ACTIVE AND POWER BALANCING TECHNIQUES:

MORE RANGE AND LONGER CELL LIFETIME IN ELECTRIC VEHICLES

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Public

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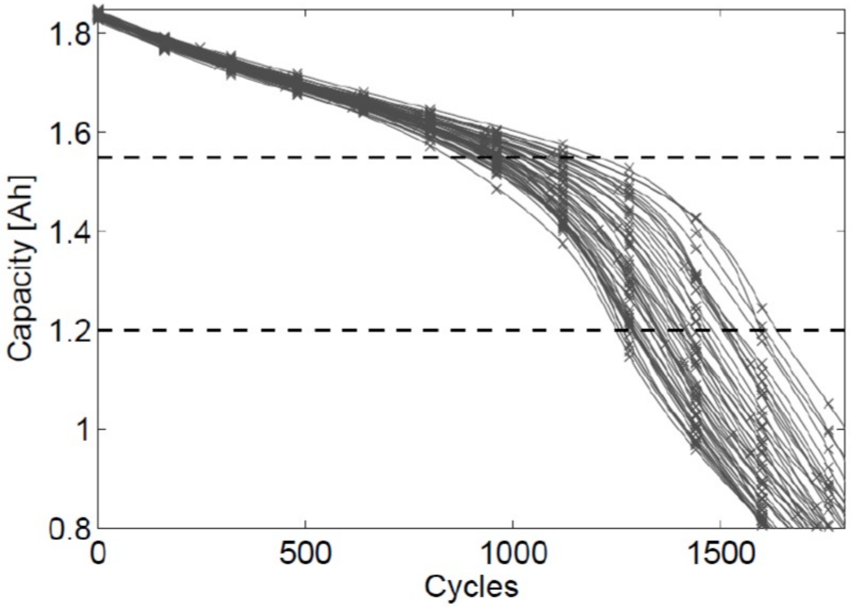
HIGH VOLTAGE BATTERIES IN BATTERY ELECTRIC VEHICLES

CHALLENGES AND OPPORTUNITIES

> **Challenges for high voltage (HV) batteries:**

- Lifetime (till EOL)
- Range (capacity utilization)
- Charging time
- Safety
- Second Life usage or recycling?

Battery pack is limited by the weakest cell(s)



[1] Capacity degradation as a function of eq. full cycles

> **Opportunities with power electronics:**

> Decouple cells/modules – better capacity utilization.

> Improve drivetrain efficiency.

> Increase redundancy for autonomous driving.

> Use modules for second life application – plug & play.

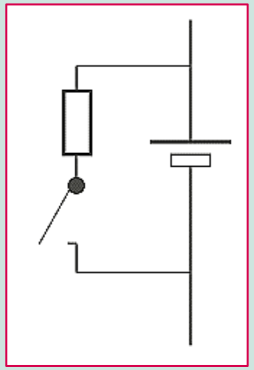
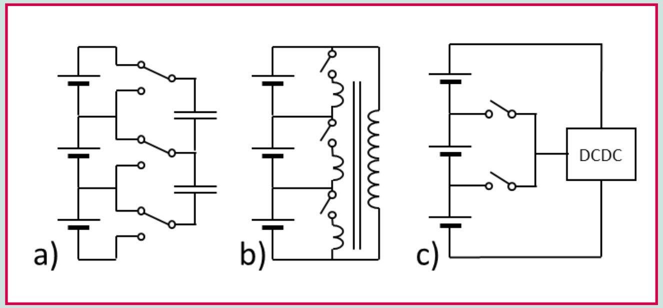
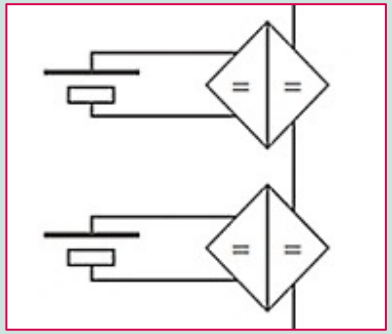
Cell balancing is the key word

BEV: Battery Electric Vehicle; EOL: End of Life

[1] Ecker M, et al. Applied Energy, 2017(206): 934-946. Lehner S, Dissertation, 2017, ISEA, RWTH Aachen

BALANCING CONCEPTS

OVERVIEW

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				

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AGENDA

ACTIVE BALANCING

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ACTIVE BALANCING

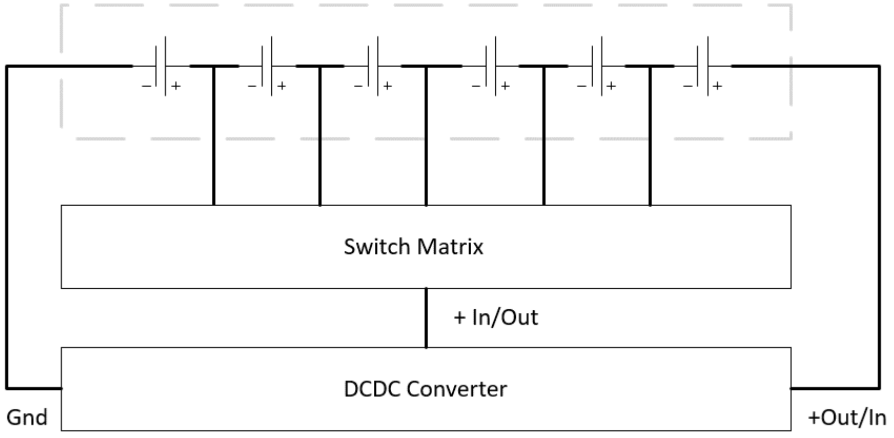
CONCEPTS

> **Cell imbalance:**
>
> > Different cell conditions: capacity, internal resistance, chemical degradation & cell temperature

