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The Smart Transformer: providing service to the electric network and addressing the reliability challenges through power routing

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24143 Kiel

Where we are, who we are, what we do . . . .

Schleswig-Holstein, Kiel, Christian-Albrechts Universität zu Kiel

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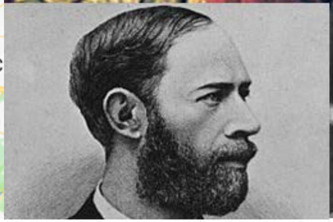
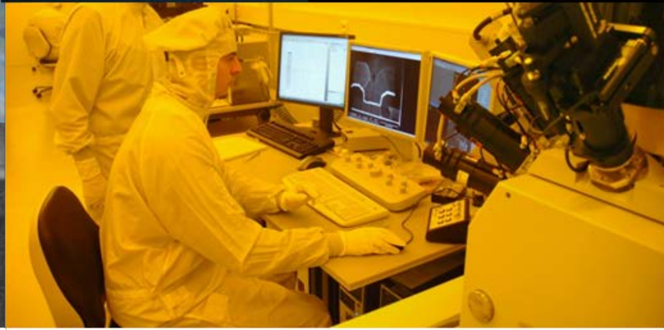
- ✓ Kiel is the Capital of SH
- ✓ Sailing City
- ✓ Kieler Woche
- ✓ 8 GW Wind Energy
- ✓ Power Electronics Region


- ✓ Founded in 1665
- ✓ 24,000 Students
- ✓ 2 Clusters of Excellence
- ✓ 3 Nobel prizes
- ✓ Hertz and Planck



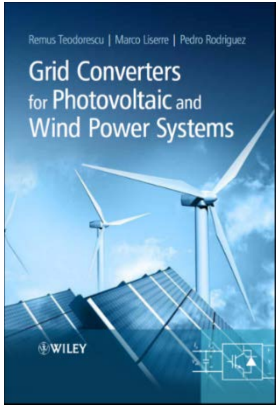


- ✓ Founded in 1990 (one of 6 fac.)
- ✓ 2400 Students
- ✓ 3 Institutes
- ✓ 26 Mill Euro Budget (Half ext.)
- ✓ 3 ERC Grants

Chair of Power Electronics

- Associate Prof. at Politecnico di Bari, Italy
- Professor – Reliable Power Electronics at Aalborg University, Denmark
- **Professor and Head of Power Electronics Chair since September 2013**

- Listed in ISI-Thomson report World's Most Influential Minds
- Active in international scientific organization (IEEE Fellow, journals, Vice-President, conferences organization)
- EU ERC Consolidator Grant (only one in EU in the field of power sys.)
- Created or contributed to the creation of several scientific laboratories
- Grid-connected converters (20 years) and reliability (last 10 years)



Chair of Power Electronics

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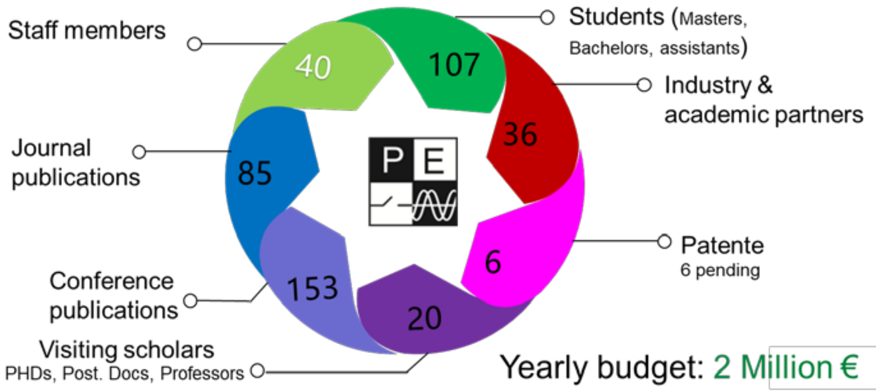
- Participating in the two major German initiatives regarding "Energiewende"
- 2 Laboratories: Power Electronics and Medium Voltage
- Battery Laboratory under construction
- 16 Industrial Partners
- Several research Partners



Yearly budget: 2 Million €

Grid Integration of inverters

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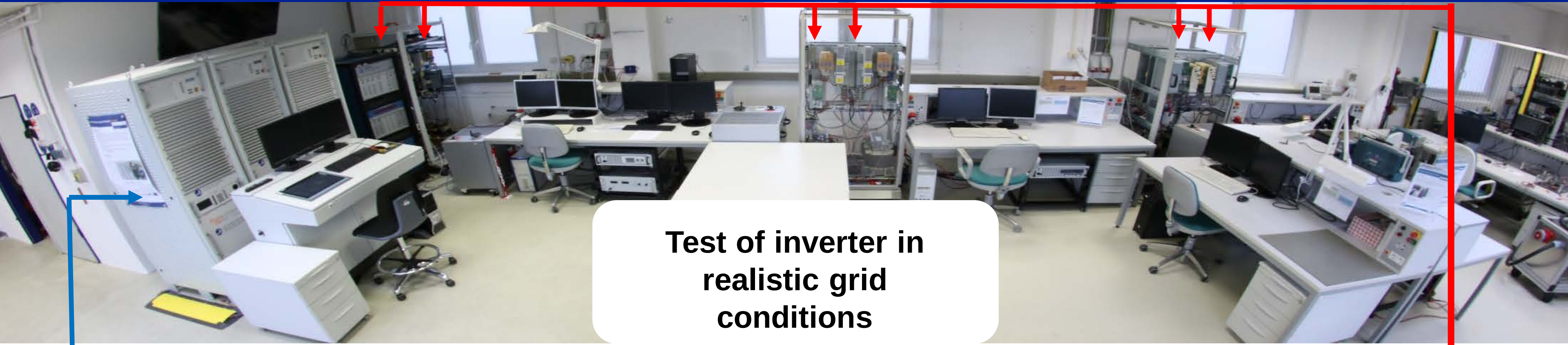
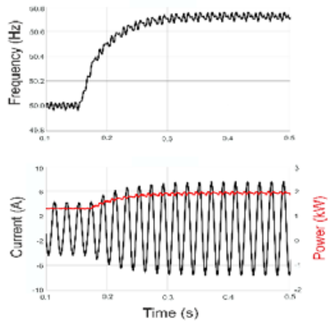


Test of inverter in realistic grid conditions

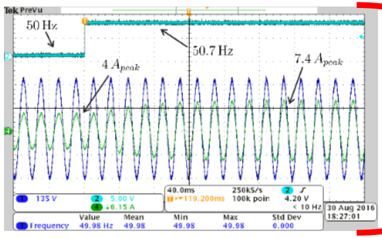
in PSCAD



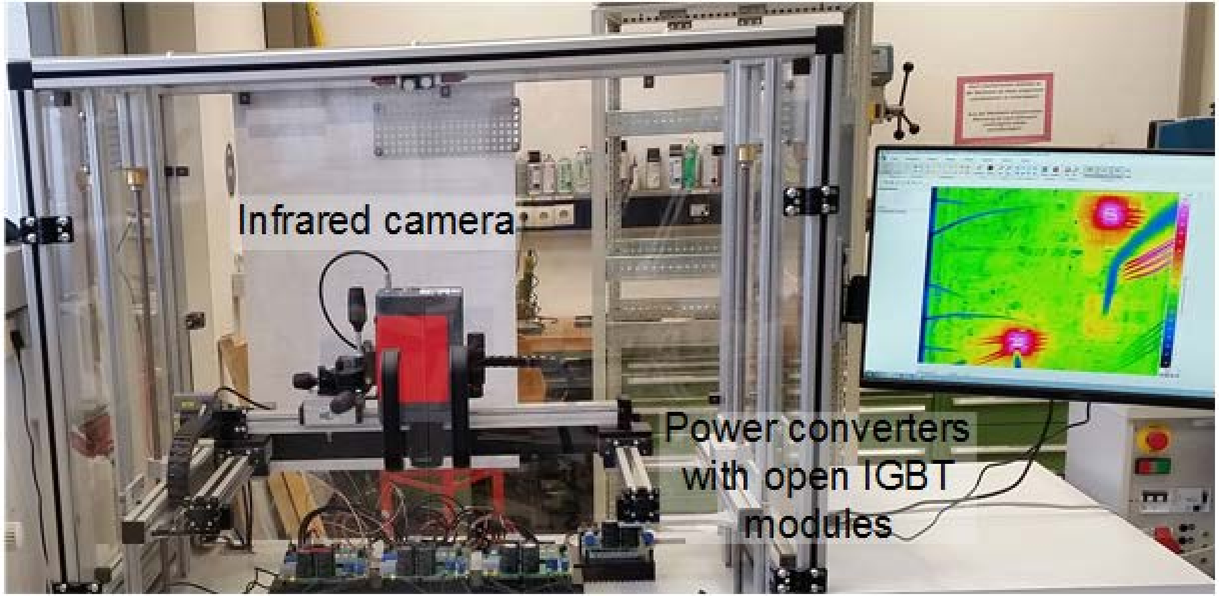
Features:

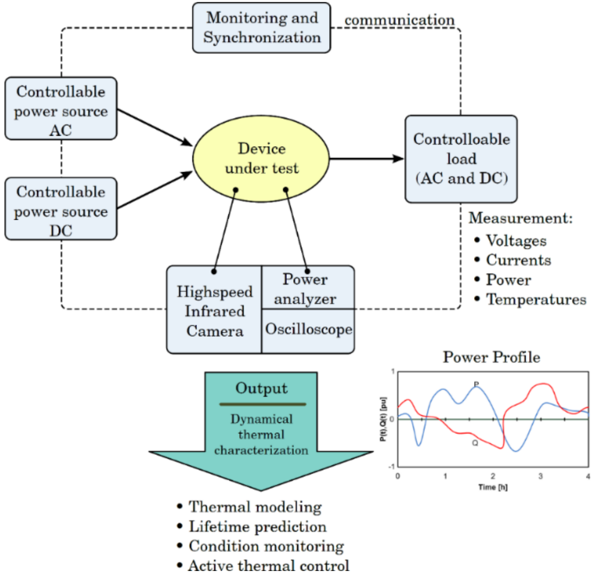
- ✓ RTDS with 2 racks
- ✓ Power Amplifier voltage or current controlled
- ✓ 7 inverters controlled through Dspace

in one of the seven inverters



Thermal Analysis of power converters





HEART-Plattform Labor: Medium Voltage Laboratory

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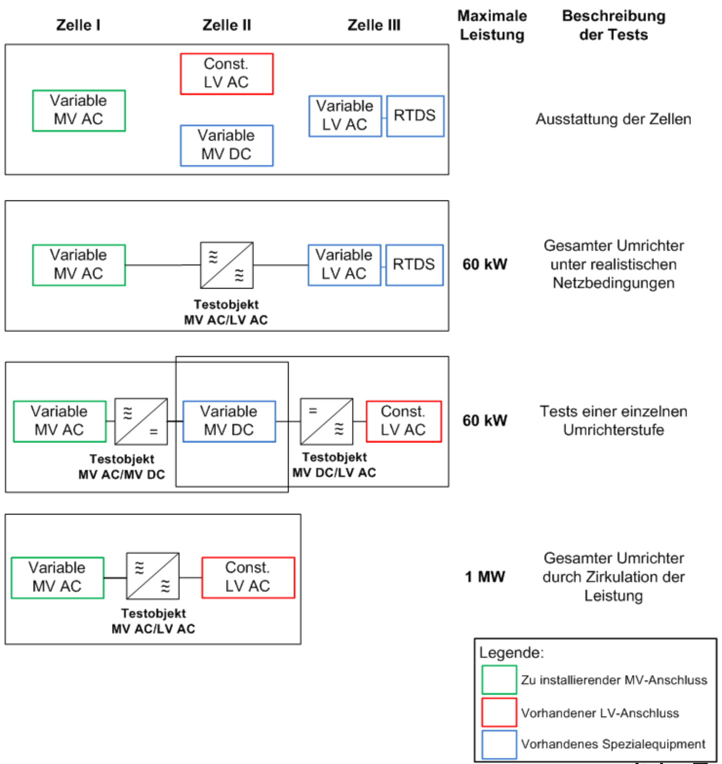
- ✓ 3 test fields (10.4 m² each)
- ✓ Autotransformer with 10,8,6,4,2 kV
- ✓ up to 1 MW circulating power
- ✓ cooling system (60 kW liquid, 10 kW air)
- ✓ maximum current 1600 A
- ✓ Availability of asynchronous MV Source controlled by a Real Time Digital Simulation System (RTDS or OPAL)

Mögliche Tests im Labor

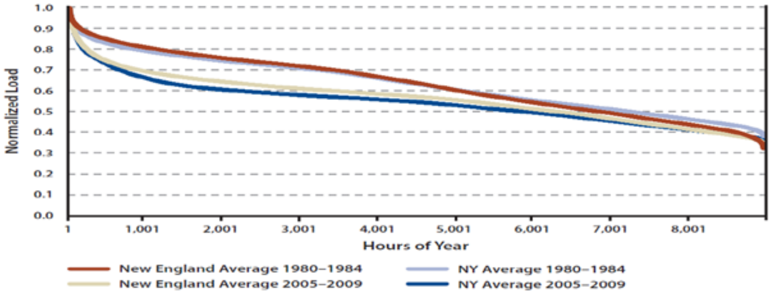


A look to the problems of the electric grids . . . .

Greater Demand Variability

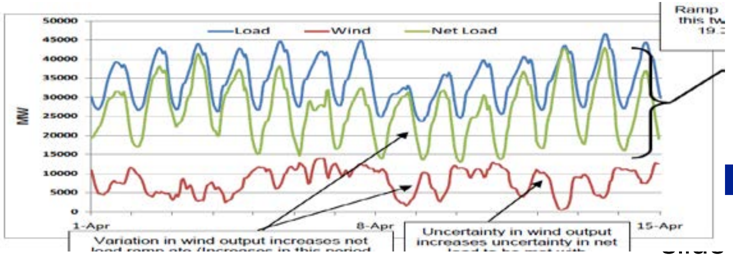
- ✓ New loads and changes in the industrialization landscape
- ✓ High Renewable production and low load request -> Low capacity utilization of the grid for great part of the time
- ✓ Low Renewable production and high load request -> High capacity utilization of the grid for small part of the time

Load duration curve for New England and New York*



Normalized load cumulative curve at substation level in New York city* → more than 30% of the time only in 12% of the time

Impact of the net load from increased us of renewable energy**



*Kassakian, J. G., et al. "The future of the electricity grid: an interdisciplinary MIT study." *Cambridge, MA, Tech. Rep* (2011).

** Denholm, P; Ela, E.; Kirby, B.; Milligan, M.; "The Role of Energy Storage with Renewable Electricity Generation", National Renewable Energy Laboratory (NREL), Technical Report, January 2010.

