Comparative Analysis of Battery Management System Topologies for Electric Vehicles

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ENERGY, POWER & SUSTAINABILITY (EPS) GROUP, ECE DEPARTMENT

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OVERVIEW

- Electric vehicles use very large high-energy density Li-ion battery stacks consisting of multiple cells connected in series (Traction Battery).
    - At a high-level of abstraction, this problem assumes that the **individual cells (in a stack) undergo charging and discharging independently, resulting in charge mismatch in the cells in every stack**.
        - This charge mismatch results in decreased battery operational life and unexpected thermal failures.
        - Traction Batteries in Electric Vehicles require continuous balancing during traction, regeneration and charging modes.
        - Differences in individual cell charges result in deferred operation of an Electric Vehicle on the whole and can also lead to overheating and ultimately burn-out.
        - Boeing 787 Jet fire in 2013 and multiple reports on Tesla Model S are some of the examples.
- This research is motivated towards the analysis and development of a battery management system's (BMS) circuit topology and algorithm to address the underlying issue in order to avoid a major failure.
    - Existing BMS topologies, namely **Switched Capacitor**, and **Single Core Multi-Winding and their application algorithms are reviewed and compared**.
- Experimental work involves lifecycle testing performed on Li-ion cells prior to implementation on a **forward flyback converter based BMS board**.
    - Algorithm in this experiment focuses on **voltage-based** highest-average-deviant **strategy**—an approach in which voltage is balanced in an evenly distributed manner by averaging the sampled cell voltages, finding the difference between the average cell voltage of each cell and applying the balancing current to the cell with the highest difference.
    - Preliminary **lifecycle tests** to analyze under and over voltage ranges are performed on the 18650 Lithium-Manganese-Cobalt-Oxide ($LiNiMnCo$ or NMC) Li-ion cells using PCBA 5010-4 battery analyzer.
    - Cells are later stacked up to **emulate an electric vehicle traction battery** for evaluation of the voltage-based strategy algorithm using forward flyback converter topology based board.
    - This evaluation set-up consists of multiple 18650 protected NMC Li-ion cells, 12 Volts lead acid battery, Texas Instruments battery management board, Hercules Safety microcontroller (MCU) and a direct current (DC) charger.
        - Standards and regulations like AEC-Q100, ISO 26262, IEEE 1679.1-2017, and IEC 62660-1 have been taken into consideration while performing this experiment.
- Existing Algorithms reviewed and compared with the experimented algorithms and topology provide solutions to overcome these failures. Lithium-Ion chemistry (NMC) is selected due to its high specific energy content and its overheating issue is resolved using a Battery Management System.
- Results are evaluated based on cost, modularity and balancing time and indicate that the **BMS topologies play a major role in defining the operational life and selection of Li-Ion cells applicability.**
    - An algorithm suggestion for future work is also mentioned.

FIGURE 1 Bidirectional Traction & Regeneration and DC Charging Mode

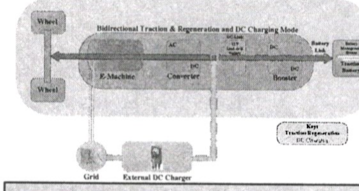


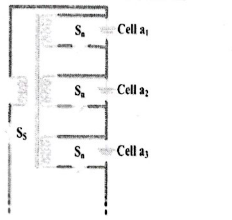
TABLE 1 Charge and Discharge Temperature Comparison of Lead Acid, NiCd/NiMH, and Li-ion Battery Types

Battery Type	Charge Temperature	Discharge Temperature	Charge Advisory
Lead Acid	-20°C to 50°C	-20°C to 50°C	Charge at 0.3C or less below freezing. Lower V-threshold by 3mV/°C when hot.
			Charge at 0.1C between -18°C and 0°C.
NiCd, NiMH	0°C to 45°C	-20°C to 65°C	Charge at 0.3C between 0°C and 5°C. Charge acceptance at 45°C is 70%.
			Charge acceptance at 60°C is 45%.
Li-ion	0°C to 45°C	-20°C to 60°C	No charge permitted below freezing. Good charge/discharge performance at higher temperature but shorter life.

DISCUSSION

Single Core Multi Winding Equalization

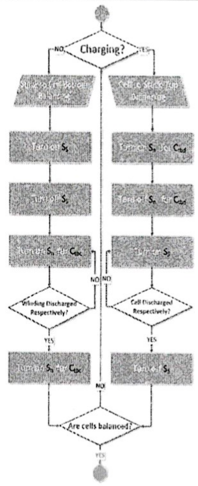
FIGURE 2 Single Core Multi Winding Equalization



For cell-to-stack equalization:
(a) switch for the specified cell (C_{nd}) is turned on and the cell is drained
(b) switch for the stack is turned on/cell switch is turned off and primary winding that received charge from secondary winding discharges and charges stack

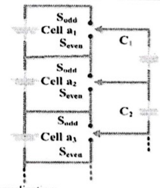
For stack-to-cell equalization:
(a) stack switch turned on and stack discharges into the winding
(b) stack switch gets turned off
(c) cell switch is turned on
(d) primary winding discharges into secondary winding and charges cell (C_{nc}).

