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Active and Power Balancing Techniques: More Range and Longer Cell Lifetime in Electric Vehicles

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Summary

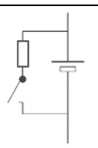
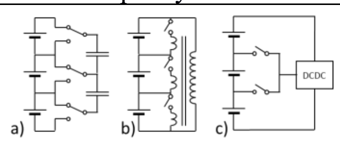
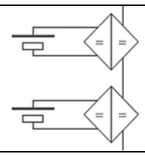
High-voltage (HV) batteries represent the most expensive and critical part in battery electric vehicles (BEV). For higher BEV market penetration, lifetime needs to be increased and costs reduced. For this, capacity utilization improvement – the use of full cell capacity regardless aging and parameter variation – is a potential approach. For future autonomous driving, redundancy and fail safe operation are needed not only for low voltage (LV) but also for HV batteries. This paper introduces innovative battery electronics beyond standard passive cell balancing with the goal to extend the battery's lifetime, increase capacity utilization, raise redundancy and reliability levels, and foster second life usage. In addition, modularity and scalability are reflected by the smart batteries to handle different power and capacity variants for different BEV segments.

Keywords: BMS (Battery Management System), battery ageing, fast charge, DC-DC, Second-life battery.

1 Introduction – Battery Cell Management

The BEV HV battery pack is built by grouping cells in parallel and in series to compose cell modules which are then connected in series to build the required voltage level on the DC link. The voltage of each cell and temperature of all cell modules are monitored by using module cell supervisor circuits (CSC). The data are sent to the battery management system (BMS). The BMS estimates the state of charge (SOC) and state of health (SOH) of the cells [1]. Accordingly, the BMS sends control signals to the cell balancers which equalize cell voltages (active or passive – see following chapters). The cells imbalance results from different cell conditions in terms of capacity, internal resistance, chemical degradation, and cell temperature [2].

Table 1: Different options for battery cell management

Balancing	Passive	Active	Power on module level	Power on cell level
Principle	Energy dissipation	Charge transfer and energy retention	Power distribution	
Components	Switched resistor	Switched energy buffer	Power electronics and switches	
Power path	Via cell		Via power electronics	
Target	Compensates self discharge SOC = 100%	Equilibrates capacity differences 100% capacity utilization	Equilibrates capacity differences 100% capacity utilization *@power*	
Example				

The standard balancing concept in batteries is passive balancing. A bypass switch with a resistor discharges high-SOC cells to the cell with lowest SOC. The "excess energy" of the strong cell is dissipated as heat till it reaches the voltage of the weakest cell. Afterwards, the battery can be fully charged with all cells reaching 100% SOC at the same time. Nevertheless, it is always the smallest or weakest cell which limits the available capacity of all cells. Thus, passive balancing can equalize different self-discharge rates of cells. Different, unmachted cell capacities cannot be utilized. The dissipated heat limits the balancing current typically to <300 mA (approx. 1 W per cell). Different strategies exist for how and when passive balancing is started.

2 Active Balancing Techniques

Active balancing empowers energy transfer from strong to weak cells. It does not dissipate but it saves this energy. Different concepts for active balancing are available [3]. It is more complex, costly and needs more components than passive balancing. Higher capacity utilization and the chance of battery system cost-reduction are strong arguments for active balancing.

The different active balancing concepts in Table 1 transfer the energy from cell-to-cell, cell-to-module, cell-to-pack, or cell-to-external by switching capacitors (a), inductors (b) or converters (c) as energy buffer. Each concept has a specific efficiency which is much higher than for passive balancing and thus, can be designed with much higher currents. The losses are less than the improvement in capacity utilization. By this, the range of the vehicle could be extended or the size of battery could be reduced assuring the same range of the vehicle. Thus, active balancing might be a good tool to optimize the battery for range homologation. For an overall view it is also crucial to understand the impact of the balancing strategy on the overall efficiency and on the cell aging mechanisms.

A new concept of cells-to-module balancing with converting the energy of varying numbers of cells to the related module is compared in Figure 1a to the classical cell-to-cell balancing concept in Figure 1b.

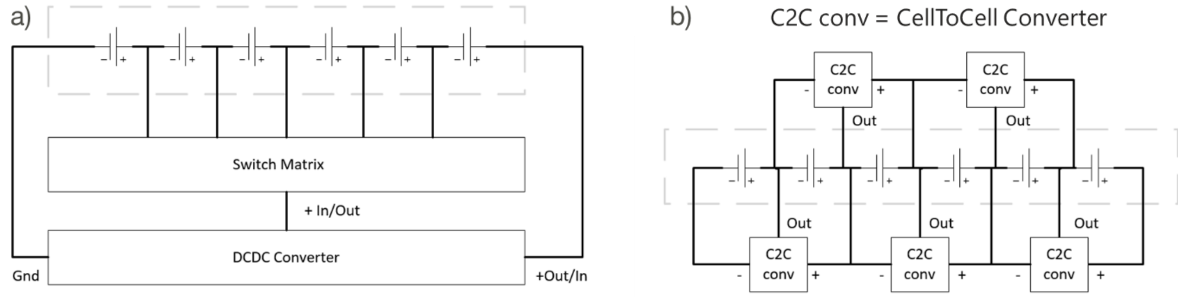


Figure 1: Schematics of two active balancing methods: (a) cells-to-module and (b) cell-to-cell (C2C)

2.1 Use case

A typical use case for the range test is to discharge the battery between defined state of charge levels with a specific profile (e.g. repeated WLTP cycles) and measure the discharged energy. For this scenario a simulation model was set up with a complete battery pack model and the equivalent model of the balancing circuits (optimized cells-to-module and cell-to-cell topology).

