Battery Energy Storage Systems

Power electronics interface and grid integration

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DCE&S
DC systems, Energy conversion & Storage

ALFEN
POWER TO ADAPT

Technolution

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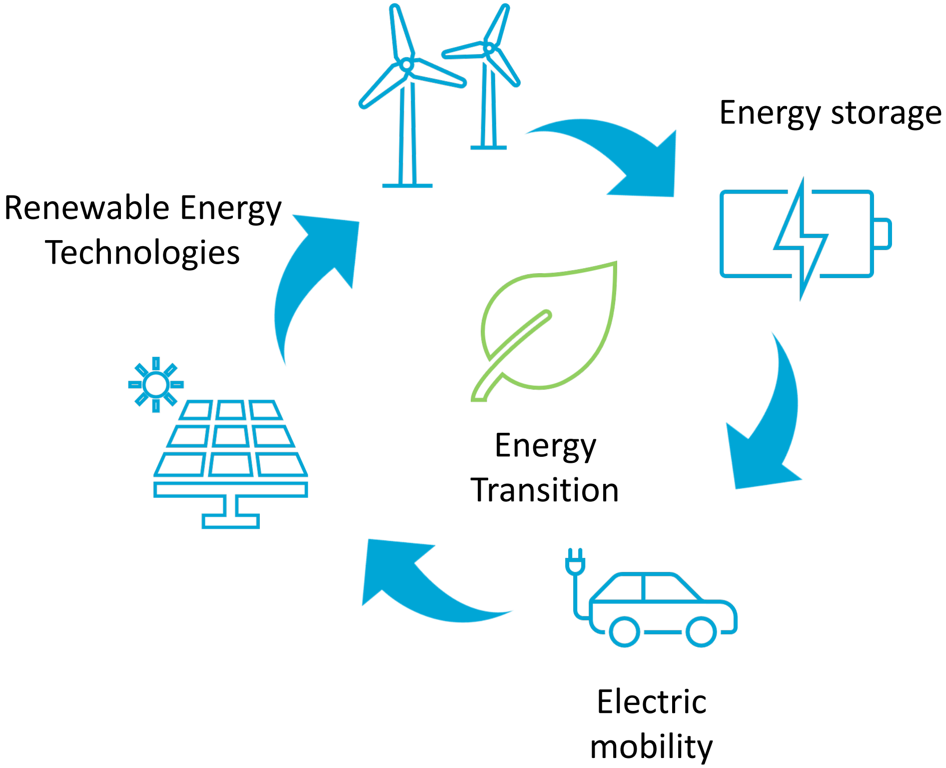
Motivation



Energy storage

Electric mobility

Renewable Energy Technologies

Energy Transition

Research objective

My PhD thesis title:

Battery Energy Storage Systems:
power electronics interface and grid integration

Power electronics interface

- Critical for BESS performance
- Enable BESS functionalities

Grid integration

- Defines BESS business case
- Defines impact of BESS on the power system

The two elements are key for a successful BESS deployment

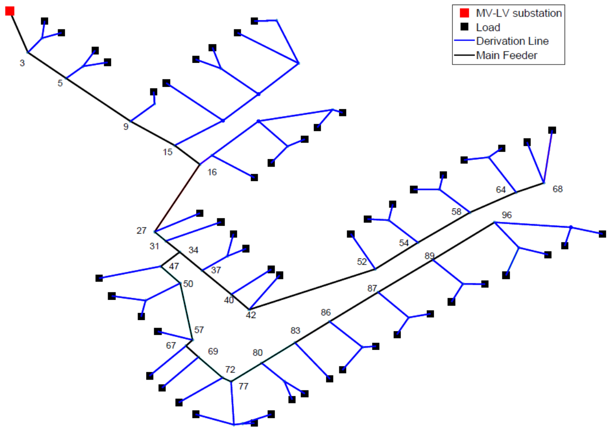
Research vision

Power electronics interface:

- Enhance efficiency while keeping costs low
- Optimize design and reliability according to mission profile
- Enable new functionalities*

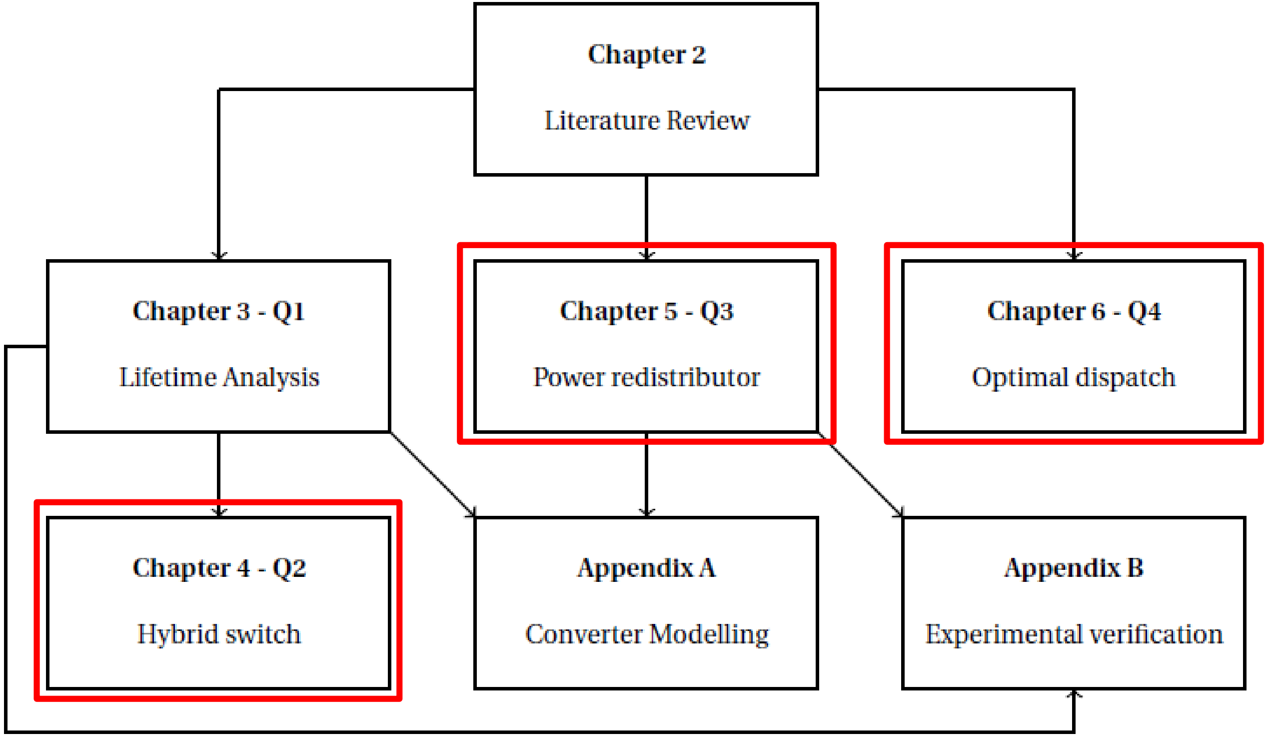
Grid integration:

- Combine multiple functionalities
- Enable new functionalities*



Structure of my thesis

Introduction Part 1 Part 2 Part 3 Conclusions



Chapter 2

Literature Review

Chapter 3 - Q1

Lifetime Analysis

Chapter 5 - Q3

Power redistributor

Chapter 6 - Q4

Optimal dispatch

Chapter 4 - Q2

Hybrid switch

Appendix A

Converter Modelling

Appendix B

Experimental verification

Part 1:

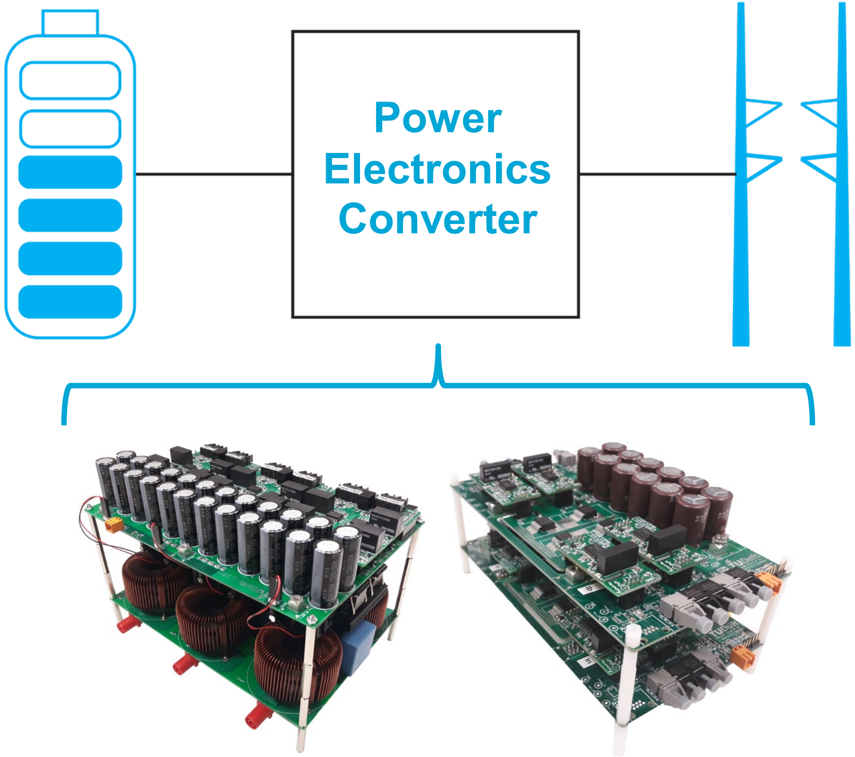
Power electronics converter

Power electronics converter

Required for grid connection

Key for:

- Enabling functionalitlies
- High system efficiency
- Safe/reliable operation



Converter requirements

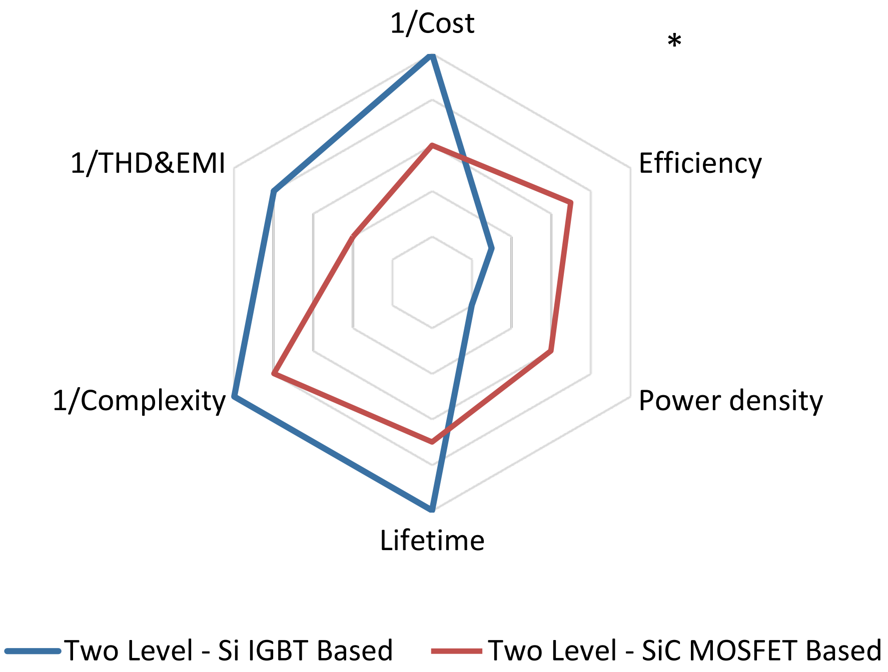
Main performance indicators:

- Cost
- Efficiency (static and of mission profile)
- Power density
- Expected lifetime
- Complexity
- EMI/THD

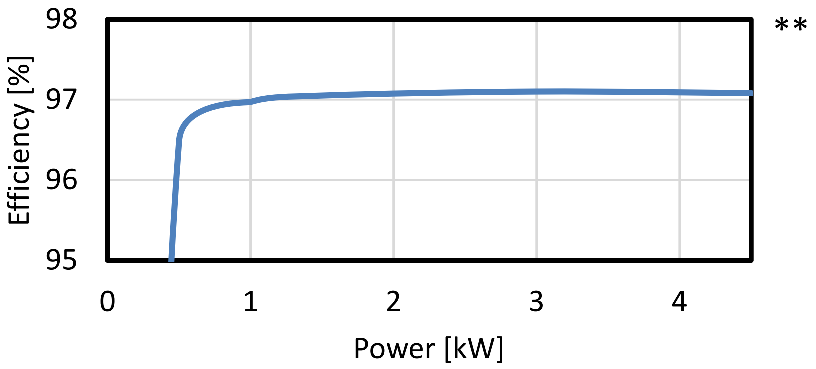
Main design variables:

- **Topology (2Level/3Level/Multi Level/…)**
- **Semiconductor technology (Si/SiC)**
- Switching frequency and modulation
- Overrating
- Passive components (magnetics, capacitors, …)

Two Level Converter



Low cost of Si IGBTs vs high efficiency of SiC MOSFETs



Si IGBTs particulary lossy at low partial power

Alternatives?

*Larger area = better

**Efficiency of a 4.5kW 2L- Si IGBT based converter

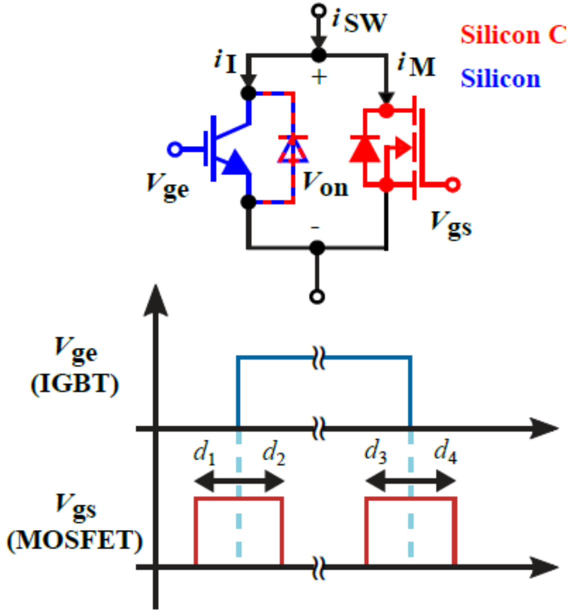
Hybrid switch

Assembled by paralleling a Si IGBT and a (small!) SiC MOSFET

- MOSFET switching losses (+)
- Current sharing at low current (+)
- Extra gate driver signal (-)

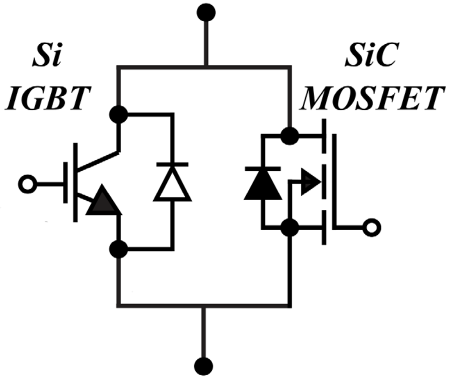
Work done

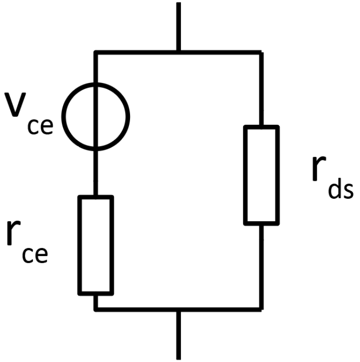
- Modelling
- Switch characterization
- Implementation in two level converter

