Modular Battery Systems' Accessible Energy Analysis

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***Abstract*—One of the main concerns regarding traditional battery energy storage systems (BESS) is how to solve issues related to cell inhomogeneities. This problem commonly ends up reducing the accessible energy level, especially in medium and big-size battery applications. In these designs a small percentage of unused energy means not only a higher initial investment, but also bigger size and weight. In order to solve these energy limitation drawbacks, reconfigurable battery solutions together with modular battery-packs are proposed in the literature. That said, the goal of this article is to present a comparison focused on the accessible energy of different battery system architectures (traditional and modular). For this aim, five BESS topologies are studied each one with its corresponding mathematical model and numerical analysis.**

***Index Terms*—Modular battery, Accessible energy, SoC balancing, Battery energy storage, Reconfigurable battery**

I. INTRODUCTION

The role of the renewable energy sources and electrical transport systems have become crucial in order to solve the current energy model issues [1], [2]. Along with the different energy generation options the solar and wind power generation sources are the best positioned technologies [3], [4]. However, as it depends on climate conditions, energy generation fluctuations cannot be controlled. This drawback could cause grid stability related problems. If the transport systems are considered, the electric vehicle together with aeronautic and maritime applications require a transition process from fossil fuels to electric systems [5]. To deal with this challenges electrochemical batteries are being increasingly implemented, that is why new and more competitive developments need to be studied.

Taking into account that for many different applications batteries are essential, it is necessary to update all the previous designs while optimizing every new solution. Especially, in medium and large size BESSs where a small percentaje of unavailable energy entails considerable economic losses. In order to avoid this issue and ensure the so-called safe operation area (SOA), there are many parameters that should be managed, such as the SoC, SoH, temperature, voltage, current, power and energy [6]. However, the typical battery-pack configuration is based on a huge amount of series and parallel connected cells. In this sense, the real challenge to be solved is the inability to manage the non-homogeneous degradation of this type of systems. Consequently, conventional battery systems are beginning to become obsolete.

Faced with this reality, new alternatives are suggested in the literature. On the one hand, the reconfigurable architectures are able to perform more accurate energy managements [7], [8]. As stated in the literature, they do not only apply passive/active balancing strategies, but they also have the capability to manage the connection/disconnection of each cell changing the configuration of the battery. Thus, this kind of solutions are promising to increase the flexibility and the efficiency of any BESS by deploying power switches in each cell and adjusting their connectivity in real time. Nevertheless, two main drawbacks must be taken into account in reconfigurable designs [9]: firstly, there is a tradeoff between the elements used in the circuit and the reconfigurability that becomes crucial in a cost or a complexity analysis; secondly, the hardware development is quite challenging in terms of reliability, scalability and the cost-efectiveness of reconfigurable BESSs.

On the other hand, modular battery solutions have a simpler hardware design than reconfigurable systems while enabling higher accessible energy levels of current BESSs [10], [11]. According to the literature, to ensure a synchronized operation of the modules, series and parallel control strategies are required. For the management of series connected modules many different control strategies have already been suggested [11], each one based on different equalization variables, objectives and algorithms. As interesting examples, in [12] the authors present a series connected module SoC balancing with decentralised control algorithm and in [13] they implement a rule based SoC balancing strategy that correctly deals with capacity imbalances. In case of need of parallel control strategies, there are already some works in the literature. For instance

[14] suggests some low difficulty static and dynamic control strategies based on module's SoC balance (BMW i3 lihitum-ion batteries), while [15] is focused on a consensus algorithm for multi-objective battery balancing of parallel connected high capacity NMC cell modules. In this sense, many new advances are expected for the near future.

To perform this study, the paper is organized in three main sections. The research begins showing the different BESS topologies along with the corresponding mathematical expressions in Section II. After introducing the theoretical models, the simulation results are presented in Section III. Finally, to sum up the work done, conclusions and future research ideas are presented in Section IV.

II. ACCESSIBLE ENERGY OF BESSS

The accessible energy research in [10] is focused on certain circuits, though this article extends this analysis considering some other topologies. Having said that, the analysed battery models are divided into two groups: conventional battery systems presented in Fig. 1 and modular battery systems shown in Fig. 2.

