Comparative Study and Evaluation of Passive Balancing AgainstSingle 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 characteristicsa 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

W_D	Total useful discharged energy [Wh]
$W_{D\text{-}BAT}$	Total discharged energy [Wh]
W_C	Total charged energy [Wh]
$W_{C\text{-}BAT}$	Total useful charged energy [Wh]
η	Energy efficiency of the battery pack [%]
W_{SB}	Standby energy consumption [Wh]
ΔT	Battery gradient between cells inside the battery pack[ºC]
T_{Max}	Maximum temperature of the battery pack [ºC]
T_{BS}	Generated temperature in the balancing system [ºC]
$C_{€}$	Balancing system cost [€]
$P_{L,n}$	Power losses of the n cell [W]
$P_{L,BS}$	Power losses of the balancing system [W]
I_{BAT}	Battery pack current [A]
$I_{C,n}$	Single cell current [A]
$I_{B,n}$	Single cell balancing current [A]
PB	Passive Balancing
AB	Active Balancing
HPF	High power fresh cells
HPA	High power aged cells
LPF	Low power fresh cells

INTRODUCTION

ENERGYstorage 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 electro mobility 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

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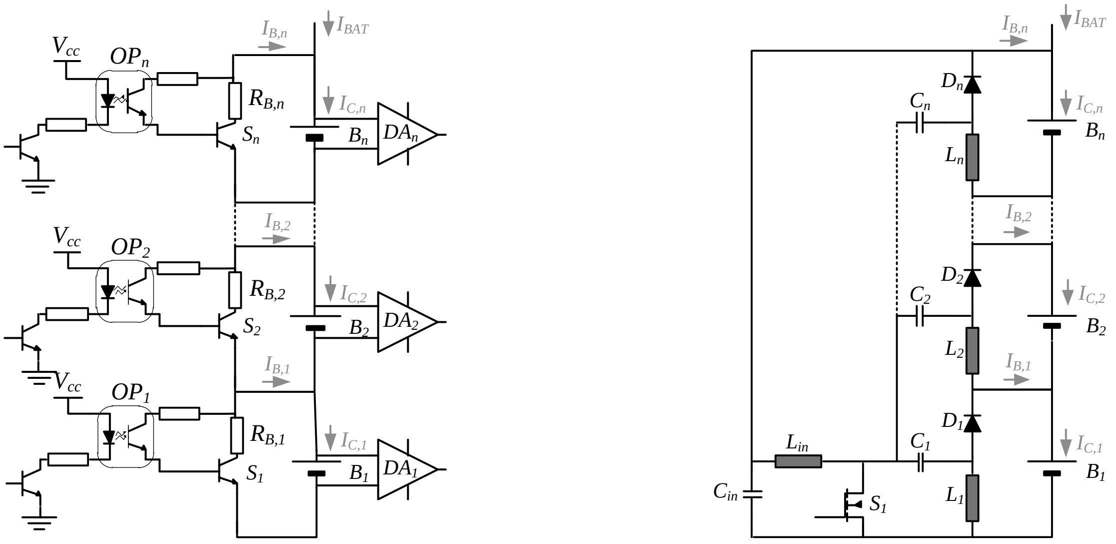


a) b)

Fig. 1.Energy storage balancing systems under comparison. a) Passive balancing system. b) Sepic based single switch active balancing system.

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 η and standby energy consumption W_S.
- *Temperature behavior:* Temperature gradient ΔT 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 $C_{€}$.

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.

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

	Passive balancing system	*Sepic single switch active balancing system*
Advantages	• Simple. • Cost.	• Simple. • Efficient. • Open loop balancing.
Disadvantages	• Energy wasting. • Useless in discharge.	• Only voltage balancing.

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 $I_{B,n}$.

$$I_{C,n} = I_{BAT} + I_{B,n} \tag{1}$$

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.

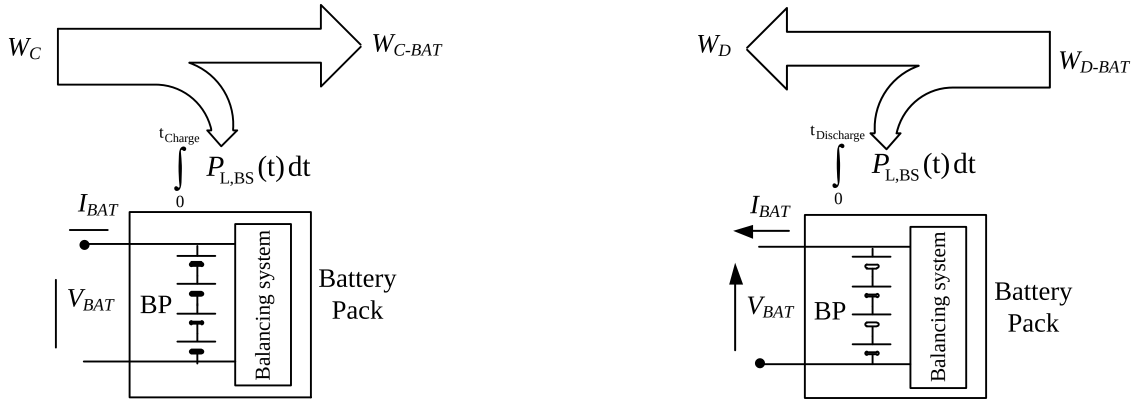
Passive balancing systems burn energy of the strong cells and do not transfer energy to the weak cells. The strong cell balancing current is proportional to the strong cell voltage $V_{B,S}$ and the balancing resistor $R_{B,n}$.