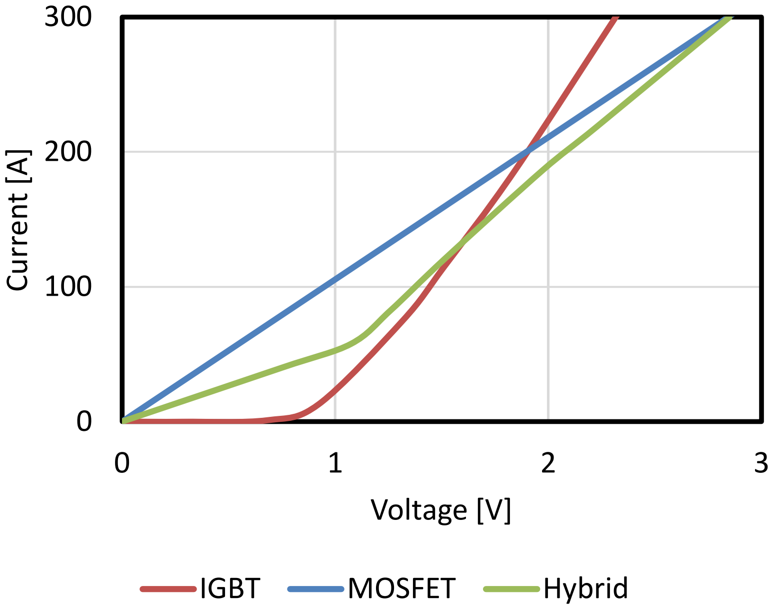


Modelling and characterization

On state behavior:







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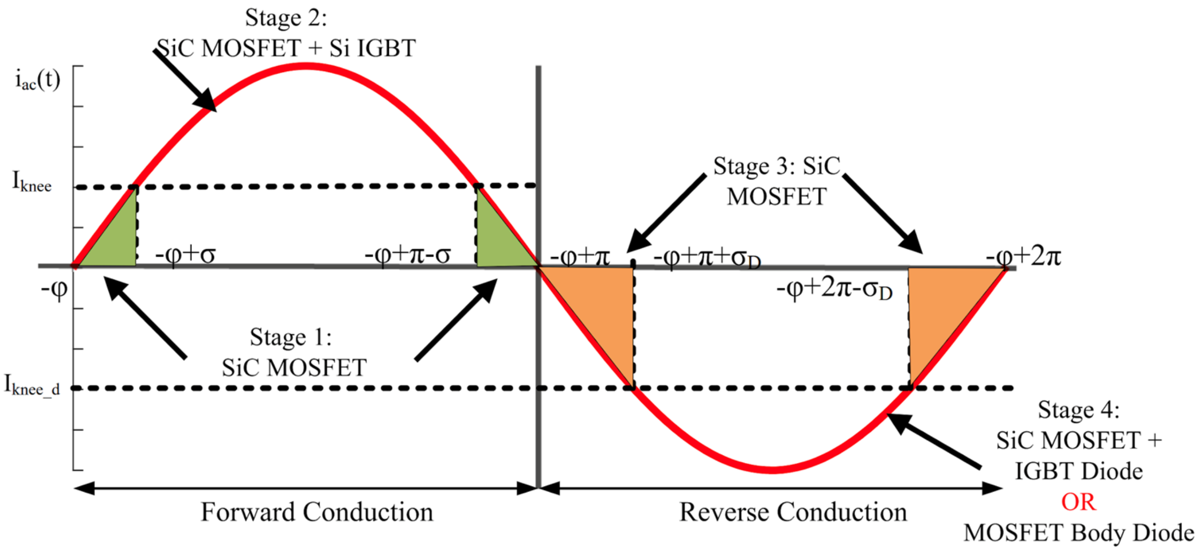
Current conduction

Current sharing changes during 50Hz period

$$I_{knee} = \frac{V_{ce}}{R_{ds}}$$

$$I_M = \frac{R_{ds}}{R_{ce} + R_{dc}} i_{ac} + \frac{V_{ce}}{R_{ce} + R_{ds}}$$

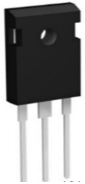
$$I_I = \frac{R_{ds}}{R_{ce} + R_{dc}} i_{ac} - \frac{V_{ce}}{R_{ce} + R_{ds}}$$



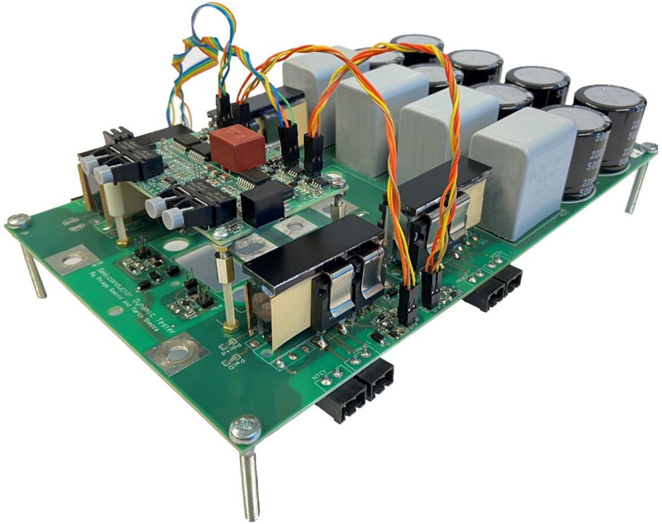
From: C. Tan, “Electric Vehicle Traction Drive using Si/SiC Hybrid Switches”, 2020.