A. Conventional battery systems

1) Passive balancing: the accessible energy of a battery-pack with a passive balancing (E$_{pb}$) is always limited by the weakest cell during the discharge process (no balancing during discharge). In this respect, the energy that can be obtained in operation is calculated using (1), where C$_n$ is the capacity value of each cell, M is the total amount of cells and V$_{nom}$ is their nominal voltage.The corresponding schematic is illustrated in Fig. 1a.

$$E_{\mathrm{pb}} = \min_{\forall n \in [1,M]} \{C_n\} M V_{\mathrm{nom}} \tag{1}$$

2) Active balancing: to reallocate the energy that is not distributed homogeneously, an external active balancing circuit can be used. A simplified schematic is shown in Fig. 1b where the R_b value represents the balancing circuit power losses. At the same time, although the power of the balancing bus is not limited, the balancing current $I_{n,ab}$ of each cell is limited to $I_{n,max}$.

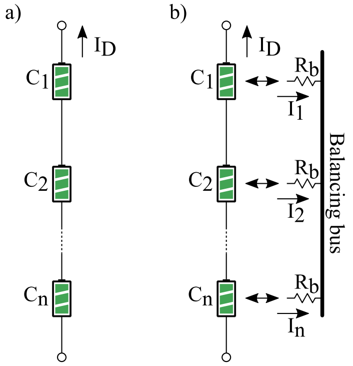

Fig. 1. Conventional battery-systems a) Passive balancing b) Active balancing.

During the discharge process of the battery-pack with an active balancing circuit, two different scenarios have to be considered: 1) the battery-pack is fully balanced before the discharge is completed, and 2) the balancing circuit is the limiting factor, so that the battery-pack energy is limited by the weakest cell capacity plus the energy transferred to it. To be able to solve this capacity limitation the balancing has to be able to manage higher current rates.

1) In this scenario, the energy storage is able to use all the energy that has been stored during the charging process. Equation (2) presents this available energy estimation (E_{ab}). However, it is mandatory to consider the power losses of (3) associated to the active cell balancing circuit ($E_{ab,losses}$).

$$E_{\mathrm{ab}} = \sum_{n=1}^{M} C_n V_{\mathrm{nom}} - E_{\mathrm{ab,\ losses}} \tag{2}$$

where

$$E_{\mathrm{ab,losses}} = \sum_{n=1}^{M} I_{n,ab}^2 R_b T_{h,ab} \tag{3}$$

In order to be able to define a discharge time period $T_{h,ab}$, (5) has been proposed derived from the initial expression of (4). In the case the system is perfectly balanced this time value is going to be the same for every cell.

$$T_{h,ab} = \frac{C_n - \int_0^{T_{h,ab}} I_{n,ab} dt}{I_D} \tag{4}$$

$$T_{h,ab} = \frac{C_n}{I_D \left(1 + I_{n,ab}/I_D\right)} \tag{5}$$

The discharge current is presented using I_D. After having defined an equal $T_{h,ab}$ for all the cells, the previous energy balance from (2) is rewritten as it is shown in (6).

$$V_{\mathrm{nom}} I_D T_{h,ab} M = \sum_{n=1}^{M} V_{\mathrm{nom}} C_n - \sum_{n=1}^{M} I_{n,ab}^2 R_b T_{h,ab} \tag{6}$$

To finish the analysis focused on this balanced scenario, a power constraint equation regarding the balance of the equalization bus is written. Equation (7) takes into account all the power inflows/outflows of each cell plus the losses of the active balancing circuit.

$$0 = \sum_{n=1}^{M} I_{n,ab}^2 R_b + \sum_{n=1}^{M} I_{n,ab} V_{\mathrm{nom}} \tag{7}$$

2) In this second scenario the maximum balancing current becomes the constraint that do not allow to balance the weakest cell. The $I_{n,ab}$ current is limited to $I_{B,max}$. As the maximum accessible energy of the weakest cell is going to be the initial one, plus the re-allocated energy during the $T_{h,ab}$ time period, (8) and (9) are established:

$$T_{h,ab} = \frac{\min_{n \in [1,M]} \{C_n\} - \int_0^{T_{h,ab}} I_{n,\mathrm{max}} dt}{I_D} \tag{8}$$

$$T_{h,ab} = \frac{\min_{n\in[1,M]}\{C_n\}}{I_D\left(1 + I_{n,\max}/I_D\right)} \tag{9}$$

