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CONNECTING STANDARD LI-ION BATTERIES IN SERIES TO FORM A HIGH VOLTAGE ARRAY

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ABSTRACT

The principles of high voltage (HV) battery array design, which is based on existing, off-the-shelf Li-Ion batteries (e.g., certified Lithium 6T Batteries), is presented. The battery array includes, besides the series connected battery modules, an HV switch controlled by a controller unit and additional safety components. The paper first reviews all the safety hazards associated with Li-Ion batteries and HV systems which generate design requirements and constraints. Then the basic design together with the principal components are described.

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1. EXECUTIVE SUMMARY

This paper presents a safe, reliable and operationally feasible method, enabling users to connect groups of standard Li-Ion batteries (e.g., certified Lithium 6T batteries) in series, to create high voltage battery systems.

By implementing the proposed method, users of such standard batteries may expand the use cases of their existing 6T battery inventories to additional applications, serving wide ranges of voltage and capacity requirements. A wide implementation of this method may reduce inventory diversity, eliminate nonstandard and unsafe items, simplify logistics and increase cross-fleet standardization. Moreover, a wide use of battery arrays based on standard 6T batteries, may open an option for a "second life cycle" for aging Li-Ion batteries which become less sufficient in classic vehicle applications.

Connecting standard off-the-shelf Li-Ion batteries (e.g., 6T Li-Ion batteries) in series to form a high voltage (HV) array of batteries (also named **"Battery String"**), requires adding to the string an HV switch and a string controller (also named **"Master BMS",** where BMS stands for battery management system) to control that switch faster than the string batteries control their safety switches. The master BMS shall protect against "slow" hazards related to off-limits voltage (disconnect required within seconds), temperature or component failure. Fuses, diodes and a pre-charge current path shall protect against fast occurring (disconnect required at less than 1ms) hazards related to off-limits current. This paper proposes the design principles of such a master BMS with HV switches and additional safety components.

2. INTRODUCTION

Standard off-the-shelf Li-Ion batteries consist, in most cases, of a pack of electrochemical Li-Ion cells, a BMS and an internal safety switch. The BMS is an electronic circuit designed to open the battery's safety switch whenever the battery's charging or discharging conditions exceed the safe operating area (**SOA**) of the Li-Ion cells.

This internal switch is usually designed to sustain, when it is "open" (i.e., in its non-conducting state), a voltage level which is higher than the pack's maximum voltage, but still in the same order of magnitude (e.g., not more than 2 or 3 times as high as the maximum). Besides safety, the internal switch also serves to protect the well-being of the battery and to prolong its service life.

When Li-Ion batteries are connected in series in a voltage loop with a load or a charger (see **Error! Reference source not found.**), if any of the batteries' safety switches open (commanded by the specific battery's BMS), the battery string's or the charger's full output voltage is dropped across that open battery switch. This voltage is likely significantly higher than that which the battery switch is designed to handle. Therefore, the open switch will likely be damaged and will either result in the battery string being unsafe to operate, or in the battery string being inoperable.

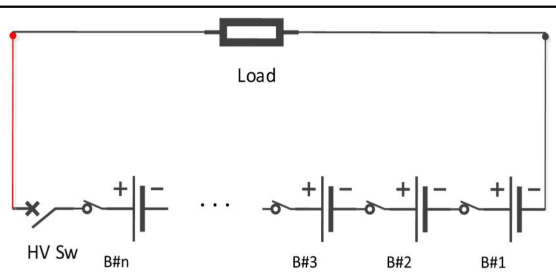

Figure 1: Battery string voltage loop

Consequently, when we connect off-the-shelf Li-Ion batteries in series to form a high voltage (HV) battery string, we must also connect a special HV switch to the battery string and we must make sure that under all the hazardous conditions which may cause any of the string batteries' switches to disconnect, the HV switch will react faster and cut the current first such that the entire string voltage will drop across its open terminals and avoid the condition which would have caused the opening of any of the string batteries' safety switches.

When coming to designing an HV battery string, besides considering the functional requirements (e.g., voltage range, energy capacity, power capability and compliance with environmental conditions and regulations), one must also consider the safe and reliable operation of the battery string. In this paper we shall first examine the hazards of Lithium-ion batteries. These hazards are dealt with by the individual battery's BMS. We shall then continue to additional hazards which exist when such batteries are connected in series. The latter hazards shall be monitored and prevented by a string controller (master BMS). Next, we shall specify the components of the string and the master BMS which are mandatory for the safe and reliable operation of an HV battery composed of standard off-the-shelf Li-Ion battery units in series.