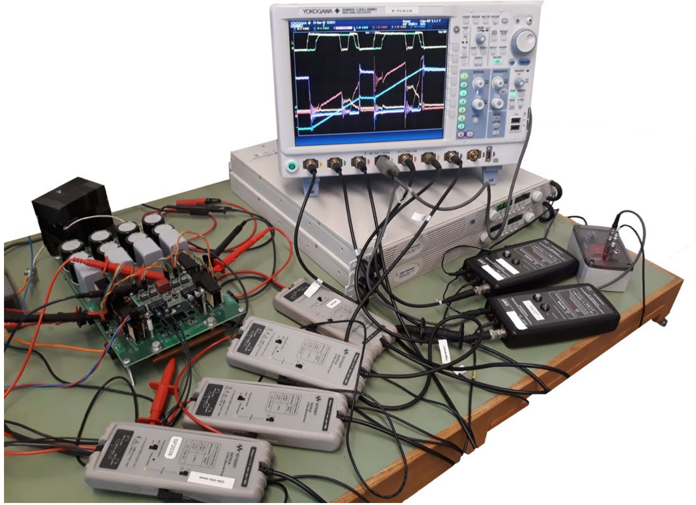
Experimental set up

Double Pulse Test for measuring conduction and switching performances



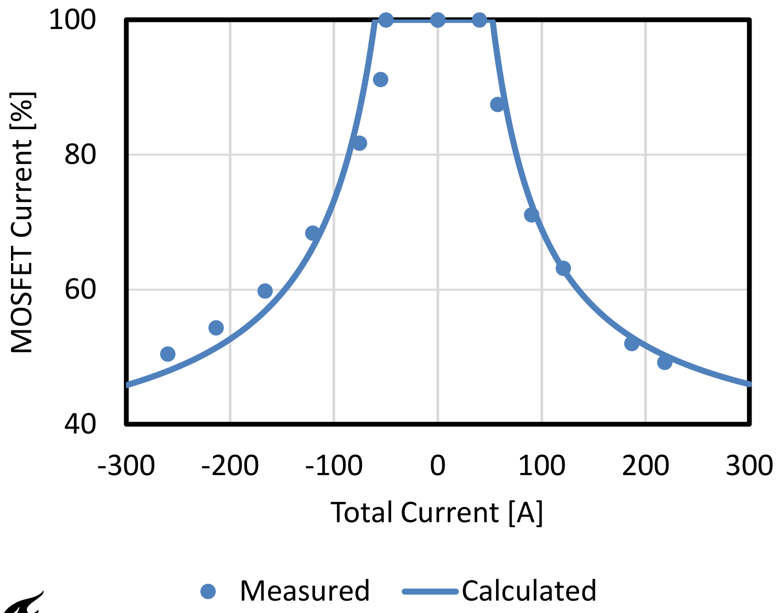
TO-247 devices



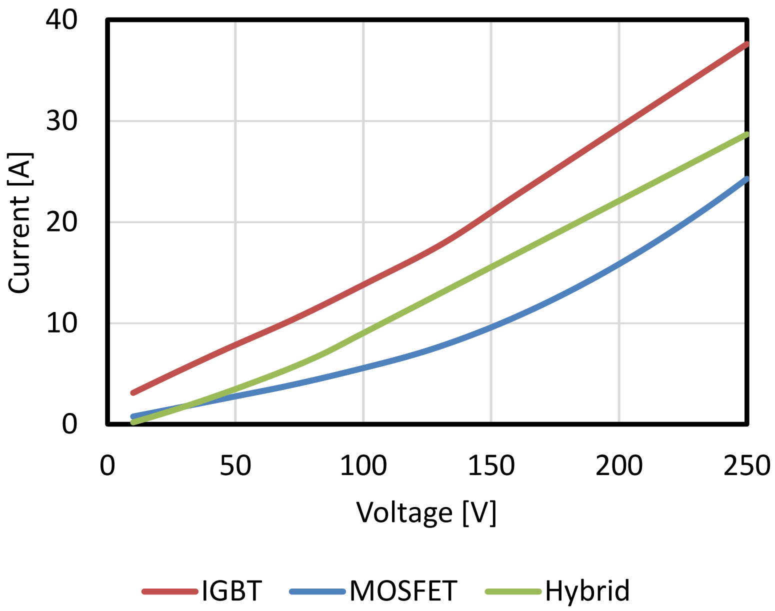


Hybrid switch performances

Verified the analytical models:

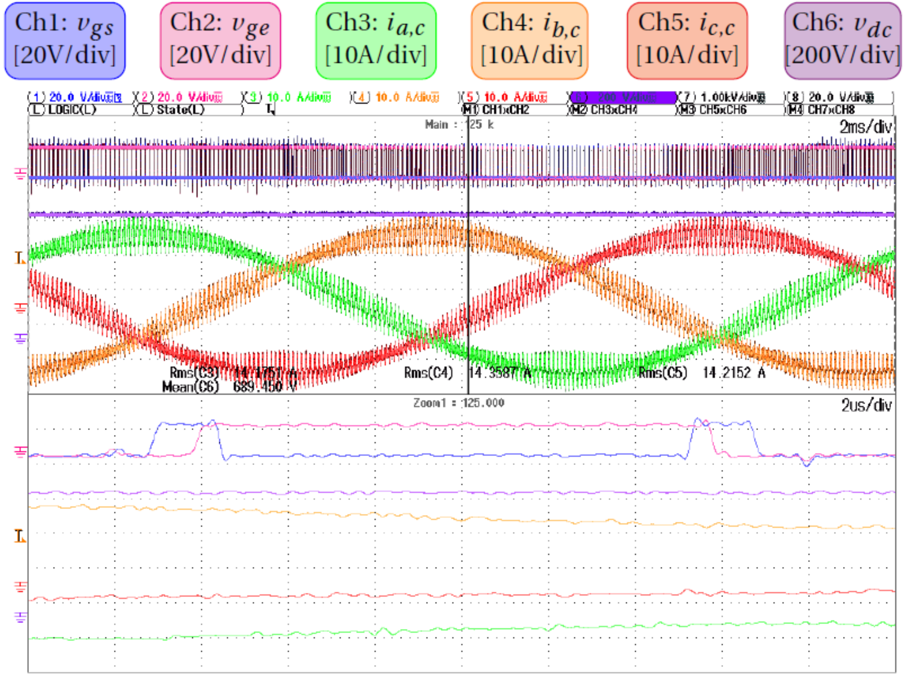


Obtained switching characteristics:



Hybrid switch in a two level converter

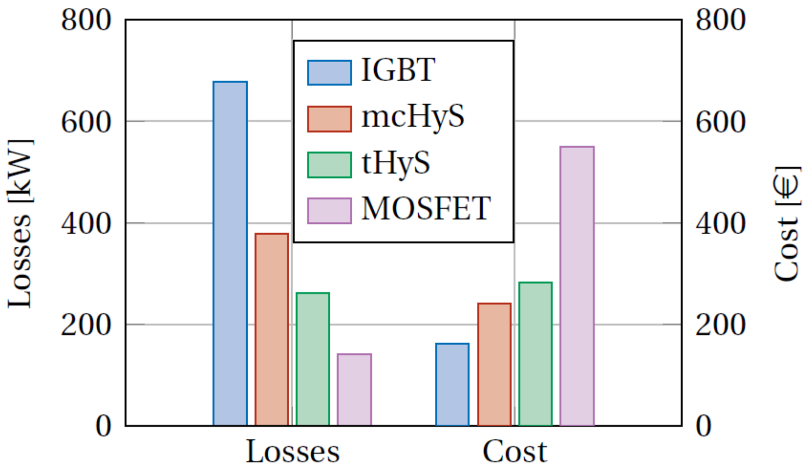
10 kW / 800Vdc / 400Vac / 12 kHz converter



Hybrid switch in a two level converter

Benchmarking of mission profile losses

- BESS performing primary frequency regulation
- 100kW system / 1 year mission profile



Loss/cost improvement ratio favourable for hybrid switches

Switch	Loss/Cost
MOSFET	33%
tHyS	82%
mcHyS	92%

Conclusions on hybrid switch

- The analytical model confirmed by experimental results.
- Modulation verified in a two level converter operation.
- Performance in between the pure Si IGBTs and SiC MOSFETs.
- Loss/cost improvement ratio is higher than SiC MOSFETs.

Part 2:

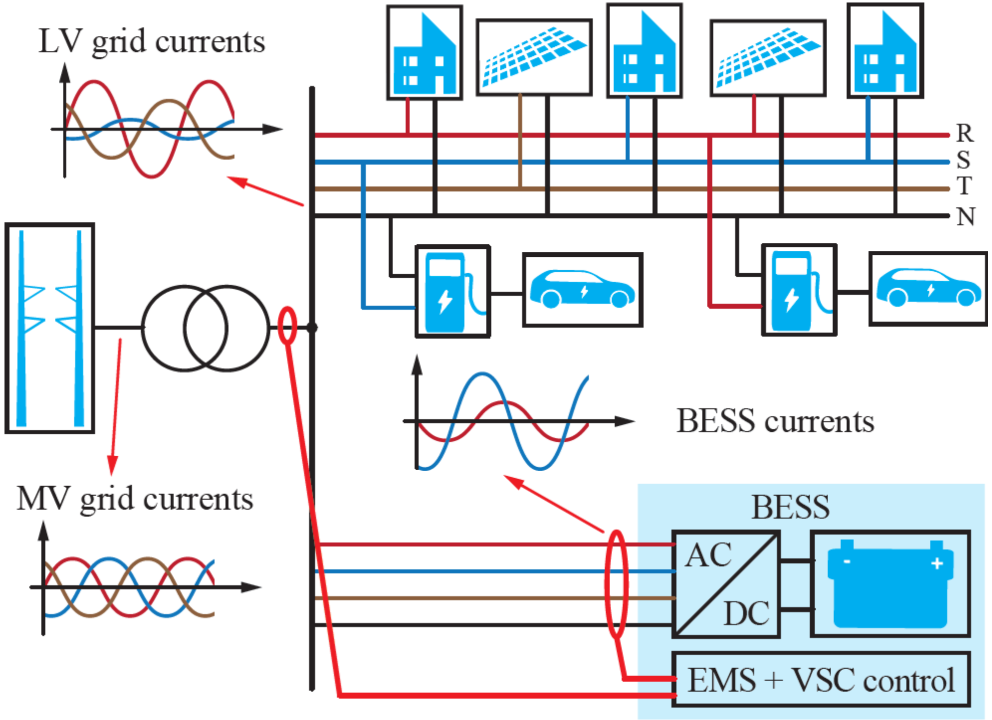
Enabling new functionalities

The power redistributor functionality

Power unbalance between three phases

- Install external compensators
- Use battery

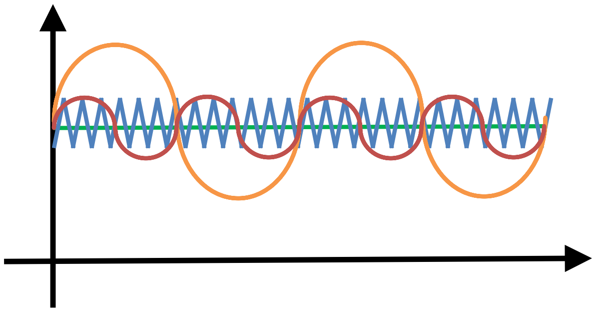
How to enable the provision of this functionality by a battery?