FIGURE 4 Single Core Multi Winding Equalization



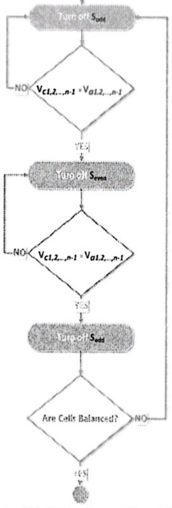
Switched Capacitor Equalization

FIGURE 3 Switched Capacitor Equalization



For cell-to-cell equalization:
(a) switch on odd switches
(b) let cells equalize with the capacitor in parallel
(c) switch off odd switches and switch on even switches
(d) let cells below equalize with the capacitor that was previously connected to the cell above
(e) switch off even switches
(f) switch on odd switches
(g) repeat for all cells until they are balanced

FIGURE 5 Switched Capacitor Equalization

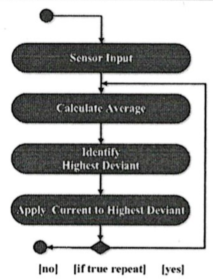


EQUIPMENT & ALGORITHM

TABLE 2 List of Equipment and Equipment/ Test Specifications

Equipment	Equipment/ Test Specifications
PCBA 5010-4 Battery Analyzer	C-Rate: $\frac{C}{4} = \frac{3500[mAh]}{4[V]} = 875\ [\frac{mAh}{V}]$
	The end of discharge voltage is three volts (3V)
Li-ion Batteries Under Test	NMC 18650 LG
	Three and seven volts (3.7V)
	Three and five amp-hour (3.5Ah)
Lead-Acid Battery	Twelve volts (12V)
Texas Instruments Battery Management Board	Fulfills the ASIL ISO 26262 requirements
Texas Instruments Hercules Microcontroller	Fulfills the Automotive AEC Q100 requirements
External DC Charger	Power Supply – five volts (5V), sixty volts (60V)

FIGURE 6 Voltage-Based Highest Average Deviant Algorithm



Voltage-Based Highest Average Deviant Algorithm

1. Collect sensor data (Voltages)
2. Store the average in a variable Avg
3. Get user input on which set of cells to balance
4. Store in a variable Set, where 6 ≤ Set length ≤16
5. Store in a variable CellV
6. Deviation of Avg from cell with higher voltage is stored in HIDelta_Max
7. Deviation of Avg from cell with lower voltage is stored in HIDelta_Min
8. If HIDelta_Max > HIDelta_Min
9. Discharge cell with higher voltage
10. Else charge cell with lower voltage
11. Repeat until cell voltages equalize

RESULTS

The results is gathered in two parts: (a) preliminary battery testing and (b) algorithm execution. On the left side is the experimental setup, and the right side is the result for each part.

FIGURE 7 Setup of Preliminary Battery Testing

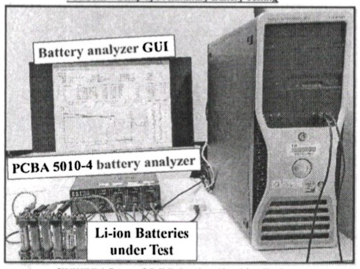


FIGURE 9 Setup of Cell Balancing Algorithm Testing

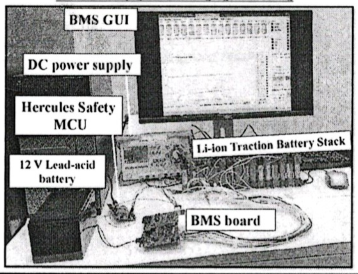
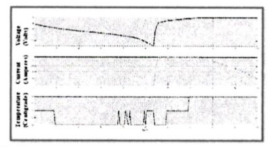


FIGURE 8 Life cycle Testing Plot



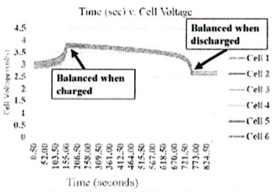
Life cycle Testing:

- Plot indicates variations in voltage, current, and temperature with respect to state of charge (%).

Forward Flyback Converter Topology:

- The cell balancing algorithm successfully balanced the cells under charging and discharging conditions.
- The converged peak on the **LEFT** side of the graph indicates the cells were successfully **balanced under charging** conditions. The converged valley on the **RIGHT** side of the graph indicates the cells were successfully **balanced under discharging** conditions.

FIGURE 10 Cell Balancing Algorithm Plot



CONCLUSION

TABLE 3 Metrics of Three Topologies

Topology	Applicability	Cost	Modular	Time to Balance	Topology Type
Switched Capacitor	Electric vehicle, UPS, Artificial satellite, telephone industry	Medium	Yes	--	Distributed
Single Core Multi-Winding	Electric vehicle	Very High	No	+++	Distributed
Forward Flyback Converter	Electric vehicle	High	Yes	+	Centralized

- A successful cell balancing algorithm has many applications, such as electric vehicles, UPS, artificial satellite, etc.
- Various topologies discussed are evaluated with respect to accuracy and efficiency on five metrics mentioned above.

FUTURE WORK

- A topology that would be cost efficient, modular, and takes least time to balance would be designed.
- To improve the accuracy of the Highest Deviant algorithm, noisy data will be filtered from the sensor data with algorithms which implement prediction techniques.
- Improved topology with prediction algorithms that can **update** the error in a prediction, predict the voltage, and **predict** the error in prediction.

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This work is a result of research supported by National Science Foundation under the Award number CNS-1553494