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Simulation and testing of self reconfigurable battery advanced functions for automotive application

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Executive Summary

This article presents the design and production work carried out jointly by Vitesco Technologies and the CEA in order to build a Self Reconfigurable Battery (SRB) demonstrator representative of an electric vehicle traction battery pack.

The literature demonstrates that the use of SRB allows for individual bypassing or serialization of each cell in a battery pack, enabling control of the voltage output and dynamic balancing of the battery pack during all phases of vehicle use. The simulations and tests presented in this article confirm that the use of SRB results in 6% reduction in energy consumption compared to a Conventional Battery Pack (CBP) on a diving profile based on WLTP cycles. Additionally, SRB enhances fast charging performance, with a charging time that is 22% faster than CBP. Furthermore, it can be directly connected to the network for charging without the need for a dedicated converter.

Keywords: electric vehicle (EV), Self Reconfigurable Battery, Battery Management System, energy consumption, fast charge.

1 Introduction

As shown in many articles [1], battery switching technologies of SRB promise significant improvements in terms of autonomy and battery life, cell balancing [2], recharging capacity [3] and even cell ageing [4].

The SRB demonstrator developed by Vitesco Technologies and CEA is defined by 120 NMC cells of 14A.h with a maximum current of 125A. The system is composed of a master controller which communicates with 20 modules. These modules are connected to each other in series regarding the power path. Each module independently controls the switching of six cells, each of which can be connected in series or bypassed. The system is flexible and allows modules to be easily added in series to increase the voltage.

This setup makes it possible to validate the operation of cell switching in an electric vehicle application.

Comparative tests between a SRB and a CBP are presented. New and aged cells with 5% to 10% loss of State of Health (SoH) have been used in order to introduce dispersion conditions representative of an aged vehicule pack [5]. This also allows to show the ability of using unsorted cells, or heterogeneous cells intended for second life.

Battery discharge following a driving profile based on WLTP cycles, direct charging without a converter on the AC grid and fast charging on a DC voltage bus will be presented.

2 Simulation

Different configurations of batteries in a representative electrical vehicle environment have been simulated. The main targets are to prove the interest of the different capabilities listed in the introduction of this paper, in comparing the SRB solutions to equivalent CBP.

Compared to a CBP for a given segment, the equivalent SRB to be considered has more cells in series and smaller cells. The comparison is relevant from an energetic point of view only. A process of adaptation is therefore required.

For the driving use case, the comparison has been presented in [6] with an improved simulation model including representative energetic cells with their actual parameters and also representative cell dispersion within the pack. The two batteries have been dimensioned in order to provide the same energy at the wheel at the beginning of life, taking into account a capacity dispersion of 2 % within the cells. In this simulation, the reference CBP is a 96S2P battery with 120 Ah cells, the SRB has 144S2P with 80 Ah cells

To reduce the cost of this technology, a grouping of cells in series is also considered: instead of having 1 cell for each bypass switch/serial switch entity, we have a group of 4 cells in series 1 cell for each bypass switch/serial switch entity. Consequently, the SRB in this simulation has 36 groups with each group consisting of 4 cells and one bypass switch/serial switch entity.

Figure 1 highlights the driven distance benefit of the aged SRB compared to the aged CBP based on capacities reduced to 70 % of the nominal capacity and with a capacity dispersion of 4.8 %. The losses are detailed within the pack (the number in brackets are delta (SRB – CBP)). Thanks to the Control DC link Voltage capability, a better global powertrain efficiency is achieved resulting in an autonomy increased by 6 % (+24 km). In the Figure 1, the values are for a SRB and the values in brackets are the difference between SRB and CBP.