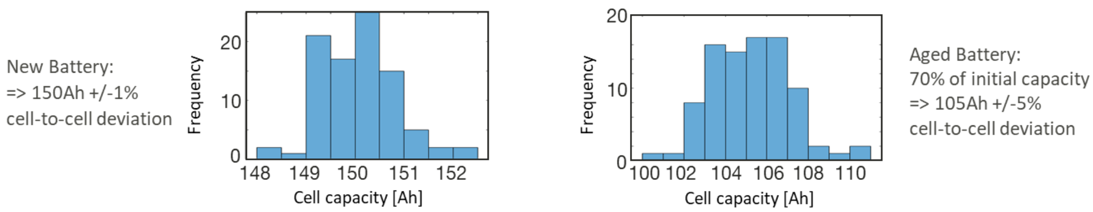


Figure 2: Cells (normal) distribution of the battery pack

The WLTP Class 3 load profile, shown later in Figure 7, was applied to a medium size vehicle resulting in a current range of -70 A charging to 125 A discharging. Repeated load cycles were applied from 90% battery SOC till the first cell reaches 5% SOC. The battery model covers the configuration of a typical battery for an electric vehicle. A 90s1p configuration of a 150 Ah cell was chosen, resulting in a close to 50 kWh capacity. The aged cells were considered with 70% of initial capacity. The cells' capacity deviation was considered with +/-1% at Begin of Life (BOL) and +/-5% at End of Life (EOL). Randomized use cases based on a normal distribution were taken for the simulation as shown in Figure 2.

2.2 Simulation results

Without balancing, the different cell SOCs continue to deviate with WLTP cycling due to the different cell capacities as can be seen in Figure 3. With cell balancing, it is possible to keep the cell SOCs close to each other. This is more effective for the cell-to-cell balancing than for the cells-to-module balancing. As Figure 3 shows, the discharge time and the energy increase from left to right with balancing getting more and more effective.

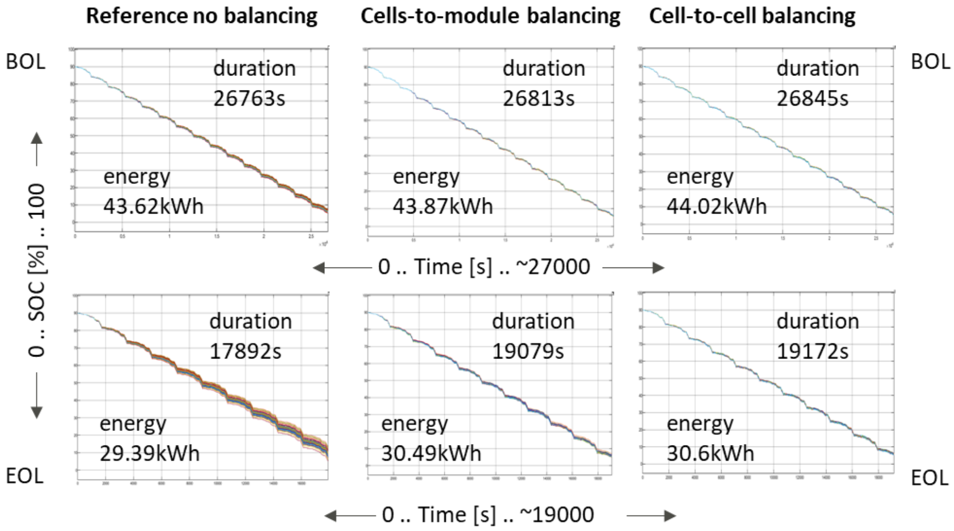


Figure 3: WLTP cycles class 3 – discharge 90% to 5% SOC for different balancing methods

For this use case and setup, the usable energy increase is between 0.6% and more than 4% (see Table 2). Especially at EOL, the usable energy of the battery and therefore the driving range of the vehicle can be improved. The higher the cell to cell deviation, the higher is the usable energy increase.

Table 2: Improved relative energy utilization by active balancing

	BOL	EOL
CellsToModule	0.57%	3.57%
CellToCell	0.91%	4.12%

Active balancing results in higher BOM cost than passive balancing. But also the different active balancing concepts show differences in costs. The additional costs must be compensated with the benefits achieved by better capacity utilization. The proposed cells-to-module approach shows the opportunity for further cost-reduction with less necessary switches. More detailed evaluation is in progress.

3 Power Balancing

By switching on and off modules or cells (reconfiguration of the battery system) during traction or charging, the load current can be controlled in the battery pack and managed for cells or modules. The smart BMS in this case can online balance the modules/cells either based on their SOCs or temperatures. With this approach the focus shifts from add-on cell balancing to actively using the load current to manage power and energy for cells and modules. This in turn leads to the following benefits:

a. Cheaper cells, by selecting cells with higher tolerances,
b. Lifetime extension and better capacity utilization: loads on weak modules/cells can be derated,
c. Higher driving performance and shorter charging time by distributing the load to the strong cells,

d. Higher system reliability and reduandancy, where defective modules/cells can be bypassed or a defect be prevented by active management,
e. Savings on HV powertrain components due to controlled DC-link voltage
f. Plug and play of the modules in second life application without new clustering or testing efforts.

Similar concepts have been applied to compensate the mismatches among photovoltaic panels [4].

