T-type Based Cascaded H-bridge Converter Operating as a Split AC Battery and Modified State-of-Charging Hierarchical Balancing Method

Reyhaneh Eskandari[a,b,*], Prasanth Venugopal[a], Alan Watson[b], Pat Wheeler[b], Thiago Batista Soeiro[a]
[a]Faculty of EEMCS, University of Twente, Netherlands
[b]Faculty of Engineering, University of Nottingham, UK
*Email: *r.eskandari@utwente.nl*

***Abstract*—This work focuses on the so-called split batteries and proposes the T-type cascaded H-bridge circuit, as a suitable candidate for this application. Furthermore, state-of-charge (SoC) balancing between the battery modules is done by a hierarchical algorithm without requiring any ancillary balancing hardware. To minimize the number of switches in the conduction path and to increase efficiency, the conventional hierarchical algorithm is modified for the T-type based cascaded H-bridge. Finally, a simulation in MATLAB Simulink is performed to verify the feasibility of the proposed AC battery and both conventional and modified balancing algorithms.**

***Index Terms*—split battery, AC battery, battery balancing, modular battery-integrated converter, cascaded H-bridge.**

I. INTRODUCTION

Battery cells commercially available today usually have low voltages. In order to meet the voltage and power requirements of industrial and transportation applications, many cells have to be connected in series and in parallel. Due to manufacturing complexity, the battery cells commonly have different intrinsic characteristics like self-discharge rates, internal resistance and impedance, and thermal performances leading to different state-of-charges (SoCs) during operation in battery packs. These disparities between the cells become wider especially when the battery ages [1], [2]. This can result in reduced battery capacity, shorter battery lifetime, and in extreme cases, safety hazards leading to battery fires and explosions [3]. Therefore, it is important to balance the SoC of different battery cells in a battery pack.

In hard-wired battery packs, where there are many cells connected in series and parallel, the current that battery cells can be charged or discharged is the same. The weak/degraded battery cells likely charge or discharge the fastest with the same amount of current due to a possible higher internal resistance. Therefore, the capacity, reliability, and lifetime of the hard-wired battery packs are strongly limited by the weakest cell/module [4]. The conventional way to balance the battery cells in a pack is the passive method, where resistors and switches are used to dissipate the excessive energy of the weak cells. Even though this method is simple, it is mainly effective in charging mode and the capacity of the battery packs is still limited to the weakest cell during discharging. Active balancing methods exist, where dc-dc converters may be used between battery cells and/or modules to transfer the energy between them. This leads to a better controllability of the SoC within the battery cells of a pack, however, the active methods are more complex and expensive as they may require active and passive components like semiconductors, inductors, capacitors, or even transformers [5]. Furthermore, this kind of balancing method can result in more losses due to the energy transfer and by a consequence it can also contribute to the battery aging. Because of all these complications and high costs, most industries rarely use active methods and typically settle for the passive methods [6]. Therefore, the need for other kinds of more efficient methods is still there. Furthermore, the lifetime and reliability of the battery pack are still dependent on the weakest cell even with applying these balancing methods [7].

Split batteries on the other side, use power switches around battery cells/modules to change the connection and configuration of the battery pack dynamically. Therefore unlike their counterpart, hard-wired batteries, the average charging/discharging current of battery cells or modules can be different which leads to an efficient way to balance the SoC between these cells/modules.

In this paper, first, an overview of DC split batteries and AC split batteries is presented. Subsequently, the article proposes a T-type based cascaded H-bridge (CHB) structure integrated with battery sub-units as an AC split battery. Additionally, a benchmark between the studied T-type CHB and the conventional CHB used for the application of AC split batteries is shown. Moreover, a hierarchical balancing method is modified to minimize the number of conducting switches and to further decrease the conduction losses of the studied T-type CHB when compared to the conventional CHB. Finally, simulation results for T-type CHB operating as an AC battery with both conventional and modified balancing algorithm is presented to validate the feasibility of the structure and balancing methods.

II. SPLIT BATTERY

The circuit concept of split batteries uses power electronics switches around subdivided group of a total battery pack which enables a dynamic restructure and by a onsequence a tailored output voltage and power. It can also prevent the imminent fault of an inner segmented battery module or it can bypass it without shutting down the whole battery pack. Furthermore, hard-wired batteries have constant high voltage at the output complicating assembly in the factory and also posing safety issues. Split batteries can have lower voltage levels because of the dynamically changeable structure. The split batteries can be either a DC split battery or an AC split battery according to the output which is explained in the following subsections.