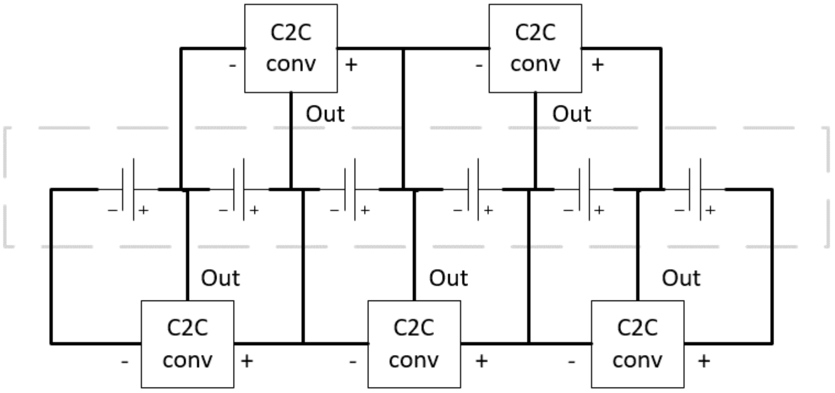
> **Concepts:**
>
> > Cell-to-cell (C2C)
>
> > Cell-to-module
>
> > Cell-to-pack
>
> > Cell-to-external

> **Important factors:**
>
> > Efficiency
>
> > Cost

Cell-to-module



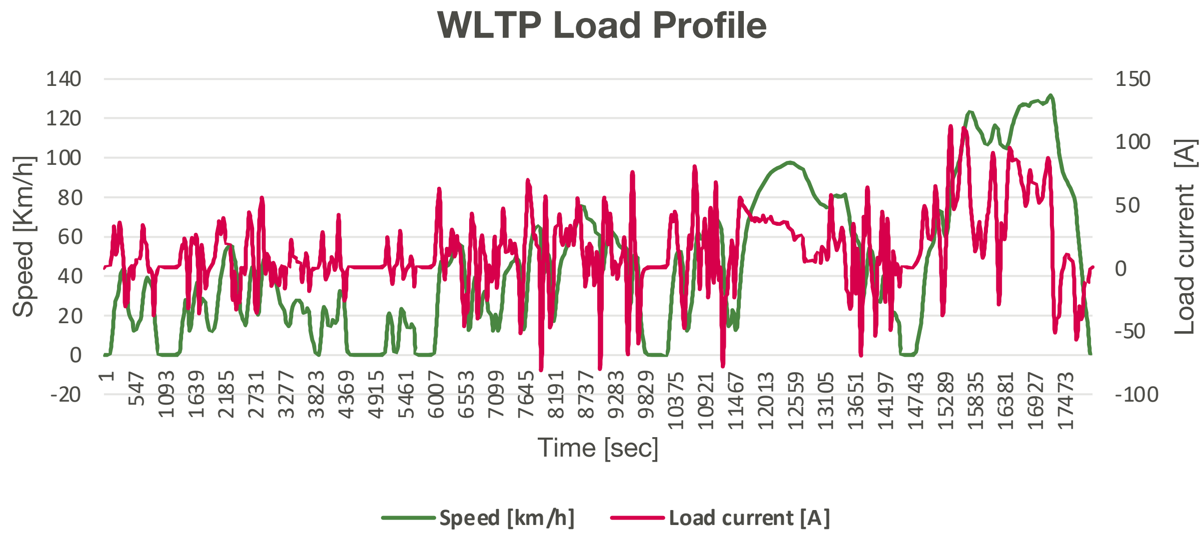
Cell-to-cell



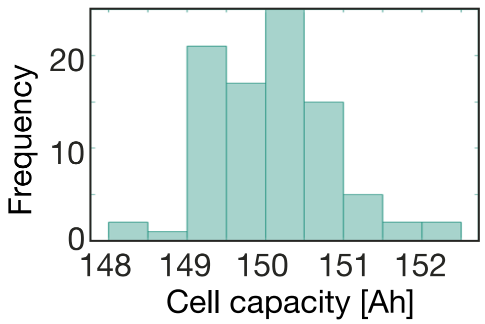
ACTIVE BALANCING

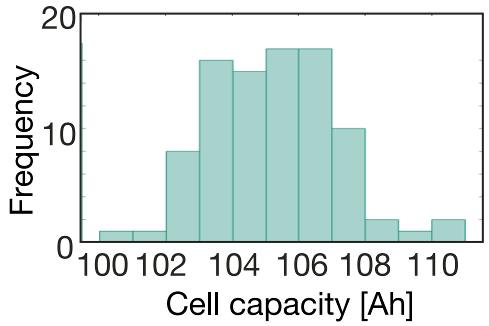
USE CASE WITH WLTP

- **Repeated WLTP:**
  - 90% to 5% SOC
  - Battery: 50 kWh (90s1p with150 Ah)
  - New and aged battery