3. LI-ION HAZARDS

Li-Ion electrochemical reactions must avoid high temperatures (> 90 °C). The higher the reaction's temperature the greater the risk for a positive thermal feedback loop where the high temperature accelerates the reaction which in turn generates more heat that continues to increase the temperature and so forth in a process named **"Thermal Runaway"** (TR). In Cobalt based Li-Ion chemistries the TR attains 800 °C and more [1] causing disintegration of the cathode material, release of oxygen and eruption of fire. There are several scenarios which lead to cells TR. The mitigation of those scenarios is done by safety means in the Li-Ion cells and by the BMS which monitors the pack and disconnects the safety switch if the SOA is breached. **Error! Reference source not found.** summarizes the hazardous scenarios, details how the scenario develops to a TR and specifies common mitigation measures.

Table 1. Hazardous Li-Ion Cells Events and Mitigation.

#	Event	Hazard	Protection
1	Over-charge (over-voltage)	Causes cells to over-heat => Solid electrolyte interphase (SEI) decomposes, electrolyte venting, separator fails => internal short-circuit => thermal-runaway => fire.	1. Intra-cell positive thermal coefficient (PTC) device 2. Cell voltage monitoring and BMS controlled switch.
2	Over-discharge (under-voltage)	Damage to cells if not recharged shortly after: plating of dendrites and SEI destabilization => separator failure => spontaneous internal short-circuit => thermal-runaway => fire.	1. Cell voltage monitoring and BMS controlled switch.
3	Over-current during charging	Damage to cells: plating of dendrites, SEI degradation and separator failure due to excessive heat => spontaneous internal short-circuit => thermal-runaway => fire.	1. Current monitoring and BMS controlled switch.
4	Over-current during discharging, or external short-circuit	Cells over-heating event. => SEI decomposes, electrolyte venting, separator fails => internal short-circuit => thermal-runaway => fire.	1. Intra-cell current interrupt device (CID). 2. Current monitoring and BMS controlled switch. 3. Fuses.
5	Over-temperature (Cells over-heating event) above 130 °C	SEI decomposes, electrolyte venting, separator fails => thermal-runaway => fire.	1. Heaters circuit thermostats, 2. Thermal-Cutoff (TCO) fuse, 3. Cell temperature monitoring and BMS controlled switch.

#	Event	Hazard	Protection
6	Charging during Under-temperature	Plating of Li dendrites => Separator piercing => spontaneous internal short-circuit => thermal-runaway => fire.	1. Charging is disabled by BMS and the charging power is used for the battery heaters if T < 0 °C. 2. Cell temperature monitoring and BMS controlled switch.
7	Forced over-discharge of weak cells due to cells imbalance	Weak cell SEI damaged, dendrites forming during following charges, => spontaneous internal short-circuit => thermal-runaway => fire.	1. Cell balancing circuit controlled by the BMS. 2. Cell balance monitoring and BMS controlled switch, tripped by the voltage of specific cells.
8	Mechanical abuse: Crushing, nail / projectile penetration	Cells internal short-circuit, => thermal-runaway => fire.	1. A robust battery case. 2. Incorporating thermal absorbing and fire suppressing materials inside the battery case. 3. Handle with care!

4. THE LI-ION BATTERY BMS

The battery's BMS together with the internal safety switch, a balancing circuit and heater circuits/components must cater for all the monitoring and protection functions required in . In addition, to facilitate operation in a serial string, the BMS should also be capable of measuring the battery's internal temperature, the pack's cell level voltages, state of charge (= the remaining capacity divided by the full charge capacity), state of health and have a communication channel on which it will transmit measurements and parameters and receive requests and commands. In the absence of internal isolation between the batteries' communication interfaces and terminals, external isolation circuitry for the communication interfaces is required to ensure safe integration into a common communication network with the master BMS.

5. HIGH VOLTAGE AND SERIAL CONNECTION HAZARDS

When standard off-the-shelf Li-Ion batteries with all the capabilities specified in the previous sections are connected in series to form an HV battery, or HV battery string (maximum voltage ≥ 120 V), additional hazards need to be mitigated. We can divide those hazards into two categories: 1. Serial connection hazards, 2. High voltage hazards.