A. DC Split Battery

DC split batteries, also known as reconfigurable batteries, have tailored output DC voltage and power. There are many topologies proposed in the literature, which are able to change the connections of the subdivided group of battery modules/cells from series to parallel or vice-versa or for bypassing some of these segmented cells/modules [8]–[10]. It is needless to say that the degree of freedom of altering the structure depends on the circuit topology and the number of switches that are used around each battery sub-unit. The work developed in [11] and [12] provide an overview of the existing reconfigurable battery circuits. In [12] the authors also provide a comparison of balancing methods in reconfigurable batteries and balancing in hard-wired battery packs with active and passive methods demonstrating that it is more beneficial compared to the conventional balancing methods. Usually, DC Split battery circuits are designed with redundancy to improve reliability and to enable the function of SoC balancing between cells/modules without the requirement of extra hardware. For SoC balancing purpose in a split DC battery, at each time step, at least one subdivided module/cell with the highest (lowest) during charging (discharging) is bypassed by the switches that are around modules/cells [13]. It is worth noting that, the time step of the balancing algorithm is relatively low and since usually a single module is bypassed at a time, the balancing time can be long. The balancing time can be shorter if there are more redundant units but this is typically not cost-effective.

B. AC Split Battery

AC split batteries take a step further than reconfigurable DC battery packs and reuse the already existing power switches around the battery units to generate a multilevel AC output obviating the need for a central high-voltage two-level dc-ac converter. This reduces the voltage stress on the power switches and MOSFETs with lower internal resistance can be employed. Furthermore, due to the multilevel voltage output, the harmonic distortion of the output current improves to a great extent that the sub-circuits can operate with reasonable switching frequencies, while requiring a relatively low AC filter volume. Lower rates of (dv/dt) in the multilevel output reduce electromagnetic interference (EMI) and common-mode voltage across the load or AC grid, i.e., in AC motors or distribution transformer windings the multilevel circuit alleviates the insulation stress, lowers iron and copper losses, among others [14]. Having an AC split battery also means the cells/modules can be charged or discharged unevenly without requiring redundant cells/modules or extra balancer circuitry, i.e., the average current passing through different cells/modules can be controlled individually according to the duty cycle of the switches around them leading to the balanced cells/modules [15]. In other words, the load current is used to balance the battery cells/modules without losing extra energy in the additional balancing hardware. A comparison between the balancing of AC split battery and conventional active balancing topologies can be found in [16]. This work shows that the SoC balancing in AC split batteries can be faster and more efficient than most of the active balancer circuits. It is worth mentioning that AC split batteries can be operated as DC batteries if needed, this feature is shown in [17].

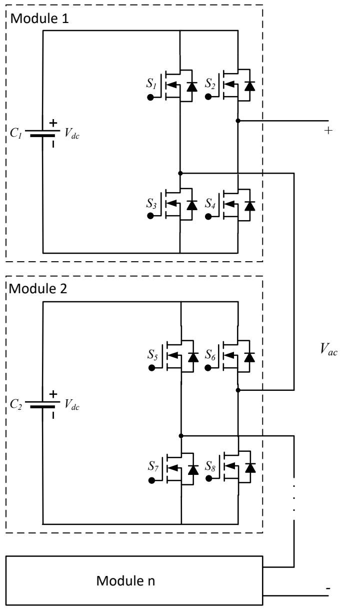


Fig. 1. Conventional cascaded H-bridge integrated with battery sub-units.

The most investigated structures for AC batteries are cascaded half-bridge, conventional cascaded H-bridge (CHB), and modular multilevel converter (MMC). Cascaded half-bridge is only capable of producing zero and positive voltage. Therefore, in single-phase cascaded half-bridge structures, an unfolding stage like an H-bridge inverter is needed to generate the negative part of the AC waveform [18]. In a MMC configuration there are two cascaded half-bridges working as an upper and lower arm for each AC phase. Therefore, this increases the number of required modules for the same voltage and also adds up to the complication of balancing control between the arms [19]–[21]. On the other hand, conventional cascaded H-bridge is able to achieve positive, negative, and zero voltage levels from each submodule. However, it needs a high number of switches, and these will be in the conduction path increasing the conduction losses [22]–[24].

