Active SOC Balancing for a Multi-Chemistry Battery Pack with Reduced Number of Converters

Preprint

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Active SOC Balancing for a Multi-Chemistry Battery Pack with Reduced Number of Converters

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***Abstract*—In energy storage systems using second-life or multi-chemistry cells, an active state of charge (SOC) balancing system can prolong pack life and enhance performance by utilizing the healthier cells more than those which are heavily degraded. However, the high cost of the active balancing system, particularly in converter-based solutions, prevents their widespread usage. Considering this, existing research has proposed numerous balancing systems utilizing only one converter. However, such systems may compromise the balancing speed too much. Therefore, this work proposes two active balancing systems with a reduced number of converters for 14-16 series-connected cells. One system uses two converters for direct cell-to-cell balancing. The other uses a time-multiplexed approach to exchange energy via an auxiliary low-voltage (LV) bus using four converters. The proposed balancing systems are compared to two baseline systems, a single converter cell-to-cell balancing system, and a 14 converter balancing system with an auxiliary LV bus.**

***Keywords*—Energy storage, Battery pack, SOC balancing, Dual active bridge, Converters, Kalman filtering.**

I. Introduction

This work considers an active state of charge (SOC) balancing system for a multi-chemistry behind-the-meter-storage (BTMS) battery pack. To meet the high energy and power demands of the BTMS application, the BTMS pack is comprised of several modules, each with many cells in series and parallel. The BTMS pack differs from electric vehicle battery packs in that the energy density is of lesser concern. Instead, greater emphasis is placed on long calendar life, e.g. 20 years, and on cycle life, e.g. more than 8000 cycles [1]. Considering these challenging lifetime requirements, the aging and degradation of the pack must be minimized through careful thermal management and controlled cycling of each cell.

The series-connected cells in a battery pack require cell balancing due to the divergence of cell voltages or SOC over repeated charging and discharging cycles. In a passive balancing method, resistors can dissipate excess energy to balance the cells. However, active balancing, where the excess energy from a cell is transferred to the other cells is more efficient, and enables SOC balancing instead of voltage balancing. In a basic voltage balancing system, cells are balanced according to terminal voltage measurements, from which open-circuit voltage (OCV) can be estimated by considering the cell current and internal resistance, or a more complex RC cell model. However, active voltage balancing is difficult in practice, since cell parameter variations may lead to inaccurate OCV estimation during operation. Additionally, for cell chemistries with relatively flat OCV-SOC curves such as lithium iron phosphate (LFP), the cell SOCs may remain significantly imbalanced even when the voltages are closely balanced. Therefore, SOC balancing is preferable. SOC balancing requires an SOC estimator for each cell, since SOC cannot be directly measured. Generally, voltage, current, and temperature measurements are used to estimate SOC, in conjunction with a model of the cell. Kalman filtering is a popular approach to realize SOC estimation, since the information from measurements can be combined with a state model to better estimate SOC than from either method alone [2].

Active SOC balancing via DC-DC converters allows for cells to be continuously balanced during charging and discharging. This allows the stronger cells to be cycled deeper than the weaker cells, driving uniform aging, and ensuring string and pack performance is not limited by the weakest cells in a string [3], [4]. An active SOC balancing system can also take temperature measurements of the cells, adjusting the available power when thermal limits are reached. Beyond SOC estimation for the SOC balancing action, the current, voltage, and temperature measurements can also enable state-of-health (SOH) estimation of the cells and therefore of the pack.

To meet the high life-time requirements and ensure safe operation of the BTMS pack, an active SOC balancing system was detailed in the authors' prior work [5]. Dual-active bridge (DAB) converters connected to each cell are used to balance the cell SOCs via an auxiliary low-voltage (LV) bus, similar to the systems of [3], [6]. This bus can support ancillary system loads, partially offsetting the balancing system cost. The scaled-down prototype BTMS pack consists of multiple strings of 14 cells in series connection, requiring 14 DABs for the active SOC balancing. Each string is connected to a high-voltage bus via a 5 kW DAB converter, enabling a multi-chemistry pack where the strings may have different chemistries with variation in string voltage, maximum charge / discharge rates, and energy capacity. DAB converters are selected for their bidirectional power flow, isolation, and high-efficiency. Given the stationary on-site application of the

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BTMS pack, energy density and space are of reduced concern. Yet the cost remains important. Therefore, in this paper we consider how the active SOC balancing system can be realized with a reduced number of DAB converters.