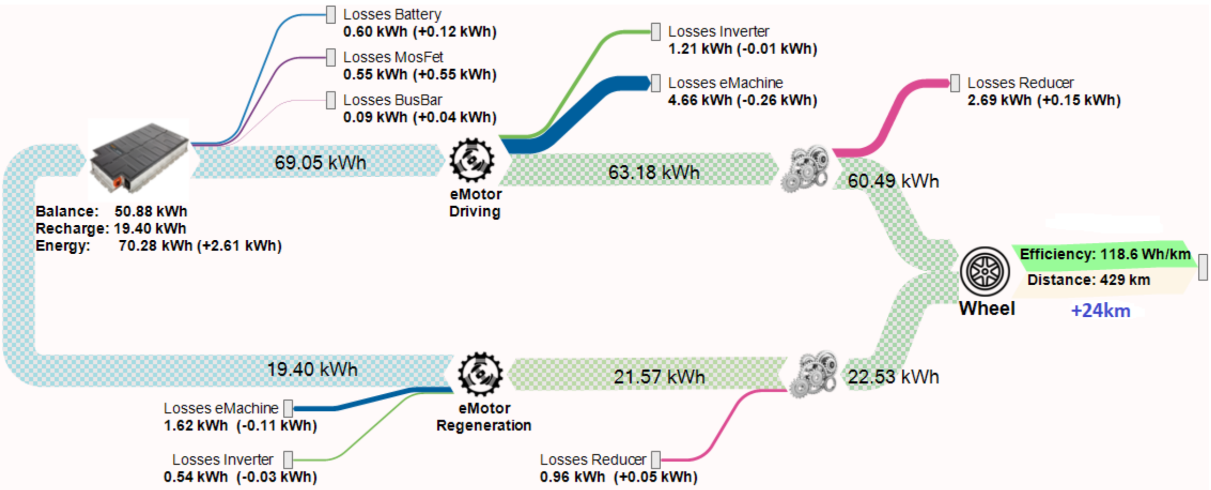

Figure 1 Sankey diagram for SRB/CBP comparison - driving use case

The simulation model has been updated with an improved thermal representativeness. 120 kW Fast DC charging simulations have been conducted in order to compare CBP and SRB solutions at the beginning of life with the same configurations than in the driving profile.

Figure 2 illustrates this comparison.

Figure 2 simulation of Fast DC charging for CBP and SRB

Thanks to the defined SRB configuration, the DC link voltage setpoint is defined at 450V. The charging current, and consequently charging power, remain maximum for a longer time than on a the CBP.

At the beginning of the charge, almost all of the SRB cells are set in serial to reach this DC link voltage setpoint. Consequently, the cell to cell dispersion within the SRB is higher than the CBP's one while the charging power remains high. Nevertheless, while the charging power decreases, less number of cells is required in serial. Then the power cell balancing is possible again, resulting in a very low cell to cell dispersion. This illustrates the great effectiveness of the SRB power cell balancing.

Table 1 highlights the energies and losses for those two configurations for Fast DC charging.

Table 1 Energies and Losses for Fast DC charging

	Battery chemical energy [kWh]	**Battery losses [kWh]**	**MosFet losses [kWh]**	**BusBar losses [kWh]**	**Battery energy [kWh]**
CBP	-50.20	0.80	0.00	0.12	-51.11
SRB	-50.19	0.83	0.60	0.10	-51.72

The losses are increased by 40 % in the SRB compared to the CBP because of the additional electronic components. The DC charging efficiencies are respectively 97.0 % and 98.2 % for SRB and CBP.

However, despite these losses increase, the charging time from 20 % SOC to 80 % SOC is reduced from 42min down to 30min, charging time is **28 % faster with SRB**.

This reduced fast charging time is a key element in the competitive BEV market.

3 System overview

The system consists of a master and modules, each composed of 6 switchable cells. The modules provide voltage and temperature measurements through an RS485 bus to the master. Figure 3 shows the testbench inside a test chamber. The master controller measures the overall voltage and current, processes the cell voltage and temperature measurements received from the modules, and sends back the switching orders to be applied. In addition, this master controller includes high-level application management capabilities such as battery pack voltage regulation, dynamic cell balancing, and safety features.

To charge and discharge the system, a secure test chamber with an 800 V 400 A power supply serving as both a source and sink is employed.