New Battery:
150 Ah +/-1%
cell-to-cell
deviation





Aged battery:
70% of initial capacity →
105 Ah +/-5%
cell-to-cell deviation

WLTP: Worldwide Harmonised Light Vehicle Test Procedure; SOC: State of Charge

ACTIVE BALANCING

RESULTS WITH WLTP

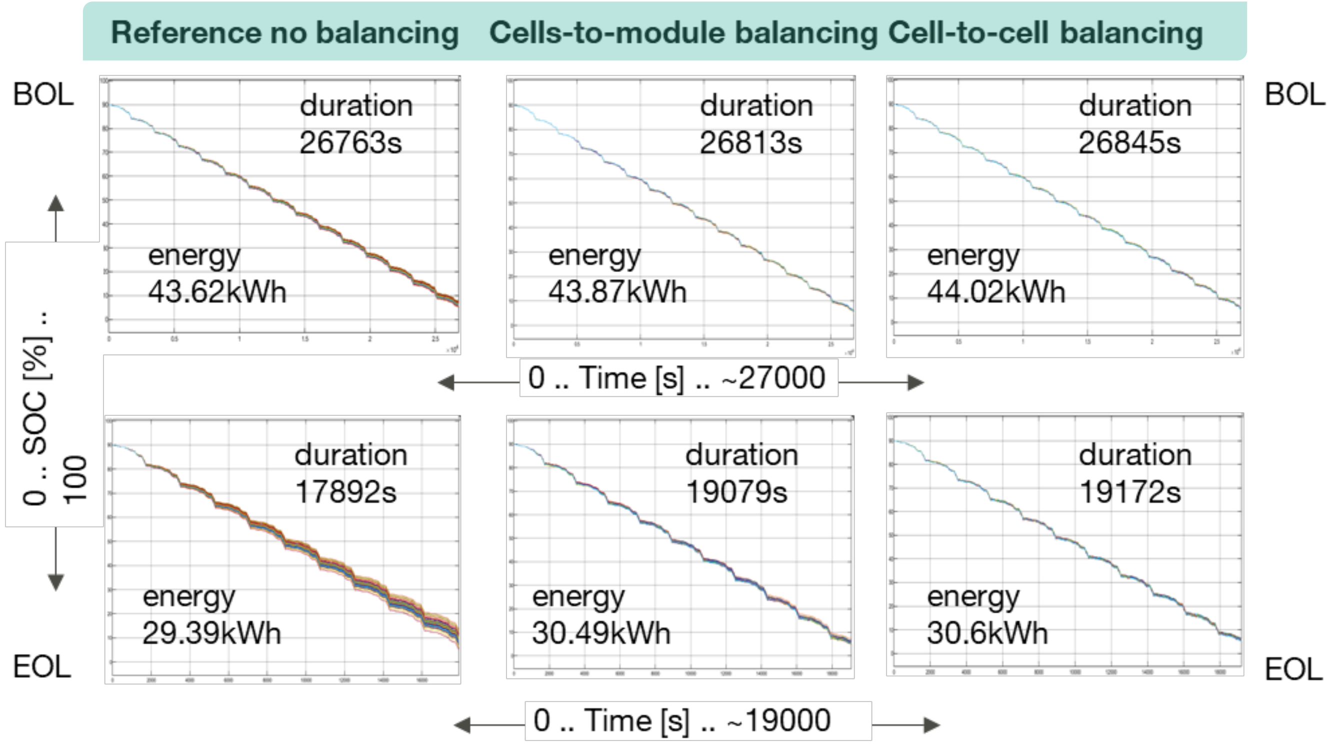
> **Results:**
> > Cell-to-cell is the best for capacity utilization.
> > Usable energy increase: 0.6% to 4% (@EOL).

> **But:**
> > Active balancing results in higher BOM cost.

> **Therefore:**
> > Additional costs must be compensated by better capacity utilization.

> **Proposed** cells-to-module approach is attractive solution with less switch number and good efficiency.

