Comparative Study and Evaluation of Passive Balancing Against Single Switch Active Balancing Systems for Energy Storage Systems

I. Aizpuru, U. Iraola, J.M. Canales, A. Goikoetxea, E. Garayalde

Abstract—Series connection of energy storage cells implies the need of a BMS and a balancing system to control and improve the performance of the battery pack. Nowadays passive balancing is the most used balancing system in industrial applications, basically due to its simplicity and low price. Active balancing systems are mostly reserved to research articles and experimental prototypes. During this research article, single switch active balancing systems will be presented as a real option of passive balancing substitution. For that purpose during the article most important characteristics of balancing systems will be presented regarding to the impact on the final battery performance, behavior and price. After detecting most important comparison characteristics single switch active balancing systems will be compared with a passive balancing system prototypes under different working situations.

Index Terms—Active balancing systems, Battery management systems, Energy conversion, Energy efficiency, Energy storage.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_D$</td>
<td>Total useful discharged energy [Wh]</td>
</tr>
<tr>
<td>$W_{D-BAT}$</td>
<td>Total discharged energy [Wh]</td>
</tr>
<tr>
<td>$W_C$</td>
<td>Total charged energy [Wh]</td>
</tr>
<tr>
<td>$W_{C-BAT}$</td>
<td>Total useful charged energy [Wh]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Energy efficiency of the battery pack [%]</td>
</tr>
<tr>
<td>$W_{SB}$</td>
<td>Standby energy consumption [Wh]</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Battery gradient between cells inside the battery pack[°C]</td>
</tr>
<tr>
<td>$T_{Max}$</td>
<td>Maximum temperature of the battery pack [°C]</td>
</tr>
<tr>
<td>$T_{BS}$</td>
<td>Generated temperature in the balancing system [°C]</td>
</tr>
<tr>
<td>$C_F$</td>
<td>Balancing system cost [€]</td>
</tr>
<tr>
<td>$P_{L,n}$</td>
<td>Power losses of the n cell [W]</td>
</tr>
<tr>
<td>$P_{L,BS}$</td>
<td>Power losses of the balancing system [W]</td>
</tr>
<tr>
<td>$I_{BAT}$</td>
<td>Battery pack current [A]</td>
</tr>
<tr>
<td>$I_{C,n}$</td>
<td>Single cell current [A]</td>
</tr>
<tr>
<td>$I_{B,n}$</td>
<td>Single cell balancing current [A]</td>
</tr>
<tr>
<td>$PB$</td>
<td>Passive Balancing</td>
</tr>
</tbody>
</table>

AB Active Balancing
HPF High power fresh cells
HPA High power aged cells
LPF Low power fresh cells

INTRODUCTION

Energy storage applications are high demand and popular applications specially in portable technologies. One single cell is used in mobile phone applications and low number of series connected cells (3-4 cells) in laptops and other small portable devices.

High number of cells connected in series/parallel configuration are necessary for renewable energy and electromobility applications. Energy storage systems permit to increase the impact and penetration of renewable energy in the electric grid [1]–[6] and are the key factor for future success of the electric vehicles [7]–[9].

High power applications require series connection of the cells to obtain high voltage working voltages reducing the power losses due to joule effect losses. Series connection of cells decreases the total energy of the battery pack and reduces the performance of the system [10], [11]. The performance reduction is due to little manufacturing and environment differences that induce a mismatching between single cells characteristics as SOC, capacity and internal resistance differences [12]–[15].

In order to improve the available battery pack energy and performance, a balancing system is connected to the Battery Pack to reduce the differences and mismatch effect of series connected cells [16].

Energy storage balancing systems are divided in passive balancing systems and active balancing systems[17]–[19]. The main difference between both topologies is that passive balancing systems balance the series connected cells burning the extra energy of the most charged cells and the active balancing systems redistribute the energy of the strong cells to the weak cells. Passive balancing systems are widely used in industry applications due to simplicity, reliability and low cost characteristics.

Single switch active balancing systems present good characteristics as low complexity, low component number and the ability to balance the series connected cells without in open loop control mode [20], [21].