III. SYSTEM CONFIGURATION AND OPERATION PRINCIPLE

A. System Configuration

As previously discussed, the conventional CHB with embedded battery cells/modules is a well-known and well-studied structure for the concept of AC split battery. Fig. 1 shows the structure of the conventional CHB with n integrated battery sub-units, where for each sub-battery unit, an H-bridge converter module with four switches is allocated. Each module according to the output voltage level and SoC of the battery sub-units can be inserted or bypassed and by this, every H-bridge module can have voltages of 0 or ±V$_{dc}$ at its output. Through cascading these bridges a multilevel AC voltage with $(2n+1)$ levels can be achieved. The switches states of three different levels for a 9-level voltage source converter are shown in Table. I. The main drawback of this conventional CHB is that there are many switches in the conduction path which reduces the efficiency of the total system.

In this paper, in order to reduce the number of switches in the conduction path a T-type based cascade H-bridge converter structure is proposed to be embedded with the battery sub-units (Fig. 2). As can be seen, every two battery sub-units require a T-type converter. Therefore, for achieving the same number of voltage levels as the conventional CHB, half of the numbers of the converter modules are needed, i.e., $n/2$. Every module can be bypassed, half inserted, or fully inserted, i.e., the T-type H-bridge module can generate voltage levels of $0V$, ±V$_{dc}$, ±2V$_{dc}$. All in all, every T-type based circuit would operate equivalently, in voltage level generating terms, as two series modules of the conventional CHB. The switches states of the same voltage levels as the conventional CHB for a 9-level voltage source converter are shown in Table. II. In the T-type based CHB, there are two ways to generate levels with absolute voltage values of more than V_{dc}. As provided in Table. II, the voltage level of $2V_{dc}$ can be achieved by two operational modes, either by choosing two battery sub-units from the same T-type module or choosing the battery sub-units from different T-type modules. Even though in both ways the number of switches compared to the conventional CHB has decreased, choosing the battery sub-units from the same T-type module further reduces the number of switches in the current path, enabling less conduction losses. However, note that the choice of battery sub-units to be inserted is based on a priority list coming from the SoC balancing hierarchical algorithm which will be discussed in the following subsection.

B. Balancing and Operation Principle

In a cascaded multilevel inverter, the number of inserted series sub-units is controlled by the switch states, i.e., at each time step, a voltage value equal to the voltage of the battery sub-unit can be inserted or bypassed. By sequential switching, a staircase-shaped output voltage with steps equal to the voltage of the battery sub-unit can be produced which follows a reference signal (Fig. 3). If the number of modules in series is high enough, there is no need for the module to operate at high switching frequencies nor to use fixed frequency carrier-based PWM modulations to reduce the total harmonic distortion (THD) of the output current. Instead, relatively low and variable switching frequency methods like the nearest level control (NLC) can also be applied. In this modulation method, the number of levels inserted at each time step is determined by rounding up the reference signal to the nearest integer value. If the number of battery sub-units is not high enough then a fixed frequency carrier-based PWM modulation technique like the level-shift PWM (LSPWM) or phase-shift PWM (PSPWM) can be used for a better power quality.

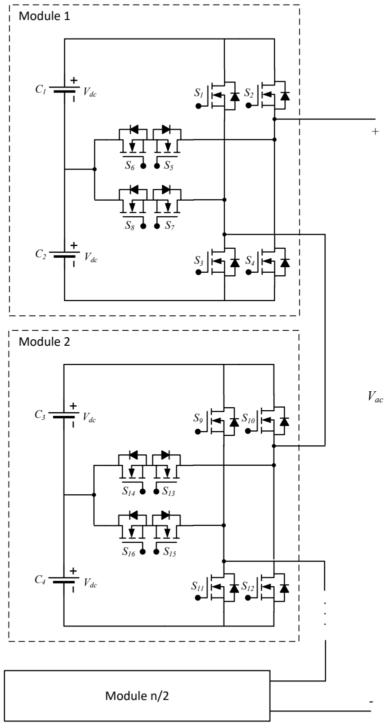


Fig. 2. T-type based cascaded H-bridge converter integrated with battery sub-units.