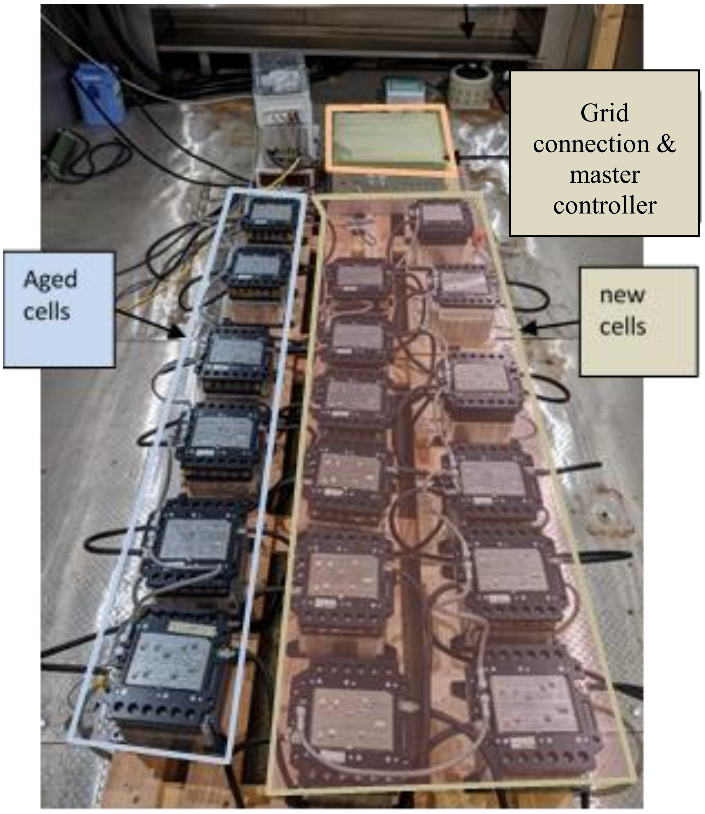

Figure 3: SRB testbench

4 Tests on driving profile based on Worldwide Harmonized Light Vehicles Test Cycles (WLTC)

The objective of these tests is to compare the behavior of a CBP (in which cells cannot be bypassed) and a SRB during a discharge imposed by a driving profile which consists of several WLTCs in a row. The comparison will be conducted using two batches of different cells. The two batches are presented in Figure 4. The first batch comprises 60 new NMC 14 Ah CALB cells, while the second batch consists of 30 aged NMC 14 Ah CALB cells. To compare a CBP versus a SRB, the same cells from batch 1 and batch 2 are used, within a self reconfigurable electrical architecture. The CBP is emulated by the SRB where all the cells of the batch are serialized without possible modification, while the SRB allows for the bypassing of cells to control its output voltage.

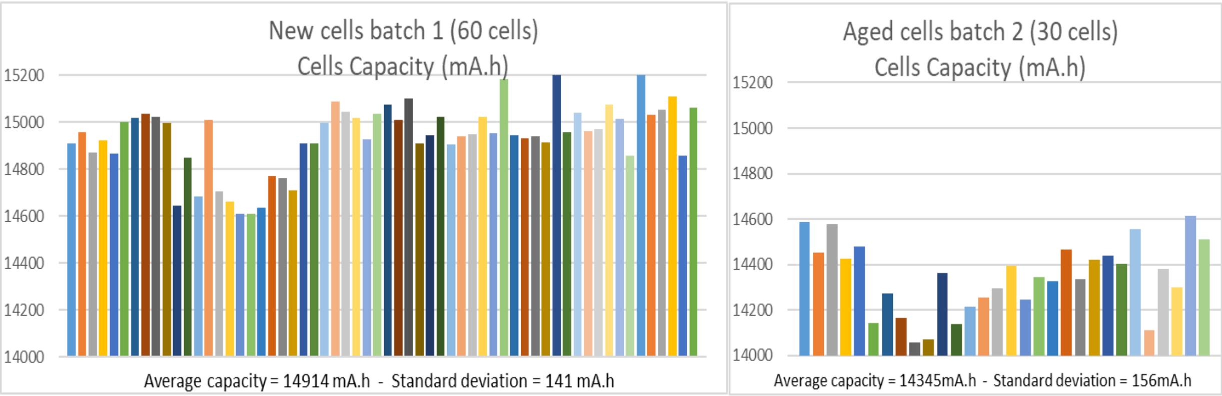

Figure 4: capacity of cells used for the tests

Starting from the same driving use case, the simulation described in chapter '2 Simulation' generates a power exchange file to apply to both the CBP and SRB packs. The optimal voltage setpoint for the SRB tests is also generated.

In contrast to the CBP, the SRB has cell balancing capability while performing a charge or a discharge. Since the cells are kept always balanced, SRB allows the extraction of the whole energy from all the cells in the pack. In a CBP, this is not possible because the discharge of the pack has to stop when a cell reaches its lower voltage limit, even if others cells still have some energy remaining.

To ensure a fair comparison between the CBP and SRB, all cells are fully charged and well-balanced before each test. All cells start at 4.18 V, and the test stops when the first cell reaches 3 V or at the end of the cycle.

4.1 Driving profile with ‘New cells batch’

The Figure 5 shows the result of driving profile with new cells (batch 1) in CBP (bottom) or SRB (top) configuration.