Voltage Violations and Line congestions

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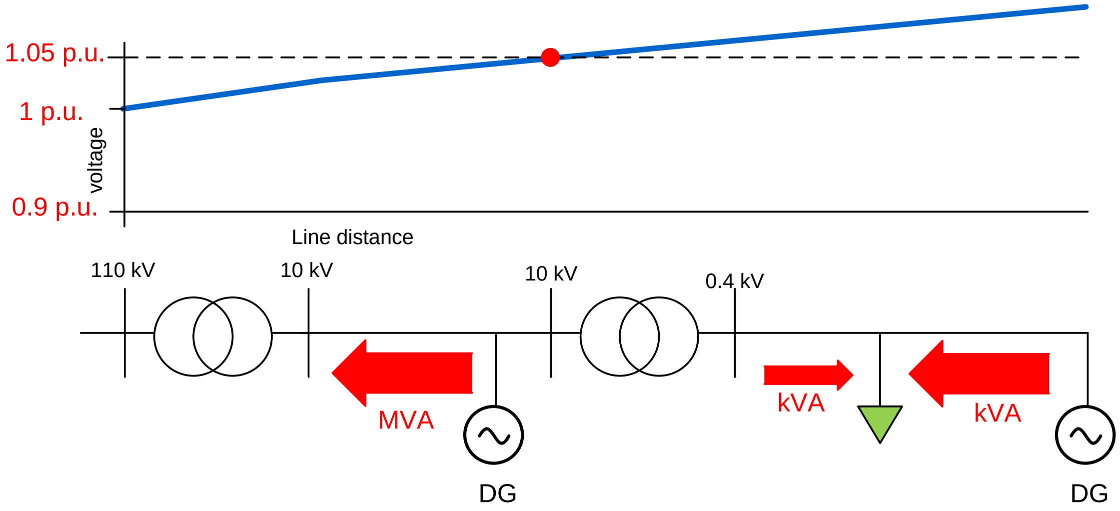
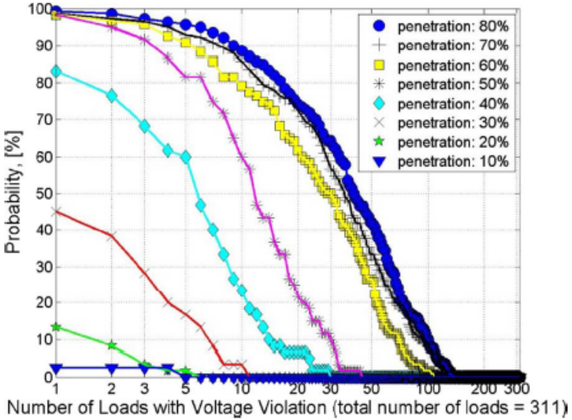
✓ The grid has been designed to be passive, the increase penetration of Distributed Generation causes voltage violations



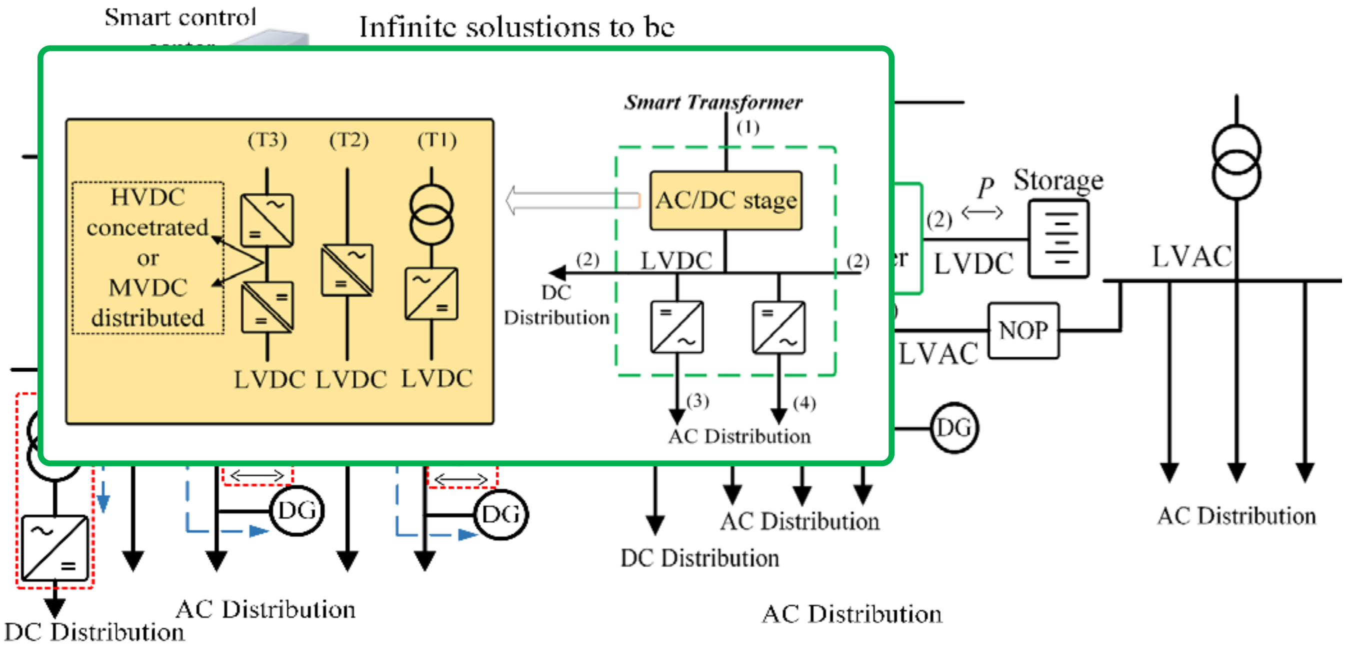


Probability of having a voltage violations of more than ±5% versus the number of loads with violation*

*Po-Chen Chen; Salcedo, R.; Qingcheng Zhu; de Leon, F.; Czarkowski, D.; Zhong-Ping Jiang; Spitsa, V.; Zabar, Z.; Uosef, R.E., "Analysis of Voltage Profile Problems Due to the Penetration of Distributed Generation in Low-Voltage Secondary Distribution Networks," *IEEE Transactions on Power Delivery*, vol.27, no.4, pp.2020-2028, Oct. 2012

is the Smart Transformer the solution ?

The Smart Transformer



M. Liserre, G. Buticchi, M. Andresen, G. De Carne, L. F. Costa and Z. X. Zou, "The Smart Transformer: Impact on the Electric Grid and Technology Challenges," in IEEE Industrial Electronics Magazine, vol. 10, no. 2, pp. 46-58, Summer 2016.

Main results of LV Engine cost/benefit analysis

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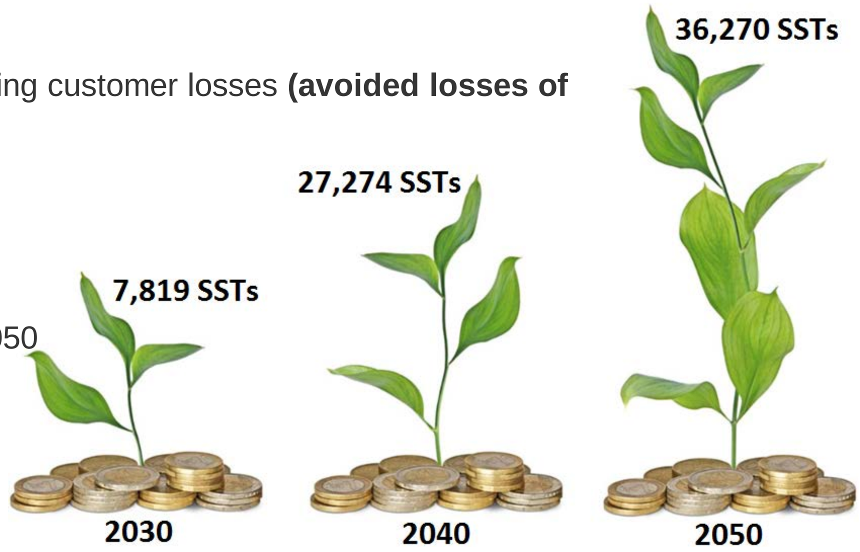
- **Releases capacity within existing LV network for connection of future LCT** generation and load prior to costly reinforcement.
- Provides distribution network with **increased flexibility and adaptability** to cope with uncertainties in how energy will be generated and consumed.
- Significant **reduction in 11kV/LV network reinforcement** caused by the uptake of LCTs & electrification of heat & transport sectors.
- **Lay ground works for future LVDC** network reducing customer losses **(avoided losses of ~£100m annually by 2040 in EV charging)**

Financial Savings:

- £62m by 2030
- £528m by 2050
- 16% of GBs 11kV/LV GM subs by 2050

Carbon Savings:

- 523 kt.CO_2 by 2030
- 2,032 kt.CO_2 by 2050



. . . to reinforce actual grid assets

Meshed LV ac grids (@ LV ac busbar)

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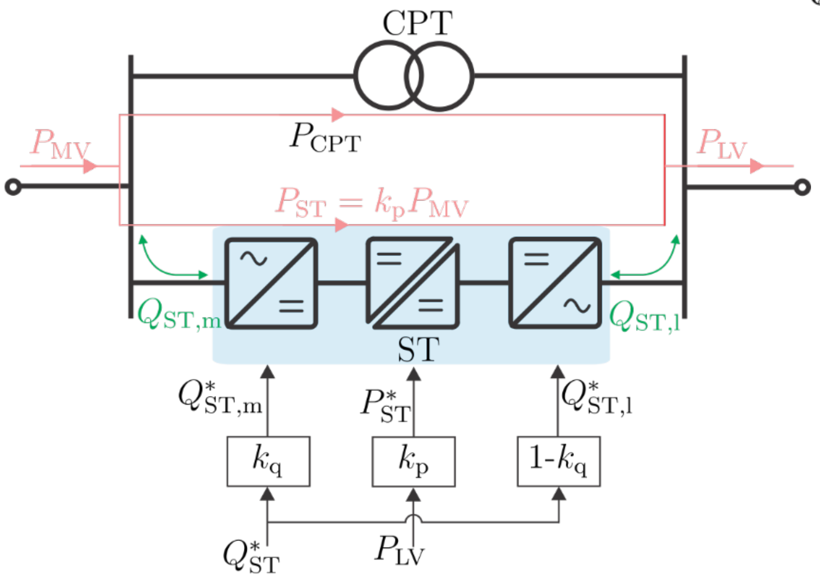
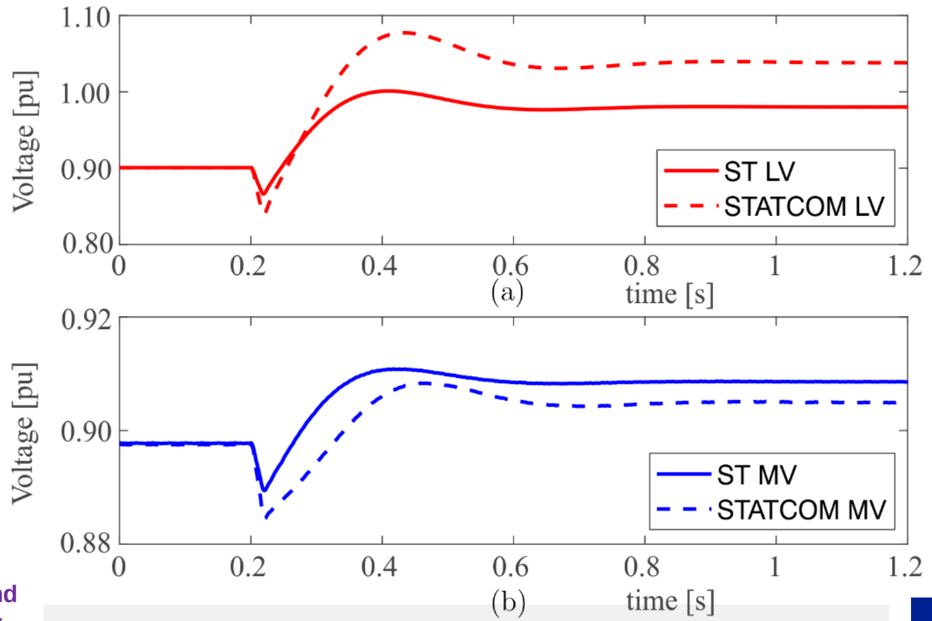
❖ Power flow control



System-level performance of voltage support is validated based on IEEE 34-bus model (bus 860: the ST, sized 200 kVA)

$$Q_{STATCOM} = 400kVar@MVac \quad Q_{ST,m} = Q_{ST,l} = 200kVar$$



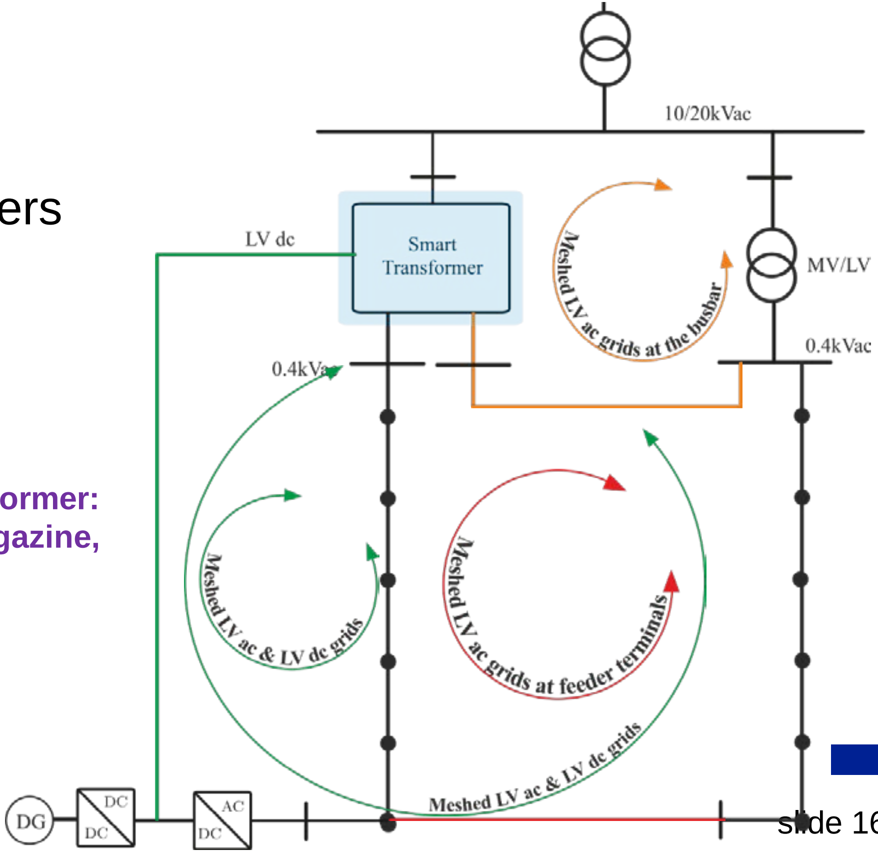
Simulation results voltage profiles before and after the reactive power step: (a) in LV grid and (b) in MV grid

R. Zhu, G. de Carne, F. Deng, M. Liserre, "Integration of large photovoltaic and wind system by means of smart transformer," IEEE Transactions on Industry Electronics, vol.64, no. 11, pp.8928-8938, Nov.2017.