Reducing the cost or size of the balancing system is of significant concern in many applications, leading to extensive exploration of single converter balancing systems in the literature. In these single converter solutions, one converter balances the entire string of series-connected cells. [7] proposes direct cell-to-cell balancing using a single push-pull converter. Each cell in the string can be connected to either side of the converter via a network of relay switches. The system balances the cells' open-circuit voltage (OCV), using voltage measurements compensated for the transient voltage drop across cell internal resistance. In a similar vein, Texas Instruments offers a BMS evaluation board design [8], in which a single converter realizes cell-to-pack balancing of up to seven series-connected cells. Compared to [7], bidirectional solid-state switches realize the cell switching, and the energy-transfer is indirect. [9] uses a single converter to achieve indirect cell-to-cell balancing, using a super-capacitor as an intermediary energy storage device. In this way, a switching network to allow connection to any cell is only required at one side of the converter. However, the energy transfer from cell-to-cell is indirect, being slower and less efficient, since it must pass through the converter twice.

Several single converter balancing systems have been proposed which realize further reductions in the number of cell connection switches. [10] proposes a direct cell-to-cell balancing system utilizing a single flyback converter with a multi-winding transformer. The multi-winding transformer reduces the number of switches required to connect the converter between any two cells in the system, while retaining direct cell-to-cell energy transfer. However, this solution requires a large multi-winding transformer which scales with the number of cells in the string. [11] uses a single buck-boost converter and a switch matrix to balance a string of cells. The reduced number of cell connection switches realizes a low part-count implementation, however, this limits the combinations of cells between which energy can be directly transferred. [12] uses a single DAB converter to balance a string via a vehicle's 12 V bus. The positive terminal of each cell shares a switch matrix connection with the negative terminal of another cell. This requires a sequential balancing process for the odd and even cells.

While these designs are highly hardware-efficient, they may compromise the balancing speed too much, especially in a 14-16 cell string. Additionally, none of these designs can support an auxiliary low-voltage bus solely from the balancing converters. Therefore, this work proposes two alternative converter-based balancing methods, which serve to reduce the cost-impact of the balancing system, while retaining the benefits of active SOC balancing. One topology implements direct cell-to-cell balancing using two converters, while the other implements cell-to-cell balancing with four converters via an auxiliary low-voltage bus, which can also support an-

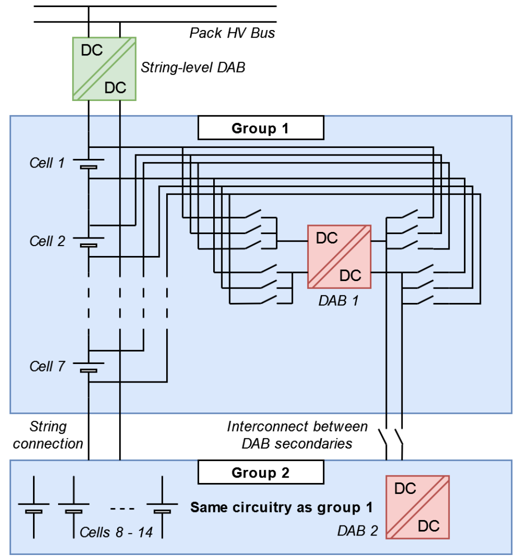


Fig. 1. The proposed direct cell-to-cell balancing system with two DAB converters.

cillary system loads. Each proposed solution explores a middle ground between balancing systems with a single converter per string, and balancing systems with one converter per cell, therefore achieving a promising compromise between cost and balancing speed. The proposed systems are compared to single converter and one converter per cell baseline systems in terms cost, efficiency, and balancing speed.

II. Proposed Reduced Converter Balancing Systems

A. Direct Cell-to-Cell Balancing System with Two Converters

Fig. 1 shows a direct cell-to-cell balancing topology using two DAB converters with two cell groups. DAB 1 enables direct cell-to-cell balancing of cells 1-7 (group 1), and DAB 2 for cells 8-14 (group 2). Therefore, to balance across all 14 cells, two operation modes are required. If the difference in mean SOCs between the two cell groups is less than 1%, mode 1 is used. Otherwise, mode 2 is used. In mode 1, cells 1-7 are independently balanced by DAB 1, while cells 8-14 are independently balanced by DAB 2. The switches between the two DABs are open and their operation is independent. The highest SOC cell from each group is connected to each DABs primary side, and the lowest SOC cell from each group is connected to the secondaries. In mode 2, the switches between DABs 1 and 2 are closed, and energy is transferred via the two DABs between the the highest and lowest cells in groups 1 and 2, thereby converging the mean SOC of the two cell groups. In mode 1, each DAB is operating independently, following a balancing current command provided by the supervisory controller. The balancing current command is set according to the difference between the two cell SOCs currently connected to the DAB converter. In mode 2, a single balancing current flows through both converters. To ensure stable operation, one DAB regulates the voltage between the two DABs to be the