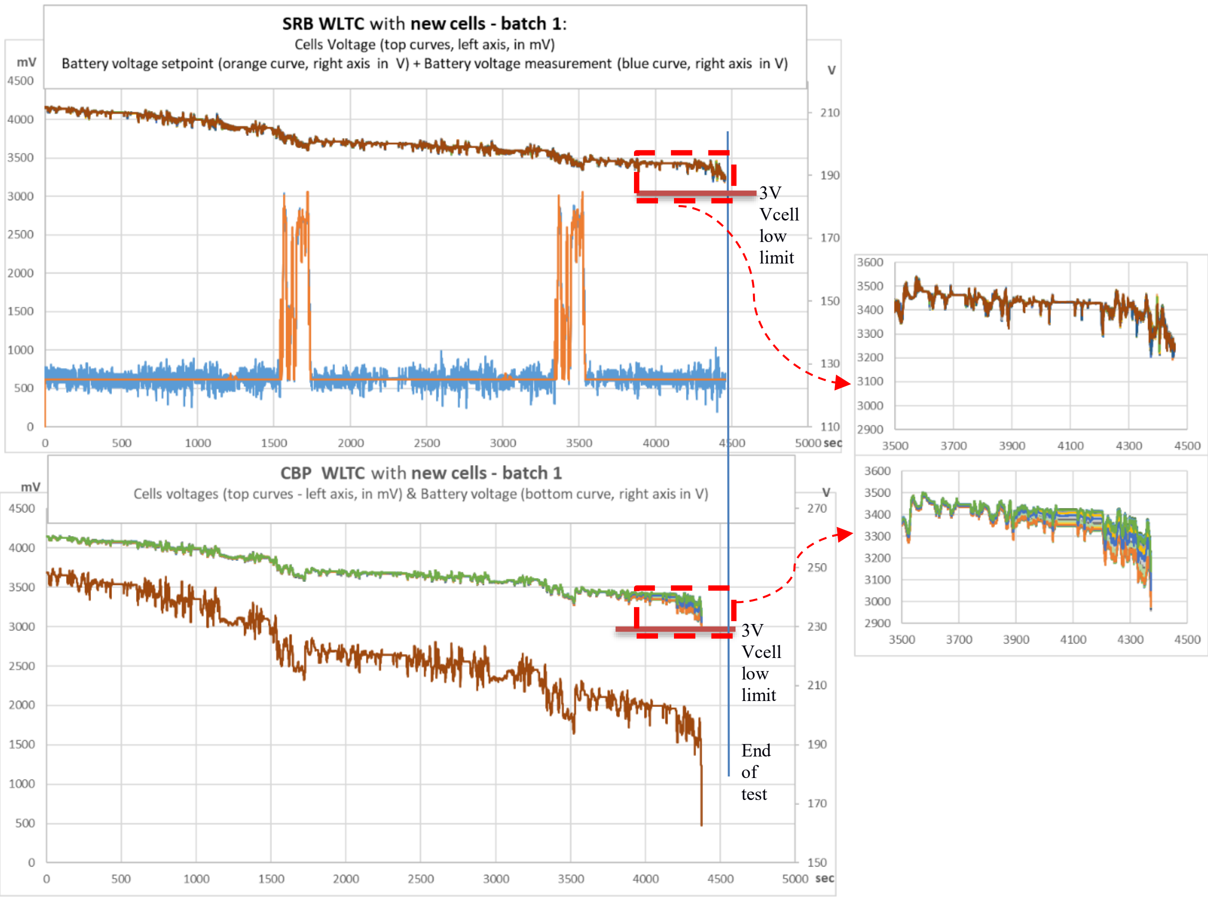

Figure 5: Driving profile with new cells batch 1

In this test, we present the controllability of the output voltage of the SRB, which allows the optimization of the inverter's yield in various driving phases. This optimization enables the SRB to complete the entire driving profile as opposed to the CBP, which stops prematurely due to one cell reaching the low voltage limit of 3 V. Over a discharge period of 4364 seconds, the SRB discharged 2886 W.h, while the CBP discharged 3060 W.h. Interestingly, the SRB consumed 6 % less energy than the CBP for the same distance when the latter came to a stop. At the end of the CBP driving profile, we observed that the cells were not well balanced, with a VCellMax –VCellMin difference of 180 mV, due to the dispersion of the cells capacity of batch 1. In contrast, the SRB was able to balance the cells at all times, resulting in a VCellMax – VCellMin difference of less than 5 mV at the end of the driving profile. Figures of this test are reported in the *Table 2*.

Table 2: figures of WLTC test with new cells batch 1

	CBP	SRB
Run time	4364 sec	4458 sec
Remaining energy at end of cycle	0 W.h	104 W.h
Cells balance @end of cycle	Δ =180 mV	Δ < 5 mV
Discharged energy – charged energy	@4364 sec: 3060 W.h (batt low)	@4364 sec: 2886 W.h @4455 sec (end cycle): 2981 W.h (104 W.h left)

4.2 Driving profile with 'Aged cells batch'

The Figure 6 shows the result of the driving profile with aged cells (batch 2) in CBP (bottom) or SRB (top) configuration.