In this case, the major limitation is related to the energy that remains stored at the end of the discharge cycle. In order to obtain an accurate result it is necessary to include the power losses of the balancing circuit. Nevertheless, the power loss estimation process is considered to be complex taking into account its low influence in the final results. As a consequence, in this analysis the power losses are considered to be equal to the worst result obtained before in the scenario 1. Equation (10) presents how to achieve the accessible energy in this scenario.

$$\begin{aligned} E_{\text{ab, limited}} = &\left(\min_{n\in[1,M]}\{C_n\} - I_{n,\max}T_{h,ab}\right) M V_{\text{nom}} \\ &- \sum_{n=1}^{M} I_{n,ab}^2 R_b T_{h,ab} \end{aligned} \tag{10}$$

B. Modular battery systems

1) Variable balancing: in this kind of structures where each cell is controlled individually, it is possible to carry out a variable charging/loading process able to continuously charge/discharge all the cells according to their stored capacity. The circuit is presented in Fig. 2a. The energy is extracted to the power bus through the R_d resistor. This resistor is associated to the power losses of the power electronic converter.

Regarding the accessible energy (E_{vl}), with this variable loading system explained in (11) it is possible to use almost all the stored energy.

$$E_{\text{vl}} = \sum_{n=1}^{M} C_n V_{\text{nom}} - E_{\text{vl, losses}} \tag{11}$$

where

$$E_{\text{vl,losses}} = \sum_{n=1}^{M} I_{m,vl}^2 R_d T_{h,vl} \tag{12}$$

$I_{m,vl}$ expressed in (14) represents the current flowing out of each cell and is dependent on individual capacity and the total mean capacity of the system ($C_{avg,vl}$) calculated in (13). $T_{h,vl}$ in (15) is the discharge time of a cell operating with the current I_D.

$$C_{avg,vl} = \frac{\sum_{n=1}^{M} C_n}{M} \tag{13}$$

$$I_{m,vl} = \frac{I_D C_n}{C_{avg,vl}} \tag{14}$$

$$T_{h,vl} = \frac{C_{avg,vl}}{I_D} \tag{15}$$

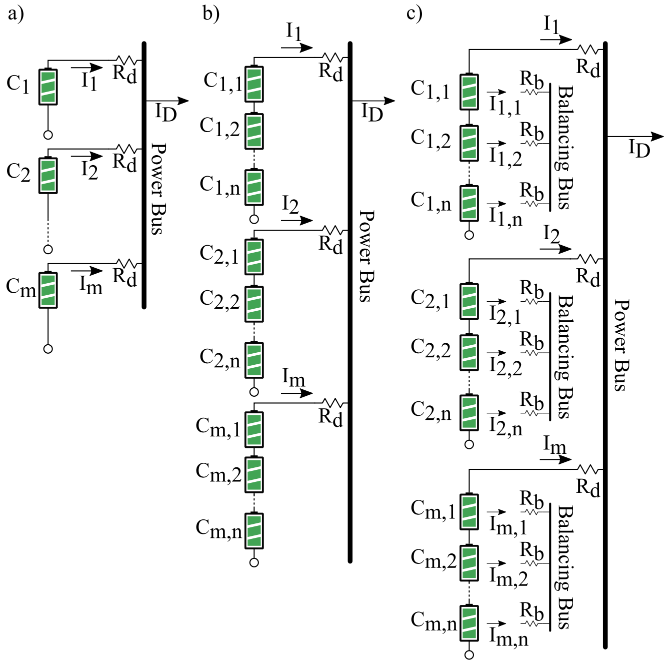

Fig. 2. Modular battery systems a) Variable balancing b) Variable + passive balancing c) Variable + active balancing.

2) Variable + Passive balancing: following the basis of the passive and variable balancing systems it is possible to develop a mixed configuration. The aim is to access higher stored energy levels than with passive balancing, while reducing the amount of power switches of the variable circuit (to avoid complexity issues). This means introducing a modular system with variable balancing that at the same time performs an intra-module passive balancing. In Fig. 2b a simplified schematic is shown.