The main goal of this article is to compare passive and
single switch active balancing systems behavior under different conditions. 3 main comparison topics are evaluated:

- **Energy considerations:** Charging energy $W_C$, discharging energy $W_D$, efficiency $\eta$ and standby energy consumption $W_S$.
- **Temperature behavior:** Temperature gradient $\Delta T$ between series connected cells, maximum temperature of cells $T_{Max}$ and temperature and losses generated in the balancing system $T_{BS}$.
- **Cost:** The total cost of the balancing system is evaluated $C_e$.

Even though passive balancing systems are the most used and popular balancing systems in industrial and commercial applications, this paper will demonstrate the performance improvement of single switch active balancing systems, and will give the industry an interesting point of view of the benefits of active balancing vs. passive balancing systems, not only in terms of behavior, but also in terms of simplicity and cost.

The paper starts with a comparative evaluation between the topologies under study in section II. During section III, the main characteristics under study will be presented under a theoretical point of view. Section IV presents the experimental results of the balancing systems, and the comparison of their behavior. Last section presents the most important conclusions about the behavior and characteristics of the balancing systems.

### TOPOLOGIES UNDER STUDY

This paper compares passive balancing systems and Sepic based single switch balancing systems. The main features presented and studied in the literature are presented in Table I. During this paper behavioral characteristics outside the literature will be presented.

The current of a single cell of a series string battery pack $I_{C,n}$ is the addition of the battery pack current $I_{BAT}$ and the balancing system current of each cell $I_{B,n}$.

$$I_{C,n} = I_{BAT} + I_{B,n}$$

The passive balancing system burns the excess energy of the most charged cell in a resistor. The energy of all the cells is finally matched to the less charged cell.

The Sepic based active balancing systems transfer the excess energy of the highest voltage cells to the less charged cell. The energy transfer is made using a single active switch reducing the complexity of the whole system.

The current transfer between the strong cells $I_{B,S}$ and the weak cells $I_{B,W}$ depend on the balancing system topology.

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The current transfer between the strong cells $I_{B,S}$ and the weak cells $I_{B,W}$ depend on the balancing system topology.

Passive balancing systems burn energy of the strong cells and do not transfer energy to the weak cells. The strong cell balancing current is proportional to the strong cell voltage $V_{R,S}$ and the balancing resistor $R_{B,n}$.

$$I_{R,S} = \frac{V_{R,S}}{R_{B,n}}$$

$$I_{B,W} = 0$$

### TABLE I

**ADVANTAGES AND DISADVANTAGES OF PASSIVE BALANCING SYSTEMS AND SEPIC BASED SINGLE SWITCH ACTIVE BALANCING SYSTEMS FROM LITERATURE KNOWLEDGE**

<table>
<thead>
<tr>
<th>Passive balancing system</th>
<th>Sepic single switch active balancing system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>Simple.</td>
<td>Simple.</td>
</tr>
<tr>
<td>Cost.</td>
<td>Efficient.</td>
</tr>
<tr>
<td></td>
<td>Open loop balancing.</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Only voltage balancing.</td>
</tr>
<tr>
<td>Energy wasting.</td>
<td></td>
</tr>
<tr>
<td>Useless in discharge.</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE II

**WEAK CELL $I_{B,W}$ BALANCING CURRENT AND STRONG CELL $I_{R,S}$ BALANCING CURRENT OF BALANCING SYSTEMS UNDER STUDY. 4S1P BATTERY PACK N=4 ONE WEAK CELL $V_{R,W}=2V$ AND 3 STRONG CELLS $V_{R,S}=3.65 V$**

<table>
<thead>
<tr>
<th>$I_{B,W}$ [mA]</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{R,S}$ [mA]</td>
<td>-304</td>
</tr>
</tbody>
</table>

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The balancing current values for the passive balancing system $R_B$ and the Sepic based active balancing system $D_{BA}$ for 4S1P unbalanced battery packs are presented in Table II.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{in}$</td>
<td>470 µH</td>
</tr>
<tr>
<td>$L_a$</td>
<td>68 µH</td>
</tr>
<tr>
<td>$D_A$</td>
<td>12 %</td>
</tr>
<tr>
<td>$f$</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

The balancing current values for the passive balancing system $R_B$ and the Sepic based active balancing system $D_{BA}$ for 4S1P unbalanced battery packs are presented in Table II. The passive balancing system has a power resistor $R_B$ of 12 Ω. The active balancing system $D_{BA}$ switches with a constant D of 13 % with a switching frequency of 100 kHz. The inductors are designed for a value of $L_{in}=470$ µH and $L_a=68$ µH. Both balancing systems are of similar characteristics (Table II presents current rate of both systems in an unbalanced situation) to obtain comparable data.