3.1 Power balancing on module level

3.1.1 System description

As shown in Figure 4, the battery pack is divided into modules were each modules is integrated with a DCDC converter that can achieve the following modes of operation:

- Buck (charge module from DC link),
- Boost (discharge module to DC link),
- Buck and Boost mode enable control to a higher module output voltage
- bypass, path-through, and open circuit.

The new battery design combines the functions of charger with simplified power factor correction (PFC), power balancer, and DC-link voltage regulator into a compact module. Each module is monitored, controlled, and protected by the corresponding power converter to follow its own optimal charge/discharge profile. The smart BMS gathers the information from the cells and converters, gets the requested DC-link voltage from the vehicle control unit, and sends out commands to adjust the mode of operation and voltage of each module. This concept is called smart, switchable, and scalable battery (3S Battery). With this concept, the DC-link voltage is totally SOC-independent. This feature can be used to increase the performance and the efficiency [5] as will be shown below in the simulation subsection.

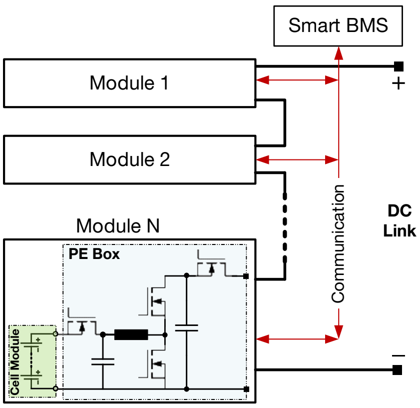


Figure 4: Smart battery with power balancing on module level (PE: power electronics)

3.1.2 Simulation results

For system simulation, the following setup was used to represent a 400 V/84 kWh battery:12 modules in series, cell configuration: 8 in series and 2 in parallel (8s2p), and 120 Ah prismatic cells. For each module, an average cell is simulated and scaled to represent 8s2p configuration. Each use case was simulated for a new and an aged cell-pack and for a topology with integrated DC-DCs as well as a conventional cell pack with serial connection. To represent the aging behaviour, cell resistances were increased and capacities decreased to the values of a generic end of life cell specified by the cell model provider. In addition, capacity variatons between the modules were considered both for the new and the aged cell pack. Those were estimated based on values for cell-to-cell deviations and later scaled to module level. Initial cell-to-cell-deviations were again specified by the cell model provider, while the increase of this deviations was estimated based on literature values [6,7], leading to the assumptions in Table 3, where variations are given as standard deviations of a normal distribution. Variations of resistances were neglected, as no consistent deriviation for the interdependency of resistance and capacity variations could be found, especially in the module case.

Table 3: Aging assumptions and capacity variations

Aging		Capacity standard deviations	
Anode capacity reduction	4.95 %	Cell-to-cell, new	0.70 %
Cathode capacity reduction	9.90 %	Cell-to-cell, aged	7.00 %
Lithium content reduction	11.88 %	Module-to-module 8s2p, new	0.30 %
Anode resistance increase	100.00 %	Module-to-module 8s2p, aged	3.00 %
Cathode resistance increase	80.00 %		

To get a representative sample from the estimated standard deviation, the values for each module were chosen based on the cumulative distribution. The simplified assumption is made, that capacity reduction and resistance increase are correlated, so that the module with the lowest capacity will also show the highest internal resistance.

Two scenarios were analyzed. The first was fast charging with the key performance indicator (KPI) “charged energy per time”. From a starting SOC of 20%, the cellpack was charged with a maximum of 250 kW for 15 minutes. To utilize the full potential of the architecture, charging current was limited by cell temperature and anode potential rather than a fixed fast charging curve. For the conventional system, the current was limited by the weakest module, while in the 3S Battery case, each module could be charged at its individual limit. The results are shown in Table 4.

Table 4: Fast charging – charged energy in 15 min

	Energy /kWh	Benefit 3S /%	Aging induced losses /%
3S new	50.20	2.00	0.33
3S aged	50.03	4.48	
Conventional new	49.21	-	2.69
Conventional aged	47.89	-	

For the fast charging case, the 3S battery was charged with 2% extra energy for the new and ~4.5% extra energy for the aged cellpack in comparison with the conventional battery. This results in a significant reduction of aging induced losses in fast charging capability from ~2.7% for the conventional system to ~ 0.3% in the 3S case. The reason for this is the passobility to individually control the charging current of each module as depicted in Figure 5 for the aged case.

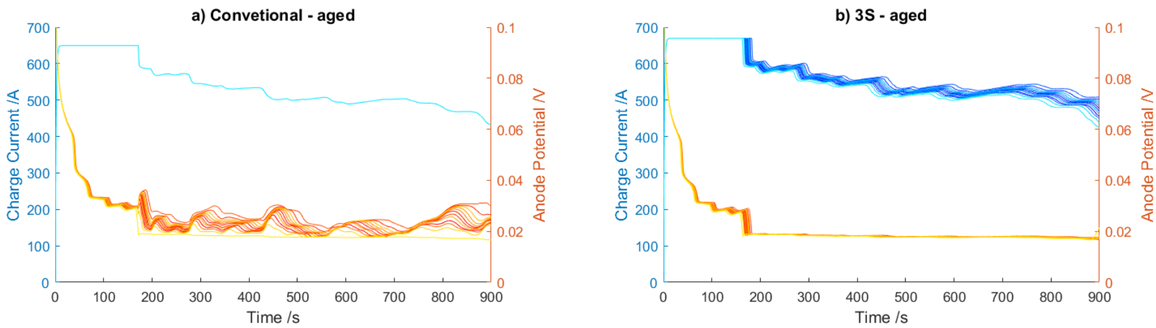


Figure 5: Charging current and anode potential for every module for conventional (a) and 3S system (b)

In both cases, the cell pack is not limiting the current in the first 2-3 minutes. During this time, anode potential constantly decreases. When the anode potential reaches its limitation the current is derated. In the conventional system this happens globally, leaving each module with the same current, but different anode potential. In the 3S system, each module can be charged in its individual limit, leading to different currents but the same anode potential per module.