$$I_{B,S} = -\frac{V_{B,S}}{R_{B,n}} \tag{2}$$

$$I_{B,W} = 0 \tag{3}$$

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

	PB	*AB*
$I_{B,W}$ [mA]	0	365
$I_{B,S}$[mA]	-304	-67



a) **b)**

Fig. 2.Arrow diagram for the energetic evaluation of the battery pack cycling performance. $P_{L,BS}$ always considered positive losses a) Charge process (I_{BAT} positive. W_C and $W_{C\text{-}BAT}$ positive). b) Discharge process (I_{BAT} negative. W_D - $W_{D\text{-}BAT}$ negative)

Sepic based single switch balancing currents depend directly in the duty cycle of the active switch, the converter inductors L_{in}, L_n and the difference between the voltage of the weak cell $V_{B,W}$ and the whole battery pack V_{PACK}. The bigger the difference between strong cells and weak cell voltages, the greater the balancing capacity is.The series connected cells are voltage balanced with an open loop control with a fixed duty cycle ratio$D$ of the active switch S_1.

$$I_{B,S} = -\frac{V_{PACK} D^2 T_s \left(L_n + nL_{in}\right)}{2L_n L_{in}} \tag{4}$$

$$I_{B,W} = \frac{V_{PACK} D^2 T_s \left(L_n + nL_{in}\right)}{2L_n L_{in}} \left(\frac{V_{PACK}}{V_{B,W}} - 1\right) \tag{5}$$

The balancing current values for the passive balancing system *PB* and the Sepic based active balancing system *AB* 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*AB*switches with a constant D of 13 % with a switching frequency of 100 kHz.The inductors are designed for a value ofL_{in}=470 µH and L_n are 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(W_C considered positive), the energy obtained during discharge W_D(W_D considered negative) and the efficiency of the battery pack respect to the energy inserted and the energy discharged η.

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 $W_{C\text{-}BAT}$is measured by the integration of the voltage $V_{B,n}$and the current $I_{C,n}$of each cell. It is also the total energy measured by the charger $W_C$subtracting the energy lost by the power losses of the balancing system $P_{L,BS}$.

$$\begin{aligned} W_C &= \int_0^{t_{charge}} V_{BAT}(t) I_{BAT}(t)dt \\ W_{C-BAT} &= \int_0^{t_{charge}} \sum_1^n V_{B,n}(t) I_{C,n}(t)\, dt = W_C - \int_0^{t_{charge}} P_{L,BS}(t)dt \end{aligned} \tag{6}$$

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

$$\begin{aligned} W_D &= \int_0^{t_{discharge}} V_{BAT}(t) I_{BAT}(t)dt \\ W_{D-BAT} &= \int_0^{t_{discharge}} \sum_1^n V_{B,n}(t) I_{C,n}(t)\, dt = W_D - \int_0^{t_{discharge}} P_{L,BS}(t)dt \end{aligned} \tag{7}$$

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

$$\eta = \left|\frac{W_D}{W_C}\right| \cdot 100 \tag{8}$$

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 temperatureT_{Max} and the deviation in temperature ΔT between different cells of the battery pack[22]. The power losses of the balancing system also increase the temperature of the balancing system boardT_{BS} that could generate a hot spot for nearby positions cells..

T_{Max} and ΔT 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 are proportional to the internal resistance of the cell $R_{in}$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}.