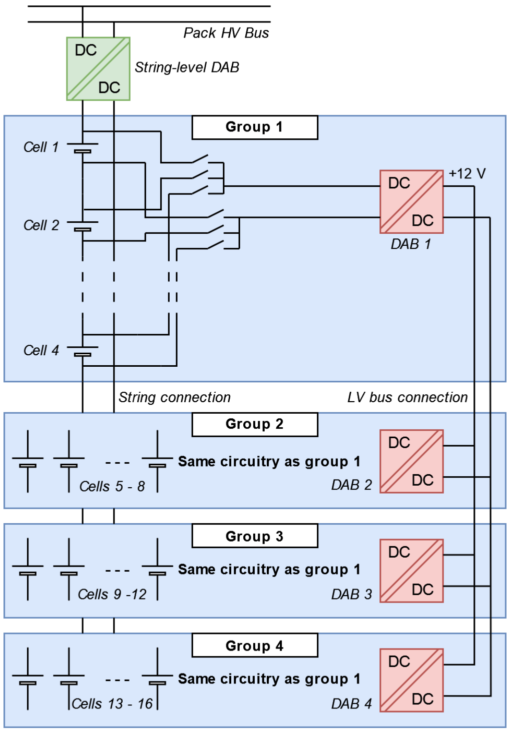
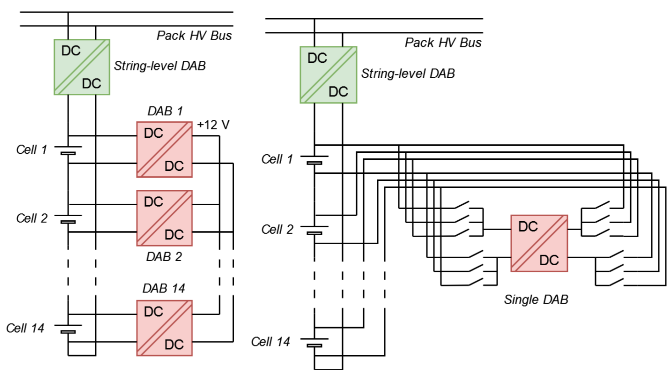


Fig. 2. The proposed LV bus balancing system with four time-multiplexed converters.



(a) (b)

Fig. 3. Baseline balancing systems for comparison. (a) Balancing via a LV bus with one converter per cell. (b) Direct cell-to-cell balancing with a single DAB converter.

nominal cell voltage, while the other tracks a balancing current command from the supervisory controller.

B. LV Bus Balancing System with Four Time-Multiplexed Converters

Fig. 2 shows a multiplexed solution in which the LV bus is retained. In contrast to direct cell-to-cell balancing systems, the four DAB converters are time-multiplexed to alternate between connecting the highest and lowest cells in each four-cell group to the LV bus. The time-multiplexing groups are shown in Table I. SOC_{max} denotes that a DAB is connected to the highest SOC cell out of its four corresponding cells. Whereas, SOC_{min} denotes a connection to the lowest SOC cell. In the time-multiplexing strategy, the system cycles sequentially through multiplex groups A through F in 60 seconds (10 seconds per group). Within each multiplex group and time window, the connected cells are balanced relative to the mean SOC of these four connected cells. This time-multiplexing strategy ensures that any set of SOCs can converge together. Similar to [5], a more complex control method is required to achieve a set of appropriate balancing currents while maintaining the LV bus voltage.

TABLE I
TIME-MULTIPLEXING STRATEGY FOR 4 DAB SYSTEM

Cells	DAB	Multiplex Grouping A	B	C	D	E	F
1-4	1	SOC_{max}	SOC_{min}	SOC_{min}	SOC_{max}	SOC_{max}	SOC_{min}
5-8	2	SOC_{max}	SOC_{max}	SOC_{min}	SOC_{min}	SOC_{min}	SOC_{max}
9-12	3	SOC_{min}	SOC_{max}	SOC_{max}	SOC_{min}	SOC_{max}	SOC_{min}
13-16	4	SOC_{min}	SOC_{min}	SOC_{max}	SOC_{max}	SOC_{min}	SOC_{max}

C. Baseline Balancing Systems for Comparison

The two proposed balancing systems are compared to two baseline systems: Balancing via an auxiliary LV bus with one converter per cell; and direct cell-to-cell balancing with a single converter. The one converter per cell system is shown in Fig. 3(a). In this system, the DABs allow for active SOC balancing via an auxiliary 12 V bus, which can also support ancillary system loads. A supervisory controller estimates cell SOCs and communicates with the converter-level controllers via a CAN bus, similar to [5]. The implemented controls for this system are described in detail in Section III and shown in Fig. 4. Fig. 3(b) shows the baseline direct cell-to-cell balancing with a single DAB converter. The converter routes power directly from the highest SOC cell to the lowest SOC cell via switch matrices on each side of the converter. These two systems represent opposite ends of the tradeoff between system cost and balancing speed, and therefore provide useful comparison points for the two proposed intermediary solutions.