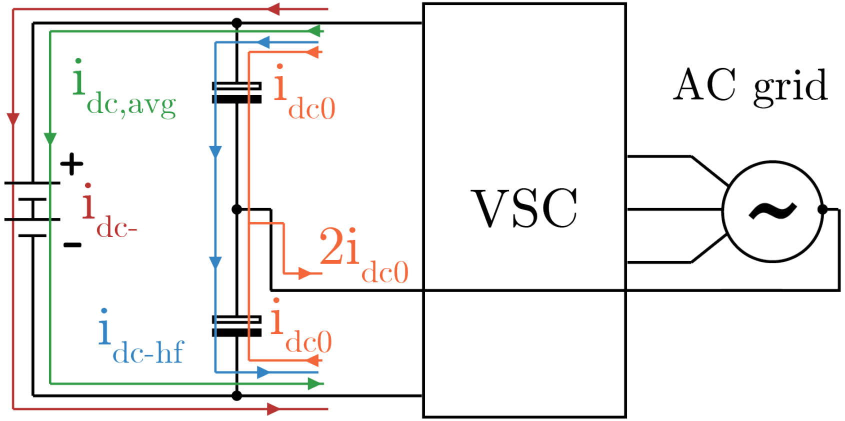


DC-link currents

Compensating the unbalance leads to current harmonics in the DC-link:

- DC current – battery
- High frequency – capacitors
- 50Hz – capacitors
- 100Hz - battery





Harmonics impact

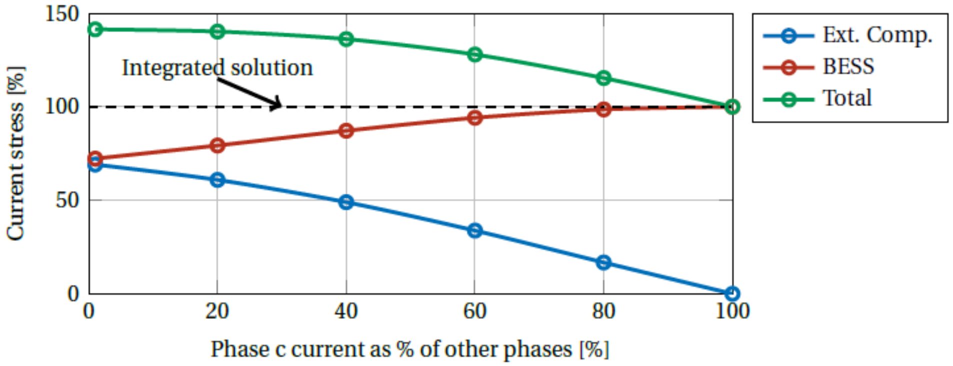
The current harmonics affect the BESS design:

- Higher voltage ripple
- Higher capacitor current stress

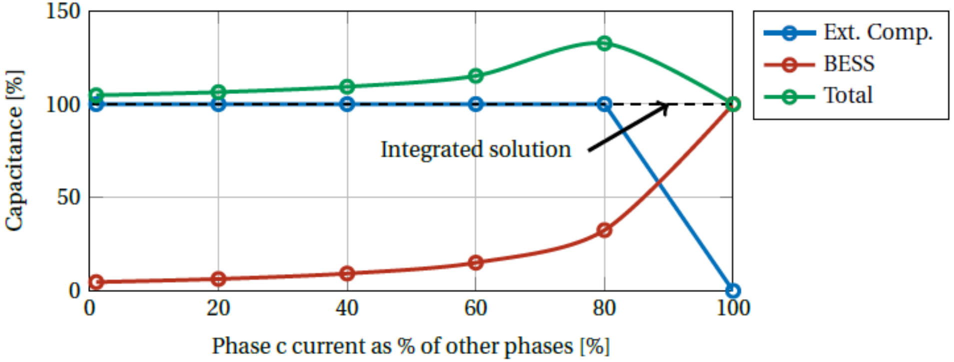
↓

Develop models to design the DC-link

Advantageous to integrate the functionality in a single unit



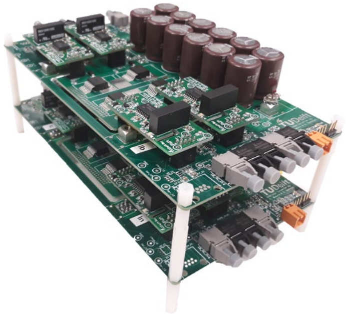
(a)