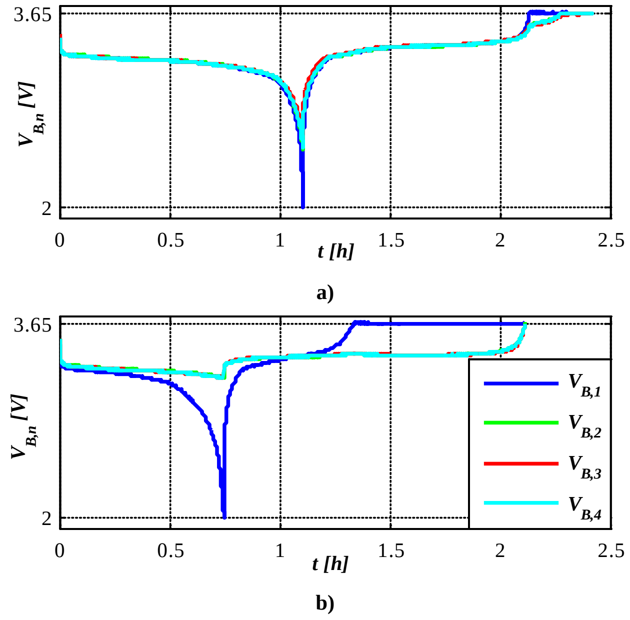
$$P_{L,n} = R_{in} I_{C,n}^{\;2} \approx \left|V_{B,n} - V_{OC}\right| I_{C,n} \tag{9}$$

Balancing systems equalize the voltage level of each cell, so they improve the temperature gradient between cellsΔT 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 deliver 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.

$$\begin{aligned} P_{L,W} &= R_{in} I_{C,W}^{\;2} = R_{in}\left(I_{BAT} + I_{B,W}\right)^2 \quad AB \quad P_{L,W} \downarrow\downarrow \\ P_{L,W} &= R_{in} I_{C,W}^{\;2} = R_{in} I_{BAT}^{\;2} \qquad\qquad PB \quad P_{L,W} \approx cte \end{aligned} \tag{10}$$

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



a)

b)

Fig. 3.Charge discharge cycle 1C current for a passive balancing system in a 4S1P battery pack a) *HPF* Fresh cells b) *HPA* Aged cells. $V_{B,1}$ 80% *SOH*.

$$P_{L,S} = R_{in} I_{C,s}^{\;2} = R_{in}\left(I_{BAT} + I_{B,S}\right)^2 \quad PB, AB \quad P_{L,S} \downarrow\downarrow \tag{11}$$

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_N 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 amplifiersDA_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 controlsystem.

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 of1,1 Ahlow capacityLiFePO4 cellshas 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.

	HPF		*HPA*		*LPF*	
	W_C	$W_{C\text{-}BAT}$	W_C	$W_{C\text{-}BAT}$	W_C	$W_{C\text{-}BAT}$
PB	97.89	97.21	70.68	68.76	13.79	13.64
AB	96.96	96.9	66.96	66.64	13.60	13.53
	W_D	$W_{D\text{-}BAT}$	W_D	$W_{D\text{-}BAT}$	W_D	$W_{D\text{-}BAT}$
PB	-92.28	-92.61	-63.25	-65.22	-12.59	-12.7
AB	-92.48	-92.5	-63.95	-64.02	-12.66	-12.69
	η		η		η	
PB	94.28		89.49		91.4	
AB	95.39		95.51		93.19	

capacity of the cell.

D. Energyconsiderations

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_{BAT}=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 25ºC ambient temperature.

During the charge process passive balancing consumes more energy from the charger to charge the battery pack. Even that 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, 0,2Wh 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_{SD}, 4S1P battery pack has been stored fully charged at 25 ºC 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 distributionΔT between the 4S1P cells.

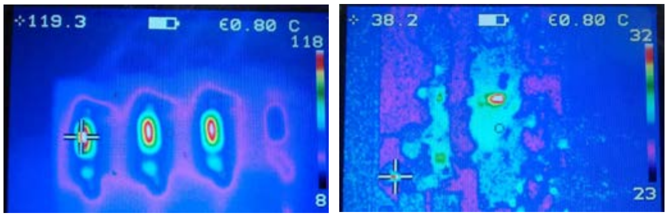
In order to avoid temperature influence between nearby positioned cells, the cells are distanced 2 cm between them.

TABLE IV
TOTAL DISCHARGED ENERGYW_D AND ENERGY WASTED DURING STANDBY OPERATION W_{SB} FOR A 4S1P LIFEPO$_4$ BATTERY PACK WITHOUT BALANCING SYSTEM, WITH *PB* SYSTEM AND WITH *AB* SYSTEM.

	W_D	W_{SB}
No balancing	-91.33 (100%)	0 (0%)
PB	-91.13 (99,78%)	0,2 (0,22%)
AB	-91.24 (99,9%)	0,09 (0,1%)

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

	HPF		*HPA*		*LPF*	
	T_{max}	ΔT	T_{max}	ΔT	T_{max}	ΔT
PB	28.61	0.4	29.59	2.07	27,86	0,59
AB	29.23	0.3	29.53	1.95	27,64	0,54



PB **AB**

$P_{L,BS}$	T_{BS}	$P_{L,BS}$	T_{BS}
3.5 W	119.3 º	0.195 W	38.2 º

Fig. 5.Thermography camera photo for temperature measurement of the *PB* and *AB* under maximum unbalancing situation. $P_{L,BS}$and T_{BS} are measured under unbalancing conditions..