III. CONTROLS

All the balancing systems in this paper use a supervisory controller, in a similar manner to [5]. The supervisory controller communicates over CAN with the balancing DABs' controllers (implemented on a microcontroller on the converter board PCB). The DAB controllers send the supervisory controller their measurements of cell voltage, the cell-side DAB current, and cell temperature. The string current is measured and sent to the supervisory controller by the string-level DAB converters which connect each string to the pack's high voltage bus. The supervisory controller estimates cell SOCs using extended Kalman filters (EKFs), and implements the highest-level, slow-timescale controls. The supervisory controller then communicates a control signal to each DAB board to control the balancing process.

An overview of the DAB board MCU controls, supervisory controller, and their CAN communication is shown in Fig. 4, applicable to the baseline balancing system with one DAB

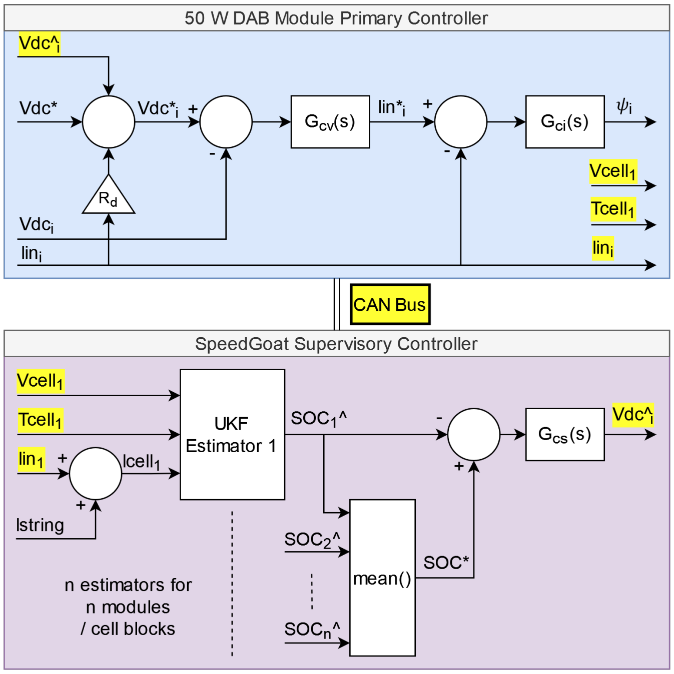


Fig. 4. Controls implementation for the baseline balancing system with one DAB converter per cell and an auxiliary low-voltage bus.

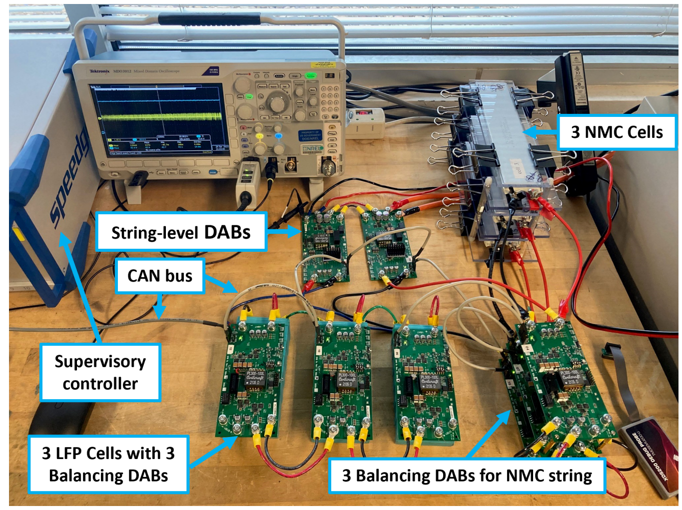


Fig. 5. Experimental testing of the small-scale multi-chemistry pack with the baseline one converter per cell active SOC balancing.