Meshed Grid Operation

- ✓ Meshed 1: at LV ac bus
- ✓ Meshed 2: the terminal of LV ac feeders
- ✓ Meshed 3: LV dc and LV ac-1
- ✓ Meshed 4: LV dc and LV ac-2

M. Liserre, R. Zhu, C. Kumar, M. Langwasser "Smart Transformer: Operation in Meshed Grids" in IEEE Ind. Electronics Magazine, 2019.



Meshed LV ac Grids (@ end of feeders)

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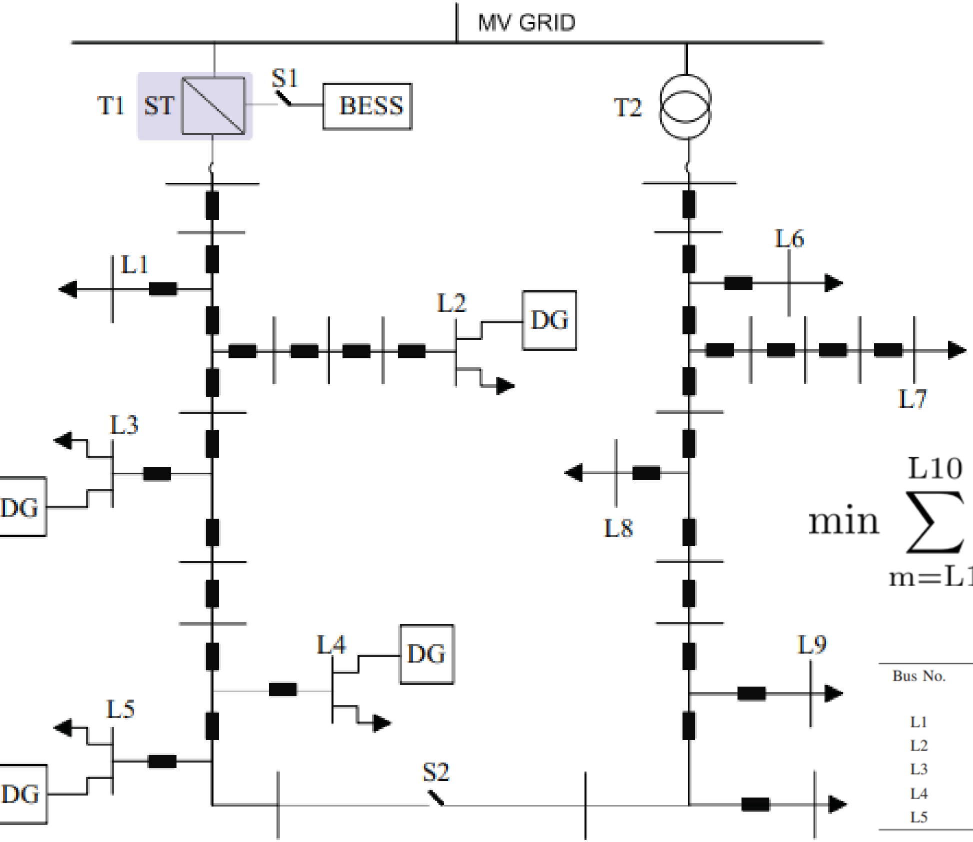


Optimal Objectives:

A. Power Balancing Control

$$P_{\mathrm{ST}} = P_{\mathrm{T2}}, Q_{\mathrm{ST}} = Q_{\mathrm{T2}}$$

B. Minimum voltage variation

$$k_{\mathrm{Q,m}} = \frac{\Delta v_{\mathrm{LV-ST}}}{\Delta Q_{\mathrm{LV-ST}}} \quad k_{\mathrm{P,m}} = \frac{\Delta v_{\mathrm{LV-ST}}}{\Delta P_{\mathrm{LV-ST}}}$$

$$\min \sum_{\mathrm{m=L1}}^{\mathrm{L10}} (\mathrm{v_{LV,m}} + \mathrm{k_{Q,m}} \Delta \mathrm{Q_{LV-ST}} + \mathrm{k_{P,m}} \Delta \mathrm{P_{LV-ST}} - \mathrm{v}^*)^2$$

TABLE I
LOAD OF FEEDER I

Bus No.	Peak penetraion		Low penetration	
	DG generation (kVA)	Load (kVA)	DG generation (kVA)	Load (kVA)
L1	0	10+j2	0	20+j4
L2	30	20+j4	10	30+j6
L3	10	20+j4	0	20+j4
L4	50	10+j2	25	20+j4
L5	100	20+j4	50	20+j4

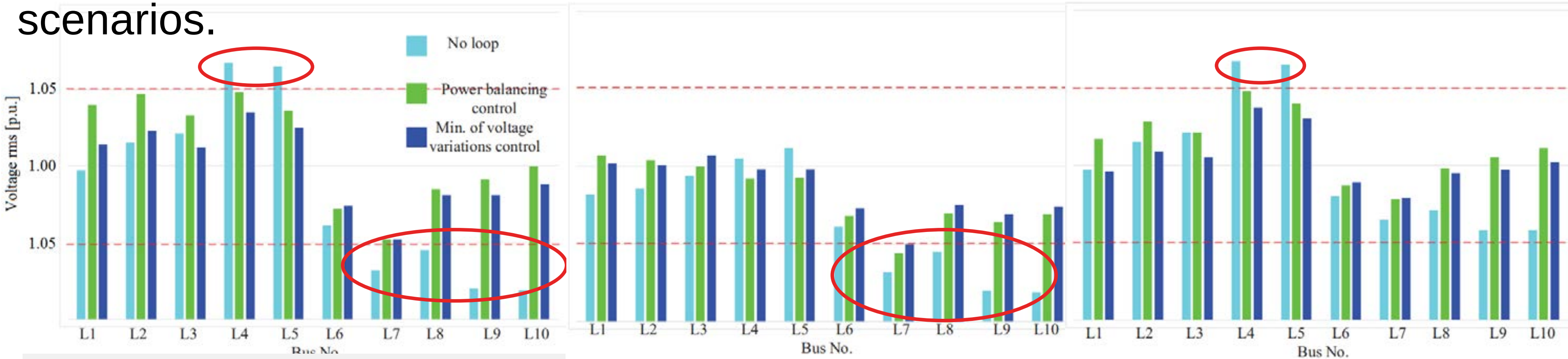
TABLE II
LOAD OF FEEDER II

Bus No.	Peak load (kVA)	Low load (kVA)
L6	30+j6	15+j3
L7	80+j16	40+j8
L8	50+j10	25+j5
L9	25+j5	12.5+j2.5
L10	60+j12	30+j6

C. Kumar, X. Gao, M. Liserre, "Smart Transformer-based Loop power controller in radial power distribution grid," In Proc. IEEE PES (ISGT-Europe) 2018.

Meshed LV ac grids (@ end of feeders)

LV ac feeder voltage profiles under three scenarios.



High DG penetration and high load demand

Low DG penetration and high load demand

High DG penetration and low load demand

C. Kumar, X. Gao, M. Liserre, "Smart Transformer-based Loop power controller in radial power distribution grid," In Proc. IEEE PES (ISGT-Europe) 2018.

. . . to integrate storage

Dispatching by means of Smart Transformer-based storage

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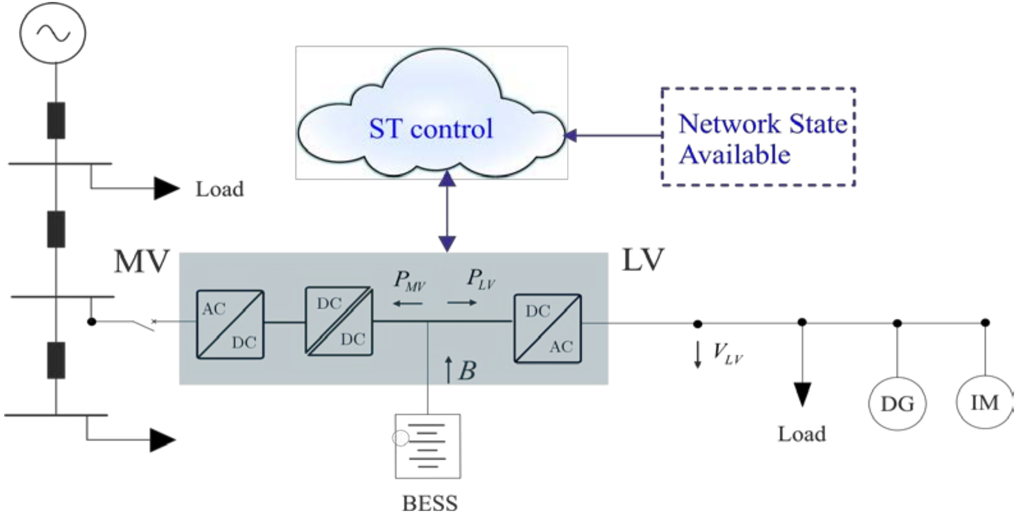
Voltage control in distribution systems is normally performed by on-load tap changer transformer and/or controllable DG. We consider a **smart transformer** where battery-based storage capacity is added on the DC bus (**ST + storage**) to extend the class of ancillary service it is possible to provide.

A **control strategy** for a ST + storage to:

1. **dispatch** the operation of the underneath distribution system;
2. **control the voltage** of the LV and MV grids on a best effort basis by exploiting **smart meters** and remote terminal units **measurements** and/or state estimation processes.



X. Gao, F. Sossan, K. Christakou, M. Paolone and M. Liserre, "Concurrent Voltage Control and Dispatch of Active Distribution Networks by means of Smart Transformer and Storage," in IEEE Transactions on Industrial Electronics

Conclusions regarding integration of storage through ST

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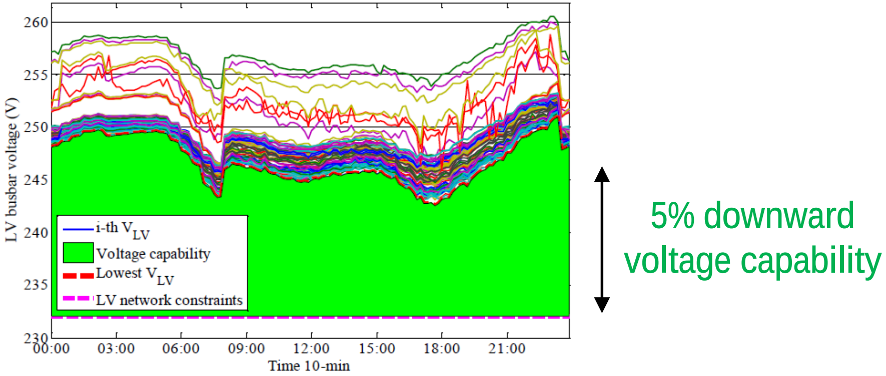
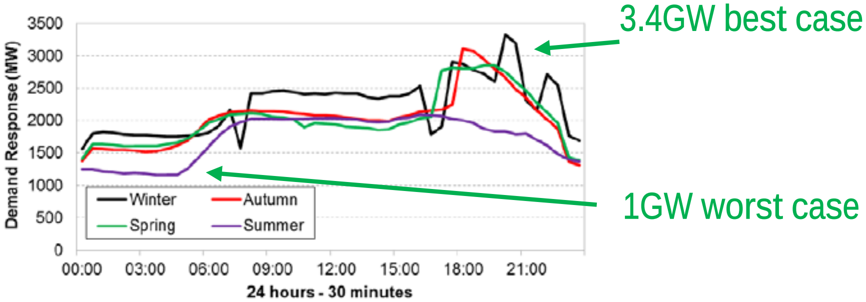
- A control strategy for a **smart transformer** with integrated storage to **stack** the following ancillary services:
  - dispatch the operation of the underneath distribution system;
  - voltage control of the MV network;
  - voltage control of the LV network.
- Simulations on the 34-bus IEEE test feeder and the CIGRE reference network for LV systems.
- Dispatched operation is attained with an mean absolute of 0.16 kW day, the average voltage deviation from the reference is reduced from 3.38% to 3.11% on the **MV** side, and 11.47% to 4.53% on the **LV**.
- **Noncomplex** architecture and IT infrastructure. All the control is localized at substation level, only **smart meters measurements** are required from remote units.

. . . to exploit ΔP capability of loads and dist. gen.

Load Demand Response by means of voltage control

- The load consumption is depending on the voltage → controlling the voltage also the load consumption can be shaped!
- UK case:
  - High availability to reduce voltage in LV grids
  - Load response to voltage variation more than linear (Kp≈1.3)
  - Demand response capability for UK varying from 1GW (worst scenario) to 3.4GW (best scenario)





A. Ballanti, L. Ochoa, "Off-Line Capability Assessment", WP2 Part A – Final Report.

Soft-load reduction

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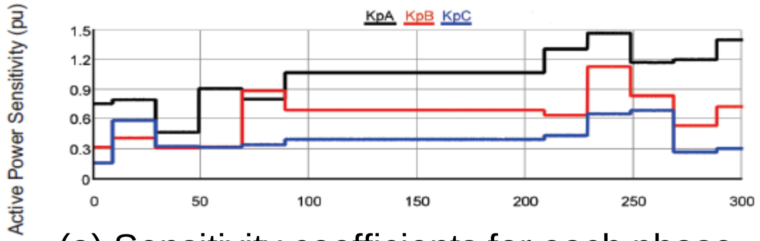
The voltage variation to impose, in order to get the desired power variation ΔP, is obtained:

$$\frac{V}{V_0} = 1 + \frac{\Delta P}{P K_p}$$

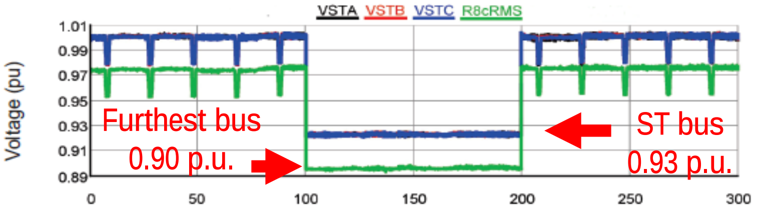
G. De Carne, S. Bruno, M. Liserre and M. La Scala, "Distributed On-Line Load sensitivity Identification by Smart Transformer and Industrial Metering," in IEEE Transactions on Industry Applications, 2019.