The second scenario focuses on the KPI “driving range”. WLTP cycles were simulated from a starting SOC of 60% until the weakest module reached 40% SOC. In the 3S case, the load is distributed on the modules according to their current SOCs. In addition, the DC-link voltage was set to yield the highest combined inverter and machine efficiency for the requested torque and speed. In partial load operation, the electric machine can operate at lower DC-link voltage. This in turn results in lower inverter switching losses and lower machine harmonic losses. To achieve this functionality, the DCDC converters operate in boost/buck, path-through, and bypass modes of operation. Table 5 shows the driven distances.

Table 5: KPI cycle driving – driven distance from 60 – 40 % SOC

	Distance /km	Benefit 3S /%	Aging induced losses /%
3S new	149.30	-1.51	11.41
3S aged	132.27	3.67	
Conventional new	151.60	-	15.83
Conventional aged	127.59	-	

The effect of the 3S System is based on two factors: one is improved efficiency due to variable DC-Link voltage, the other is improved battery utilization due to SOC balancing on module level. These effects are counteracted by DCDC losses and increased battery losses, due to higher battery current on the remaining modules, when modules are bypassed. At the same time, to utilize the full potential of variable DC-link voltage, an optimized balancer would be required, which was not considered here. To highlight the meachanisms, the SOC of each module and the delta SOC between the modules, as well as the output voltage of each module and the resulting DC-link voltage in case of aged case is shown in Figure 6.

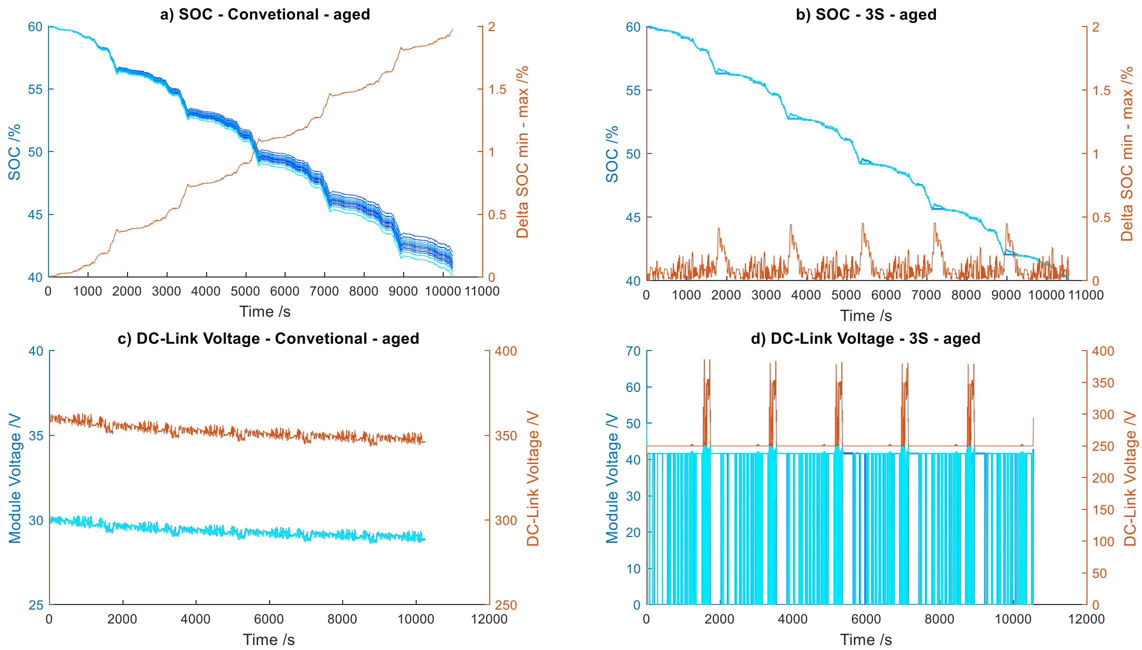


Figure 6: SOC of each module and resulting SOC differences for conventional (a), 3S system (b). Output voltage of every module and resulting DC-link voltage for conventional (c) and 3S system (d)

The conventional system shows a constant debalacing of the SOC between modules and a slow decrease of DC-link voltage with decreasing SOC, overlayed with the polarization of the double layer capacity. The 3S system actively controlles the DC-link voltage, keeping it at the lower limit of 250 V during partial load and only increases it during the high load periods of WLTP. To achieve this, some modules are bypassed most of the time, which causes a certain disbalancing. By alternating the bypassed modules and balancing the active modules however, this disbalancing is kept within the predefined limits, allowing an overall improved battery utilization compared to the conventional system.