**IMPACT CHARACTERISTICS OF BALANCING SYSTEMS**

Balancing systems are connected to energy storage systems with the main target of improving battery pack characteristics. The effect of the balancing system can be presented in improvements of power and energy specifications, energy efficiency of the system and extension of the cycle life.

**A. Energy considerations**

The energy evaluation of the battery pack is usually evaluated under two different criteria, considering cycle life and calendar life issues.

Cycle life issues will be related to the energy inserted to the battery pack during a charging process $W_C$ (considered positive), the energy obtained during discharge $W_D$ (considered negative) and the efficiency of the battery pack respect to the energy inserted and the energy discharged $\eta$.

Charging energy $W_C$ is the total energy inserted from the point of view of a battery charger. The total energy inserted to the battery pack $W_{C,BAT}$ is measured by the integration of the voltage $V_{BAT}$ and the current $I_{BAT}$ of each cell. It is also the total energy measured by the charger $W_C$ by subtracting the energy lost by the power losses of the balancing system $P_{LBS}$.

$$W_C = \int_0^{t_{charge}} V_{BAT}(t)I_{BAT}(t)dt$$

$$W_{C,BAT} = \int_0^{t_{charge}} \sum_{n=1}^{k} V_{BP}(t)I_{BP,n}(t)dt = W_C - \int_0^{t_{charge}} P_{LBS}(t)dt$$

During the discharge process, active balancing redistributes energy to the weak cell improving the total discharge energy $W_D$ by increasing the weak cell current $I_{C,W}$. As during charge, the battery discharged energy $W_{D,BAT}$ is reduced due to power losses of the balancing system $P_{LBS}$. The term reduced means that it is more negative.

$$W_D = \int_0^{t_{discharge}} V_{BAT}(t)I_{BAT}(t)dt$$

$$W_{D,BAT} = \int_0^{t_{discharge}} \sum_{n=1}^{k} V_{BP}(t)I_{BP,n}(t)dt = W_D - \int_0^{t_{discharge}} P_{LBS}(t)dt$$

The efficiency $\eta$ of the battery pack is the ratio between the energy inserted and the energy obtained from a battery pack.

$$\eta = \frac{W_C}{W_D} \times 100$$

This ratio defines the performance of the battery pack and the behavior due to the balancing system.

Calendar life behavior of the battery pack is represented by the aging process due to battery pack time degradation. For this issue the self-discharge current of the battery pack will be measured due to stand by energy discharge $W_{SB}$. The effect of the balancing system during the stand-by process should be analyzed to estimate their influence in the calendar life process.
B. Temperature behavior

The balancing system influences in the temperature behaviour of the battery pack, in parameters as the maximum temperature $T_{Max}$ and the deviation in temperature $\Delta T$ between different cells of the battery pack[22]. The power losses of the balancing system also increase the temperature of the balancing system board $T_{BS}$ that could generate a hot spot for nearby positions cells.

$T_{Max}$ and $\Delta T$ of the single cells composing a battery pack are directly dependent on the power losses of each single cell. The power losses of each cell is proportional to the internal resistance of the cell $R_{\text{in}}$ and increase quadratically due to cell current $I_{C,n}$. The internal resistance could also be approached to the difference between the cell voltage $V_B$ and the open circuit voltage $V_{OC}$.

\[
P_{L,n} = R_{\text{in}} I_{C,n}^2 \approx |V_{B,n} - V_{OC}| I_{C,n} \tag{9}
\]

Balancing systems equalize the voltage level of each cell, so they improve the temperature gradient between cells $\Delta T$ respect to no balancing systems, assuming equal aging of cells.