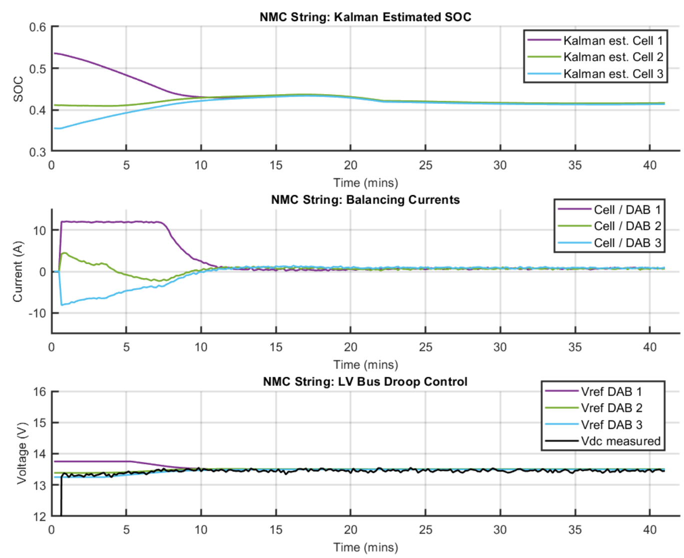


Fig. 6. Experimental active SOC balancing results corresponding to the baseline system with one converter per cell in which energy is exchanged via an auxiliary LV bus.

converter per cell and an auxiliary low-voltage bus. However, a similar control implementation is used for all the balancing systems in this work. For direct cell-to-cell balancing, the voltage regulation loop is omitted since there is no longer an auxiliary low-voltage bus. Instead of sending a voltage reference shift, the supervisory controller sends the DAB converter a current reference. Additional logic and controls are necessary to operate the bidirectional switches used to implement the cell switching in the two proposed balancing systems and the baseline system with one converter per cell. These controls can also be implemented in the supervisory controller, with CAN communication to additional board-level MCUs which then generate PWM signals to control the cell switching matrices.

IV. Experimental Validation

Fig. 5 shows the experimental test setup for a small-scale multi-chemistry demonstration pack with active SOC balancing. The multi-chemistry pack has two strings, one with three LFP cells and the other with three NMC cells. String-level converters control the power flow from each string while balancing SOCs between the multi-chemistry strings. Within each string, the cell SOC balancing is performed by exchanging energy via a LV bus with one 50 W balancing DAB converter per cell, i.e. the LFP string and NMC string each use a three-cell / three-DAB version of the baseline balancing system shown in Fig. 3(a). Therefore, this experimental test validates the controls strategy and SOC estimation technique described in Section III. While the exact control implementations are different for the proposed balancing systems, the core elements of Kalman filter SOC estimation, CAN communication between DABs and the supervisory controller, and current control loops remain the same.

The balancing operation during an experimental test is shown in Fig. 6. The top subplot shows the SOC convergence achieved by the balancing system for the NMC cell string. The SOC convergence is achieved in around 10 minutes by the balancing converters driving appropriate balancing currents to/from each cell, with the energy exchanged via the auxiliary LV bus. Using the control strategy of Section III, cell voltage, cell-side DAB currents, and string current measurements are communicated via CAN to a supervisory controller running on the Speedgoat real-time target platform. This supervisory controller then estimates cell SOCs using Kalman filters. Using the errors between individual cell SOCs and the mean

TABLE II
SIMULATION INITIAL CELL SOCS

Cell	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15*	16*
Initial SOC	0.515	0.640	0.717	0.315	0.534	0.485	0.256	0.419	0.331	0.647	0.406	0.514	0.333	0.551	0.382	0.577

*Cells 15 and 16 are only present in the proposed four DAB / 16 cell system.

cell SOC, LV bus voltage reference shifts are set for each balancing DAB converter. The modified voltage references are then communicated via CAN back to each balancing DAB converter.

This control action is shown in the middle and bottom subplots of Fig. 6. When an individual DAB has an LV bus voltage reference lower or higher than the actual bus voltage, its control loops will drive a negative or positive balancing current via the DAB converter to try to reduce the voltage error. This control action realizes LV bus regulation while simultaneously realizing an appropriate set of balancing currents in line with the SOC imbalance.

V. SIMULATION OF BALANCING SYSTEM OPERATION

MATLAB Simulink simulation is used to evaluate the balancing performance of the proposed reduced converter balancing systems, relative to the two baseline balancing systems. The cell switches shown in Figs. 1 - 3 are assumed to be bidirectional solid-state switches with an efficiency of 99.3%. Meanwhile, the DAB converters are assumed to be 95% efficient. A simplified DAB converter model is used in which a first-order transfer function captures the DAB's transient response to a change in reference current. A common test case is used with the initial cell SOCs as shown in Table II.

A. Baseline Balancing Systems Results

The SOC convergence (driven by the operation of the balancing system) for the baseline systems are shown in Fig. 7. Fig. 7(a) shows the balancing operation of the baseline LV bus balancing system with one converter per cell (14 DABs). The 50 W DAB converter dedicated to each cell allows for all the cells to balance simultaneously, with SOC convergence in around 19 minutes. The balancing currents are constrained not only by the DAB converters' 50 W power limit, but also the requirement that the net current at the auxiliary LV bus is zero (to maintain voltage regulation). Fig. 7(b) shows that the SOCs converge in around 62 minutes for the baseline direct cell-to-cell balancing system with a single DAB converter. The total balancing time is several times longer than that of the one converter per cell system, since only two cells can be balanced simultaneously. In this case, the cell balancing currents are highly discontinuous, as the single DAB converter is switched to the highest/lowest SOC cells every 10 seconds.