3.1.3 Prototype results

To test the BMS functionality and modes of operation of the DCDC converters, a prototype with the following components was build:

- Three automotive modules in series (85 Ah capacity)
- Cell configuration: 8 in series and 3 in parallel (8s3p)
- Converter power:10 kW each

A smart algorithm distributes the load on the three modules based on their SOCs. Figure 7 shows the results, especially how the three modules are balanced during WLTPs driving. The difference in SOC dropped from 4.4% to < 0.3%. The three modules were also tested with a 22 kW charging scenario with a SOC starting difference of ~ 7%. Figure 8 shows the balancing process during charging. At the end of the charging cycle the modules ended with the same SOC levels, while the three modules were charged with different energies of 718, 732, and 770 Wh.

In addition to traction and charging tests, the bypass and path-through modes of operation were also investigated. For this test case, the first module was bypassed while the two other modules were in boost mode. Figure 9 highlights the results, where the output voltage of the first module is 0 V and the corresponding SOC did not change during the test. These test cases validate the main concept of the presented topology such as every module can adjust its own voltage and can be driven in bypass in case of a defect.

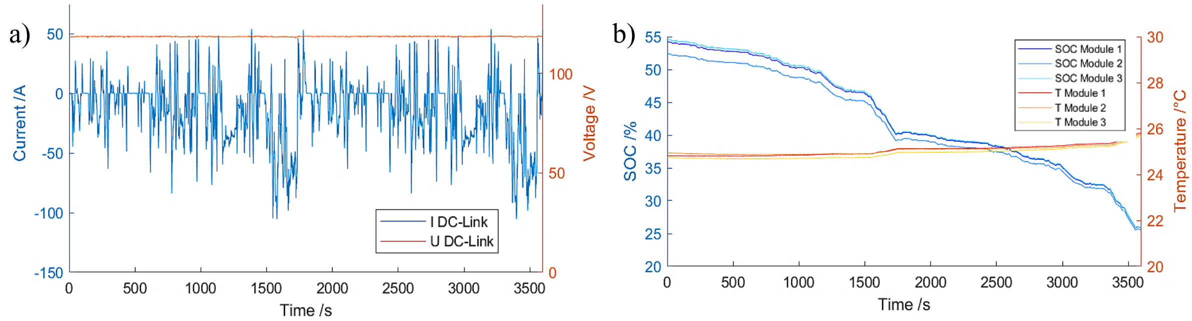


Figure 7: Results from two WLTP cycles: DC-link voltage and current (a), modules' SOCs and temperatures (b)

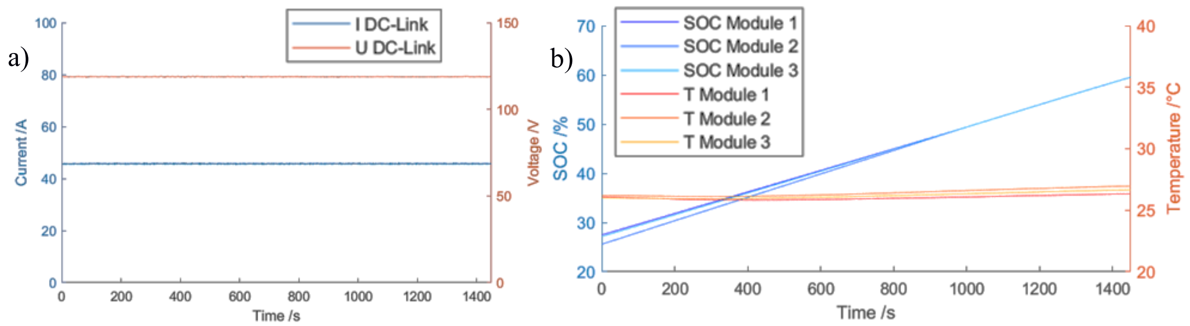


Figure 8: Results with 22 kW charging power: DC-link voltage and current (a), modules' SOCs and temperatures (b)

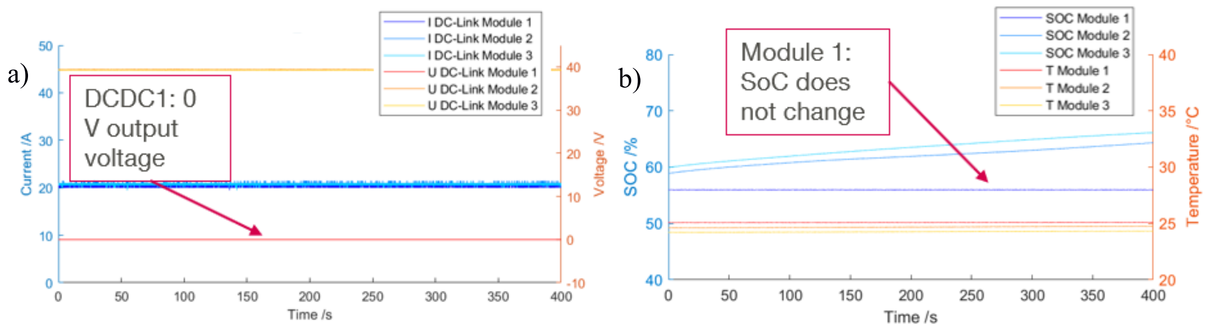


Figure 9: Results with first module in bypass: DC-link voltages and currents (a), modules' SOCs and temperatures (b)

3.2 Power calancing on cell level

3.2.1 System description

Power balancing at cell level is done by using low voltage switches close to the cells [8,9]: one for bypass and one for serial connection (see Figure 10b). In this way, each cell can be connected individually and dynamically. This self reconfigurable battery has consequently far more degrees of freedom and can achieve a very efficient power cell balancing and enables new features for power conversion (AC or DC output with dynamic control).