Maximum temperature $T_{Max}$ is improved in series connected cells thanks to active balancing systems during discharge processes. Passive balancing systems do not allow any balancing current to the weak cell, however active balancing systems insert current to the weak cell decreasing the total current that flows through the cell during discharge.

\[
P_{L,W} = R_{\text{in}} I_{C,W}^2 = R_{\text{in}} (I_{BAT} + I_{B,W})^2 \quad \text{AB} \quad P_{L,W} \downarrow \downarrow \\
P_{L,W} = R_{\text{in}} I_{C,W}^2 = R_{\text{in}} I_{B,W}^2 \quad \text{PB} \quad P_{L,W} \approx \text{cte} \tag{10}
\]

During charge both passive and active balancing systems decrease the maximum temperature of the cell due to decrease in current of the strong cell $I_{C,S}$.

\[
P_{L,S} = R_{\text{in}} I_{C,S}^2 = R_{\text{in}} (I_{BAT} + I_{B,S})^2 \quad \text{PB, AB} \quad P_{L,S} \downarrow \downarrow 
\]

High temperatures in the balancing system $T_{BS}$ could induce a mismatch in the temperature of different cells of a battery pack due to heat concentration next to the balancing system. Passive balancing systems burn all the energy in the balancing resistor, while active balancing systems only generate heat due to power losses in the balancing converter. Passive balancing systems can generate a hot spot in the battery pack.

C. Cost

Balancing system cost is one of the most important parameters, if not the most important one, why passive balancing is the principal balancing architecture in industrial applications.

Active balancing systems usually are complex architectures requiring several active switches. Each active switch requires a high frequency isolated driver increasing the cost, and decreasing the reliability of the whole system.

Passive balancing systems typical architecture presented in Fig. 1 a) require an optocoupler $OP_n$ to isolate the system and a power switch $S_h$ in conjunction with a balancing resistor $R_{B,n}$ to discharge the excess energy of the cells. The voltage measurement of each cell is made via differential amplifiers $DA_n$ for voltage balancing control, even if specific ICs for BMS operation have decreased the complexity and the price of passive balancing systems.

Single switch balancing topologies, as the Sepic architecture presented in Fig. 1 b) only need one single switch to balance one series string of cells. Voltage measurement is not necessary as the balancing process is made naturally and the switching of the active switch is made in open loop, decreasing the complexity of the driver and the control system.

The specifications of single switch open loop systems could be a key point as the main architecture to change the industry position from passive configurations to active balancing systems.

**EXPERIMENTAL RESULTS AND COMPARISON**

The evaluation and comparison of passive and active balancing systems is made under 3 different environments. The comparative evaluation is made for a 4S1P battery pack with the PB and AB systems presented in section II. The comparative results are presented in Fig. 4.

- **High power fresh cells (HPF)**: a 4S1P battery pack of 6.5 Ah LiFePO$_4$ fresh cells has been connected to prove the balancing systems behavior under a newly assembled battery pack.
- **High power aged cells (HPA)**: An 80% SOH 6.5Ah nominal capacity LiFePO$_4$ cell has been connected with 3 fresh cells making a 4S1P battery pack with one cell in an advanced aging stage.
- **Low power fresh cells (LPF)**: A 4S1P battery pack of 1.1 Ah low capacity LiFePO$_4$ cell has been implemented to view the effect in lower capacity cells, where the balancing current $I_{B,n}$ is closer to the nominal
TABLE III  
TOTAL CHARGE, DISCHARGE AND EFFICIENCY BEHAVIOR OF 3 DIFFERENT 4S1P BATTERY PACKS UNDER CCCV CHARGE AND CC DISCHARGE PROCESSES.

<table>
<thead>
<tr>
<th></th>
<th>HPF</th>
<th>HPA</th>
<th>LPF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_C$</td>
<td>$W_{D,AB}$</td>
<td>$W_C$</td>
</tr>
<tr>
<td>PB</td>
<td>97.89</td>
<td>97.21</td>
<td>70.68</td>
</tr>
<tr>
<td>AB</td>
<td>96.96</td>
<td>96.9</td>
<td>66.96</td>
</tr>
<tr>
<td></td>
<td>$W_D$</td>
<td>$W_{D,AB}$</td>
<td>$W_D$</td>
</tr>
<tr>
<td>PB</td>
<td>-92.28</td>
<td>-92.61</td>
<td>-63.25</td>
</tr>
<tr>
<td>AB</td>
<td>-92.48</td>
<td>-92.5</td>
<td>-63.95</td>
</tr>
</tbody>
</table>

$\eta_{PB}$ = 94.28, $\eta_{HPF}$ = 89.49, $\eta_{LPF}$ = 91.4

$\eta_{AB}$ = 95.39, $\eta_{HPF}$ = 95.51, $\eta_{LPF}$ = 92.19

capacity of the cell.