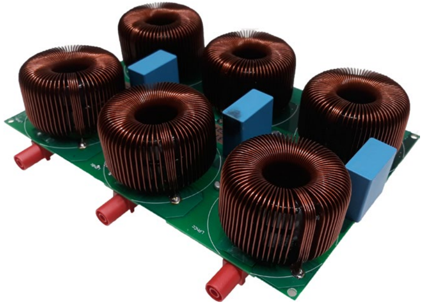


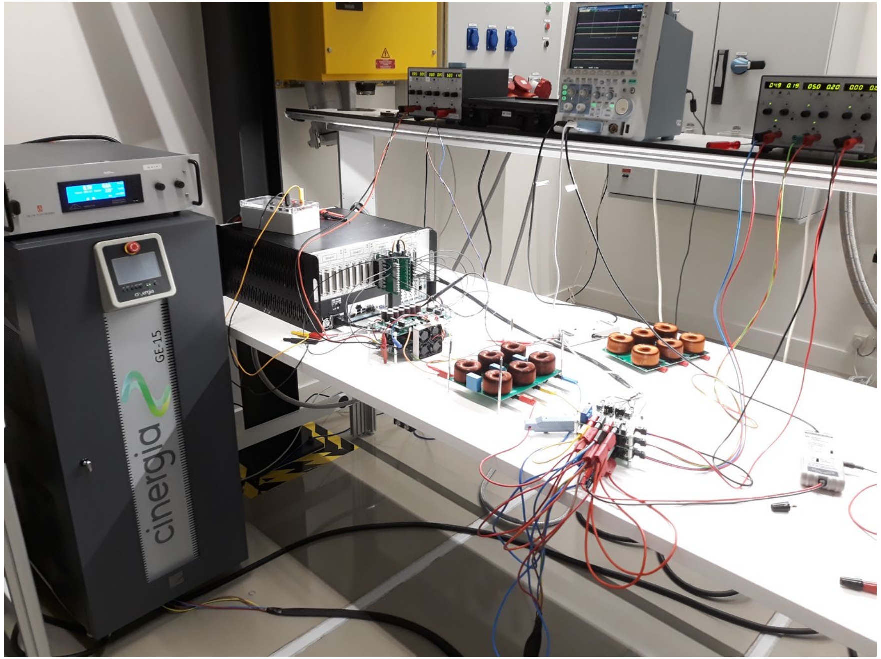
Test set up

Hardware in the loop set up to verify the model and functionality

- OPAL-RT based
- Two level converter and LCL filter
- 3kW prototype

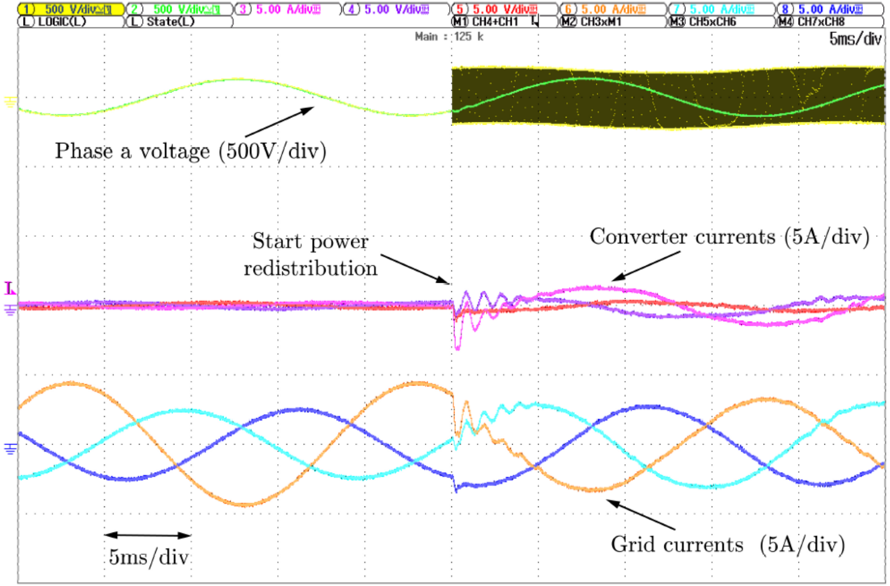




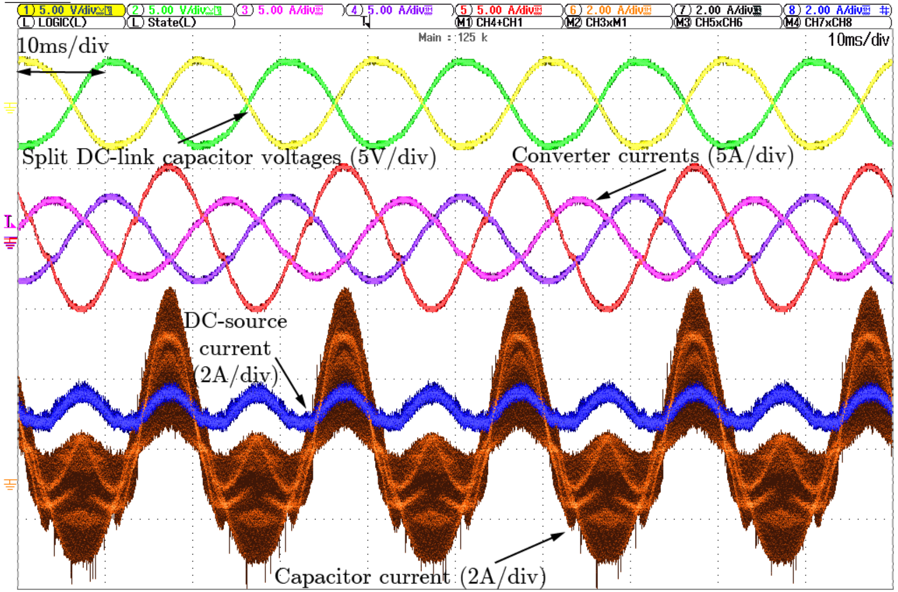


Test set up

Battery is capable to provide functionality

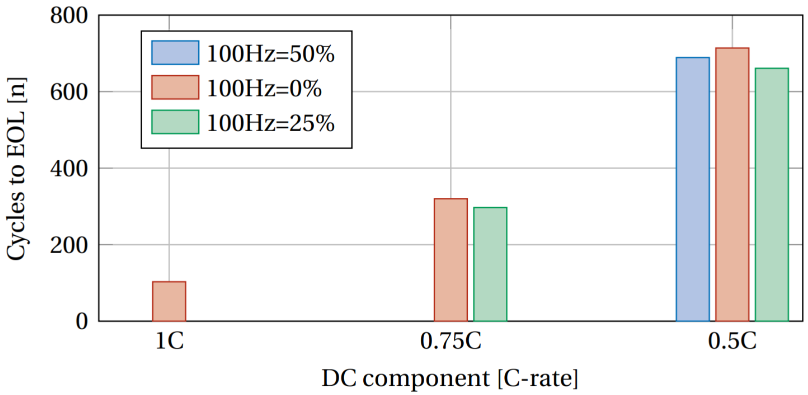


Current harmonics as predicted

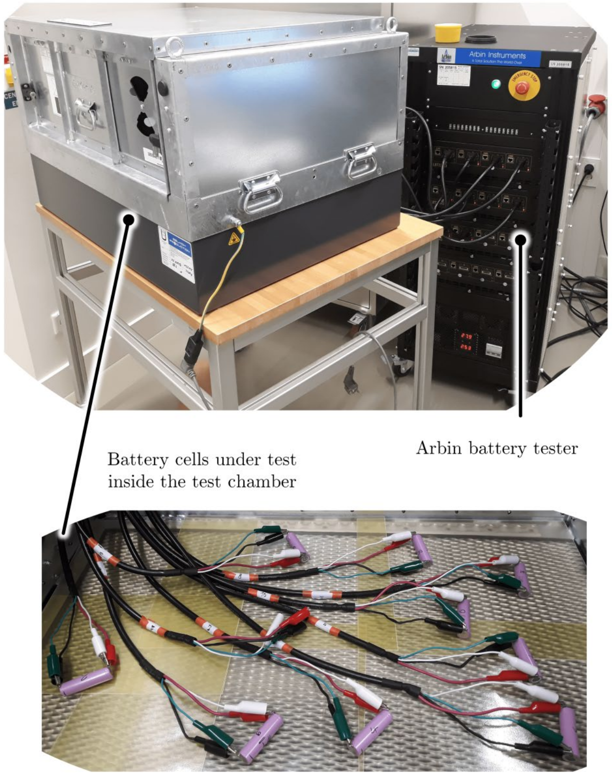


Impact on battery cells

Arbin battery tester to evaluate the impact of the 100Hz current on 18650 Li-ion cells



AC ripple leads to ~ +10% degradation



Conclusions on power redistributor

- Provided design method for BESS providing the functionality.
- DC-link capacitors can satisfy the thermal and capacitance requirements.
- AC ripple’s leads to an increase in battery degradation of 10%.
- Power redistributor functionality can be added without significant hardware expansions.

Part 3:

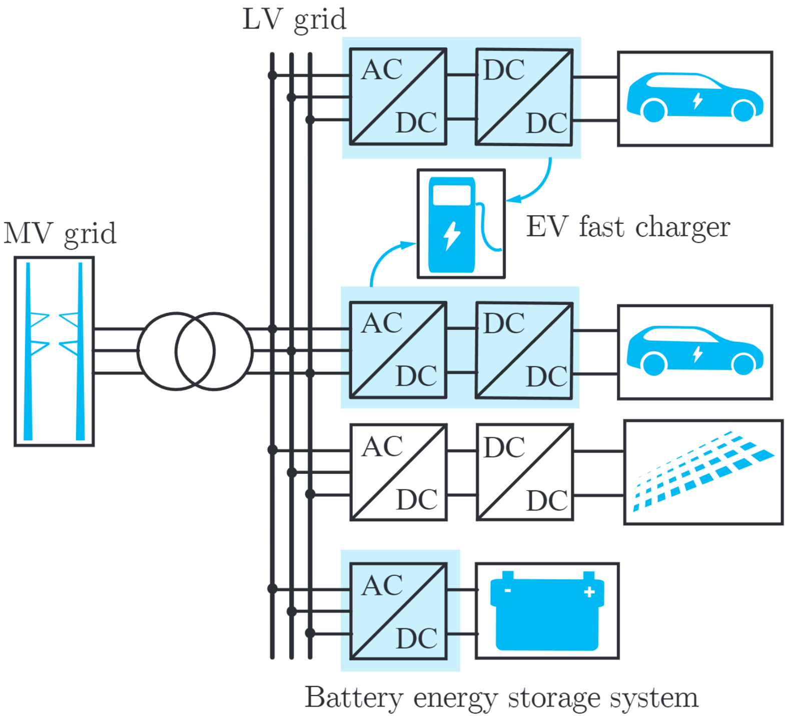
Combining multiple functionalities

Combining multiple functionalities

Batteries typically deployed to participate in energy and ancillary services markets:

- Day ahead market
- Primary frequency regulation

How to combine market activities with services to grid users, for example a PV-EV charging station?