5.1. Serial Connection Hazards

Error! Reference source not found. lists the hazardous scenarios in a string of batteries. Since every unit is protected by its own BMS, the risk is mostly damage to one of the units' internal switches. Current related faults can be mitigated immediately by the master BMS, provided it has independent means to measure the string current. In the event of a full short circuit all the battery string units will attempt to react instantaneously, within a few milliseconds. The first switch to open will have all the string's voltage drop on its terminals. Even if a self-triggering pyro-fuse is incorporated on the current path, it cannot be expected to disconnect faster than the internal MOSFET switches of the batteries. Therefore, each battery must be coupled with a parallel bypass diode (see **Figure 2**). With the bypass diode, when a battery unit disconnects during a short-circuit, the string's current continues to flow through the parallel diode. The diode also limits the reverse voltage-drop on the disconnected battery to be small (equals the diode forward voltage-drop ≤1 V). If the diode cables are short, the amount of inductive energy in the cables, which translates to a back-emf transient on the open switch terminals is small and can be sustained by the battery's switch without damage.

Voltage and Temperature related faults can be tolerated by the batteries for seconds before the current is cut-off, especially if the string voltage or temperature threshold occurs before that of the batteries. Therefore, these faults can be dealt with by the master BMS MCU after it receives voltage and temperature reports from the string batteries over the communication network. Still, since the first switch to open must be the HV switch, the triggering voltage and temperature thresholds and trip times for the HV switch must ensure that it cuts off the current before any of the batteries does. If the master BMS cannot communicate with each of the configured battery units, it opens the HV switches and disconnects the string.

A string of batteries with coupled diodes does not require protection against over-discharge (undervoltage) at the string level. Any of the string batteries which attains its undervoltage threshold may disconnect and be bypassed by its parallel diode. The discharge circuit with the load remains closed and the load is kept under power although the voltage on the load decreases by the voltage of the battery which disconnected. As the discharge continues, the remaining connected batteries will attain their undervoltage (UV) threshold and disconnect. The voltage on the load will step down with each disconnecting battery. This process will continue until the voltage on the load is too low for it to draw power and the string (what remained of it) will be effectively disconnected. This strategy of discharge enables the load to exploit more electricity from the battery string than what is defined by the Ah capacity of its weakest battery.

Applying charge when the batteries' temperature is below the under-temperature limit can be treated in the following method by the master BMS: First the master BMS will disconnect the HV switches to disable charging. Next it will command all the batteries to open their internal safety switches and close their heaters' switches. When all the internal packs are disconnected and all the heaters are connected to the batteries' terminals, the master BMS can close the HV switches and enable the heaters to bring the batteries' temperature up to around 20 °C. Once the batteries are warm enough, the master BMS can disconnect the HV switches, reconnect all the internal packs to the batteries' terminals and disconnect the heaters. Finally, the master BMS can reconnect the HV switches and start charging the battery string.

Table 2. Hazardous Serial Connection Events and Mitigation.

#	Event	Hazard	Protection
1	String Over-charge (over-voltage)	Causes at least one battery to be in over-voltage state => battery disconnects => damage to battery switch due to high voltage drop.	1. The master BMS shall monitor the external side (charger side) of the HV switch. 2. The master BMS shall disconnect or refrain from connecting the HV switch if external voltage is above the overvoltage threshold. 3. The HV switch overvoltage threshold per battery shall be lower and/or the trip time shall be shorter than that of the batteries' switches 4. The master BMS shall receive periodical pack cell level voltage reports from each battery. 5. The master BMS shall trip the HV switch if any of the batteries' cells exceed a high cell voltage limit, where this limit shall be set to be met before each battery BMS meets its own configured limit and/or with a shorter trip time.
2	String Over-discharge (under-voltage)*	Causes at least one battery to be in under-voltage state => battery disconnects => damage to battery switch due to high voltage drop.	1. The master BMS shall receive periodical pack cell level voltage reports from each battery. 2. The master BMS shall trip the HV switch if any of the batteries' cells exceed a low cell voltage limit, where this limit shall be set to be met before each battery BMS meets its own configured limit and/or with a shorter trip time.
3	String Over-current during charging	Causes all the batteries to be in over-current-charging state => first battery disconnects => damage to battery switch due to high voltage drop.	1. String current monitoring and master BMS controlled HV switch. 2. The string over-current-charge threshold shall be lower than that of the batteries and/or the HV switch trip time shall be shorter.