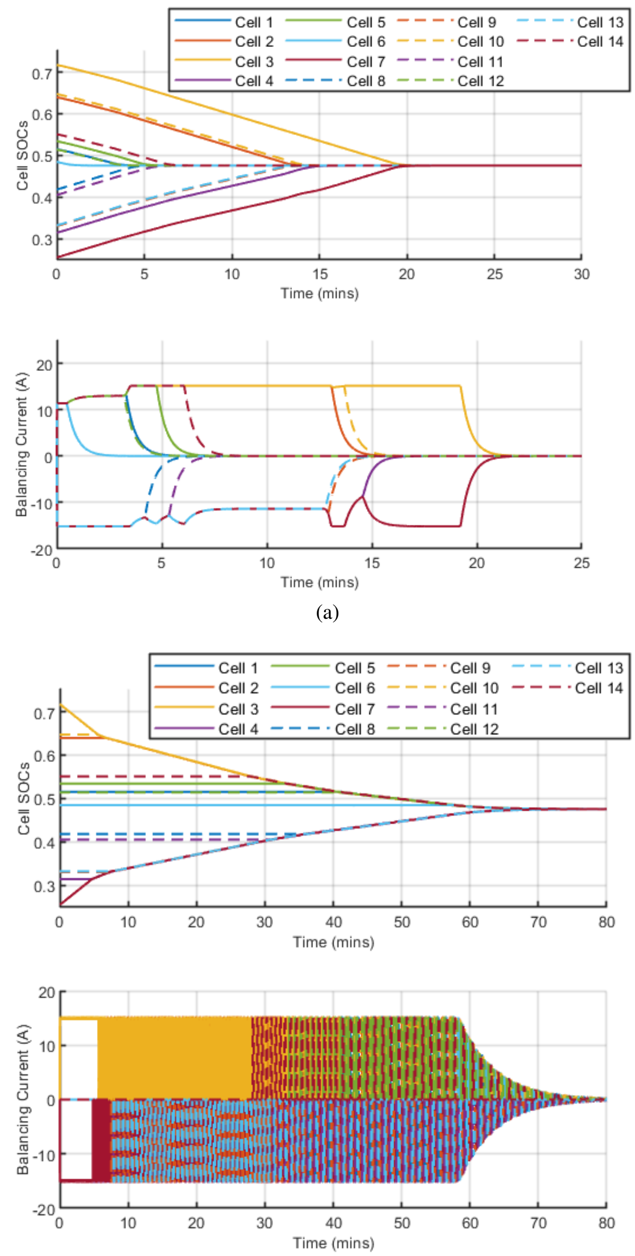
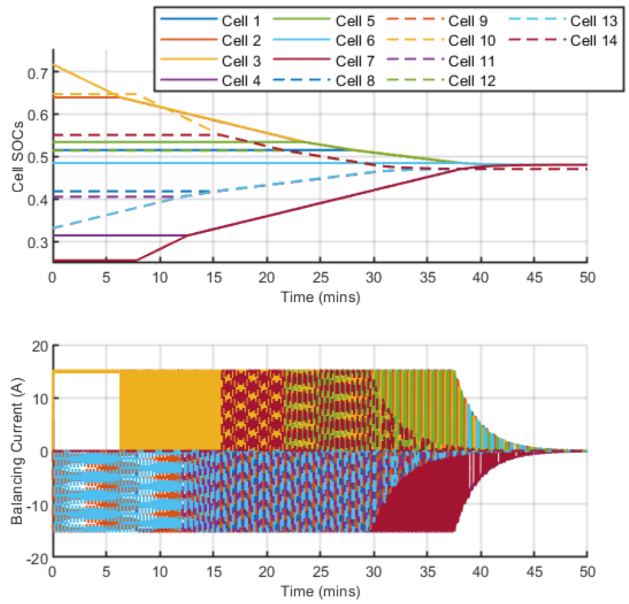