The SoC balancing of the battery sub-units is not only important for extending the battery pack capacity and lifetime but also for output quality. In order to do this, the battery sub-units are sorted in an ascending/descending order during charging/discharging according to their calculated SoCs $(B_{L1}, B_{L2}, ...)$. At each voltage level, the battery sub-units with higher ranks are inserted as shown in Fig. 3. As an example, in the voltage level of three, the three battery sub-units with the highest ranks are inserted and all remaining battery sub-units are bypassed. In other words, during the charging process, the battery sub-units with lower SoCs are prioritized and are charged for a relatively longer time and during the discharging process the battery sub-units with higher SoCs are prioritized and are discharged for a relatively longer time $(D_{L1} > D_{L2})$. By implementing this algorithm, not only a sinusoidal reference can be followed but also battery sub-units are balanced without requiring any extra hardware.

As illustrated in the previous section, for voltage levels above V_{dc} there are two ways to generate the output voltage in the T-type based CHB, either choosing two battery sub-units from the same T-type module or choosing them from separate T-type modules. The conventional hierarchal balancing algorithm can be modified so that at each voltage step, the two battery sub-units are chosen from the same T-type module in order to minimize the number of conducting switches. The

TABLE I

SWITCHES STATES OF THE CONVENTIONAL CASCADED H-BRIDGE CONVERTER FOR A 9-LEVEL VOLTAGE SOURCE CONFIGURATION

V_{out}	Module 1				Module 2				Module 3				Module 4				ON switches
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	
0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	8
V_{dc}	0	1	1	0	1	1	0	0	1	1	0	0	1	1	0	0	8
$2V_{dc}$	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0	8

TABLE II

SWITCHES STATES OF THE T-TYPE BASED CASCADED H-BRIDGE CONVERTER FOR A 9-LEVEL VOLTAGE SOURCE CONFIGURATION

V_{out}	Module 1								Module 2								ON switches
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	
0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	4
V_{dc}	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0	0	5
$2V_{dc}$	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	4
	0	1	0	0	0	0	1	1	0	0	1	0	1	1	0	0	6

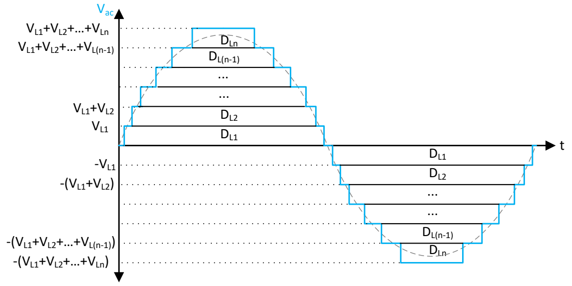


Fig. 3. Stepped output waveform of the CHB with $(2n + 1)$ voltage levels.

modified balancing algorithm ranks the battery sub-units not only according to their individual SoCs but also takes the average SoC between two battery sub-units in the same T-type module (SoC of the module) into account. In other words, for the even voltage levels, the battery sub-units from the same T-type module are selected according to the modules SoC ranking and the remaining battery sub-unit in the odd voltage levels is chosen by the individual battery sub-unit SoC ranking. By implementing this, not only balancing between modules but also between battery sub-units can be achieved. Although the balancing time can be longer compared to the conventional hierarchal algorithm, it reduces the number of switches in the conduction path considerably. It is worth mentioning that both the modified and non-modified balancing algorithms can be used according to the user priorities i.e. balancing time or efficiency without any need for changes hardware-wise.

IV. COMPARISON OF CASCADED H-BRIDGE AND CASCADED T-TYPE

To evaluate the merits of T-type based CHB as an AC split battery, it is compared with the conventional CHB. As provided in Table. III, for the same number of voltage levels $(2n + 1)$, the T-type CHB needs half of the number of converter modules of the conventional CHB because every T-type converter module requires two battery sub-units but the number of required switches are the same for both topologies (considering a four-quadrant switch as two switches). As it can be seen, conventional CHB is leading in terms of the voltage stress of switches since the voltage stress of the bridge leg switches for the T-type CHB is double the voltage stress for the conventional CHB; therefore, the T-type CHB needs half the number of switches with higher voltage ratings. However, the conventional CHB is lagging in terms of the number of switches in the conduction path which impairs the efficiency especially when there is a higher number of modules. The T-type CHB reduces the number of switches in the conduction path to a great extent, especially with the modified balancing algorithm reducing the number of conducting switches from $2n$ in conventional CHB to n (even voltage levels)/ $n+1$ (odd voltage levels) (shown in Table. IV).