This dynamic switching optimizes the cell usage according to working mode beyond the options of power balancing on module level, because the function is applied to the cell level. This power balancing at cell level is more efficient because it is done dynamically, in operation and not only while the battery is not used. With a properly chosen topology, the approach provides different features: AC and DC bi-directional charging, low-voltage power supply, high-voltage power supply, and electrical machine AC supply. Beyond isolating a defective module, the ability to isolate an individual defective cell provides an increased availability with no impact on performances or second life usage.

Modules with this switching technology have been designed by integrating the power and control electronic boards. 10 modules, comprised of 6 prismatic cells each, were realized (Figure 10). Tests of the following different features started with these modules: control variable DC-link voltage, balance cells in real-time, provide AC voltage, fast DC charge, charge on AC grid, and limit ageing effects.

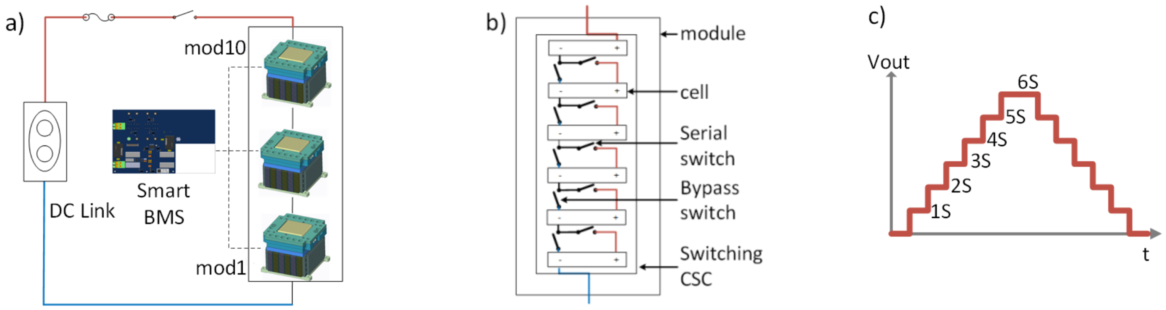


Figure 10: Topology (a) of smart battery with power balancing on cell level: 1 Smart BMS and n modules with cells and switching CSC (b) and an exemplar switching voltage profile (c)

3.2.2 Simulation results

Simulations have been conducted with WLTP load profile in order to estimate the benefits of this technology with the main goal to achieve a variable DC-link voltage and balance the cells during operation.

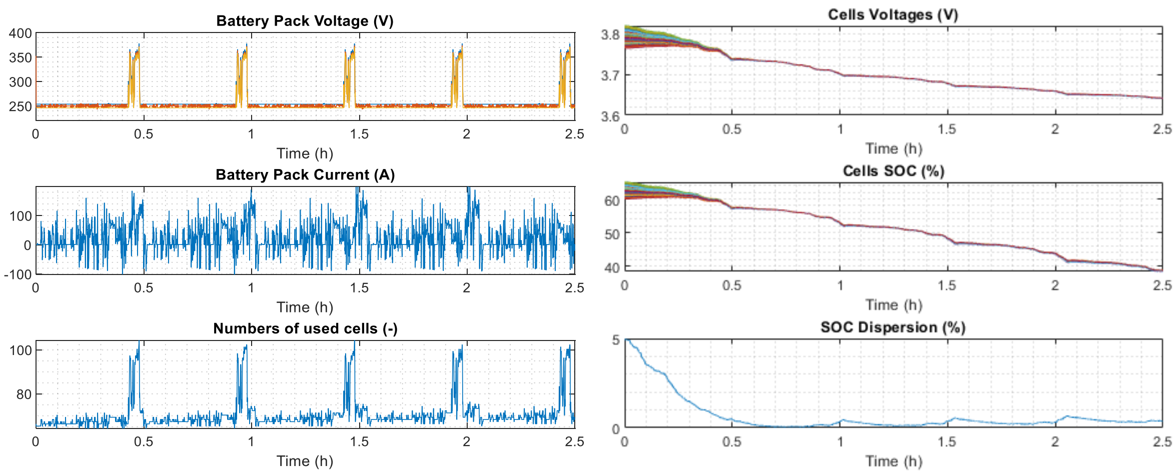


Figure 11: Simulation results with variable DC-link voltage and balanced cells

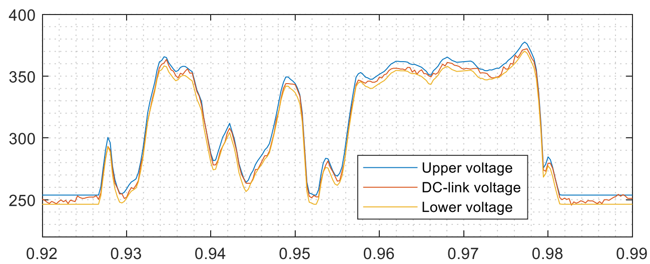


Figure 12: Zoom into Figure 11. Simulation of the battery pack voltage

The simulation of this ‘variable DC-link voltage’ feature is shown in Figure 11. The configuration is 140s3p with cells having an initial capacity of 55Ah. Four WLTP cycles are conducted with a chosen voltage setpoint that maximize the efficiency of the traction inverter and the electrical machine. The starting condition is a SOC of 60% ± 5% applied to aged cells with 75% ± 10% of initial cell parameters (capacity and internal resistance).

The battery pack voltage is controlled around a voltage set point ±1 times the cell voltage as shown in Figure 12. By adding or removing cells in serial when necessary and in accordance with their voltage / SOC, the battery is capable to follow the voltage set point and to provide the requested current. The tracking error during voltage ramp up / ramp down is limited. This dynamic response is achieved by the very fast MOSFETs in the module whatever the voltage setpoint variations are.