* This hazard is not applicable to a string of batteries with coupled diodes.

#	Event	Hazard	Protection
4	1. String Over-current during discharging, or 2. External short-circuit, or 3. Application of charge voltage in reverse polarity.	1. Causes all the batteries to be in over-current-discharging or short-circuit state => first battery disconnects => damage to battery switch due to high back-emf or high inverse voltage drop. 2. HV switch damage (e.g. contactor welding).	1. String current monitoring and master BMS controlled HV switch. 2. The string over-current-discharge threshold shall be lower than that of the batteries and/or the HV switch trip time shorter. 3. A HV fuse shall be connected in series with the HV switch for fast short-circuit disconnection. The fuse minimum breaking capacity shall overlap the main HV switches maximum breaking capacity. The fuse maximum breaking capacity must exceed the full short circuit current rating of the battery. 4. An additional pre-charge HV switch connected in series to a ballast resistor on the positive terminal shall be used to limit inrush current to capacitive loads and to probe for a short-circuit on the load side before connecting the main + HV switch. 5. Each battery must be coupled with a bypass diode attached directly to the battery's terminals with the shortest cables possible.
5	Over-temperature (Cells over-heating event) above 130 °C	High temperature battery(s) disconnects first => damage to the battery switch due to high voltage drop.	1. The master BMS shall receive periodical temperature reports from each battery. 2. The master BMS shall control the HV switch such that it trips at a lower high temperature and/or a shorter trip time than that of the batteries. 3. The master BMS shall be capable of commanding each battery's heaters OFF.
6	Charging during Under-temperature	First battery disconnects => damage to the battery switch due to high voltage drop.	1. The master BMS shall receive periodical temperature reports from each battery. 2. The master BMS shall control the HV switch such that it trips at a higher low temperature and/or a shorter trip time than that of the batteries. 3. The master BMS shall be capable of commanding each battery's internal switch ON and OFF. This is required to enable activation of the batteries internal heaters while their packs remain disconnected. 4. The master BMS shall be capable of commanding each battery's heaters ON and OFF.

Table 3. High Voltage Hazardous Events and Mitigation.

#	Event	Hazard	Protection
1	Open HV contacts	Personnel electrocution by accidental contact with both polarities concurrently.	1. A high voltage interlock loop (HVIL) running through all the HV units in series with a current source and current monitoring on the master BMS. 2. HV connectors with HVIL pins in each HV DC interface. 3. If the HVIL is open, the HV switches stay open, isolating the battery from the network. 4. Manual Service Disconnect device: a device to manually break the continuity of the HV conductors during service.
		fails.	
4	Arcing	DC arcs at very high temperatures => fire.	1. Proper insulation, termination and grounded shielding of conductors. 2. Sufficient clearance and creepage between conductors. 3. Use of arc-rated contactors as HV switches.

5.2. High Voltage Hazards

Error! Reference source not found. details the hazards of a high voltage electric network. These hazards are mostly catastrophic events which may result in severe harm to personnel or even loss of life. Great care and attention must be given to those hazards in the design and the implementation of an HV battery string.

6. PRINCIPLE DESIGN OF THE BATTERY STRING

The HV battery string requirements derived in **Error! Reference source not found.** & **Error! Reference source not found.** are consolidated to the principle HV battery design which is presented in **Figure 2**. In the presented scheme the dashed gray rectangles on the left side are the standard batteries (e.g., 6T Li-Ion). The batteries are coupled with parallel bypass diodes and connected in series to form the HV battery string. Additional components are the Insulation Monitoring Device (IMD), the main switches (+ and −) the pre-charge path (switch and resistor), the fuse and Manual Service Disconnect (MSD) and the shunt resistor for current sensing. The master BMS shall also sense the voltage with respect to the low side of the battery string, on the external side (The HV connector, positive and negative), the internal high side of the battery string and between every two components on the positive current path. The master BMS shall drive and monitor the high voltage interlock loop (HVIL) and condition the closed HV switches on the continuity of the HVIL and a high insulation resistance between the poles and the chassis. The master BMS shall communicate with all the battery units on an internal network. The master BMS shall have additional functions which are not safety related such as monitoring the battery string's state-of-charge and state of health, fault detection, communicating with external systems on an external network and optionally outputting auxiliary low voltage power.