V. SIMULATION RESULTS

In order to assess the proposed AC split battery, simulations with both conventional hierarchal balancing algorithm and modified balancing algorithm are carried out in MATLAB Simulink. The simulation consists of 3 T-type modules and each T-type module is connected to two NMC battery sub-units with a nominal voltage of 28.8V, varying from 27 V to 33 V according to their corresponding SoCs. Further specifications of the simulation are shown in Table. V. A maximum 5% of an initial unbalance between the battery sub-units is assumed to limit the simulation time as provided in Table. VI.

Fig. 4 shows the output voltage and output current of the split AC battery; as can be seen, a 13-level output voltage with a high-quality current is achieved. The choice of which battery sub-units to insert at each voltage level is determined by the balancing algorithm. The conventional balancing algorithm sorts battery sub-units as individuals allocating the battery sub-unit (B_4) the highest duty cycle to be discharged for the longest time followed by B_5, B_3 in a descending order and ending in B_2 with the lowest SoC and lowest duty cycle (Fig. 5). By implementing this conventional sorting algorithm, balancing can be achieved in $140s$; as it can be seen in Fig. 7 (a). Although this algorithm does not take into account which converter module battery sub-units belong to,

TABLE III
Comparison of Conventional Cascaded H-bridge and T-type Based Cascaded H-bridge in terms of the Number and Voltage Stress of Semiconductors

	Number of converter modules for an n level output voltage	*Number of switches*	*Voltage stress of switches*
Conventional CHB	n	$4n$	V_{dc}
T-type based CHB	$n/2$	$4n$	$2n$ switches with $2V_{dc}$ $2n$ switches with V_{dc}

TABLE IV
Comparison of Conventional Cascaded H-bridge and T-type Based Cascaded H-bridge in terms of the Number of Semiconductors in the Conduction Path for Different Voltage Levels

	Number of Switches in the Conduction Path			
	for the voltage level of 0	**for the voltage level of V_{dc}**	**for the voltage level of $2V_{dc}$**	**for the voltage level of mV_{dc}**
Conventional CHB	$2n$	$2n$	$2n$	$2n$
T-type based CHB	n	$n+1$	n (two battery sub-units are chosen from the same T-type module) $n+2$ (two battery sub-units are chosen from different T-type modules)	$n+p$ (p is the number of T-type modules with one battery sub-unit inserted)

TABLE V
Simulation Characteristics

Parameter	**Value**
Number of battery sub-units	6
Nominal voltage of battery sub-unit	28.8 V
Capacity of battery sub-unit	10 Ah
PWM carrier frequency	5 kHz
Nominal rms output voltage	110 V
Load Resistance	3.9 Ω
Load Inductance	6 mH

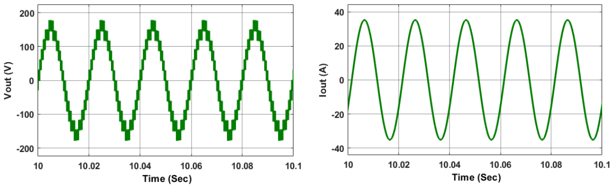
TABLE VI
Considered Initial SoC of Battery Units

	Initial SoCs of Battery units	**Initial SoCs of Modules**
Battery Unit 1	77%	76%
Battery Unit 2	75%	
Battery Unit 3	78%	79%
Battery Unit 4	80%	
Battery Unit 5	79%	77.5%
Battery Unit 6	76%	

the number of switches in the conduction path is still lower than the conventional cascaded H-bridge. Fig. 6 shows the duty cycle allocated to different battery sub-units with the modified balancing algorithm, as can be seen, they are not in the descending order of the individual SoCs and the SoC of modules are also considered. Fig. 7 (b) shows that even with a longer balancing time ($255s$), the balancing between individual battery sub-units is perfectly achieved and with both balancing algorithms, after a discharging time of $300s$, all the battery sub-units SoC has dropped to the mutual point of 66%.

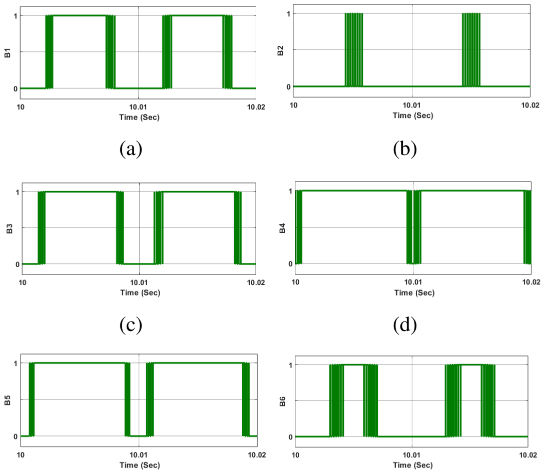
VI. Conclusion

This paper proposed a T-type based cascaded H-bridge structure with embedded battery sub-units as an AC split battery. The proposed structure reduces the number of switches in the conduction path considerably compared to the most common structure of AC battery, the conventional cascaded H-bridge. Furthermore, the conventional sorting balancing algorithm is modified to minimize the number of switches in the conduction path. A small-scale 13-level T-type based CHB with integrated battery sub-units with both conventional