Battery dispatching model

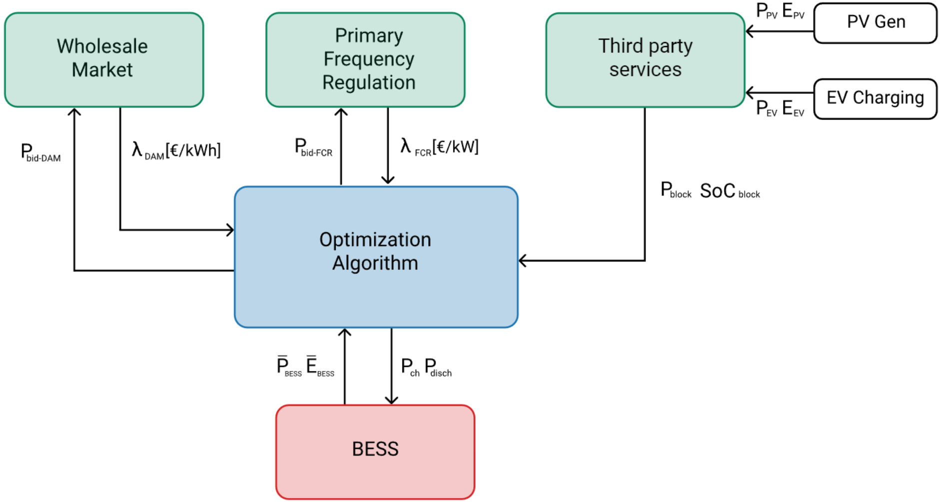
Mixed integer linear program to dispatch battery in the three sectors.

Objective function:

$$\max_{P_d, P_c, P_{fcr}} \; DAM[t] + FCR[z]$$

Constraints:

- Battery operation ($P_d, P_c, SoC, \ldots$)
- Market operation (bid time step, energy reserve, …)
- EV charging station power/energy demand



PV-EV charging station

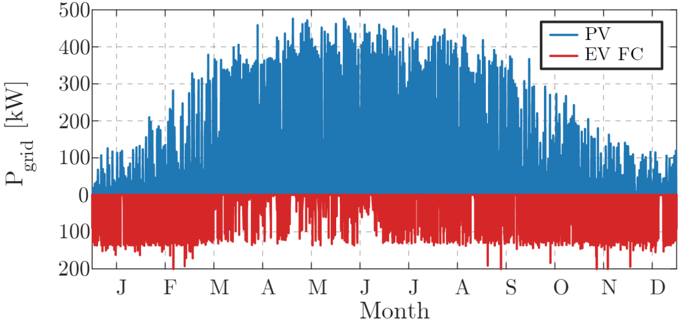
System specifications:

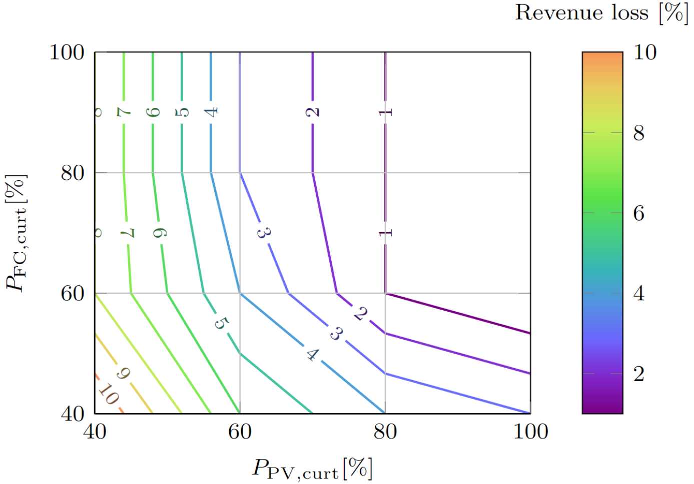
- 4x50 kW EV chargers
- 500kW PV system
- 500kW/kWh Battery

Battery task:

- Shave load/generation power peaks
- Increase self consumption of PV energy

One year mission profile

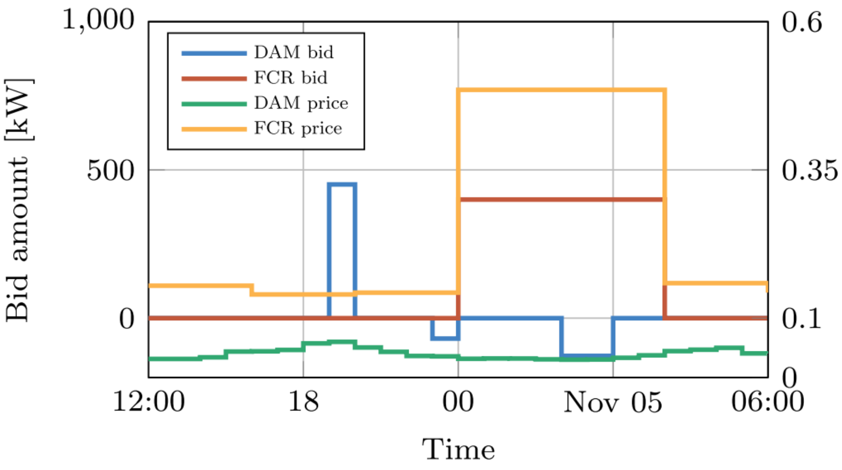




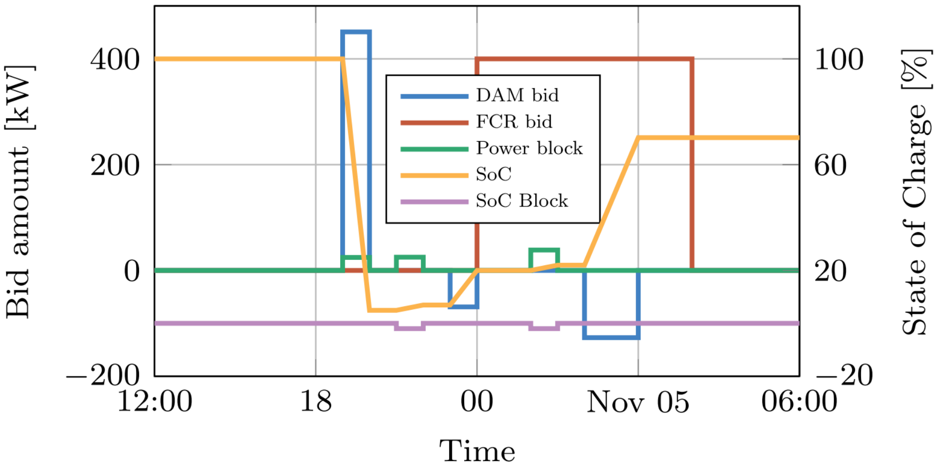
Example of dispatch

Introduction Part 1 Part 2 **Part 3** Conclusions

Bids price and amount

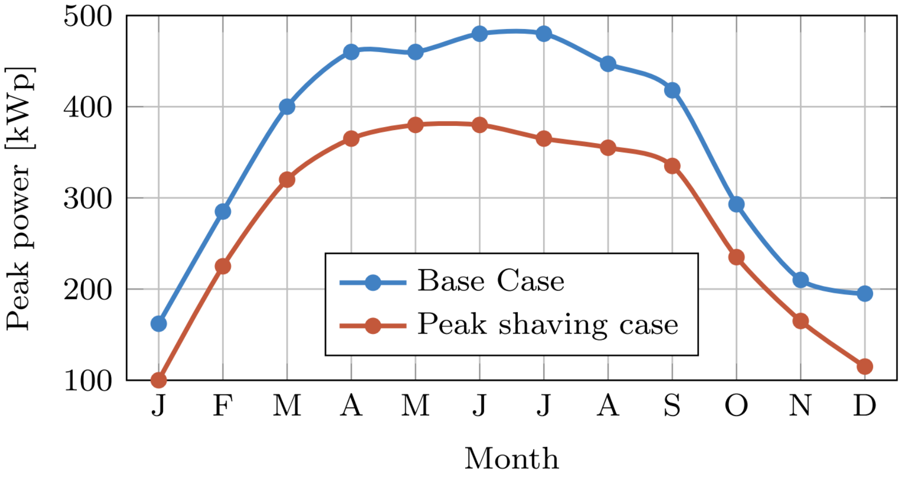


State of charge

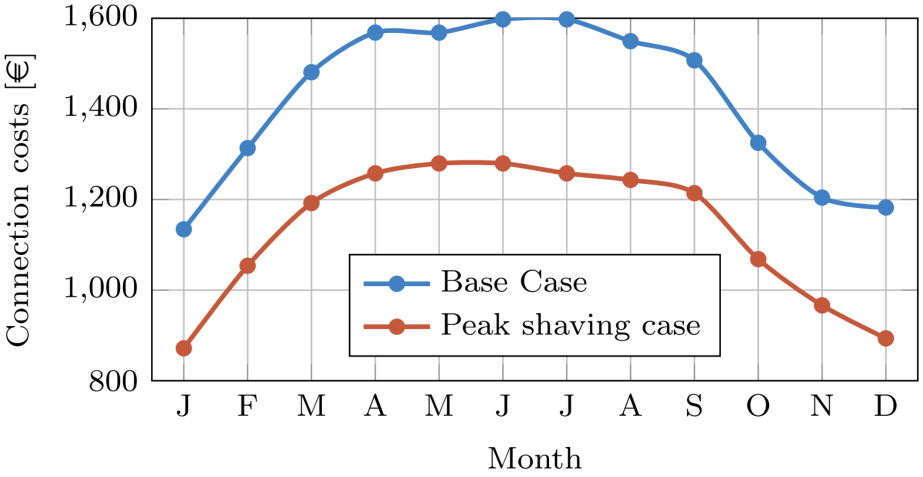


Connection cost reduction

Monthly peak power



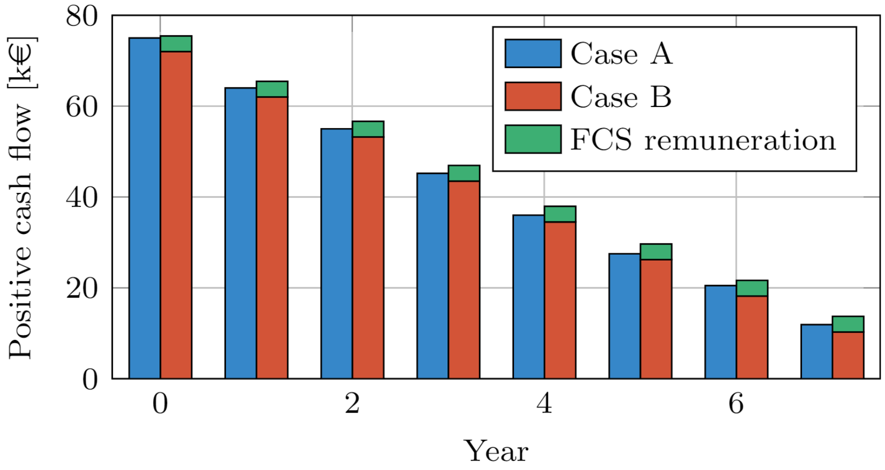
Monthly connection costs



Battery can successfully reduce peak power and therefore connection costs

Net Present Value Analysis

Overall the provision of services to the EV charging station has a positive economic impact



Parameter	Case A only market	Case B FCS addition	Difference
Cycles [n]	233	243	+4%
NPV [k€]	95	108	+14%
IRR [%]	11	12	+9%
PBT [years]	4	3.9	-2.5%

NPV=Net Present Value
IRR=Internal Rate of Return
PBT = Pay Back Time

Conclusions on battery dispatch

- Provided dispatch algorithm which could be integrated with forecasting tool
- Integrating multiple functionalities can benefit all the involved players in the distribution grids
    - Battery owner will have higher revenues
    - EV charging station owner will pay less connection costs and a lower energy bill
    - DSO will have less congestions in the grid

Conclusions

Summary

- Optimization of the battery power electronics can lead to lower total cost of ownership, and enable new functionalities
- Power redistributor functionality can be added without significant hardware expansions
- Integrating multiple functionalities can benefit all the involved players in the distribution grids

Future work

- Application of three-level and multi-level topologies in BESS and how to optimize their design, so to achieve higher performances.
- Further optimize the hybrid switches exploiting the internal delays, boosting the partial load efficiency.
- Aggregation of multiple BESSs, implementing a coordination layer between multiple units in the same network, not only to optimize the grid performance, but also to avoid conflicting actions.
- Address how to allow a BESS owner to provide services to the various grid players, such as generators, loads, and operators from the regulatory point of view.

Publications - 1

Journal papers of this thesis:

- 1. M. Stecca, L.R. Elizondo, T.B. Soeiro, P. Bauer, P. Palensky, “A Comprehensive Review of the Integration of Battery Energy Storage Systems Into Distribution Networks”, IEEE Open Journal of the Industrial Electronics Society, 2020, vol.1, pp. 46-65;
- 2. M. Stecca, T.B. Soeiro, L.R. Elizondo, P. Bauer, P. Palensky, “Lifetime Estimation of Grid-Connected Battery Storage and Power Electronics Providing Primary Frequency Regulation”, IEEE Open Journal of the Industrial Electronics Society, 2021, vol.2, pp. 240-251;
- 3. M. Stecca, C. Tan, J. Xu, T.B. Soeiro, P. Bauer, P. Palensky, “Hybrid Si/SiC Switch Modulation with Minimum SiC MOSFET Conduction in Grid Connected Voltage Source Converters”, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2022, vol.10, pp. 4275-4289;
- 4. M. Stecca, T.B. Soeiro, A.K. Iyer P. Bauer, P. Palensky, “Battery Storage System as Power Unbalance Redistributor in Distribution Grids Based on Three Legs Four Wire Voltage Source Converter”, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2022, early access;
- 5. L. Argiolas, M. Stecca, L.M. Ramirez Elizondo, T.B. Soeiro, P. Bauer, “Optimal Battery Energy Storage Dispatch in Energy and Frequency Regulation Markets while Peak Shaving an EV Fast Charging Station”, IEEE Open Access Journal of Power and Energy, 2022, vol. 9, pp.374-385

Publications - 2

Conference papers of this thesis:

- 1. M. Stecca, L.M. Ramirez Elizondo, T.B. Soeiro, P. Bauer, “Energy Storage Sizing and Location In Distribution Networks Considering Overall Grid Performance”, 2020 IEEE Power&Energy Society General Meeting (PESGM), 1-5;
- 2. M. Stecca, T.B. Soeiro, L.M. Ramirez Elizondo, P. Bauer, P. Palensky, “Comparison of Two and Three-Level DC-AC Converters for a 100 kW Battery Energy Storage System”, 2020 IEEE 29th International Symposium on Industrial Electronics (ISIE), 677-682;
- 3. M. Stecca, T.B. Soeiro, L.M. Ramirez Elizondo, P. Bauer, P. Palensky, “LCL Filter Design for Three Phase AC-DC Converters Considering Semiconductor Modules and Magnetics Components Performance”, 2020 22nd European Conference on Power Electronics and Applications (EPE’20 ECCE Europe).

Acknowledgements

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Batteries are and will be a key technology for future grids