BOL: Beginning of Life, EOL: End of Life



Improved relative energy utilization	BOL	EOL
Cells-to-module	0.57%	3.57%
Cell-to-cell	0.91%	4.12%

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POWER BALANCING ON MODULE LEVEL

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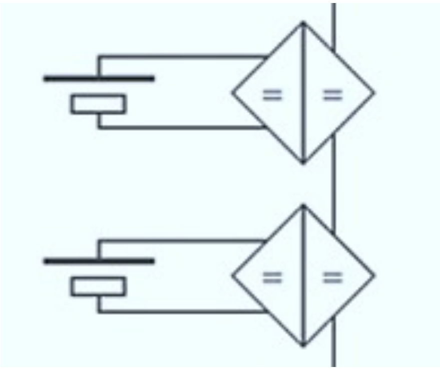
POWER BALANCING

FEATURES

> **Concept:**

- By switching on and off modules/cells
- BMS: balances modules/cells SOCs/temperatures
- Use load current to manage power and energy for cells & modules



> **Features:**

Lifetime extension & battery utilization	> Weak cells can be protected to age slower → extended lifetime. > Grouping the cells leads to better capacity utilization.
Higher reliability & redundancy	> Defective cells/modules to be bypassed. > Thermal balancing is possible.
Higher charging & driving performances	> Variable DC-link voltage strategy. > Loading modules with different current/power.
Savings on cells & powertrain comp.	> Better capacity utilization. > Controlled DC-link voltage.
2nd life applications	> Modules can be used directly (e.g., fast EV charging stations). > No testing/clustering efforts.

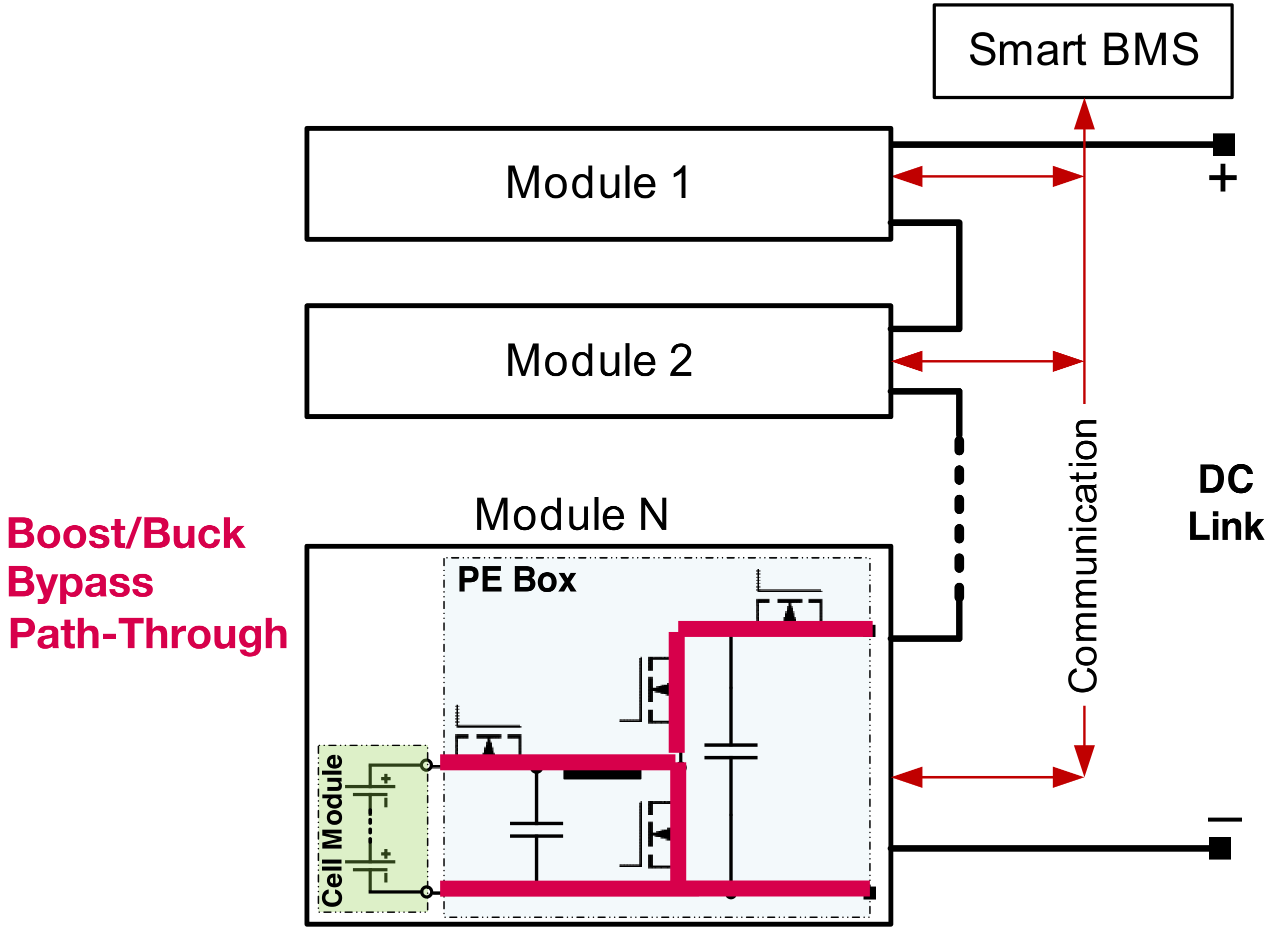
BMS: Battery Management System; SOC: State of Charge