TABLE VI
COST DISTRIBUTION OF BALANCING SYSTEMS.

	PB			*AB*	
	Part ref.	*€/pcs*		*Part ref.*	*€/pcs*
OP_n	TLP523	0.71	D_n	SL13-E3/61T	0.26
$R_{B,n}$	ER7412RJT	0.28	L_n	74459168Würth	2.18
S_n	BD437	0.233	C_n	C1206C106K3PACTU	0.195
DA_n	INA 148	3.49	L_{in}^*	74459247 Würth	2.02
			S_1^*	IRF8721PBF	0.6
4S1P	18.852 €		*4S1P*	13.16 €	

Price of components for minimum order of 10 pieces in www.farnell.com
* Only one element per battery pack

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_{max} and the maximum temperature gradientΔT, 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_{OC}), and higher R_{in} reached. The temperature dispersion between cells is reduced from 0.4 ºC on the *PB* to 0.3 ºC on the *AB*.

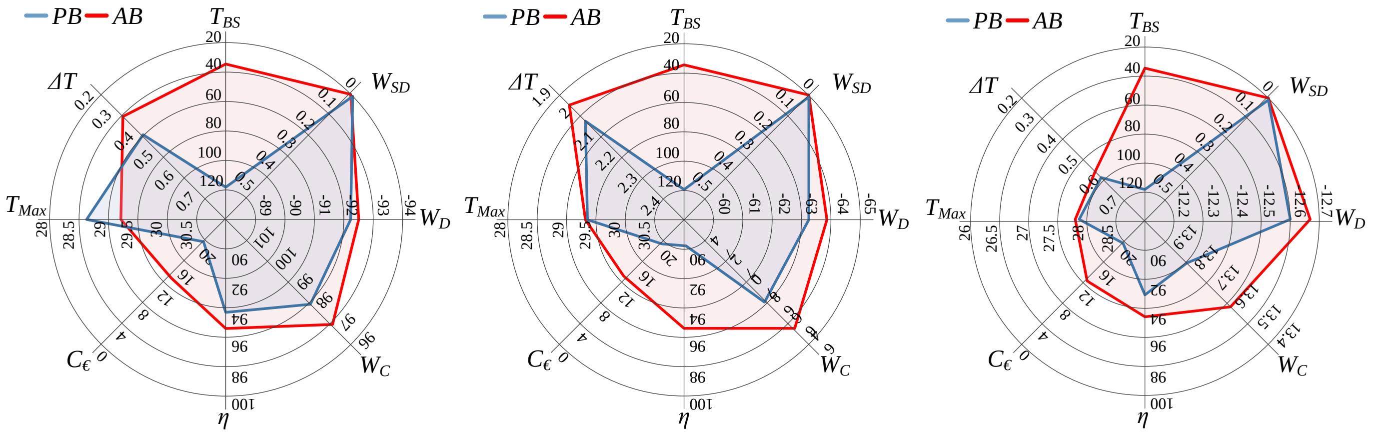
The results for the *HPA* configuration present that the PB reaches higher temperature than AB, if an aged cell is presented in the battery module. The temperature dispersion increases more than 1.5 ºC from the *HPF* case, so it is also concluded that low SOH dispersion cells have lower temperature dispersions.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

For the *LPF* battery module configuration the *AB* presents better characteristics regarding T_{Max} and ΔT 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 ºC less respect to T_{Max} and 0.05 ºC less temperature dispersion ΔT.

The power losses $P_{L,BS}$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_{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 are set to 3.65 V and the weak cell is simulated to 2V to evaluate the extreme unbalancing situation.

The power losses of the balancing circuits are experimentally measured and the temperature hot spots in the balancing system are measured by a thermography cameraFig. 5.

The *AB* system has a hot spot of 38.2 ºC, 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 *PB* system dissipates 3.5 W in 3 balancing resistors, generating 3 dangerous hot spots of 119.3 ºC. 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.



a) b) c)

Fig. 4.Spyder chart comparison for energy, temperature and cost characteristics of a passive balancing system and an active single switch Sepic balancing system. a) High Power Fresh cells *HPF*b) High Power Aged cells *HPA* c) Low power fresh cells *LPF*.

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*: OptocouplerOP_n, Balancing resistor $R_{B,n}$, power switchS_n and differential amplifierDA_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 isindispensable. If aspecific 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 ºC in the passive balancing system to 38.2 ºC 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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