G. De Carne, G. Buticchi, M. Liserre and C. Vournas, "Load Control Using Sensitivity Identification by Means of Smart Transformer," in IEEE Transactions on Smart Grid, vol. 9, no. 4, pp. 2606-2615, July 2018.

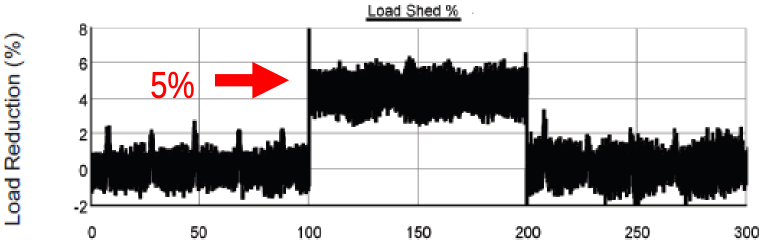
G. De Carne; M. Liserre; C. Vournas, "On-Line Load Sensitivity Identification in LV Distribution Grids," in IEEE Transactions on Power Systems, vol. 32, no. 2, pp. 1570-1571, March 2017.



(a) Sensitivity coefficients for each phase



(b) ST voltage and lowest grid voltage



(c) Load reduction (%)

Real Time Frequency Regulation service

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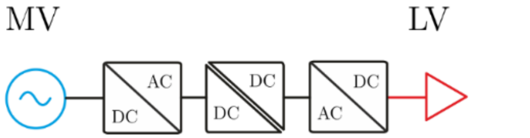
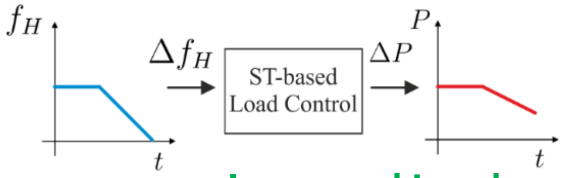
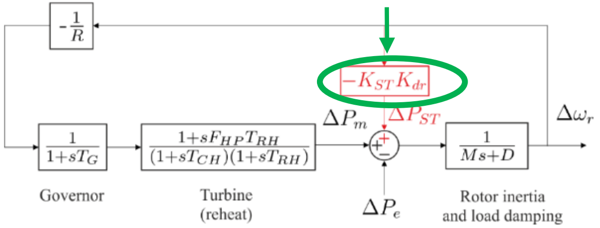


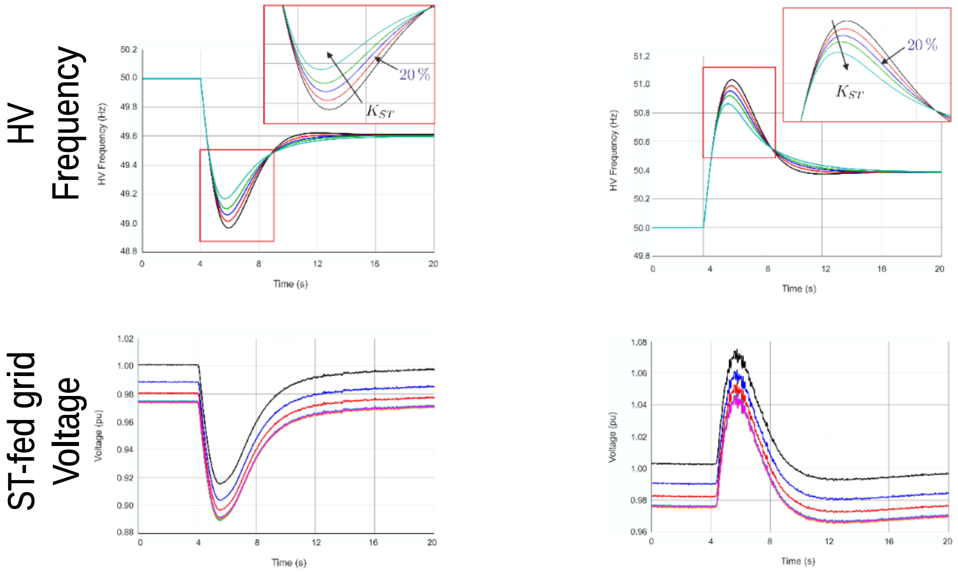


Increased Load Damping



Regulation downwards (+20% load)

Regulation upwards (-20% load)



G. De Carne, G. Buticchi, M. Liserre and C. Vournas, "Real-Time Primary Frequency Regulation using Load Power Control by Smart Transformers," IEEE Transactions on Smart Grid, 2019.

Real Time Frequency Regulation: Irish test case

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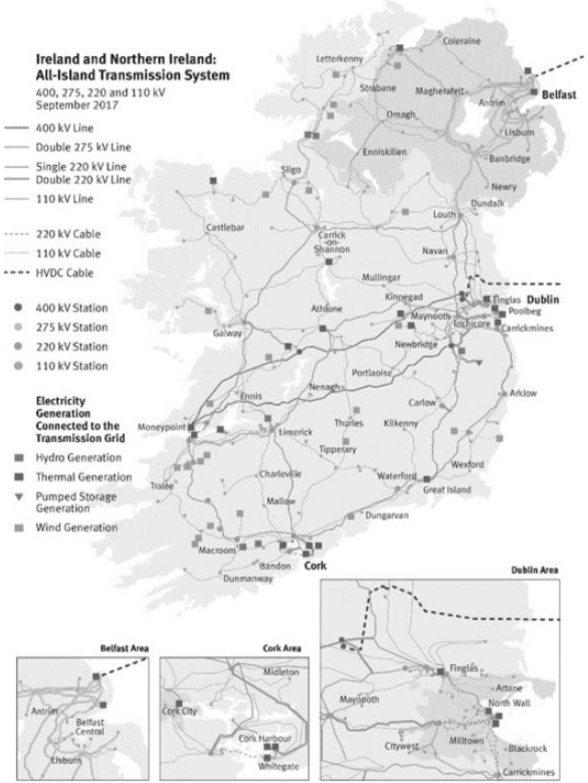
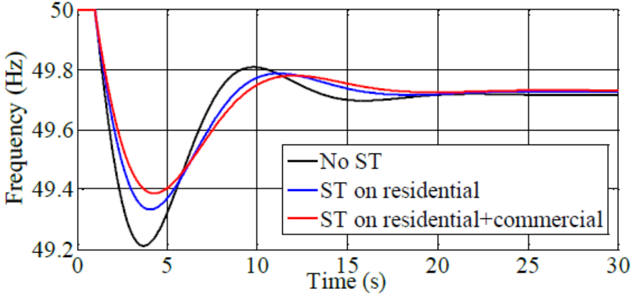
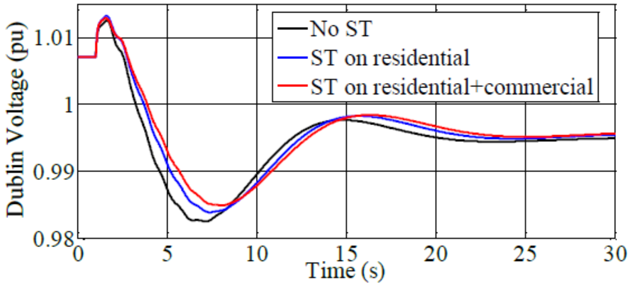


Impact on the Irish system

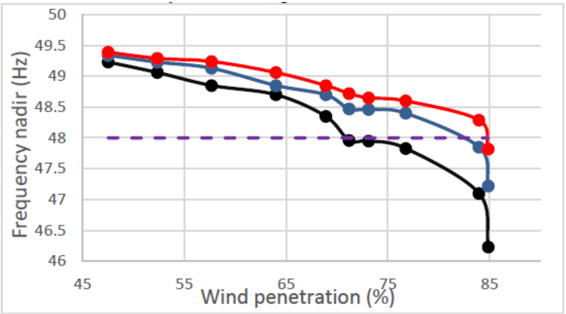


(a) Grid frequency



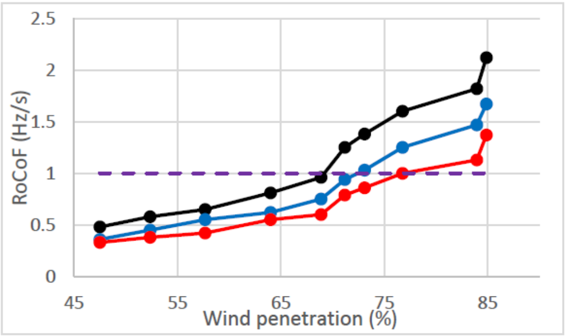
(b) Dublin bus voltage

Max Wind penetration



(a). Frequency nadir vs. wind penetration

No ST | ST on residential + commercial | ST on residential | Irish code limit

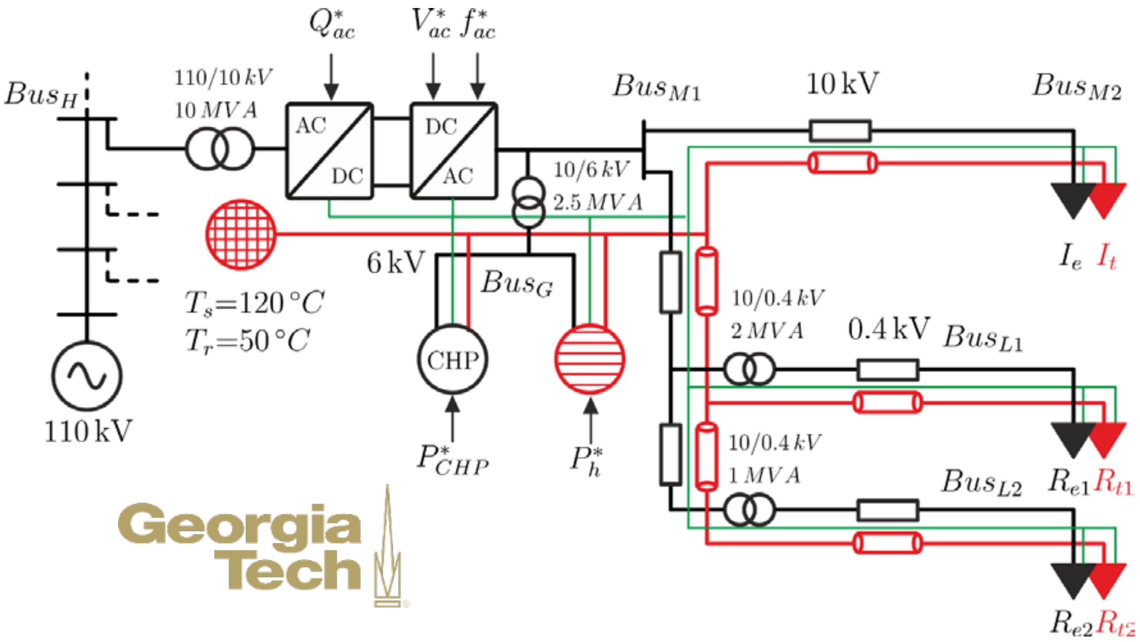


(b). RoCoF vs. wind penetration

University College Dublin
Ireland's Global University

. . . even in multimodal grids

Multimodal grid regulation



Electrical elements:
- B2B connection
- Industrial load (*Ie*)
- Residential loads (*Re1*, *Re2*)

Thermal elements
- Regional grid
- Industrial load (*It*)
- Residential loads (*Rt1*, *Rt2*)

Coupling elements
- CHP
- Electrical Heater

G. De Carne, M. Liserre, B. Xie, C. Zhong, S. A. P. Meliopoulos and C. Vournas, "Multiphysics Modelling of Asynchronously-Connected Grids," 2018 Power Systems Computation Conference (PSCC), Dublin, 2018, pp. 1-8.

Focusing on a 3-stage Solid-State Transformer

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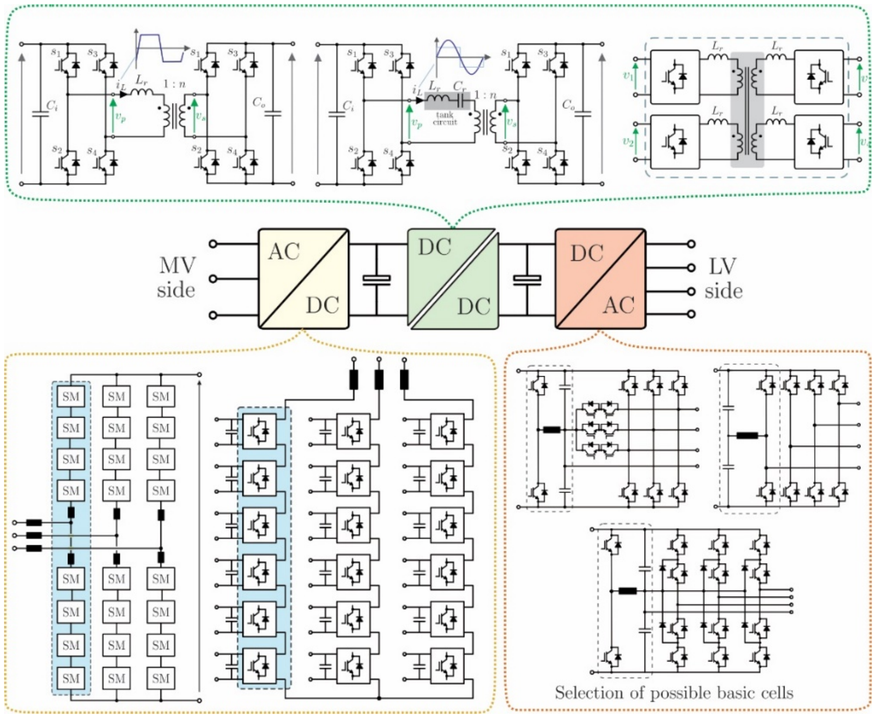
Smart Transformer Architectures Classifications



- **1st Stage - Medium Voltage (MV):**
  - Cascaded H-Bridge (CHB)
  - Modular Multilevel Converter (MMC)
- **2nd Stage - Isolated DC-DC:**
  - Modular
    - Dual-Active-Bridge (DAB)
    - Series-Resonant Converter (SRC)
  - Semi-Modular
    - Quadruple-Active-Bridge (QAB)
- **3rd Stage - Low Voltage (LV) :**
  - Voltage source inverter
  - NPC
  - T-type