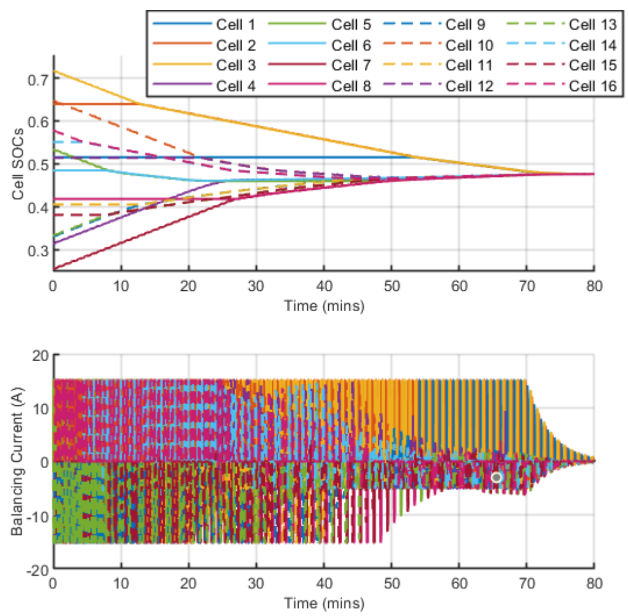
Fig. 7. SOC convergence for the baseline balancing systems for comparison. (a) Balancing via a LV bus with one converter per cell. (b) Direct cell-to-cell balancing with a single DAB converter.

B. Proposed Reduced Converter Balancing Systems Results

Fig. 8(a) shows the balancing operation for the proposed balancing system in which direct cell-to-cell balancing is realized with two DAB converters. The balancing system first operates in mode 2 for around 7.8 minutes, where the mean SOC of the two cells groups (cells 1-7 and cells 1-14) are matched. Then the system operates in mode 1 until the cells are balanced at around 45.5 minutes. Similar to the baseline cell-to-cell balancing system with a single converter, the DAB cell connections are reevaluated every 10 seconds, leading to discontinuous cell balancing currents. Fig. 8(b) shows the



(a)



(b)

Fig. 8. SOC convergence for the proposed reduced converter balancing systems. (a) Direct cell-to-cell balancing with two DABs converters. (b) Balancing via a LV bus with four time-multiplexed DAB converters.

SOC convergence for the proposed balancing system with an auxiliary LV bus and four time-multiplexed DAB converters. The SOCs converge in around 61 minutes. The LV bus system with four DABs is slower, since the currents at the LV bus must be balanced to maintain its voltage. This means that the balancing currents are not the optimum set. Additionally, since the four DABs are time-multiplexed to alternate between different cells in each group, the balancing process is inherently less effective. Again, the DAB cell connections change every 10 seconds causing a discontinuous set of cell balancing currents.

TABLE III
DAB Converter Cost Breakdown

Component	Part Number	#	Unit Cost ($)	Subtotal ($)
Opamp	OPA376AIDR	6	2.01	12.06
Gate Driver	LM5113	4	6.36	25.44
NAND gate	MC74VHC132DTR2G	4	0.61	2.44
Iso. Buffer	ISO7520CDW	4	4.93	19.72
Current Sensor	GO 20-SMS/SP3	1	7.35	7.35
Iso. Amplifier	AMC1350QDWVRQ1	1	14.79	14.79
Current Sensor	GO 30-SMS/SP3	1	7.35	7.35
CAN Isolator	ISO7821DWW	1	9.44	9.44
CAN Transceiver	XR31234ED	1	2.84	2.84
5V Power Supply	TPS61030PWPG4	1	3.75	3.75
Iso. Power Supply	LTM8068	2	30.33	60.66
3V Linear Reg.	ADR433BRZ	1	11.55	11.55
3.3V Linear Reg.	ADP124ARHZ-3V3-R7	2	2.66	5.32
MCU	TMS320F280025C	1	9.24	9.24
GaN MOSFET	EPC2024	8	7.32	58.56
Transformer	PL300-100L	1	11.64	11.64
			Total	262.15

TABLE IV
Bidirectional Solid-state Switch Cost Breakdown

Component	Part Number	#	Unit Cost ($)	Subtotal ($)
MOSFET	SIR178DP-T1-RE3	2	1.76	3.52
Gate Driver	UCC5304DWVR	1	2.46	2.46
Isolated Power Supply	PDME1-S3-S12-S	1	3.53	3.53
			Total	9.51

VI. Comparison

Tables III and IV provide the cost breakdowns of a single DAB converter and a single bidirecitonal solid-state switch. While the cost breakdowns are not exhaustive, these components cover the majority of the cost of these systems. Similarly, while the balancing systems comprise additional components and circuitry beyond the converters and switches, these elements represent most of the balancing system cost. Other elements such as the supervisory controller, which performs the SOC estimation and higher-level control tasks, do not change between the presented balancing systems, and are not included in the cost comparison.