POWER BALANCING ON MODULE LEVEL

SMART, SWITCHABLE, SCALABLE BATTERY (3S BATTERY)

> **Concept:**
  > DCDC converter is integrated to each battery module.
    > Buck, boost, bypass, path-through
  > Smart BMS

> **Use case:**
  > 400 V/ 84 kWh battery: 12 modules in series
  > Module configuration: 8s2p (120 Ah prismatic cells)
  > DC-link voltage: 60-470V (SOC independent)



BMS: Battery Management System; SOC: State of Charge

POWER BALANCING ON MODULE LEVEL

SIMULATION RESULTS

> **Simulation parameters:**
> - Use case: with new & aged cell-pack for 3S & conventional battery

> **Fast charging performance:**
> - 15 minutes fast charging from SOC 20%
> - KPI: charged energy!

	Cell-to-cell	Module-to-module
	relative standard deviaton	
Capacity New	0.7%	0.3%
Capacity Aged	7.0%	3.0%

> **Control strategy:**
> - No fixed charging curve
> - Current limits: by charging station, temp. & anode potential

> **Results:**
> - 3S: 2% to ~4.5% extra charged energy
> - But: 3S adds ~40% losses to the battery

	Energy [kWh]	Benefit 3S [%]
3S new	50.20	2.00
3S aged	50.03	4.48
Conventional new	49.21	-
Conventional aged	47.89	-

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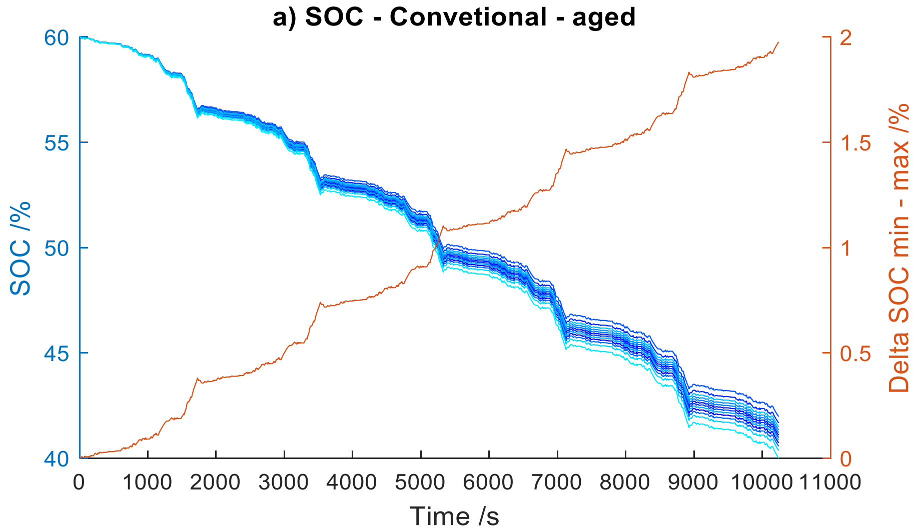
POWER BALANCING ON MODULE LEVEL

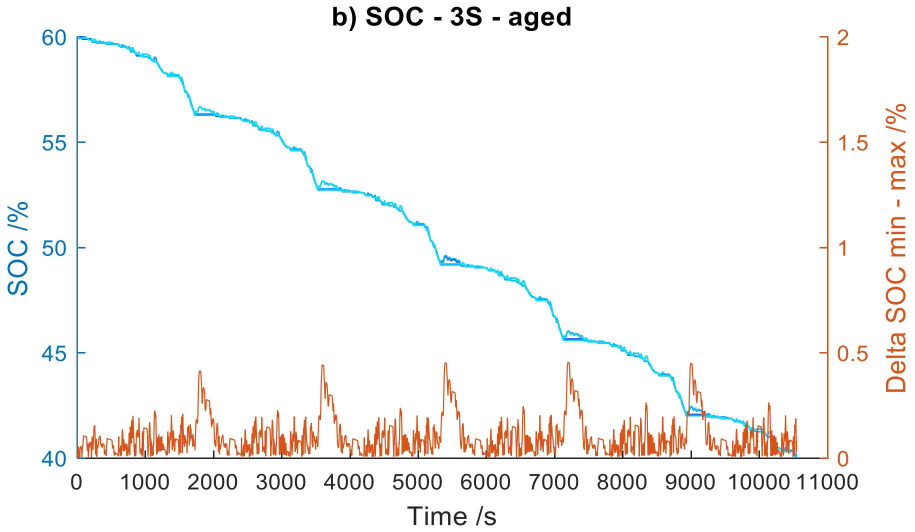
SIMULATION RESULTS - WLTP

> **WLTP:**
  > SOC: 60 – 40 %
  > KPI: driving range!