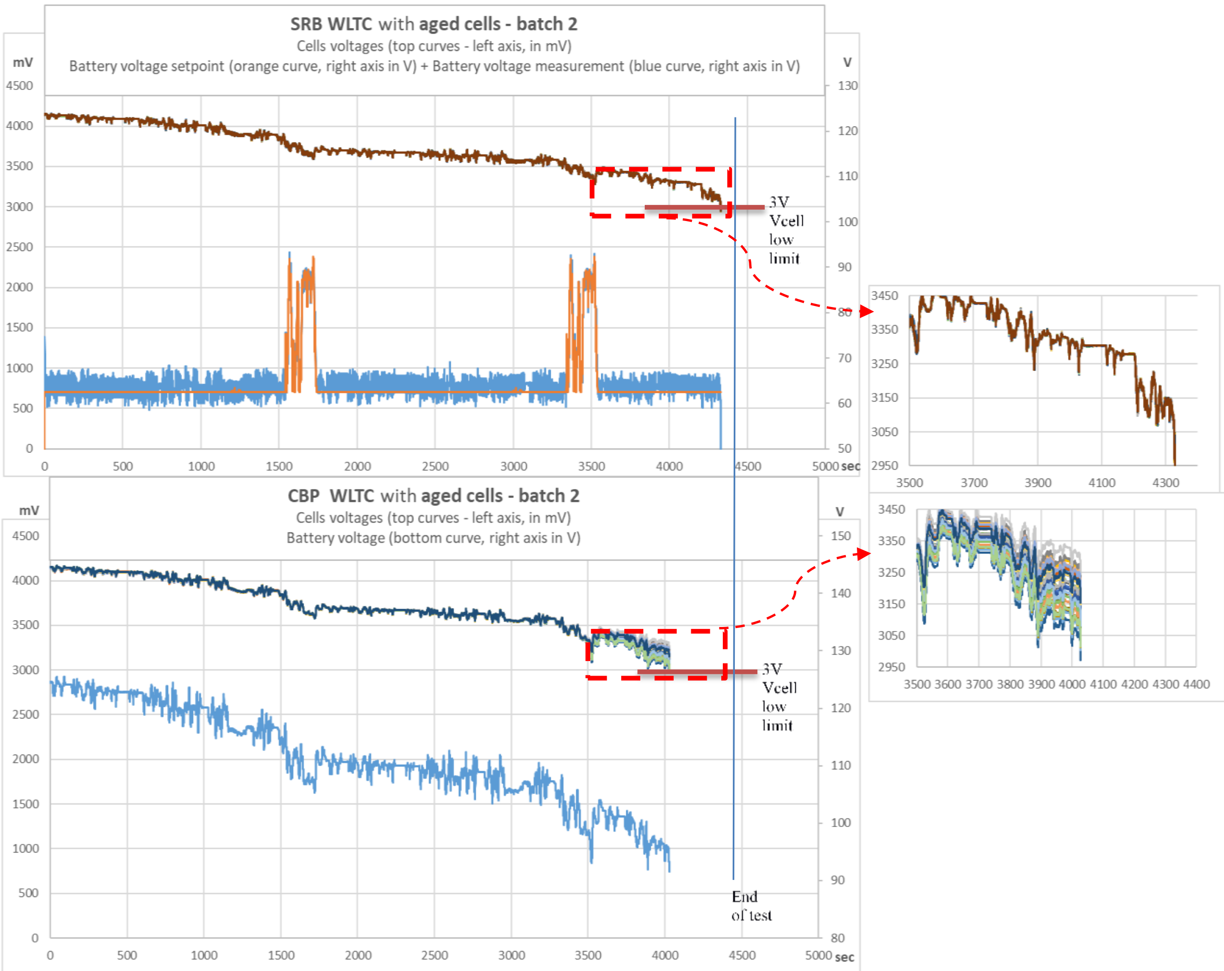

Figure 6: Driving profile with aged cells batch 2

Since the cells in batch 2 have a lower average capacity, neither the CBP nor the SRB configuration reached the end of the test. During a discharge period of 4027 seconds, the SRB discharged 1388 W.h while the CBP discharged 1468 W.h. The SRB consumed 6 % less energy than the CBP for the same duration. This test once again demonstrates the advantage of yield optimization, which is due to battery voltage control, and dynamic balancing of the SRB. Figure 6 clearly shows the dispersion of cell voltages in the CBP configuration from 3500 seconds until the end of the test. Figures of this test are presented in Table 3.

Table 3: figures of WLTC test with new cells batch 2

	CBP	SRB
Run time	4027 sec	4329 sec
Remaining energy at end of cycle	0 W.h	0 W.h
Cells balance @end of cycle	Δ =220 mV	Δ < 5 mV
Discharged energy – charged energy	@4027 sec: 1468 W.h	@4027 sec: 1388 W.h @4329 sec: 1436 W.h

4.3 Driving profile with heterogenous cells

The repairability of battery packs is becoming increasingly of interest to industry for the purpose of maintenance and optimizing system lifespan. Heterogeneous cells in terms of capacity, and even different chemistries, can then constitute a reconditioned battery pack. The transition of a used electric vehicle battery to stationary storage is one example. To illustrate this, we conducted a driving profile with cells of heterogenous capacities and compared the operations of the CBP and the SRB.

