

Abstract

Lithium-ion battery packs develop charge imbalances over time due to manufacturing variations in cell characteristics, environmental factors such as temperature gradients, the presence of weaker cells within the pack, and differences in rate of health degradation among cells. To address these effects, modern Battery Management Systems (BMS) incorporate Charge Equalization Circuits (CECs) that balance charge among series-connected parallel cell modules (PCMs). By maintaining uniform cell parameters, such as voltage or state of charge (SOC), the CECs maximize capacity utilization, improve battery life, and ensure safer operation under varying load and environmental conditions.

This work focuses on enhancing balancing efficiency and minimizing charge losses associated with CEC operation, while maintaining lower equalization complexity, particularly under high C-rate balancing across all operational conditions. The conventional passive equalization suffers from charge dissipation and slow balancing speed, making it unsuitable for high-power battery systems. In contrast, active equalization can efficiently redistribute charge among series-connected PCMs and is generally categorized into three groups: direct cell-to-cell (D2C), adjacent cell-to-cell (AC2C), and multi-cell-to-multi-cell (MC2MC), along with hybrid variants, such as cell-to-pack-to-cell (C2P2C) architectures. Among these, the AC2C topology offers a cost-effective, modular solution with reasonable balancing time for medium-power battery packs (≤ 48 V, 2 kW) by balancing adjacent PCMs using non-isolated DC-DC converter-based CECs.

Conventional switching strategies in AC2C equalization often fail to address inherent transient imbalances, and under certain imbalance conditions among PCMs, the overall PCM current may exceed safe C-rate limits, leading to increased losses and safety concerns. To improve AC2C CEC performance, novel adaptive switching strategies are developed by introducing interleaved switching and variable PWM parameter control. The interleaving operation of CECs reduces both

peak-to-peak and RMS current stress in PCMs during switching transitions under extreme imbalance scenarios, while variable PWM parameter control utilizes the modulation parameters such as switching frequency, duty cycle, and phase-shift, to dynamically regulate the equalization current of each PCM independently, based on the imbalance state between adjacent PCMs connected to CEC.

The proposed equalization strategies are validated using conventional AC2C CECs such as buck-boost and Cuk converters. However, due to higher voltage stress on switches and significant CEC losses, a non-isolated dual half-bridge (NiDHB) CEC is proposed for modular (pack-to-pack) AC2C equalization. The NiDHB CEC offers low voltage stress on switches, a symmetric inductor current profile, and zero-voltage switching (ZVS) capability. Further performance improvement is achieved through the integration of the adaptive strategy, which minimizes equalization loss and achieves maximum efficiency. The equalization processes are simulated in the PLECS environment for four imbalance scenarios under no-load and charge-discharge conditions, using two battery pack models: a 48 V, 20 Ah LCO pack and a 25.6 V, 10 Ah LFP pack. Experimental validations are carried out on an equalization setup using BMS, an 18.2 V, 10 Ah pack with buck-boost CEC and a 14.6 V, 10 Ah pack with NiDHB CEC.

Overall, the research presented in this thesis addresses key limitations of AC2C equalization by improving the control strategy and CEC performance. The NiDHB-based AC2C CEC demonstrates high equalization efficiency and faster balancing under various imbalance scenarios, establishing it as a reliable and cost-effective balancing solution for medium-power modular battery pack systems.

Keywords: Active charge balance, Adjacent cell-to-cell (AC2C) equalization, Adaptive switching strategy, Battery management system (BMS), Buck-Boost converter, Charge equalization circuits, Non-isolated dual half-bridge converter (NiDHB).