D. Energy considerations

In order to evaluate energy characteristics related to cycle life and cycling behavior due to balancing systems a charge discharge cycle has been designed.

- **Charge cycle**: A 1CConstant Current CC until $V_{B,n}$=3.65 Constant Voltage CV until $I_{AB,t}=C/20$ charge cycle has been defined to evaluate charging energy $W_C$.

- **Discharge cycle**: A 1CCC discharge cycle until $V_{B,n}$=2V is designed to evaluate the total discharge energy $W_D$.

Both cycles are repeated 10 times to evaluate the balancing system performance during repetitive cycling. The balancing systems are controlled by voltage difference. The threshold voltage for balancing switching on is set to 10 mV difference between two cells. The 4S1P battery packs are cycled inside a temperature chamber with a constant 25°C ambient temperature.

During the charge process passive balancing consumes more energy from the charger to charge the battery pack. Even if energy excess consumption, the battery pack is more charged with PB than with the AB. However the charging efficiency is much lower in the PB system than in the AB due to higher power losses of the PB. The power losses in the PB system are easily calculated knowing the balancing resistor $R_{B,n}$, the cell voltage $V_{B,n}$ and the balancing time when PB is connected. The AB power losses are measured experimentally as 0.195 W for an unbalance situation of 2 V for the weak cell $V_{B,W}$ and 3.65 V for the strong cells (presented in Fig. 5). When AB is active constant 0.195 W power losses are considered, even the real losses will be smaller. However, even if the power losses are overestimated the AB power losses are much lower than the PB system power losses.

Discharge process is greatly improved by the AB. The passive balancing only burns energy in order to decrease the voltage difference between cells reducing the total energy of the battery pack. The AB redistributes the energy to the lowest voltage cell, increasing the discharge time and the total discharge energy. The power losses during discharge are higher in PB than in AB.

The cycling results presented in Table III, conclude that -92.48 Wh are discharged $W_D$ with the PB system, 0.2 Wh less than with the AB system although 97.89 Wh are charged, 0.93 Wh more than with the AB for HPF cells.

The results with HPA cells are even better for the AB system. $W_C$=70.68 Wh are charged with the PB system, 3.72 Wh more than with the AB system. However the AB system discharges $W_D$=-63.95 Wh 0.6 Wh more than the PB system.

The results for the LPF cells are also superior for AB system compared with PB system. The charged energy $W_C$ is decreased 0.19 Wh for the AB system, and the discharged energy increased $W_D$ is increased 0.07 Wh in AB system.

The AB system charges less energy in the battery pack and discharges more energy being superior than the PB system.

Due to the excessive energy wasted, during charge and discharge process in PB, the battery pack efficiency is greatly improved with the AB,+1.11% with HPF cells, 6,02% for HPA cells and 1.79% for LPF cells. The AB system is much superior than the PB system in efficiency requirements. For continuous charge discharge applications as electro mobility, the efficiency requirement is primordial.

For standby energy consumption $W_{SOH}$, 4S1P battery pack has been stored fully charged at 25 °C ambient temperature, during the standby period PB and AB balancing systems have been connected to evaluate the leakage current of the balancing systems. The balancing systems have been connected during 3 weeks consecutive periods. After the storage time a full discharge of the battery pack is evaluated, with 1C constant current, to compare the energy decrease with a non-balancing system battery pack.

The results presented in Table IV conclude that the balancing system do not contribute in an accelerated self-discharge process of the battery pack. The PB system increases the self-discharge only 0.22% and the AB system 0.1% respect to a 4S1P battery pack without balancing system.

E. Temperature behavior

To compare the temperature improvement and behavior of the 4S1P battery packs due to balancing systems, 2 K type thermocouples have been connected to each cell to evaluate the maximum temperature $T_{max}$ in the surface and the temperature distribution $\Delta T$ between the 4S1P cells.