> **Control strategy (for 3S):**
  > module voltage is controlled to:
    > balance SOC
    > set optimal DC-Link voltage

	Distance [km]	Benefit 3S [%]
3S new	149.30	-1.51
3S aged	132.27	3.67
Conventional new	151.60	-
Conventional aged	127.59	-





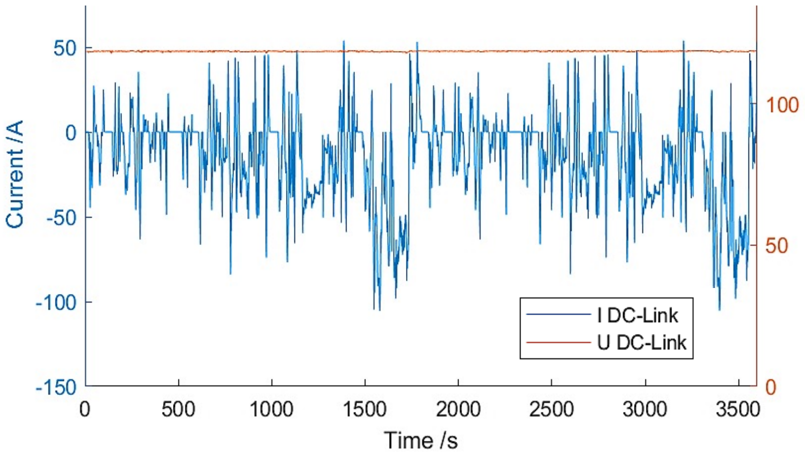
EOL: End of Life; BOL: Beginning of Life

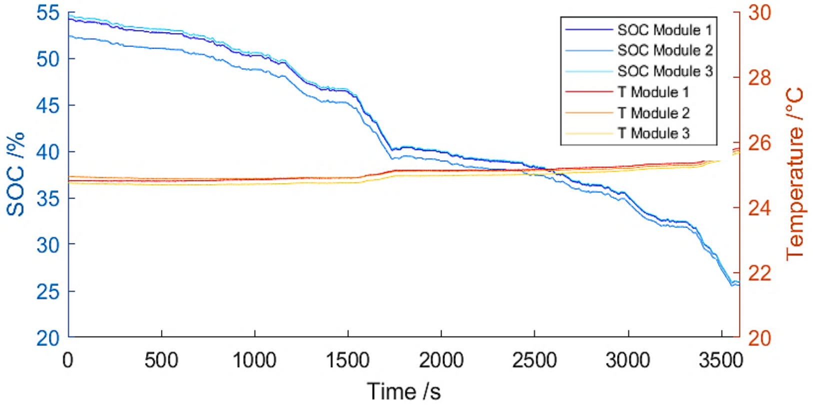
POWER BALANCING ON MODULE LEVEL

EXPERIMENTAL RESULTS

> **3S Prototype:**
  > 3 modules in series: 85 Ah
  > Module: 8s3p
  > DCDC converter power: 10 kW

> **Results:**
  > In 2 WLTPs, difference in SOC dropped from 4.4% to < 0.3%
  > every module: adjusts its own voltage and can be bypassed in case of defect





Results from two WLTP cycles: DC-link voltage and current & modules' SOCs and temperatures

EOL: End of Life; BOL: Beginning of Life

POWER BALANCING ON CELL LEVEL

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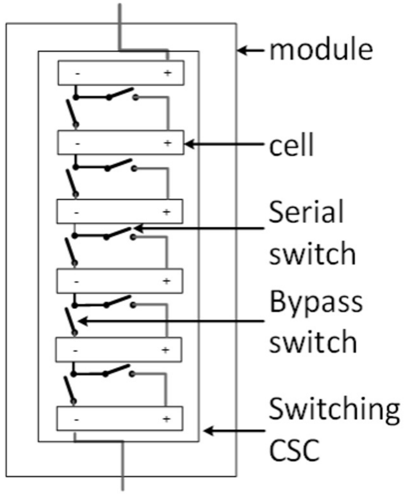
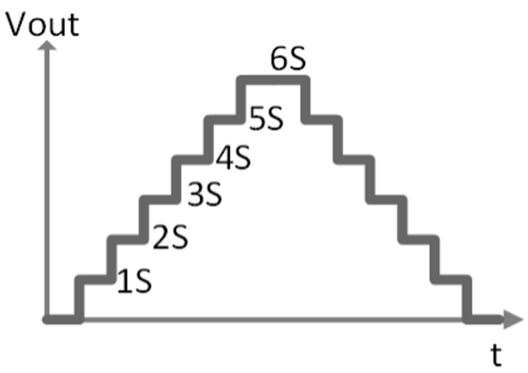
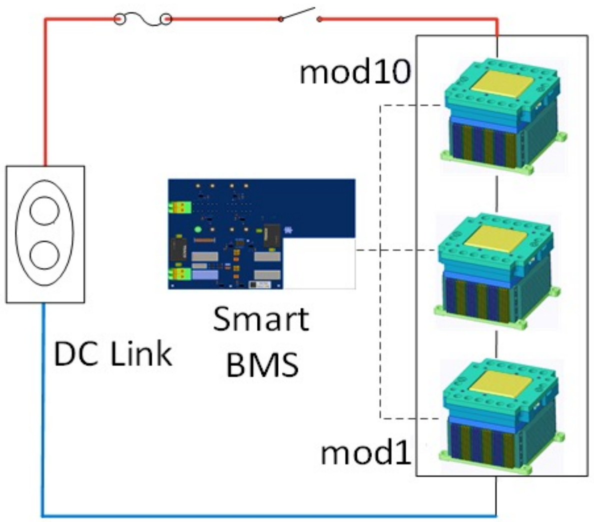
POWER BALANCING ON CELL LEVEL

CONCEPT – SWITCHED BATTERY (SWIBA)

> **Concept:**
  > Using two low-voltage switches for each cell: serial connection or bypass
  > Overall system control in a Smart BMS.
  > Precise and dynamic control of output voltage.
  > High degree of freedom:
    > Best cell sorting according to use cases & cell parameters.