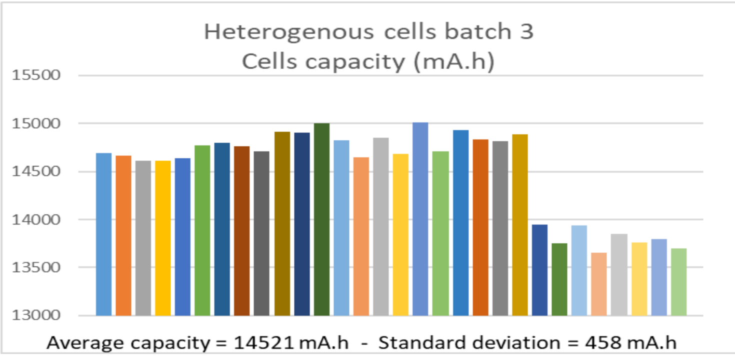

Figure 7: Heterogenous cells capacity batch 3

Figure 7 shows the capacity of cells used for this test. Eight cells in the batch have a lower capacity than the others.

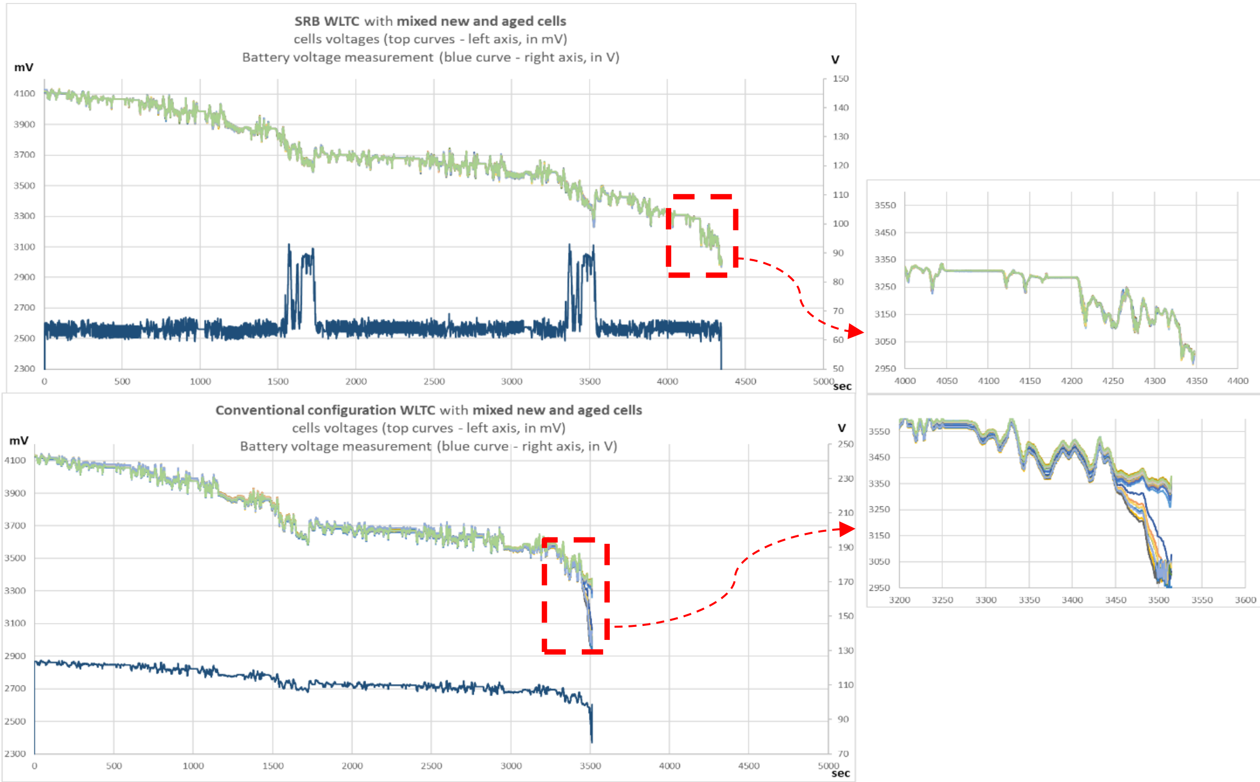

Figure 8: Driving profile with heterogenous cells

In the CBP configuration (shown in the bottom curves of Figure 8), we see that the voltage of the weakest cells drops before that of the others, causing the cycle to be halted before completion. In SRB configuration (shown in the top curves of Figure 8), cells are well balanced during the driving profile, while Vbatt is controlled to maximize the inverter yield. SRB allows weaker cells to be set aside while energy is extracted from all the other cells. Additionally, perfect balancing helps avoid voltage drop due to high discharge current peaks, allowing the driving profile to continue. Here the CBP stops 1000 seconds before SRB.