MV-side inverter

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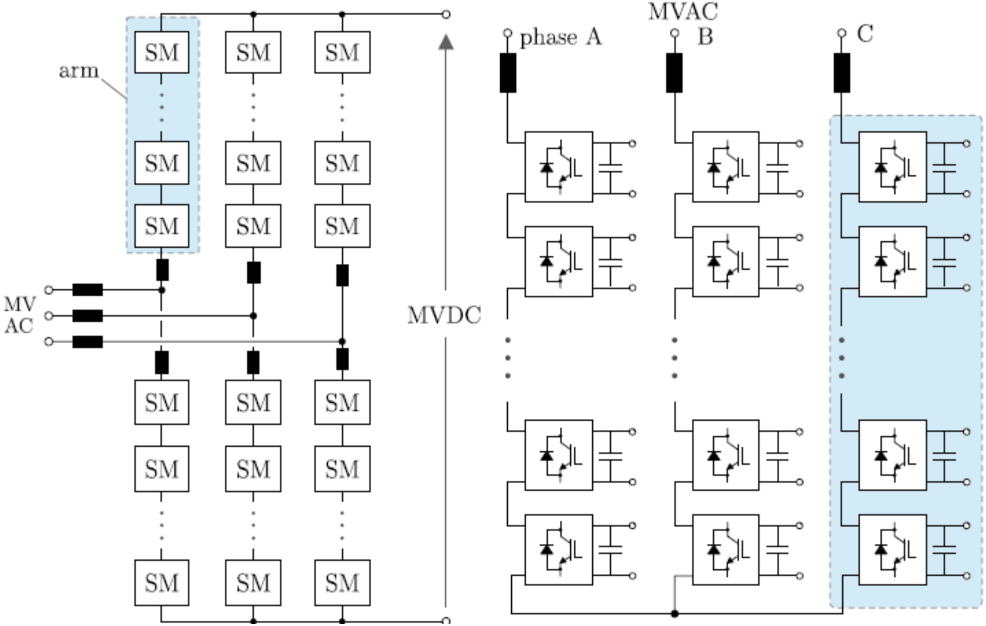
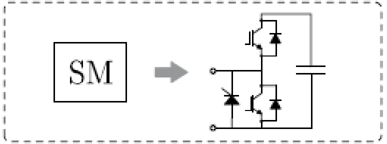
Modular Multitlvel Converter (MMC)

Cascaded H-Bridge (CHB)

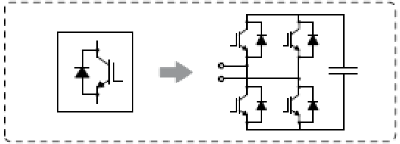


Possible basic cells:

Half-bridge



Full-bridge



MV-side inverter

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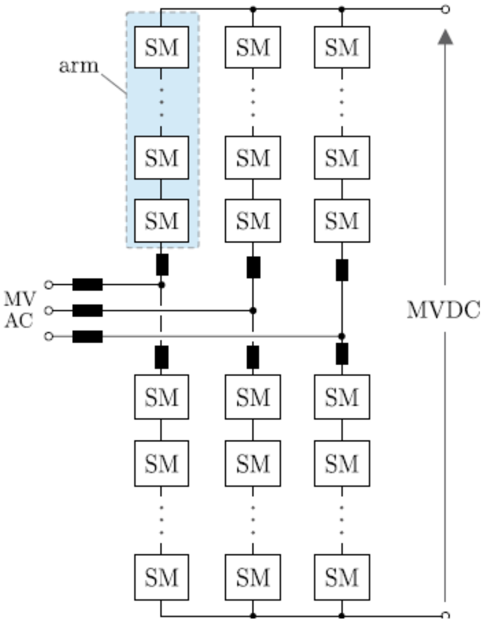
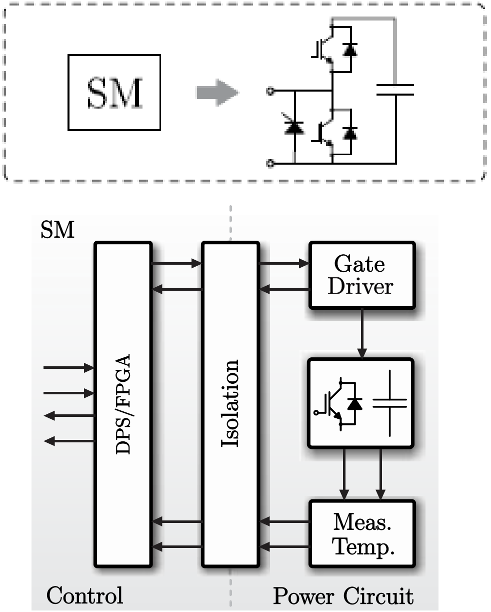
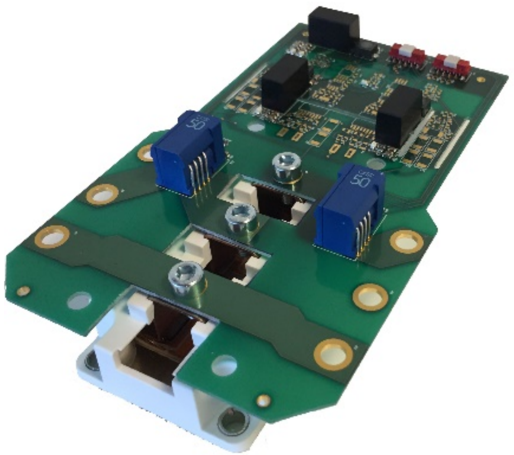
Advanced gate-driver design

(MMC)





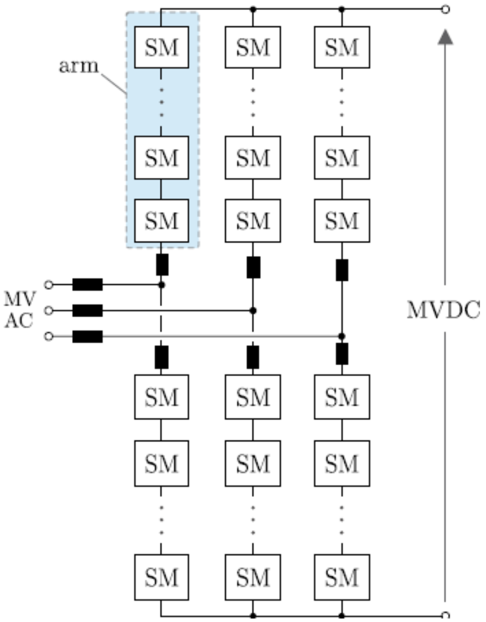
- 1.7kV dual IGBT Driving Capability
- Overcurrent Protection
- V_{CE} measurement
- Current Measurement
- 3 kV Isolation



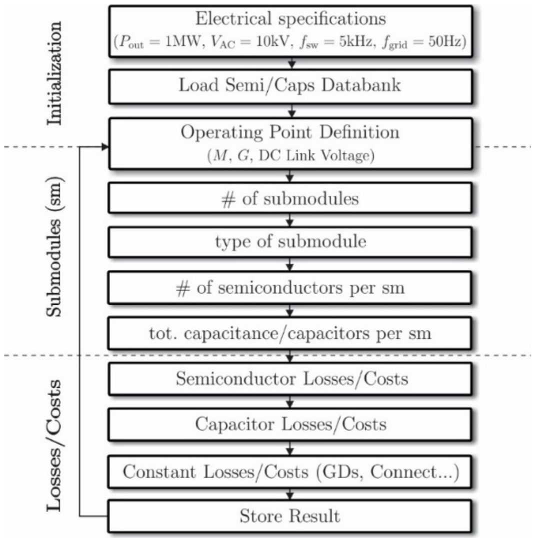
MV-side inverter

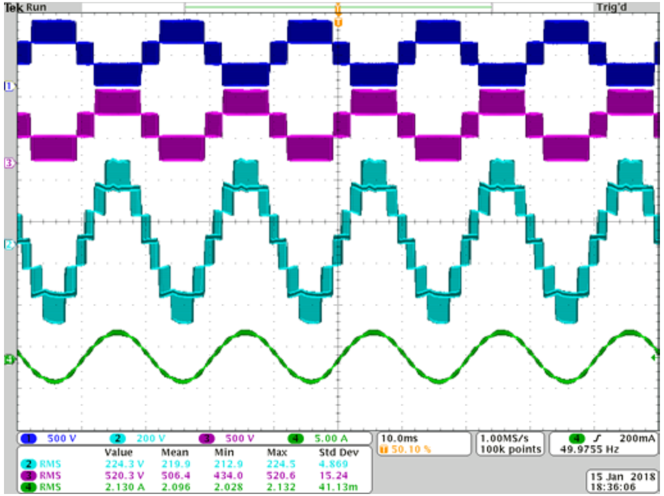
Optimum converter design

(MMC)



Optimization Routine





Pos arm volt **Neg arm volt**

Output volt **Output cur**

Stress Balancing in MMC Converters

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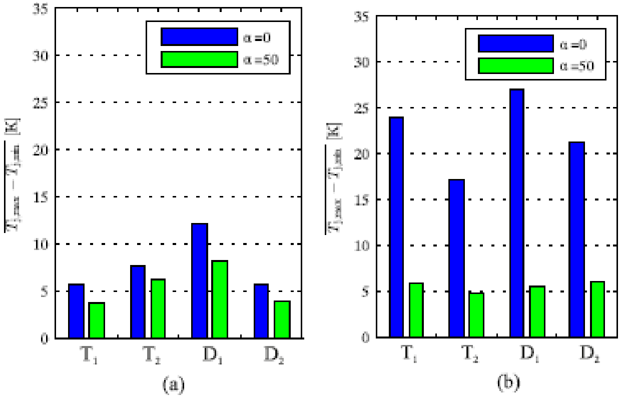
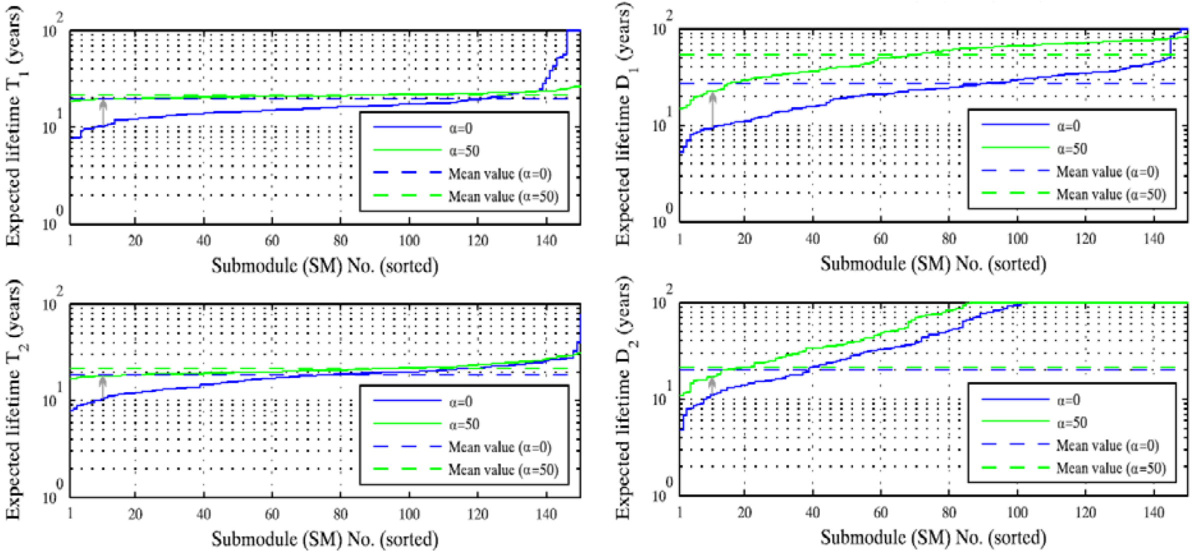


Maximum temperature difference (averaged) among all 150 SMs in the upper arm (phase 1). (a) OP1 (steady state: P_{grid}=300 MW, cos(φ)=0.95. (b) OP2 (steady state: Q_{grid}= 300 Mvar, Cos(φ)=0.



Lifetime expectation for the power semiconductors of all SMs in the upper arm (phase 1).

F. Hahn, M. Andresen, G. Buticchi, M. Liserre "Thermal analysis and balancing for modular multilevel converters in HVDC applications." IEEE Transactions on Power Electronics, vol. 33 No. 3, pp. 1985-1996, 2018.

Review on high efficiency dc-dc converter

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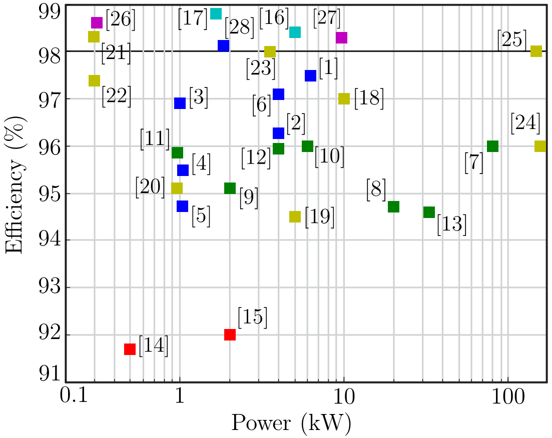
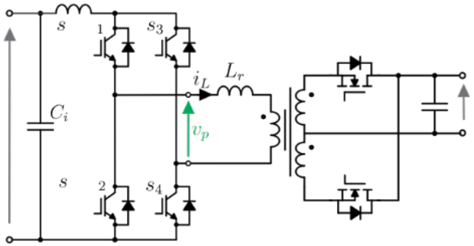
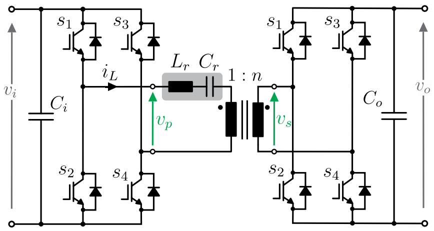
Relevant converters:



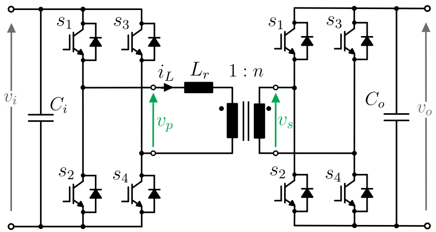
Phase-shift Full-Bridge



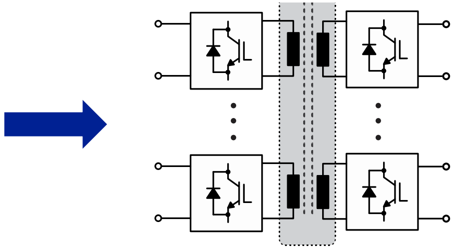
Series-Resonant Converter



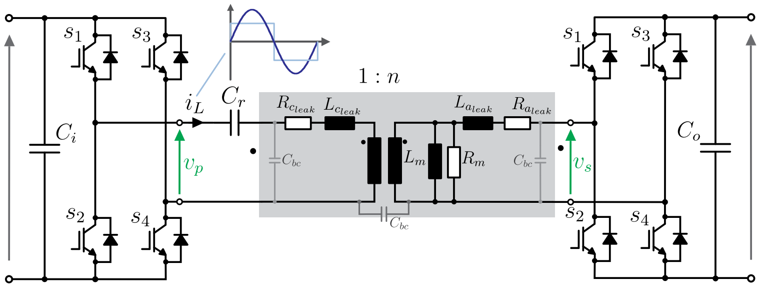
Dual-Active-Bridge



Multiple-Active-Bridge



Series-Resonant Converter



Target:

Efficiency

Reliability

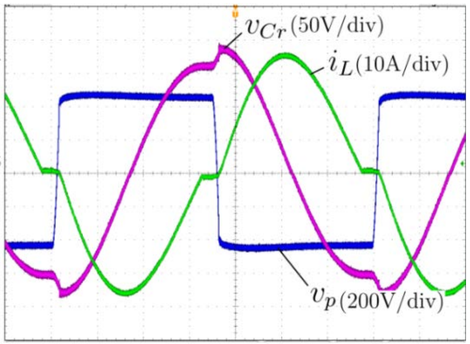
Accurate losses modeling

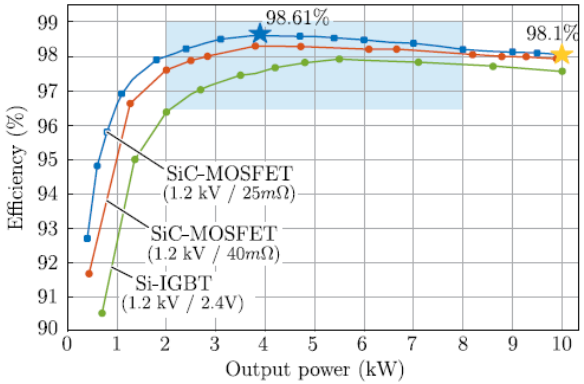
Automatic design - (optimum parameter selection)

Wideband gap devices

Fault tolerant topology

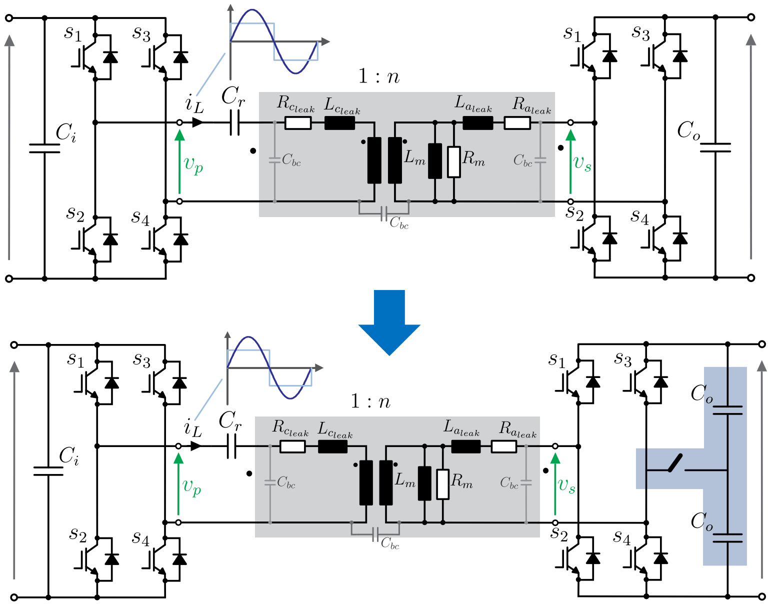
Lifetime devices considerations

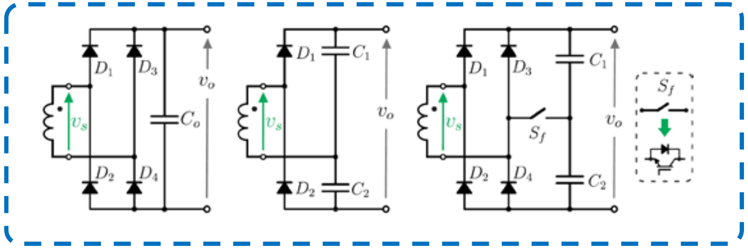


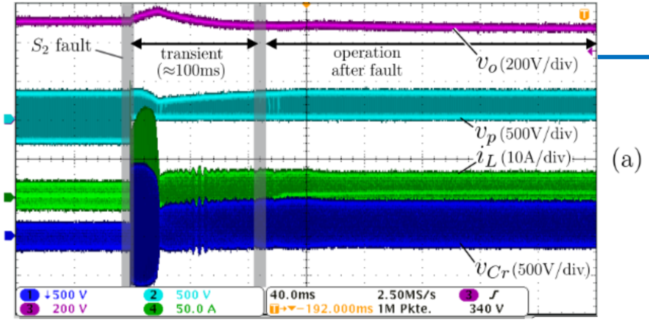


Series-Resonant Converter

Fault Tolerant Series-Resonant Converter







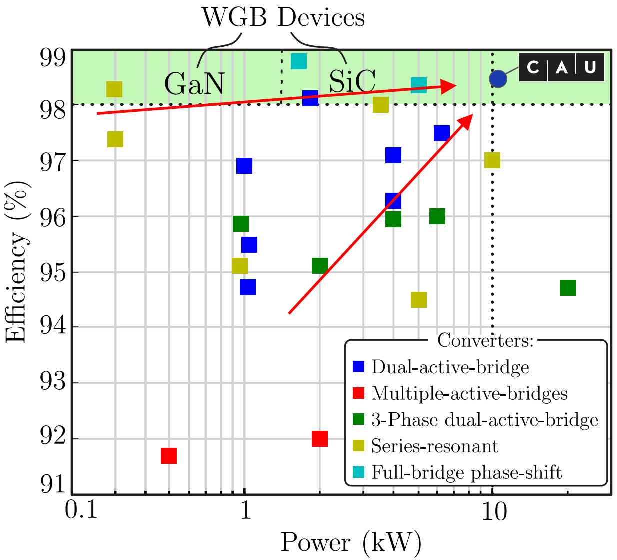
Regulated output voltage

L. F. Costa, G. Buticchi, M. Liserre, "Highly Efficient and Reliable SiC-Based DC-DC Converter for Smart Transformer" in IEEE Transactions on Industrial Electronics, vol. 64, no. 10, pp. 8383-8392, Oct. 2017.

Series-Resonant Converter

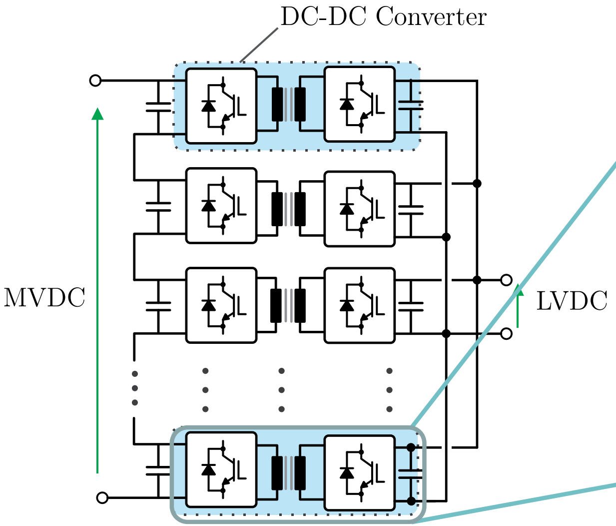
Christian-Albrechts-Universität zu Kiel

Overview of basic dc-dc topologies suitable to be used as a building block of the ST dc-dc stage



Influence on efficiency:

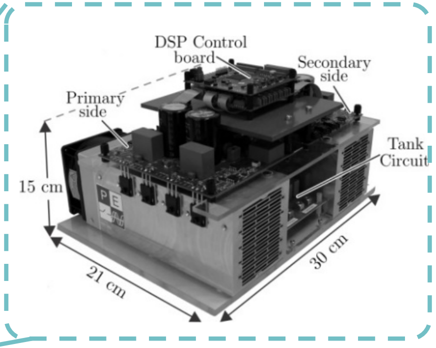
- Wideband-gap devices plays an important role
- Design: correct parameters selection



CAU Kiel dc-dc converter

Max Eff = 98.61%

Eff (@P_{max}) = 98.1%

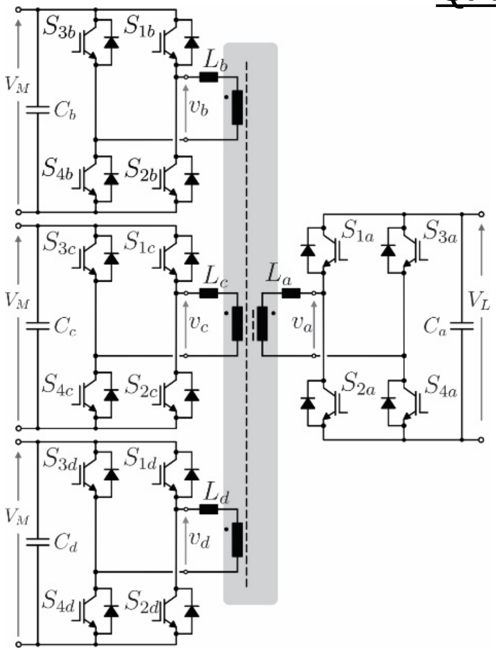


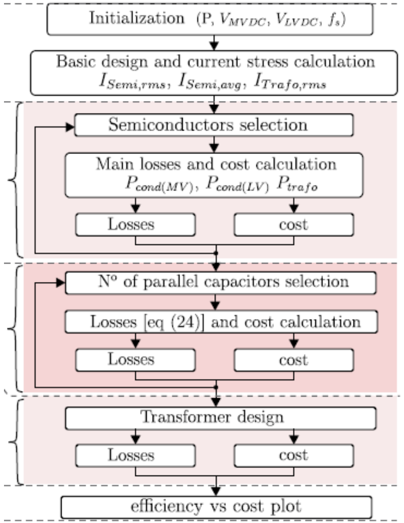
L. F. Costa, G. Buticchi, M. Liserre, Highly Efficient and Reliable SiC-based DC-DC Converter for Smart Transformer, in IEEE Transactions on Industrial Electronics

Quadruple Active Bridge

Christian-Albrechts-Universität zu Kiel

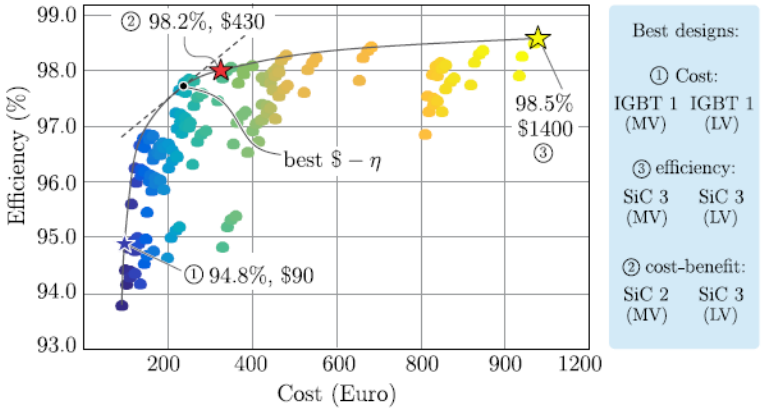
QAB Converter





Multi-objective design:

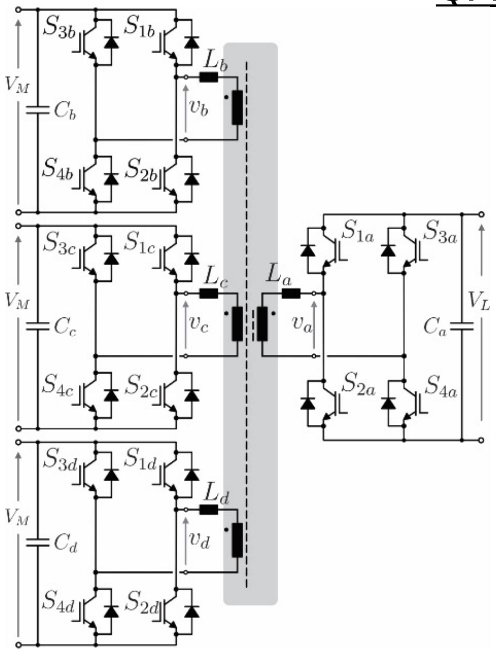
Target: ⬆ Efficiency & cost ⬇

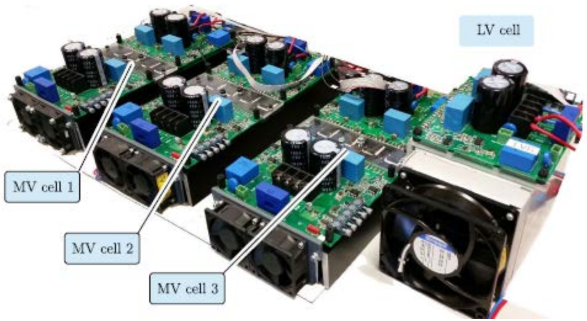


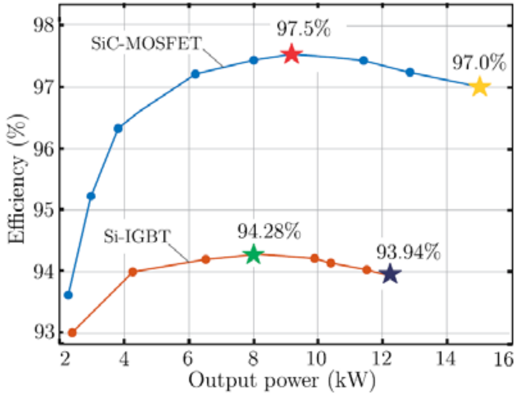
L. F. Costa, G. Buticchi and M. Liserre, "Optimum Design of a Multiple-Active-Bridge DC–DC Converter for Smart Transformer," in IEEE Transactions on Power Electronics, vol. 33, no. 12, pp. 10112-10121, Dec. 2018.