Table V provides an overall comparison of the two proposed balancing systems, relative to the two baseline systems. This comparison considers the number of converters, number of bidirectional solid-state switches, total cost, balancing time, and energy loss. First, considering the two baseline systems, the tradeoff between balancing system cost and speed is clear. Compared to the LV bus system with a DAB converter per cell (14 DABs), direct cell-to-cell balancing with a single DAB converter is 4.62 times cheaper. However, the balancing in the randomized test case is 3.21 times slower. This comparison shows that the two baseline cases represent either end of a broad spectrum of possible balancing systems. Therefore, systems such as the BTMS battery pack may require an intermediary option, which achieves a more reasonable tradeoff between cost and speed.

TABLE V
COMPARISON OF ACTIVE CELL BALANCING SYSTEMS

System	Baseline: LV bus with 1 DAB / Cell	Baseline: Cell-to-cell with 1 DAB	Proposed: Cell-to-cell with 2 DABs	Proposed: LV bus with 4 muxed DABs
# of cells	14	14	14	16
# of converters	14	1	2	4
# of bidirectional solid-state switches	0	56	58	32
Max LV bus aux load power (W)	700	N/A	N/A	200
Initial pack energy (kJ)	378	378	378	425
Balancing system energy loss (kJ)	18.92	11.65	13.03	24.56*
Balancing system cost ($)	3670.10	794.71	1075.88	1183.81*
Normalized balancing time (mm:ss)	19:18	61:56	45:30	60:52*

*Scaled by x14/16 for direct comparison to the 14 cell systems.

Now considering the proposed balancing systems, the cell-to-cell balancing system with two DAB converters achieves a cost slightly higher than that of the baseline cell-to-cell balancing system with a single converter (1.35 times). This results in a balancing time which is around 1.36 times faster. Compared to the baseline system with one converter per cell, this two converter system is still 3.41 times cheaper, with 2.36 times the balancing speed.

The proposed balancing system which exchanges energy via an auxiliary LV bus with four time-multiplexed DAB converters is 3.10 times cheaper than the comparable baseline system with one DAB converter per cell (14 DABs). However, the balancing time is increased by 3.15 times. Compared to the baseline system with direct cell-to-cell balancing with a single DAB converter, this proposed four DAB system is only marginally faster but 1.49 times more expensive. Comparing it to the other proposed system (cell-to-cell balancing with two DAB converters), it is considerably slower and slightly more expensive. However, it should be noted that the auxiliary LV bus through which the four DAB system exchanges energy, can also support ancillary system loads, which may partially offset its cost. Indeed, if this auxiliary LV bus is a desired feature of the balancing system, then the proposed four converter balancing system is an attractive solution compared to the baseline one converter per cell system, due to its considerable cost reduction.

Now considering the energy loss and efficiency of each system. In the systems which use an auxiliary LV bus, the energy transfer between any two cells is via two DAB converters. This inherent inefficiency is reflected in higher energy losses than in the cell-to-cell systems. In these direct cell-to-cell balancing systems, energy transfer is via a single converter. However, as Table V shows, it is not twice as efficient, since there are losses incurred in the solid-state bidirectional switches at either side of the converter. Both of the proposed systems are less efficient compared to their respective baseline systems. In the LV bus system with four converters, this is caused by the bidirectional switch matrices, as well as the DAB time-multiplexing, which prevents energy transfer in an optimal manner. Similarly, in the cell-to-cell system with two DABs, balancing each group independently, then balancing the two groups, leads to a non-optimal balancing operation.

VII. CONCLUSION

The results show that the proposed balancing systems offer a promising intermediary option between one converter per cell, and single converter balancing systems. If the auxiliary LV bus is not required, then direct cell-to-cell balancing with two DABs offers efficient balancing for less than a third of the cost of the baseline one converter per cell system. Compared to the baseline system with direct cell-to-cell balancing with a single converter, it is 1.35 times more expensive, while being 1.36 times faster. If the auxiliary LV bus is required, then the time-multiplexed four DAB converter system can support it solely from the cells through the balancing system, while still offering a cost saving of 3.10 times over the LV bus balancing system with one converter per cell. Although the balancing times remain slower than the single converter per cell baseline system, the systems are expected to have adequate capacity to continuously balance SOCs during normal operation.

The projected cost savings of the two proposed balancing systems can improve the economic viability of active SOC balancing in second-life or multi-chemistry battery pack applications. Compared to existing balancing systems, which generally use one converter per cell, or single converter per string approaches, these systems realize a middle-ground in cases where the lowest-cost or fastest balancing system may not be the optimum. This trade-off between cost and balancing speed can be further explored by considering additional groupings of cells and converters. In future work, an optimal design process could be followed, in which the required balancing current / power is determined. Then, the lowest-cost or most efficient system which meets the required balancing demand should be selected.

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