-pause and resume passive balancing, using microcontroller & fuel gauge with front-end filters.

The passive balancing works on the principle of ‘resistor bleeding’, thus, to balance SoC in a certain group of cells, the energy from the most charged cell is dissipated as heat. So, with discrete implementation, each BMS will dissipate heat, and the temperature of adjacent cells will get affected; few cells of the adjacent array may overheat or fail or their aging cycle (which is dependent on temperature). At the same time, the voltage stresses in the switch usually MOSFET (or IGBT or SiC) $V_{DS}$ or $V_{CE}$, carrying the route to bleeding resistor, increases. Even if ‘only a single cell’ gets affected and if it is not being taken care of, this will eventually cause the entire battery bank to ignite or rupture by short-circuiting between cells.

The second drawback is there is no coordination between separate BMS. One BMS do not know the SOC of other BMS maintaining the different group of cells. This of course can be mitigated using software monitoring and regular state of health (SoH) check ups.

With time factor, the non-linearities increase in the cells.

A difference in cell voltages is the most common manifestation of unbalance, which can be corrected either instantaneously or gradually through bypassing cells with higher voltage. This application report describes a simple method of passive cell balancing based on the differences between the cell voltages.

The third drawback with this approach is that it is impossible to know from the market brands, what balancing criterion & how many algorithm steps, one company has followed.

The temperature imbalance changes cells and thus, array chemistries differently. Those cells or array having higher temperature are more prone to SEI (Solid Electrolyte Interphase) formation and the cells having lower temperature may result in lithium plating and thus, low electrolyte conductivity.

B. Table 2

Table 2 calculations are manual and was for the previous prototype with capacity of 1.5 A (1500 mA), not 1.8 A.

| Column 1 is C-rate of one Cell | Column 2 is Discharge current of one | Column 3 is Charge in a Single Cell | Column 4 is Run time to supply full capacity - 1 cell | Column 5 is Run time to supply full capacity | Column 6 is Charge in the bank | Column 7 is Discharge current of the bank |

1 Due to complete computer crash, all simulation files included this paper was completely lost. As during simulation, I had done analysis, so I could re-write this paper again using the already analyzed result mentioned in [1]
### III. SHORT CIRCUIT DUE TO FAULTS INSIDE BMC ALONE

This section lists the faults due to BMC alone, that is, due to faults inside the design of battery management system (BMS) alone in which nine faults are studied where the simulation was run for 20 hours (72,000 seconds) of simulation time for each of the nine faults, that is 180 hours or 648,000 seconds of simulation time.

Referring to data of [1]

**A. BMC1_Fault1.zip**

For design 1, the simulation was run for 27 minutes (1,620 seconds) of simulation time.

The automatic recovery from short-circuit protection completely failed for 27 minutes.

**B. BMC1_Fault2.zip**

For design 1, the simulation was run for 27 minutes (1,620 seconds) of simulation time.

The automatic recovery from short-circuit protection completely failed for 27 minutes.
C. BMC2_Fault1.zip

For design 2, the simulation was of 4 minutes (240 seconds).

The fault1 happened due to failure of booster inductor of BMC. The automatic recovery from short-circuit protection completely failed in 4 minutes and lead to short circuit.

D. BMC2_Fault2.zip

This is fault 2, which happened in the same design 2 with change of component. The fault2 happened due to the failure due to output inductor and capacitor. The short-circuit protection completely failed and lead to short circuit.

E. BMC2_Fault3.zip

This is fault 3, which happened in the same design 2 with change of component. The fault happened due to the failure due to output capacitor. The short-circuit protection completely failed and lead to short circuit.

F. BMC2_Fault4.zip

This is fault 4, which happened in the same design 2 with change of component. The fault happened due to the failure due to temperature increase in one MOSFET. The short-circuit protection completely failed and lead to short circuit.

G. BMC3_Fault1.zip

For design 3, the fault happened due to short circuit in one MOSFET itself. The short-circuit protection completely failed and lead to short circuit.

H. BMC4_Fault1.zip

For design 4, Fault1 was the minor fault, in which still the batteries could still get charged but the voltage & current rating at which the charge should take place was fallen. This is pre fault before the final fault in the next subsection : BMC4_Fault12 happens.

I. BMC4_Fault2.zip

This fault happens in the same design in which the performance of LLC transformer deteriorated. The LLC SMPS transformer finally saturated. The short-circuit protection completely failed and lead to short circuit.

In BMC/BMS, design 1, two faults happened.

In BMC/BMS, design 2, four faults happened.
In BMC/BMS, design 3, one fault happened.
In BMC/BMS, design 4, two faults happened.

IV. SHORT CIRCUIT DUE TO MIXED FAULTS

The second fault cause is attributed due to mixed faults which comprises faults due to batteries in battery bank and due to faulty BMS which resulted in improper charging of the cells. Eleven faults are found in the second case, where again, the simulation was run for 20 hours (72000 seconds) of simulation time for each of the eleven faults, that is 220 hrs or 792000 seconds.

Referring to data of [1]

1) For Bat_Fault1.zip, consisting 400 cells, short-circuit happens due to array No. 11.

2) For Bat_Fault2.zip, consisting 400 cells, short-circuit happens due to array No. 7.

3) For Bat_Fault3.zip, consisting 400 cells, short-circuit happens due to array No. 27.

4) For Bat_Fault4.zip, consisting 400 cells, short-circuit happens due to array No. 32.

5) For Bat_Fault5.zip, consisting 400 cells, short-circuit happens due to array No. 23.

6) For Bat_Fault6.zip, consisting 400 cells, short-circuit happens due to array No. 13.

7) For Bat_Fault7.zip, consisting 400 cells, short-circuit happens due to array No. 13.

8) For Bat_Fault8.zip, consisting 400 cells, short-circuit happens due to array No. 40.

9) For Bat_Fault9.zip, consisting 400 cells, short-circuit happens due to array No. 39.

10) For Bat_Fault10.zip. This is similar to Bat_Fault6.zip, consisting 400 cells but here short-circuit happens due to array No. 23 and array No. 25, instead array No. 13. The dataset shows the cause of short circuit overrides the array No. 13, even when the conditions remain same.

11) For Bat_Fault11.zip. This is similar to Bat_Fault7.zip, consisting 400 cells but here short-circuit happens due to array No. 6 and array No. 16, instead array No. 25. The dataset shows the cause of short circuit overrides the array No. 25, even when the conditions remain same.

CONCLUSION

The author has shared his simulation study of 1440 000 seconds or 400 hrs or 16.666 days. The data leading to this study and conclusions has also been shared despite
due to complete computer crash in which all simulation files included this paper was completely lost, the author has re-written this paper again using the already analyzed result mentioned on IEEE Dataport.

As the previous short circuit study was carried out with battery capacity of 1.5 A (1500 mA), not 1.8 A ; the manually earlier calculated and tabulated results are also shared.

The paper is rewritten as the author is making some prototype in which he needs to refer his old analysis for his safe design.

In BMC/BMS, design 1, two faults happened. In BMC/BMS, design 2, four faults happened. In BMC/BMS, design 3, one fault happened. In BMC/BMS, design 4, two faults happened.

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The author declares no potential conflict of interest.

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**REFERENCES**

References are known and elementary for any school student or graduate, degree holder or Phd or DSc.