(a) (b)

Fig. 4. Simulation results (a) Output voltage (b) Output Current

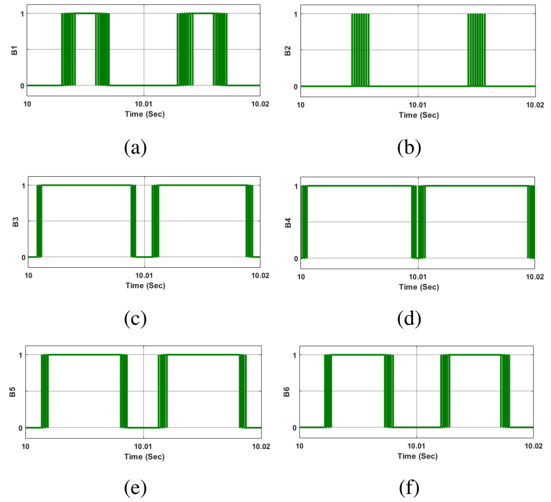


(a) (b)

(c) (d)

(e) (f)

Fig. 5. Battery sub-units insertion commands with conventional hierarchal balancing algorithm.

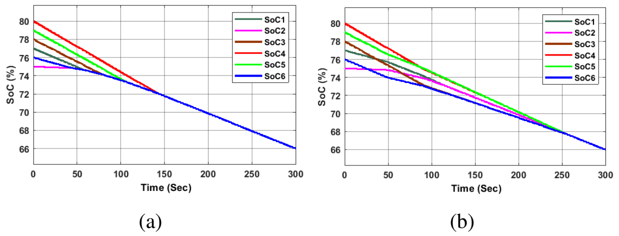


(a) (b)

(c) (d)

(e) (f)

Fig. 6. Battery sub-units insertion commands with modified hierarchal balancing algorithm.



(a) (b)

Fig. 7. Simulation results of the state of charge of different battery sub-units during discharging (a) with conventional balancing algorithm (b) with modified balancing algorithm.

and modified balancing algorithms is simulated in MATLAB Simulink. The results for an initial 5% SoC unbalance show that even though the balancing time with the modified algorithm is increased but eventually the balancing between the battery sub-units is perfectly achieved.

ACKNOWLEDGMENT

This work is supported by MSCA Actions ITN EJD ETUT - European Training network in collaboration with Ukraine for electrical Transport. This project has received funding from the European Union's Horizon 2020- Research and innovation program under grant agreement no. 955646.

REFERENCES

[1] S. Azizighalehsari, P. Venugopal, D. P. Singh, and G. Rietveld, "Performance evaluation of retired lithium-ion batteries for echelon utilization," in *IECON 2022–48th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1–6, IEEE, 2022.

[2] S. Azizighalehsari, P. Venugopal, D. P. Singh, M. Huijben, J. Popovic, and B. Ferreira, "High-performance lithium polymer battery pack for real-world racing motorcycle," in *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe)*, pp. P–1, IEEE, 2021.

[3] R. Eskandari, P. Venugopal, and G. Rietveld, "Advanced battery management systems with integrated battery electronics," in *2022 IEEE 20th International Power Electronics and Motion Control Conference (PEMC)*, pp. 55–61, IEEE, 2022.

[4] E. Chatzinikolaou and D. J. Rogers, "Cell soc balancing using a cascaded full-bridge multilevel converter in battery energy storage systems," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 9, pp. 5394–5402, 2016.

[5] H. Nazi, E. Babaei, and M. Sabahi, "Bidirectional active charge equaliser for series-connected cells," *IET Power Electronics*, vol. 12, no. 5, pp. 1229–1240, 2019.

[6] F. Helling, S. Götz, and T. Weyh, "A battery modular multilevel management system (bm3) for electric vehicles and stationary energy storage systems," in *2014 16th European Conference on Power Electronics and Applications*, pp. 1–10, IEEE, 2014.