The dispersion among the cell parameters is voluntary exaggerated. Even with this large initial SOC dispersion, a good performance is achieved regarding cell balancing and DC-link voltage control. Moreover, the SOC dispersion of the cells which is initially around 5%, decreases very quickly below 0.5% after one WLTP as shown on the right side of Figure 11.

3.2.3 Experimental results

Preliminary tests have been realized on a low capacity demonstrator composed of 2 modules of 6 cells each with 14 Ah. The measurements of a charge test are visible in Figure 13a. The cells have initialy a very wide spread of voltages, between 2.819 V and 3.084 V. The cells are charged with a constant current of 5 A. During the complete charge, the voltage of the two modules is stabilized around 30 V [26 V; 33 V]. To achieve this, the number of cells engaged in serial varies between 11 to 8. The fast switching of this ‘number of used cells’ is the demonstration of the actual power balancing. In the end, all the cells are balanced around 3.930 V.

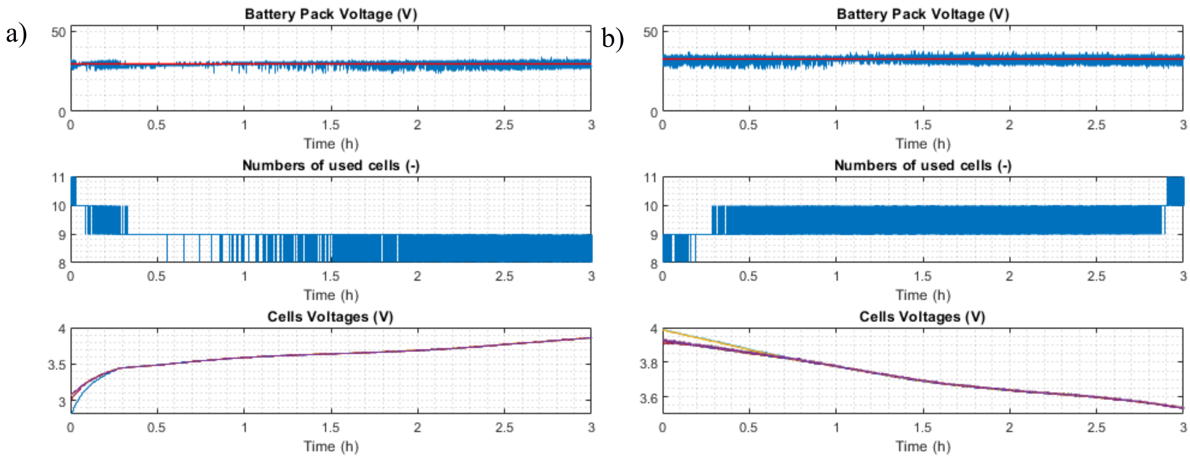


Figure 13: Expermiental results for a charge with a constant DC-link voltage: charging (a), discharging (b)

In the same way, the measurements of a discharge test are shown in Figure 13b. The cell initial voltages are between 3.910 V and 3.992 V. The cells are discharged with a constant current of 5 A. During the complete discharge, the DC-link voltage is stabilized around 30 V. The number of cells engaged in serial to achieve this voltage variates from 8 to 12. In the end, all the cells are balanced around 2.960 V

4 Conclusion and Discussion

This paper introduces different active and power balancing techniques that aim to increase the battery lifetime and better utilize its capacity. Simulation and experiments results regarding efficiency, balancing feasibility, and performance that show the effectiveness of these strategies were introduced.

Active balancing can utilize up to ~4% more energy at EOL. Excess energy is distributed between the cells. Larger batteries and less quality of the cells make active balancing more feasible. The extra cost can be paid off by the battery capacity and energy utilization.

Power balancing at module level: A prototype for the 3S Battery has been built and results regarding efficiency, balancing, and performance simulations were shown. With the fast charging case, the 3S battery was charged with 2% extra energy for the new and ~ +4.5% extra energy for the aged cellpack in comparison with the conventional battery. In addition, ~3,7% extra range was achieved for the aged cell pack with WLTP due to the variable DC-link strategy. Moreover, test cases with the prototype validate the concept of the presented topology such as every module can adjust its own voltage and can be driven in bypass in case of defectiveness.

Power balancing at cell level: The power balancing on cell level is known for years in the literature. An automotive application has been studied and simulated for different features. The first tests on a demonstrator prove the feature of controlling the DC-link voltage on top of cells balancing and show the benefits of such a technology.

Active and power balancing techniques show the following opportunities:

First, energy or charge of cells with higher capacity deviation become accessibly by the proposed balancing methods. Therefore, it would be consequent to accept larger cell deviations. Less quality constraints might make cells cheaper. Unfortunately, it is difficult to find data on this approach. A certain quality standard is achieved today. Relaxing this requirement is not very popular in automotive industry. To get an idea about the value of relaxed requirements we consider some ballpark numbers: The cells cost around $100/kWh in 2025 and have a capacity deviation of 1%. Nevertheless, the production might show 20% of "bad" cells with a capacity deviation of up to 10%. So, the cell manufacture would have different options: (i) consider these "bad" cells as scrap which would mean that 20% of the cell price is caused by scrap. This is a less realistic scenario, because cell price would have to be 20% higher. (ii) Cell manufacture introduces different grades of cell, e.g. premium grade with deviation of <1% for automotive and <10% for other applications sold with a 10% discount or $90/kWh. This is the situation which we expect to have today. (iii) If no requirements are defined for a tight capacity deviation and selection of the cells is not necessary, the price would be a mixed calculation with 80% of cells at $100/kWh and 20% of cells at $90/kWh, resulting in $98/kWh as an average price. This is a ~2% reduction of the cell price just because of relaxed cell requirements with larger capacity deviation which becomes possible by advanced balancing technologies.