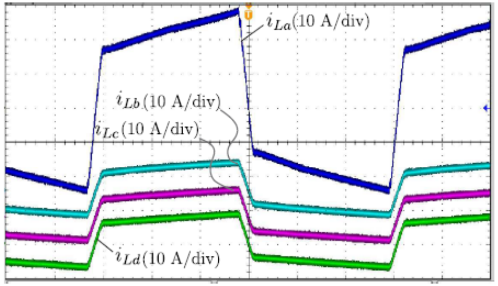
Quadruple Active Bridge

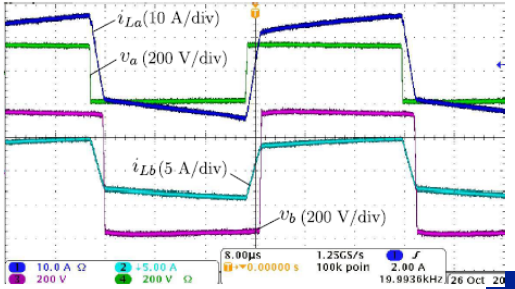
QAB Converter











Quadruple Active Bridge

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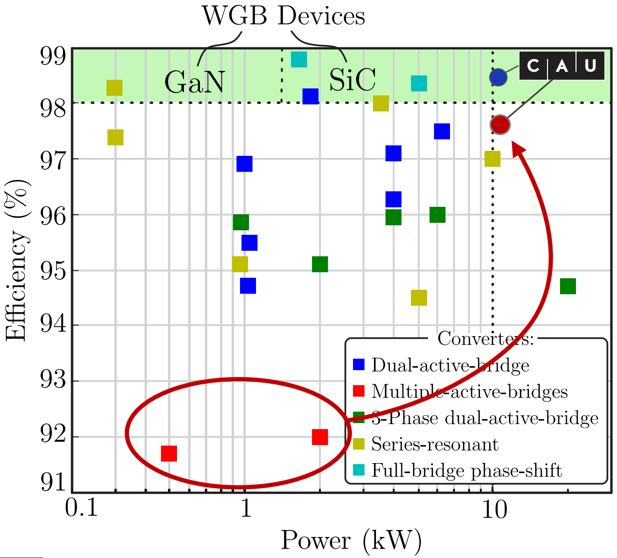
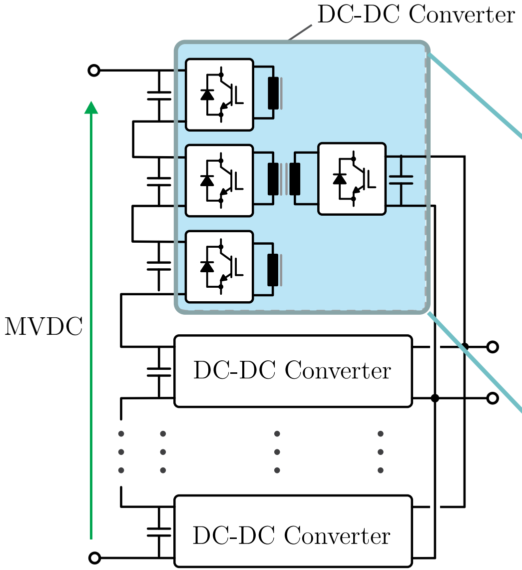
Overview of basic dc-dc topologies suitable to be used as a building block of the ST dc-dc stage



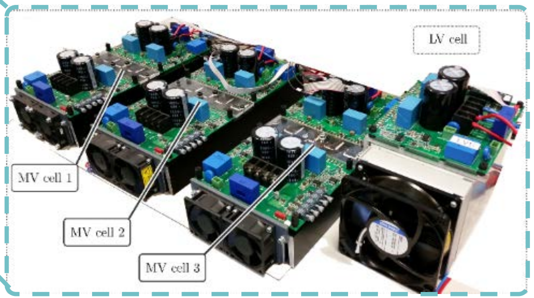
Influence on efficiency:

- Wideband-gap devices plays an important role
- Design: correct parameters selection



CAU Kiel dc-dc converter

Max Eff = 97.5% **(SiC)**



Highest efficiency of a MAB converter

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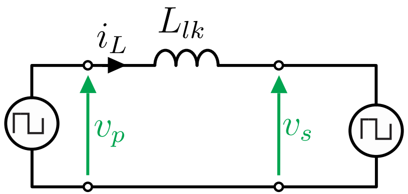
DC/DC for the Smart Transformer

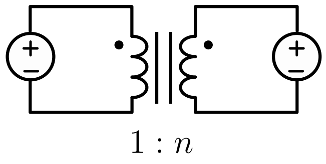
Dual/Quad Active Bridge



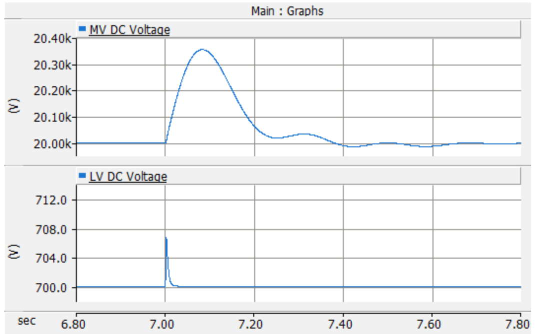
$$P = \frac{n v_{in} v_{out}}{2\pi L_{lk} f_{sw}} \varphi \left(1 - \frac{\varphi}{\pi}\right)$$

Serie Resonant Converter

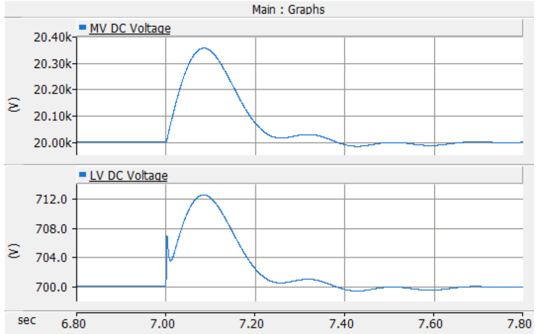
dc transformer



$$V_o = nV_i$$



DAB		VSI
↑	**controlability**	↓
↑	**Voltage and current sensors**	↑
↓	**simplicity**	↑
DAB	**LVDC link control**	**VSI**



DAB or QAB ?

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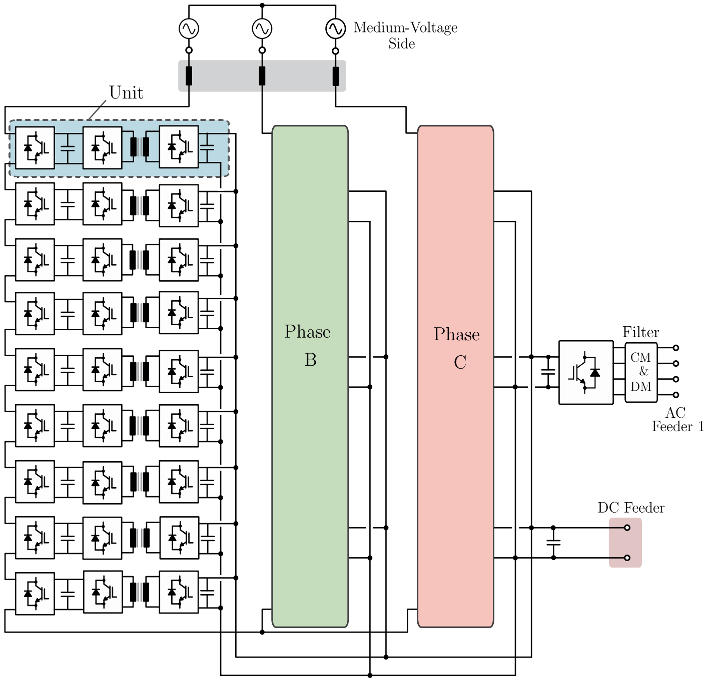
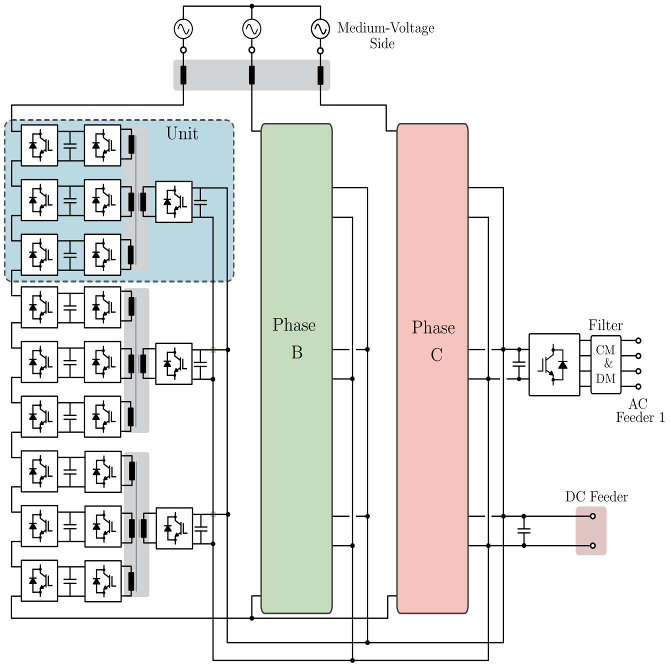




DAB or QAB ?

Table III. Comparative analysis of the DAB and QAB converters

Parameter	DAB	QAB	
	LV side	MV side	LV side
Number of cells	27	27	9
IGBT current rating	50 A	50A	150A
IGBT voltage rating	1.2 kV	1.7 kV	1.2 kV
Nº semiconductor	108	108	36
Total semiconductor cost	U$ 4336,74	U$ 6480	U$ 1986,66
Auxiliary Power Supply	27	27	9
Gate Driver Unit	54	54	18
Control and comm system	27	27	9
Nº of MFT	27	9	
Isolation requirement	10 kV (prim-sec)	10 kV (prim-sec) 1.2 kV (sec-sec)	
TOTAL COST	**U$ 10816,74**	**U$ 8466,66**	

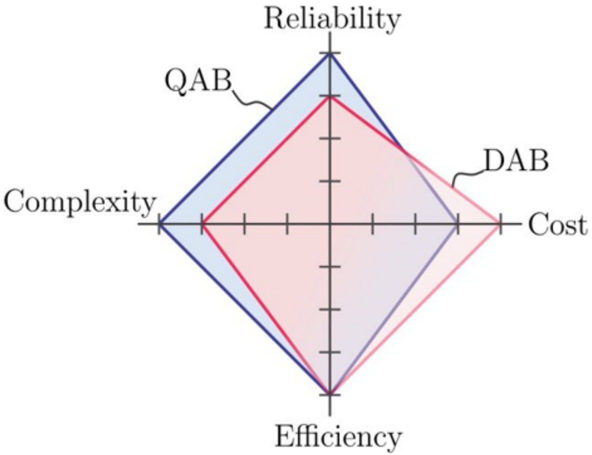
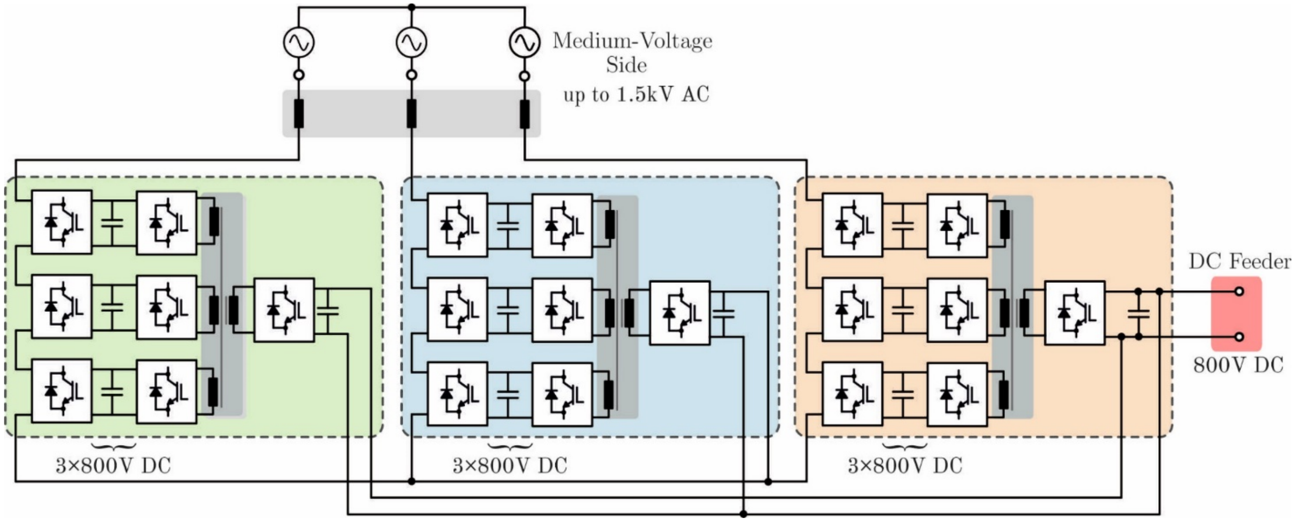


Fig. 4. Qualitative comparison of QAB and DAB performance characteristic.



Specification of the System:

Three-phase system

Output power:
100 kVA

MV voltage (line-to-line):
2.6 kV rms

LV voltage:
800 Vdc

Unit Power:
30 kW

Scaled Prototype: results

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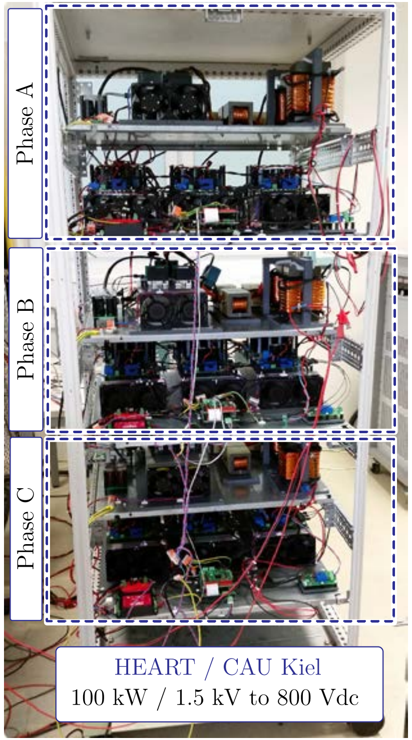
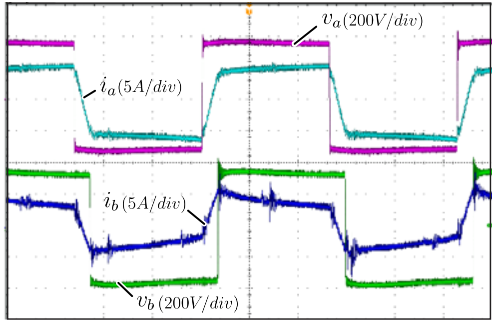
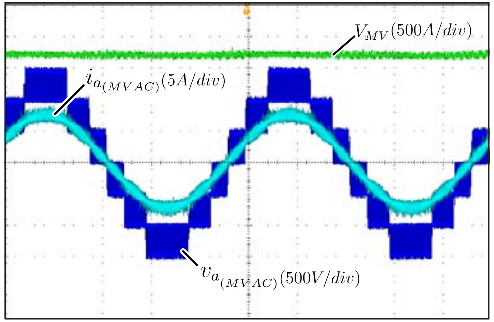
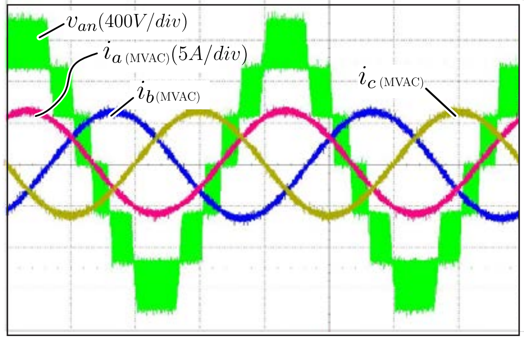
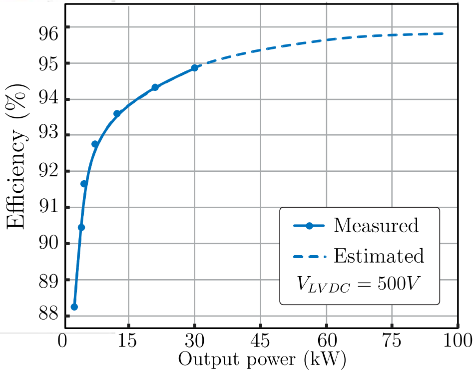