4.4 Conclusion on driving profile.

In both configurations tested, the conclusion is that SRB saves 6 % more energy compared to CBP, due to yield inverter optimisation. This value is consistent with the results of the simulation presented in chapter 2 and both tests demonstrate good reproducibility. Furthermore, the balancing capabilities of the SRB makes it possible to achieve a longer range with this driving profile.

5 Direct charging on the network

Thanks to the high control frequencies of the master controller, the SRB can produce an arbitrary voltage at its output. This is necessary to charge the battery pack directly from the electrical grid whithout charger, while perfectly balancing the battery cells. Removing the AC-DC inverters permits to increase the charge yield [7][8]. For this function, the master controller drives the output voltage in order to synchronize it to the grid, and runs a charge current control loop to regulate the current. A Simulink algorithm has been created to allow the SRB to be charged through a standard 16 A single phase grid, without dedicated charger. The master controller contains a charge controller block based on this algorithm. This block receives as input the mean charge current set-point, the feedback current value, and the grid voltage value. The output of this block is the number of cells to be connected in series, used to drive the output voltage in accordance of current regulation.

In order to test this function, and considering that this SRB has no H-bridge and can only provide a positive voltage, the elements of Figure 9 were connected between the SRB and the grid.

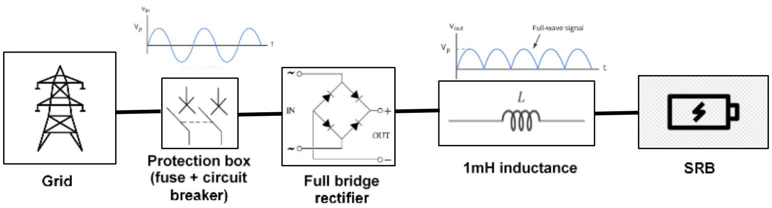

Figure 9: elements between SRB and the grid

At the beginning of the charge phase, the algorithm drives the SRB pack voltage until it matches the rectified grid voltage. When signals are well synchronized, a contactor is closed to start the charge. The Figure 10 shows the grid voltage (blue curve), the rectified grid voltage (green curve) and the charge current (pink curve). The test was carried out on a real electrical grid, so the sinusoidal curves are not perfect, nevertheless the algorithm is able to perfectly match this voltage and its imperfections.

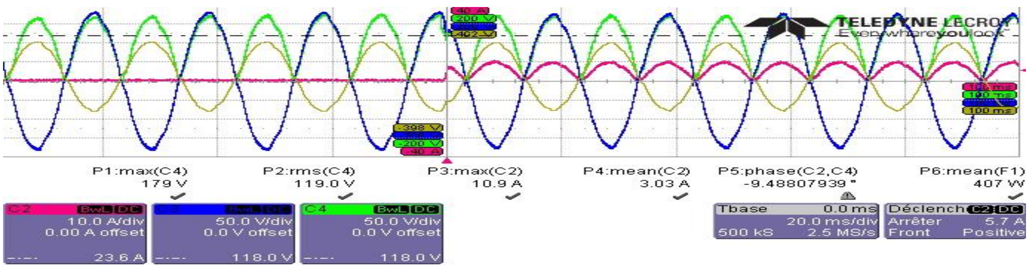

Figure 10: SRB charge on AC grid

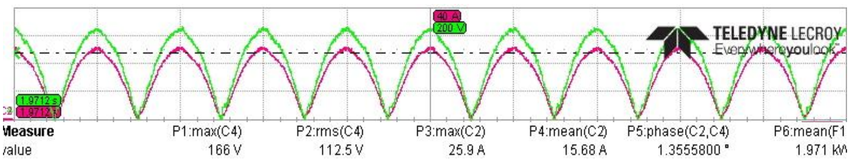

Figure 11: Rectified grid voltage (green) and charge current (pink) @16A mean

The Figure 11 shows a charge at 16A. The current shape is always a rectified sinus-like, regardless of the current value.

6 Fast charge comparison

The objective of this test is to compare the behaviour of the CBP and SRB during fast charging on a DC link, using the new cells batch 1.