Second, power balancing topologies allow a controlled DC-link voltage. On one hand, this feature is used to design the other HV powertrain components at higher voltage than the battery nominal voltage. With this, the HV inverter and electric machine could be designed for lower currents. Additionally, the on-board charger can be simplified by removing the DCDC conversion unit due to the flexibility of the DC-link voltage. For DC fast charging, the battery can be easily adjusted to the charging station voltage (400-800V) without an extra DCDC converter. All these features result in cost savings in the HV powertrain components. On the other hand, the variable DC-link strategy is used during traction to improve the efficiency of the drivetrain as shown above and mentioned in [5].

Third, nowadays most of the HV batteries are composed of one kind of lithium-ion battery cell. Due to the fixed ratio of the cells' maximum power to nominal energy, the possibilities for designing power and energy of the battery pack independently are limited. One way to overcome this limitation is to form a hybrid battery system comprised of more than one pack and different cell technologies. Such system can only be enabled by using DCDC converter like the 3S Battery system. This allows for individually designing each battery pack and thus optimizing the overall battery system specification. The optimized hybrid battery system can lead to weight and volume savings and further advantages in total cost of ownership, for example, by enhanced battery lifetime or reduced investment costs [10].

Finally, power balancing enables 2nd life applications of batteries. They range from stationary energy storage, to internal energy buffers for EV charging stations, and even mobility applications with less demanding low speed vehicles. Critical aspects for all these applications are the refurbishing cost of the battery and a suitable use case for the specific cell [11]. The balancing techniques shown here help to decrease these costs by allowing a more flexible pairing of used modules. In addition, the variable output voltage of the power balancing techniques enable a broader range of possible use cases.

Active and power balancing techniques add the following challenges:

First, if the cell-to-cell variation will be more and more improved in the future, then the impact of the balancing techniques will be reduced. Second, adding power electronic devices inside the battery allows more functionalities, but also increases the losses especially with fast DC charging. For instance, DC fast charging with 500 A could generate high on-state losses that can be equal to the cells' losses. Investigations are still ongoing to find a way to bypass these losses. Finally, new battery topologies with cell-to-pack or cell-to-chassis as recently announced [12] will have different requirements to the BMS and the balancing.

An important factor is the cost of the installed electronics in comparison with the expected cell savings due to the better capacity utilization. For a rough target cost estimation with ball-park numbers for year 2025, we consider 100$/kWh for the cells in the battery. The battery shall have an energy density of 180Wh/kg. Car manufacture count weight reductions for the car worth between $1 and $14 per kilogram [10] or even up to €20 [14]. We consider an average value of $4/kg.

For active balancing, we consider a 50kWh battery for the mid-size car (Figure 14a). With a maximum of 4% improved energy utilization, we can downscale the battery by 2kWh, which would correlate with a maximum benefit of $200 (Figure 14b). Additionally, the battery would be lighter (11kg @ 180Wh/kg specific energy) and smaller. This gives an additional benefit for the car manufacture of ~$50 on vehicle system level. The cell price is reduced by $2/kWh due to the relaxed deviation requirement (Figure 14c). If this is applied to the reduced battery pack of only 48kWh another ~$100 savings is estimated. Round about $350 can be expected as price savings for the vehicle manufacture. This value scales directly with the capacity of the battery or the quality of the cells. Larger batteries and less quality of the cells make active balancing more feasible. Cost of the additional electronics must be lower than this value times the individual cost-to-price factor.

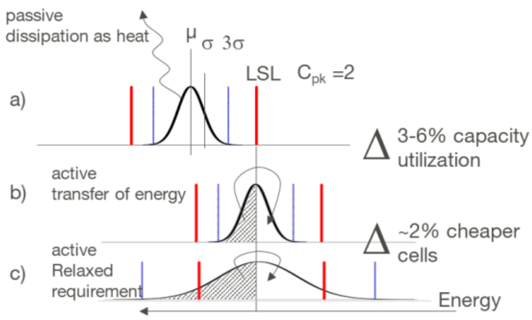


Figure 14: Visualization of the different aspects of the cell capacity deviation and the impact of the different balancing aspects on capacity utilization and cell costs. μ = mean value, σ = standard deviation. C_{pk} = 2 defines enough distance of the 3σ value from the low side limit (LSL) that failure rate is less than 1 ppm.

For the power balancing techniques additional benefits on system level are available. Therefore, cost analysis is done on powertrain level in comparison with a conventional system that has a conventional battery with a passive balancing circuit. The 800 V powertrain includes a 100 kWh battery, 250 kW traction performance, 11 kW AC on-board charger after considering the cost of the power electronics and the savings on the HV components, it was found that the power balancing techniques results in ~2-4% extra cost on powertrain level. By assuming 5% cell saving, the cost of the powertrain with power balancing is comparable with the reference system.

As a final conclusion, for batteries below 50kWh and for cells with less than 1% initial deviation in capacity, active or power balancing might not generate an added value. For long range vehicles with larger batteries it is beneficial.

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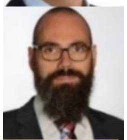
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