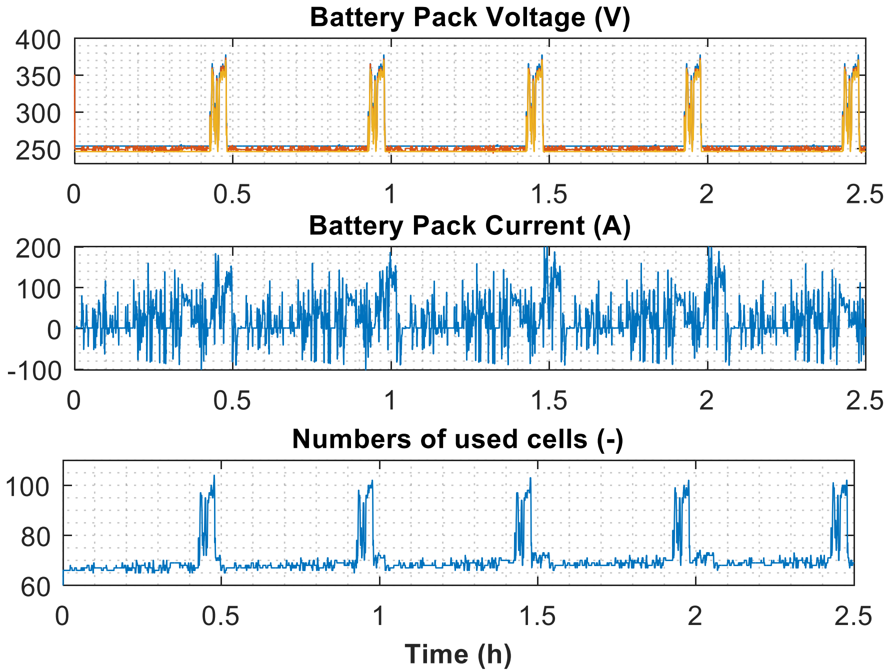


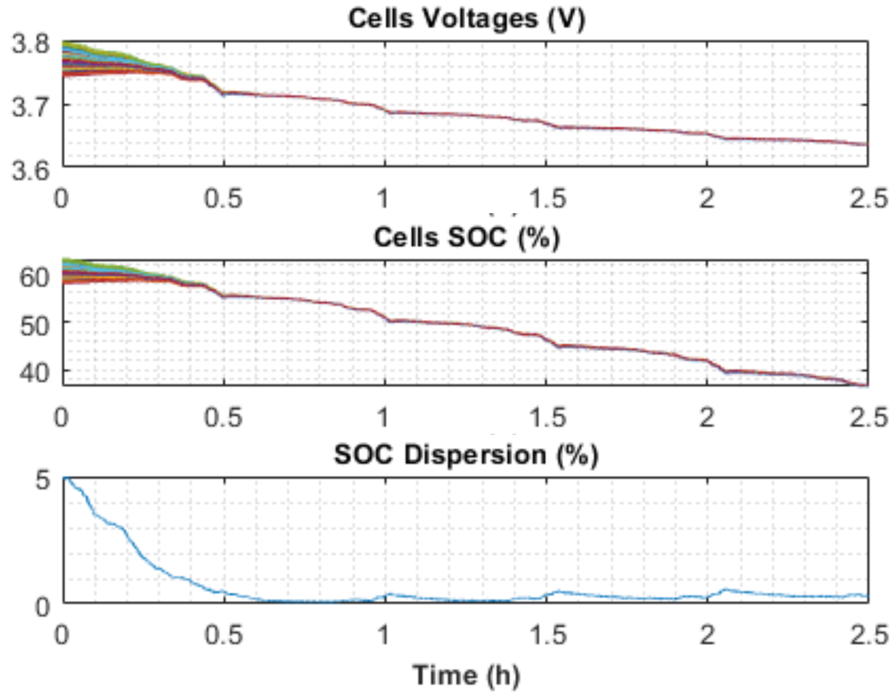


POWER BALANCING ON CELL LEVEL

SIMULATION RESULTS – SWITCHED BATTERY (SWIBA)