The following procedure is applied for CBP:

- Constant charge current = 125 A for Vcellmax < 4.1 V
- Constant charge current = 24 A for 4.1 V < Vcellmax < 4.15 V
- Constant charge current = 12 A for 4.15 V < Vcellmax < 4.18 V

In this condition, the full charging duration is **768 seconds** and the charge energy reaches **3340 W.h.**

The following procedure is applied for SRB:

Cells are bypassed when Vcell>4.18 V and serialized when Vcell<(4.18 V-hysteresis).

Hysteresis [mV] = Current[A]/1000

- Constant charge current = 125 A until <10 cells are connected in series
- Constant charge current = 25 A until <10 cells are connected in series
- Constant charge current = 12 A until <10 cells are connected in series

In this condition, the full charging duration is **600 seconds** and the charge energy reaches **3418 W.h.**

Figure 12 shows a comparison between CPB and SRB in fast charge phase.

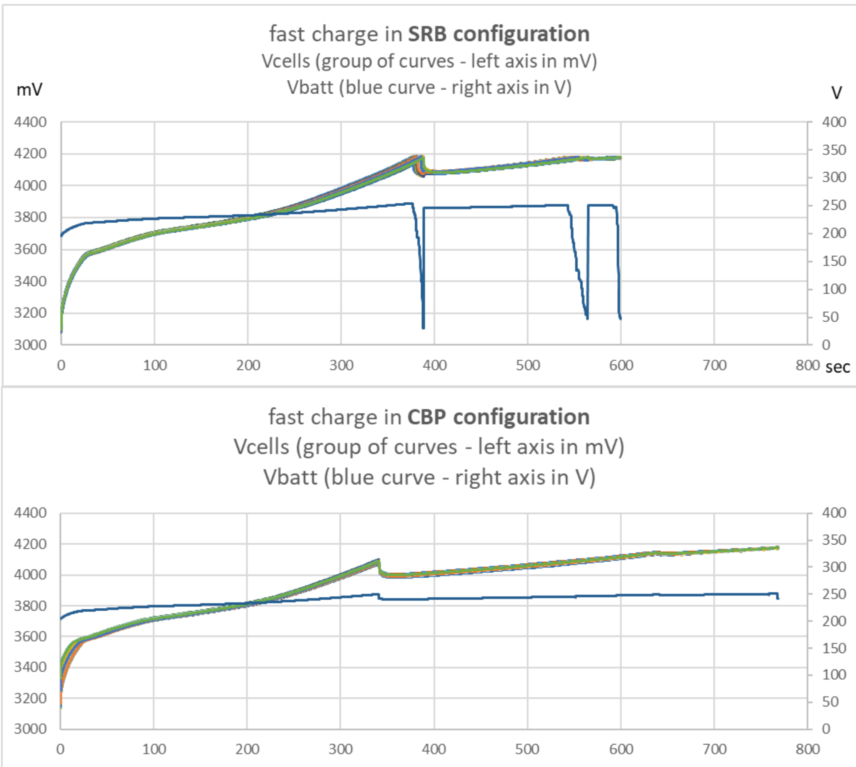

Figure 12: comparison of charge for CBP and SRB configuration

The SRB is able to bypass a Cell reaching VCellMax = 4,18 V, and to connect it again in series when its voltage falls below a parametric threshold, in order to avoid overvoltages on cells when connected in series at high current.

Charging time is **22 % faster with SRB**.

7 Conclusion

This paper reports on simulation and experimental results of advanced features enabled by a SRB, including controllable battery voltage, active balancing during operation, AC network charging without an inverter, and fast charging in DC. The performance of the SRB as a power source for DC/DC is compared with that of a CBP, revealing improved efficiency and faster charging rates. Specifically, the SRB increased the driving range by 6% and reduced charging time by 22%. Additionally, the experimental results demonstrate the SRB's ability to correctly operate heterogeneous cells and extend battery life by replicating the aging observed in real automotive battery packs.

To broaden this study, since SRB introduces many electronic components compared to CBP, to achieve a fair comparison between both solutions for automotive application, other items than performances are to be taken into account, such as cost, reliability and safety aspects. This project is a unique opportunity to work on these items and first analysis show that a SRB designed in robust and safe way by automotive standards could be a competitive solution by considering the powertrain as whole including its complete lifetime.

Overall, this study showcases the impressive capabilities of the SRB and its potential for use in a variety of applications.

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8 Presenter Biography

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Remy Thomas received a master's degree in electrical and electronics engineering from the French School Phelma of Grenoble Institute of Technology, France, in 2008. He joined the CEA-LITEN Laboratory in 2010 as research engineer to work on Battery Management Systems as well as Fuel Cell Management Systems, and more specially on real-time embedded systems for which he has developed a good expertise in both software and hardware. (remy.thomas@cea.fr)

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