7. REFERENCES

[1] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia and X. He, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," *Energy Storage Materials,* vol. 10, p. 246–267, 2018.

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9. ACRONYMS

BMS	Battery Management System
CID	Current Interrupt Device
HV	High Voltage
HVIL	High Voltage Interlock Loop
IMD	Insulation Monitoring Device
MCU	Microcontroller Unit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MSD	Manual Service Disconnect
PTC	Positive Thermal Coefficient
SEI	Solid Electrolyte Interphase
SOA	Safe Operating Area
TCO	Thermal Cutoff
TR	Thermal Runaway
UV	Under Voltage

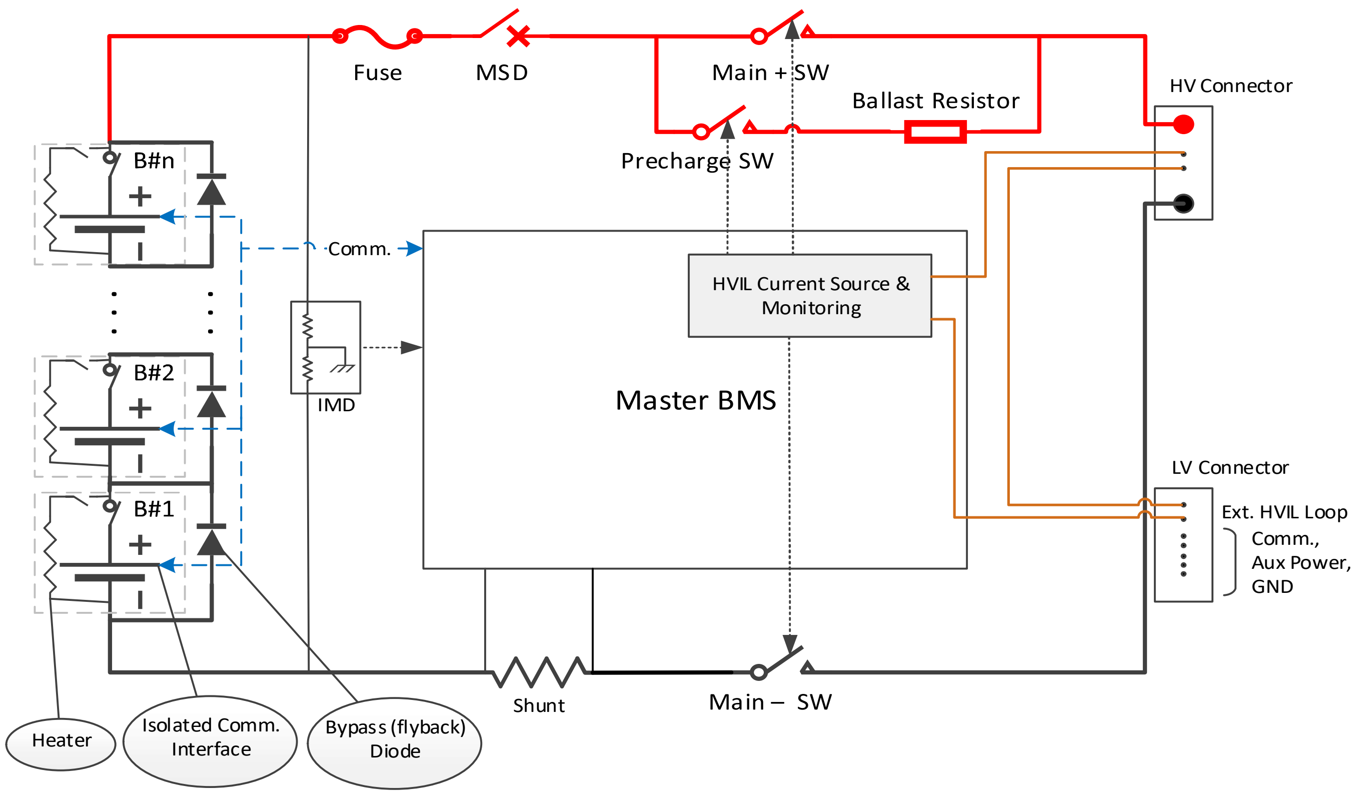

Figure 2: Schematic HV Battery String