In order to avoid temperature influence between nearby positioned cells, the cells are distanced 2 cm between them.

TABLE IV  
TOTAL DISCHARGED ENERGY $W_D$ AND ENERGY WASTED DURING STANDBY OPERATION $W_{SB}$ FOR A 4S1P LIFEP04 BATTERY PACK WITHOUT BALANCING SYSTEM, WITH PB SYSTEM AND WITH AB SYSTEM.

<table>
<thead>
<tr>
<th></th>
<th>$W_D$</th>
<th>$W_{SB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No balancing</td>
<td>-91.33 (100%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>PB</td>
<td>-91.13 (99.78%)</td>
<td>0.2 (0.22%)</td>
</tr>
<tr>
<td>AB</td>
<td>-91.24 (99.9%)</td>
<td>0.09 (0.1%)</td>
</tr>
</tbody>
</table>

TABLE V  
TEMPERATURE BEHAVIOR DURING END OF DISCHARGE OF 3 DIFFERENT 4S1P BATTERY PACKS UNDER CCCV CHARGE AND CC DISCHARGE PROCESSES.

<table>
<thead>
<tr>
<th></th>
<th>HPF</th>
<th>HPA</th>
<th>LPF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{max}$</td>
<td>$\Delta T$</td>
<td>$T_{max}$</td>
</tr>
<tr>
<td>PB</td>
<td>28.61</td>
<td>0.4</td>
<td>29.59</td>
</tr>
<tr>
<td>AB</td>
<td>29.23</td>
<td>0.3</td>
<td>29.53</td>
</tr>
</tbody>
</table>

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Distancing the series connected cells isolates the impact of each cell from the heat generation of adjacent cells, taking only into account the performance of the balancing system for the temperature behavior.

The maximum temperature $T_{\text{max}}$ and the maximum temperature gradient $\Delta T$, take place at the end of the discharge process. The temperature behavior has been evaluated during the cycles presented for the energy considerations during the previous subchapter. The temperature values are the mean value of the 10 consecutive discharge cycles. The mean value permits to filter temperature measurement errors and dispersion.

Table V presents the temperature behavior results for 10 consecutive charge discharge cycles. For HPF cells PB reaches lower maximum temperature than AB. This result conflicts with equation (10). However the temperature increase in AB could be generated due to a deeper SOC reached (Lower $V_{\text{OC}}$), and higher $R_{\text{in}}$ reached. The temperature dispersion between cells is reduced from 0.4 °C on the PB to 0.3 °C on the AB.

The results for the HPA configuration present that the PB reaches higher temperature than AB, if an aged cell is presented in the battery module. The temperature dispersion increases more than 1.5 °C from the HPF case, so it is also concluded that low SOH dispersion cells have lower temperature dispersions. The temperature dispersion $\Delta T$ is 0.12°C lower for AB than the 2.07 °C dispersion presented for the PB system configuration.

For the LPF battery module configuration the AB presents better characteristics regarding $T_{\text{max}}$ and $\Delta T$ compared to the PB system. The balancing current rating of the AB system is closer to the nominal capacity of the LPF configuration than for the HPF configuration, presenting better results than the PB system for fresh cells. 0.22 °C less respect to $T_{\text{max}}$ and 0.05 °C less temperature dispersion $\Delta T$.

The power losses $P_{\text{LBS}}$ of the balancing system could generate a temperature increase near the battery pack decreasing the life span of the battery by accelerating aging mechanisms. In order to evaluate the temperature generated in the balancing system $T_{\text{BS}}$ a test bench with 4 power supplies connected in series has been designed. The power supplies are bidirectional with power sinking capability. 3 power supplies losses of 0.195 W. The hot spot is presented in the mosfet driver and in the diode which inserts energy in the simulated 2 V weak cell. The $T_{\text{BS}}$ system dissipates 3.5 W in 3 balancing circuits are experimentally measured and the temperature hot spots in the balancing system are measured by a thermography camera.

The AB system has a hot spot of 38.2 °C, with total power losses of 0.195 W. The hot spot is presented in the mosfet driver and in the diode which inserts energy in the simulated 2 V weak cell. The $P_{\text{LBS}}$ system dissipates 3.5 W in 3 balancing resistors, generating 3 dangerous hot spots of 119.3 °C. The excess temperature in the PB could increase the temperature of the battery pack significantly, or even could make a temperature unbalance between cells of a battery pack. The losses are independent of the battery pack cell, only depend on the battery pack cell voltage.