To analyse this system many different operating conditions can be considered. However, each individual cell capacity is determined based on the data of Table I. Once all the capacity values are defined the best and the worst scenarios for modular configurations are analysed, so as to estimate the accessible energy range of this balancing topology: the maximum available energy is achieved in the case where the low capacity cells are joined together in the same module, while the high capacity cells are joined in another module; the minimum available energy is calculated considering the case where the cells with the lowest capacity are connected to the cells with the higher capacity in the same module. That said, C_{limit_m} represents the lowest capacity value of each M_n module.

The first step is to estimate every operating module current ($I_{m,pvb}$) and the time ($T_{h,pvb}$). For this aim, it is necessary to calculate the average capacity ($C_{avg,pvb}$) considering the most discharged cell's stored Ah C_{limit_m} as it is shown in (16).

$$C_{avg,pvb} = \frac{\sum_{m=1}^{M_n} C_{limit_m}}{M_n} \tag{16}$$

Then, using (17) and (18) it is possible to define the discharge current and discharge time values of the modules.

$$I_{m,pvb} = \frac{C_{limit_m} I_D}{C_{avg,pvb}} \tag{17}$$

$$T_{h,pvb} = \frac{C_{avg,pvb}}{I_D} \tag{18}$$

The last step is to approach the available energy E_{pvb} of the whole system, taking into account the power losses of the power electronic devices as it is presented in (19) (the power through the converter is higher so the power losses may be higher too, that is why the R_d is multiplied by the amount of cells *n* in every module).

$$E_{pvb} = \sum_{m=1}^{M_n} C_{limit_m} V_{nom} N_m - \sum_{m=1}^{M_n} I_{m,pvb}^2 R_d N_m T_{h,pvb} \tag{19}$$

These modular passive-variable balancing structure results, may vary depending on the size of the module. Therefore, two different module sizes (N_m), 10 modules (10 cells per module) and 25 modules (4 cells per module), are considered in the results presented in Section III.

3) Variable + Active balancing: in the same way that a modular BESS can be designed with a passive/variable balancing strategy, this can be build up with an active/variable balancing strategy (variable loading/charging is applied at module level). The aim of this mixed topology is to improve the total accessible energy, while reducing the variable balancing circuit complexity. The figure 2c shows the simplified schematic considered in the research.

To analyse this system many different operating conditions can be considered. However, each individual cell capacity is determined based on the data of Table I. Once all the capacity values are defined the best and the worst scenarios for modular configurations are analysed, so as to estimate the accessible energy range of this balancing topology: the maximum available energy is achieved in the case where the low capacity cells are joined together in the same module, while the high capacity cells are joined in another module; the minimum available energy is calculated considering the case where the cells with the lowest capacity are connected to the cells with the higher capacity in the same module. That said, C_{limit_m} represents the lowest capacity value of each M_n module.

To begin with the available energy estimation it is necessary to carry out the analysis developed for active balancing circuits (presented in Section II-A2) over each module. It has to be taken into account that the amount of cells *n* in this case depends on the amount of modules.

Once the energy estimation method of each module is obtained (active balancing: 1 or 2) it is possible to follow with the next step. The system operation is limited by the most restrictive module operating condition. Following this criteria, two scenarios have to be considered again: 1) the case in which all the modules are capable of equalizing their internal SoC, and 2) the case where any of the modules is not able to balance the cells limiting the operation of the rest of the modules.

1) If the condition of full charge balance is achieved in every module the accessible energy is estimated using (20).

$$\begin{aligned} E_{avb_{min}} = \sum_{m=1}^{M_n} \sum_{j=1}^{N_m} C_{[m,j]} V_{nom} - \sum_{m=1}^{M_n} I_{m,avb}^2 R_d N_m T_{h,avb} \\ - \sum_{m=1}^{M_n} \sum_{j=1}^{N_m} I_{[m,j]_{ab}}^2 R_b T_{h,avb} \end{aligned} \tag{20}$$

The values corresponding to $I_{[m,j]_{ab}}$ and $T_{h,avb}$ are obtained following (5), (6) and (7), while the variable $I_{m,avb}$ is approached using (21), (22) and (23). This current value is dependent on the module's average capacity $C_{M_n,avg,avb}$ and the system's average capacity $C_{avg,avb}$

$$C_{M_n,avg,avb} = \frac{\sum_{j=1}^{N_m} C_j}{N_m} \tag{21}$$

$$C_{avg,avb} = \frac{\sum_{m}^{M} C_m}{M} \tag{22}$$

$$I_{m,avb} = I_D \frac{C_{Mn,avg,avb}}{C_{avg,avb}} \tag{23}$$

2) In this second scenario, the operation time of the system is limited by the module without the ability to equalize the cells. If this happens, the operating time of the rest of the modules is established by the weakest module. The operating time value is achieved using (9) in the analysis of the cells of the worst module.