[7] S. Azizighalehsari, J. Popovic, P. Venugopal, and B. Ferreira, "A review of lithium-ion batteries diagnostics and prognostics challenges," in *IECON 2021–47th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1–6, IEEE, 2021.

[8] A. Farakhor and H. Fang, "A novel modular, reconfigurable battery energy storage system design," in *IECON 2021–47th Annual Conference of the IEEE Industrial Electronics Society*, pp. 1–6, IEEE, 2021.

[9] F. Ji, L. Liao, T. Wu, C. Chang, and M. Wang, "Self-reconfiguration batteries with stable voltage during the full cycle without the dc-dc converter," *Journal of Energy Storage*, vol. 28, p. 101213, 2020.

[10] N. Tashakor, J. Kacetl, J. Fang, Z. Li, and S. Goetz, "Dual-port dynamically reconfigurable battery with semi-controlled and fully-controlled outputs," *arXiv preprint arXiv:2206.01435*, 2022.

[11] S. Ci, N. Lin, and D. Wu, "Reconfigurable battery techniques and systems: A survey," *IEEE Access*, vol. 4, pp. 1175–1189, 2016.

[12] M. A. Rahman, K. De Craemer, J. Büscher, J. Driesen, P. Coenen, and C. Mol, "Comparative analysis of reconfiguration assisted management of battery storage systems," in *IECON 2019-45th Annual Conference of the IEEE Industrial Electronics Society*, vol. 1, pp. 5921–5926, IEEE, 2019.

[13] A. Manenti, A. Abba, A. Merati, S. M. Savaresi, and A. Geraci, "A new bms architecture based on cell redundancy," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 9, pp. 4314–4322, 2010.

[14] L. M. Tolbert, F. Z. Peng, T. Cunnyngham, and J. N. Chiasson, "Charge balance control schemes for cascade multilevel converter in hybrid electric vehicles," *IEEE transactions on industrial electronics*, vol. 49, no. 5, pp. 1058–1064, 2002.

[15] E. Chatzinikolaou, *Deep integration of power electronics in battery systems*. PhD thesis, University of Oxford, 2018.

[16] M. Quraan, T. Yeo, and P. Tricoli, "Design and control of modular multilevel converters for battery electric vehicles," *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 507–517, 2015.

[17] N. Li, F. Gao, X. Shang, H. Jia, S. Li, B. Guo, K. Hou, and X. Zhao, "Operation principles of modular multilevel conversion system for electric vehicles," in *2020 5th Asia Conference on Power and Electrical Engineering (ACPEE)*, pp. 1199–1203, IEEE, 2020.

[18] R. Thomas, G. Despesse, S. Bacquet, E. Fernandez, Y. Lopez, P. Ramahefa-Andry, and L. Cassarino, "A high frequency self-reconfigurable battery for arbitrary waveform generation," *World Electric Vehicle Journal*, vol. 12, no. 1, p. 8, 2021.

[19] S. D'Arco, M. Quraan, P. Tricoli, and L. Piegari, "Low frequency operation of modular multilevel converters with embedded battery cells for traction drives," in *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, pp. 1375–1382, IEEE, 2016.

[20] C. Burgos-Mellado, M. Orchard, D. Munoz-Carpintero, T. Dragičević, L. Reyes-Chamorro, and J. Llanos, "Ac battery: Modular layout with cell-level degradation control," in *2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe)*, pp. 1–11, IEEE, 2022.

[21] F. Gao, X. Gu, Z. Ma, and C. Zhang, "Redistributed pulsewidth modulation of mmc battery energy storage system under submodule fault condition," *IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 2284–2294, 2019.

[22] E. Chatzinikolaou and D. J. Rogers, "Hierarchical distributed balancing control for large-scale reconfigurable ac battery packs," *IEEE Transactions on Power Electronics*, vol. 33, no. 7, pp. 5592–5602, 2017.

[23] A. Pirooz, Y. Firouz, M. Berecibar, and J. Van Mierlo, "Battery voltage equalisation using single-phase cascaded h-bridge converters," *IET Power Electronics*, vol. 13, no. 18, pp. 4158–4167, 2020.

[24] C.-M. Young, N.-Y. Chu, L.-R. Chen, Y.-C. Hsiao, and C.-Z. Li, "A single-phase multilevel inverter with battery balancing," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 1972–1978, 2012.