### Table VI: Cost distribution of balancing systems.

<table>
<thead>
<tr>
<th></th>
<th>PB</th>
<th>AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part ref.</td>
<td>€/pcs</td>
<td>Part ref.</td>
</tr>
<tr>
<td>$OP_x$</td>
<td>TLP523 0.71</td>
<td>$D_x$</td>
</tr>
<tr>
<td>$R_{\text{BS}}$</td>
<td>ER7412RJT 0.28</td>
<td>$L_x$</td>
</tr>
<tr>
<td>$S_{\text{BS}}$</td>
<td>BD437 0.233</td>
<td>$C_{\text{BS}}$</td>
</tr>
<tr>
<td>$DA_{\text{BS}}$</td>
<td>INA148 3.49</td>
<td>$L_{\text{BS}}$</td>
</tr>
<tr>
<td>$V_{\text{BS}}$</td>
<td>IRF8721PBF 0.6</td>
<td>$\text{WH/pcs}$</td>
</tr>
</tbody>
</table>

Price of components for minimum order of 10 pieces in www.farnell.com

* Only one element per battery pack
F. Cost

Cost issue is the biggest constraint, why PB is the most used balancing system and why is widely used in industry applications. However, single switch balancing systems are good candidates to deal with cost issues. A voltage measurement system is not required. Single switch systems operate in open loop, reducing the complexity of the control system.

To evaluate the cost of the PB and AB systems, the cost of each cell balancing unit will be evaluated, taking into account the price per each element.

- **PB**: Optocoupler $O_{p,n}$, Balancing resistor $R_{B,n}$, power switch $S_n$ and differential amplifier $DA_n$ per each cell.
- **AB**: Diode $D_n$, Inductor $L_n$ and capacitor $C_n$ per each cell, and one input inductor $L_{in}$ and one power switch $S_1$ per battery pack.

The results presented in Table VI present that the AB is cheaper 13.16 € than the PB, mainly due to the high price of differential amplifiers $DA_n$, AB open loop control strategy avoids the use of a measurement system for each cell voltage, however due to the natural unsafe behavior of Li-ion cells voltage monitoring is indispensable. If specific Battery Management System IC is used for PB systems the PB cost could be reduced.

CONCLUSIONS

A comparative study has been presented where a single switch Multi stacked Sepic active balancing system has been compared with a passive balancing system. Single switch active balancing systems are a good candidate to substitute passive balancing due to low complexity and open loop control in DCM.

The main conclusion claims that active single switch active balancing are good candidates to replace passive balancing systems in industrial applications.

The passive balancing system and the active balancing system are compared in 3 different scenarios with high power fresh cells, high power aged cells and low power fresh cell in a 4S1P configuration. The 3 different configurations are compared for energetic considerations temperature behavior and cost issues.

Regarding to energetic results, active balancing is much superior to the passive balancing system. Inserts less energy from the battery charger (reducing the electric bill), and increases the discharged energy (increasing battery energetic availability). The efficiency of the battery pack is greatly increased. 1% for high power fresh cells, 6% for high power aged cells and nearly 2% for low power fresh cells. Active balancing and passive balancing systems connection to a battery pack do not affect in self-discharge increase.

Temperature behavior results present a better behavior of the passive balancing system only regarding maximum temperature in high power fresh cells. Maximum temperature in aged and low power cells is reduced in active balancing system respect to passive balancing system. The temperature dispersion between cells is always lower in the active balancing system than in the tested passive balancing system. The balancing system temperature is dramatically reduced from 119.3 °C in the passive balancing system to 38.2 °C in the active balancing system, reducing the possibility of generating hot spots inside the battery pack.

The cost issue presents a lower cost for the active balancing system 13.16 € than for the passive balancing system 18.852. This is because single switch balancing systems can balance the cells without the need of a voltage measurement system. However the natural unsafety behavior of Li-ion cells forces to use a voltage monitoring system. Passive balancing system price could also be reduced by the use of commercial ICs for battery management systems.

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