The total accessible energy is obtained by means of (24) and (25). However, in this case, the estimation of the power losses related to the active balancing circuit is not that straightforward. To solve this issue a generalisation is done, the maximum balancing power losses calculated in the previous scenario are considered as constant for this second scenario.

$$\begin{aligned} E_{avb_{min}} = \sum_{m=1}^{M_n} (C_{limit_m} - \Delta C_{limit,N_m}) V_{nom} N_m \\ - \sum_{m=1}^{M_n} I_{m,avb}^2 R_d N_m T_{h,avb} - \sum_{m=1}^{M_n} \sum_{j=1}^{N_m} I_{[m,j]_{ab}}^2 R_b T_{h,avb} \end{aligned} \tag{24}$$

where

$$\Delta C_{limit,M_n} = \min[I_{b,max} T_{h,avb}, C_{avg,m} - C_{limit,m}] \tag{25}$$

III. RESULTS

With the analysis conducted in Section II, calculations regarding the accessible energy of each BESS are performed. The analysis is focused on three different operating current levels, low/medium/high (0.1C/1C/5C) at various capacity deviations values (between 0% and 10%). The data used for

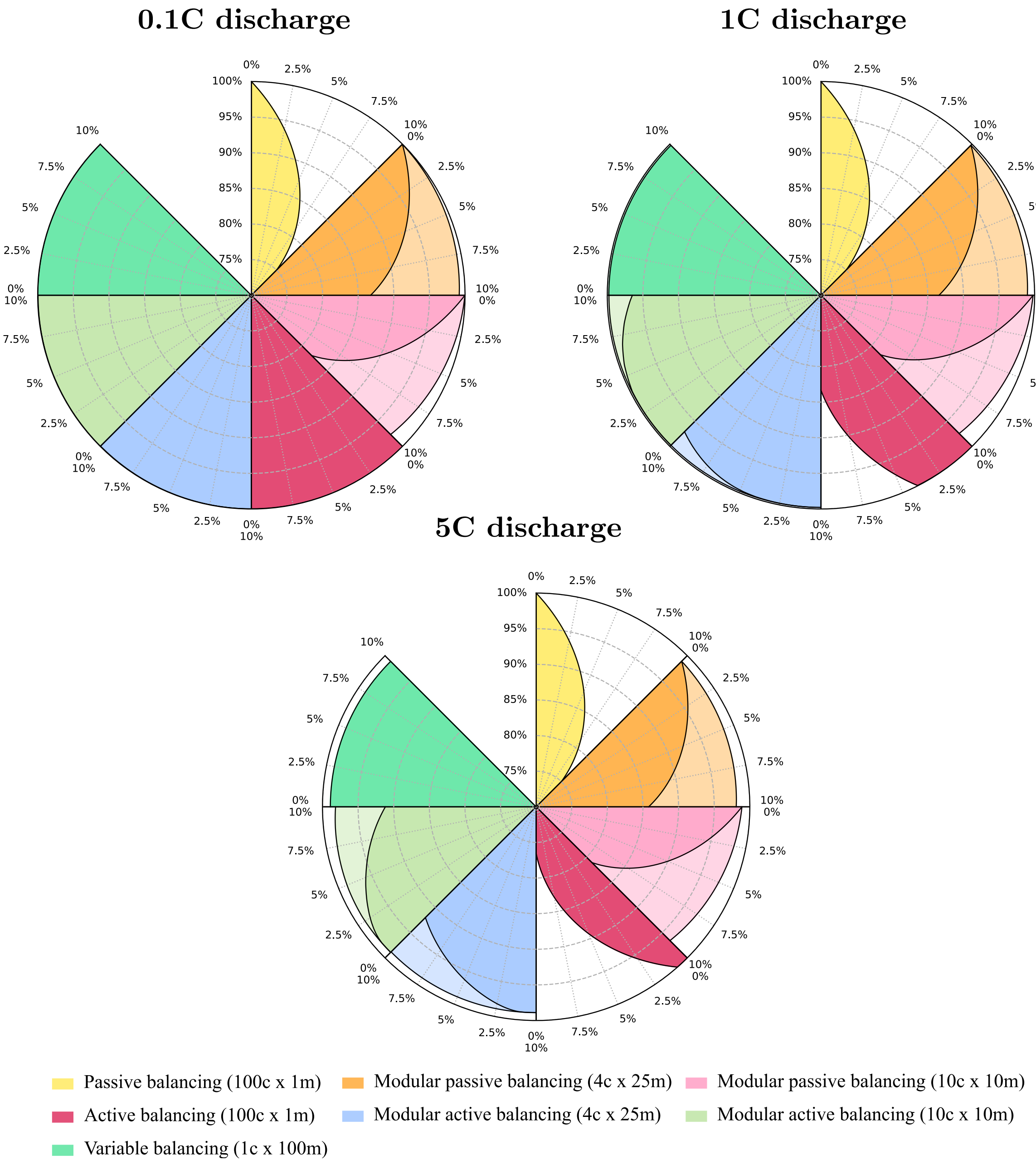

Fig. 3. Accessible energy results at different discharge current: 0.1C, 1C and 5C. Each radius length represents different accessible energy levels (%), while the perimeter constitutes the capacity deviation of the cells (%).

TABLE I
DATA USED TO COMPARE THE DIFFERENT BALANCING STRATEGIES [10].

Parameter	**Value**
V_{nom}	3.6 V
R_d	0.8 mΩ
R_b	108 mΩ
C_{avg}	10 Ah
σ_{C_k}	0.0 to 1 Ah
M	100 cells
I_d	1 A, 10 A, 50 A
$I_{n,max}$	1A
M_n	10 and 25 modules

the theoretical analysis is shown in Table I and the obtained results are presented in Fig. 3 (the larger radius of the circles, the higher the accessible energy, while the perimeter of each circle indicates the different capacity deviation values).

Initially, the results presented in [10] are replicated to verify the correct development of the theoretical models. Thus, it is shown that although the available energy of the passive balancing is independent of any relation between capacity deviation and discharge current, both active and variable balancing configurations will always present a better result than the former. That said, when it comes to comparing the active and the variable equalization systems, the latter is capable of being always close to 100% of the accessible energy regardless of the capacity deviation. This is because the only energy losses are coming from the power electronic devices. However, in active balancing designs the accessible energy limitation is also dependent on the relation between the discharge and equalization current, as it is shown in Fig. 3. Therefore, despite the fact that variable balancing is the most sophisticated topology, is the one that achieves the best results whatever the discharge current and capacity deviations are.