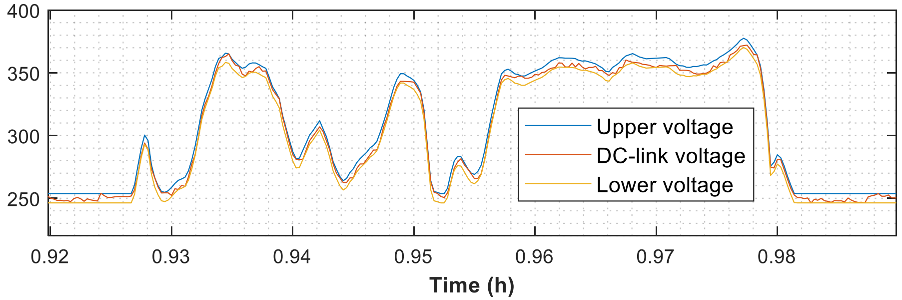
> **Battery:**
- > Cells: 140s3p (55 Ah)
- > SOC: 60%
- > ±5% cell-to-cell deviation





> **WLTP:**
- > 4 cycles
- > Battery voltage is dynamically controlled.
- > Use optimum machine efficiency.
- > Voltage error is ±1 cell voltage.

Zoom in: battery pack voltage



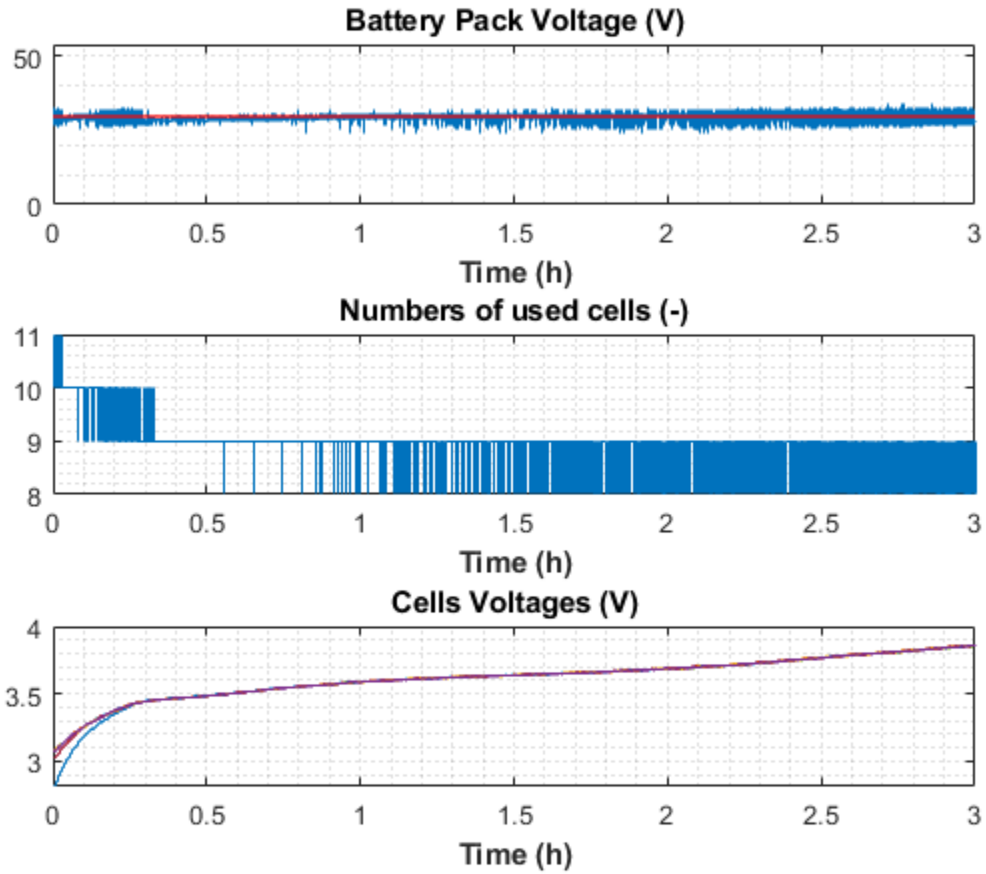
POWER BALANCING ON CELL LEVEL

EXPERIMENTAL RESULTS – SWITCHED BATTERY (SWIBA)

> **Battery:**
>
> > 2 modules: 6s1p (14 Ah)
> >
> > Initial cell voltages: 2.82 V to 3.08 V
> >
> > Requested voltage: constant 30 V

> **Test case:**
>
> > Charge with 5A constant current

> **Results:**
>
> > 8 to 11 cells needed to achieve requested voltage
> >
> > cells are converging to 3.93 V
> >
> > Full prototype is under test



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SUMMARY

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BALANCING TECHNIQUES

SUMMARY

Active balancing can utilize up to ~4% more energy with WLTP at EOL.

Larger batteries and less quality of the cells make active balancing more attractive.

The extra cost can be paid off by the battery capacity and energy utilization.

3S concept enables 2 to 4.5% extra charged energy in 15 minutes, but adds extra losses to the battery.

1.5% extra range can be achieved over lifetime due to capacity utilization.

More benefits are needed to pay off the extra electronics' cost.

Power cell balancing allows dynamic DC-link voltage.

Only on-state losses for the switches.

Prototype to be tested end of 2022.

THE FUTURE IS ELECTRIC!