Regarding the contribution of this work, the paper presents new results of accessible energy that correspond to passive modular and active modular solutions. Firstly, in order to interpret correctly the results of modular topologies shown in Fig. 3, it is necessary to understand that the double area represents all the possible distributions of the cells among the modules as stated before (in case there is a modular result without double area, this means their lower and higher limits are so close).

On the one hand, if the results of modular configurations are compared with their equivalent not-modular design, it is shown that in overall terms the formers are suitable to achieve higher available energy levels. On the other hand,when it comes to modular structures, active balancing systems present higher accessible energy ranges than the passive ones. Such is the improvement, that if other factors like the hardware and software complexity are considered, it becomes more difficult to make a choice between the modular active balancing and the variable balancing solutions.

In short, building on the aforementioned results, the emerging designs based on modular concepts present a very interesting energetic performance that should be studied in more detail.

IV. CONCLUSIONS

According to the theoretical analysis performed throughout this document, it is feasible to conclude that the most traditional BESSs, the ones with active and passive balancing, are outperformed by the variable balancing solution. However, the complexity of the hardware and software is a crucial challenge in real-life medium and big size storage applications. In order to deal with these issues, modular solutions based on passive and active balancing topologies are applied to achieve high energy levels, while reducing the complexity of the variable balancing design. Therefore, this theoretical analysis serves as a base on the road to modularization of the current BESSs. It is relevant to mention for future research that modular systems might integrate a kind of redundancy control strategy that should enhance even more the accessible energy of the battery systems.

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