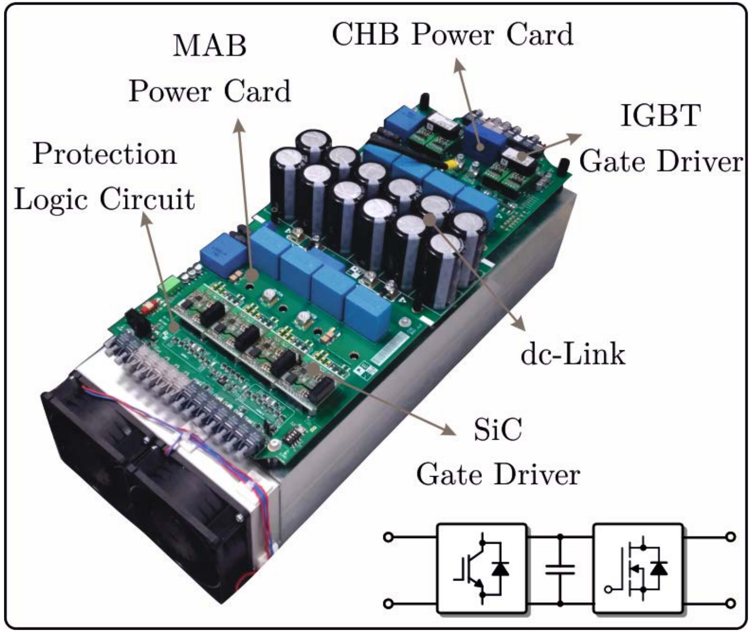


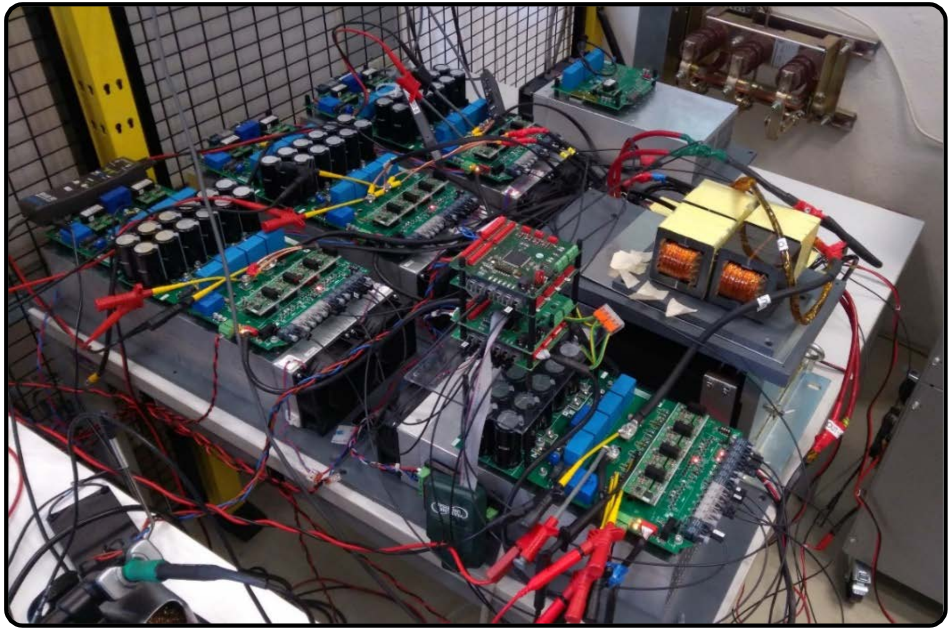




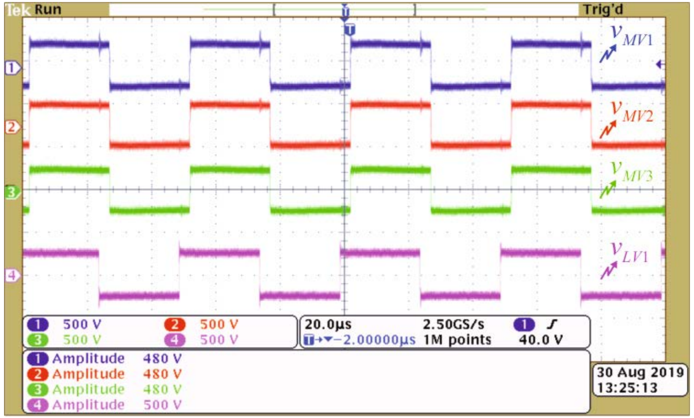


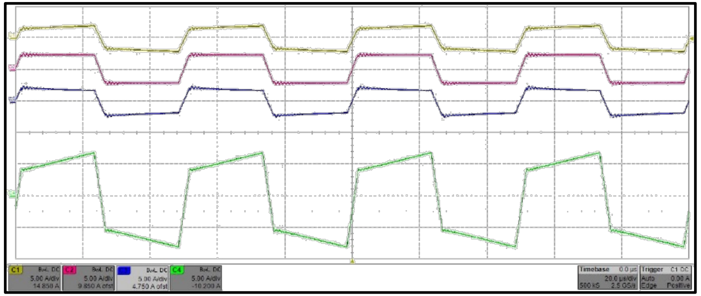
Scaled Prototype: results

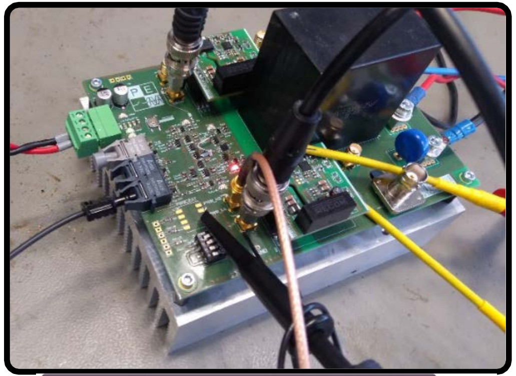


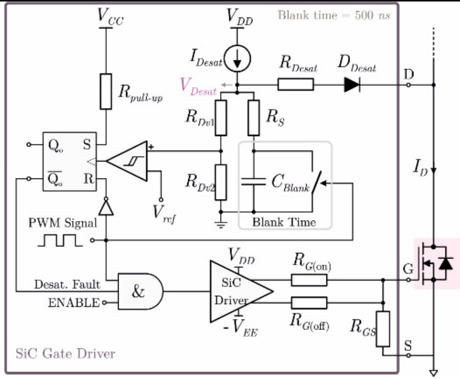


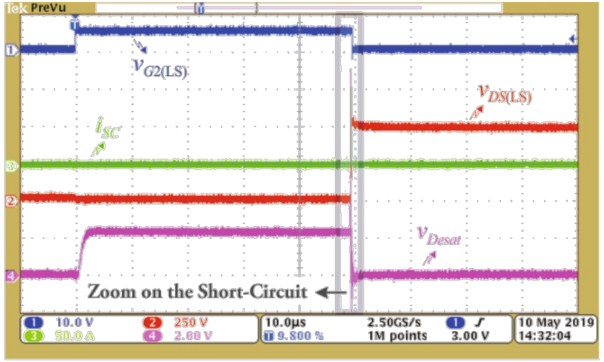
Scaled Prototype: results

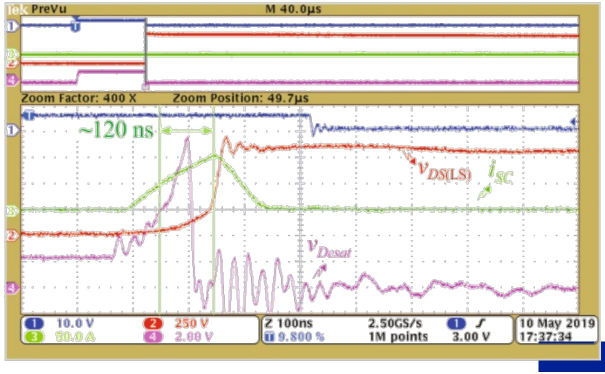








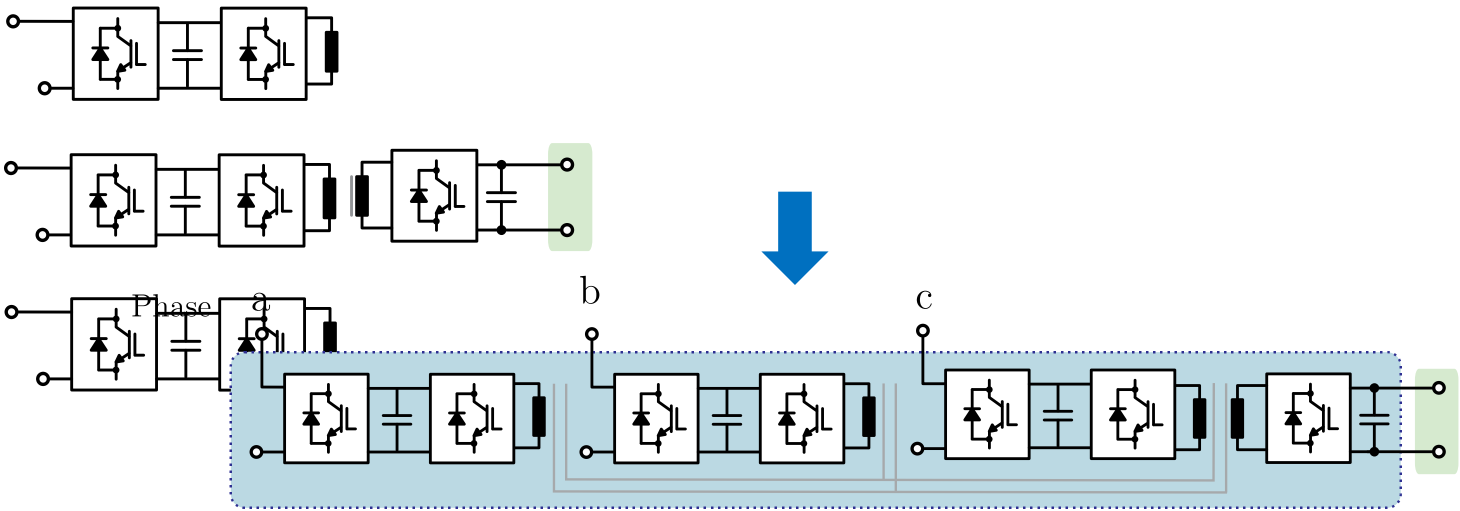




New Interleaved solution

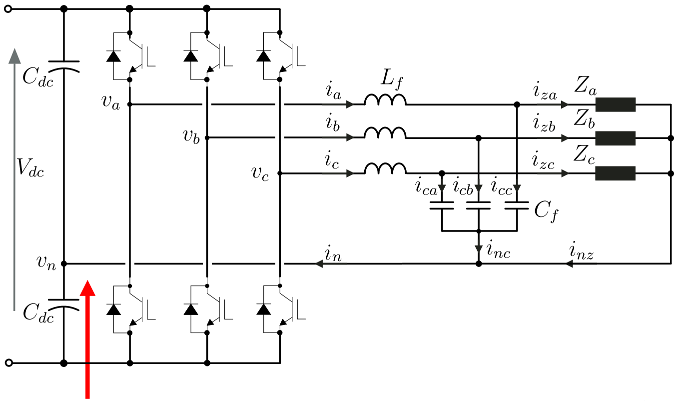
Christian-Albrechts-Universität zu Kiel

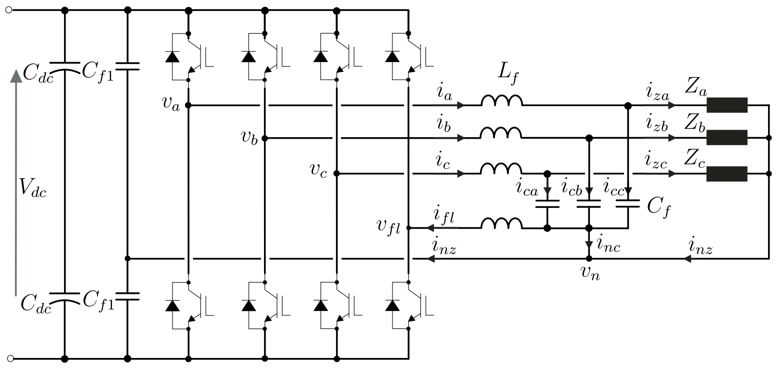
Same unit circuit, but… **NEW configuration**



LV-side inverter

3-leg inverter VS 4-leg inverter





connection
to mid point
is critical

- ✓ common mode in LV-grid
- ✓ dc-link capacitors lifetime
- ✓ power quality

+ filter
+ mod. strategy

R. Zhu, G. Buticchi, M. Liserre "Investigation on Common Mode Voltage Suppression in Smart Transformer-fed Distributed Hybrid Grids", IEEE Transactions on Power Electronics.

LV-side inverter

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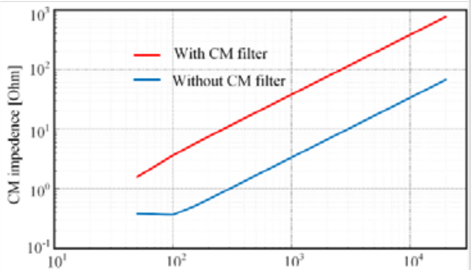
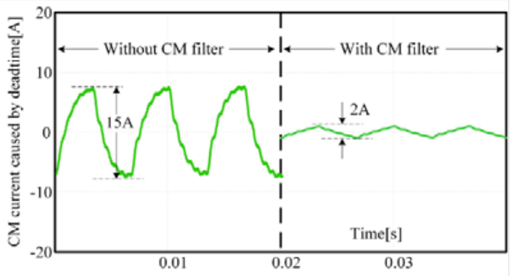
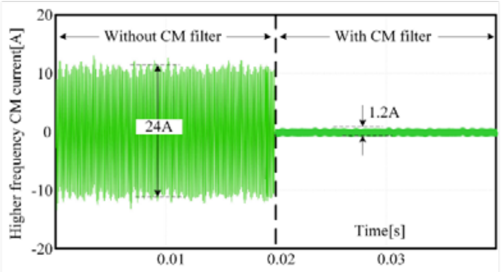
Solution 1: CM filter-based suppression (CM current caused by deadtime and witching frequency)



CM impedance w/wo CM filter

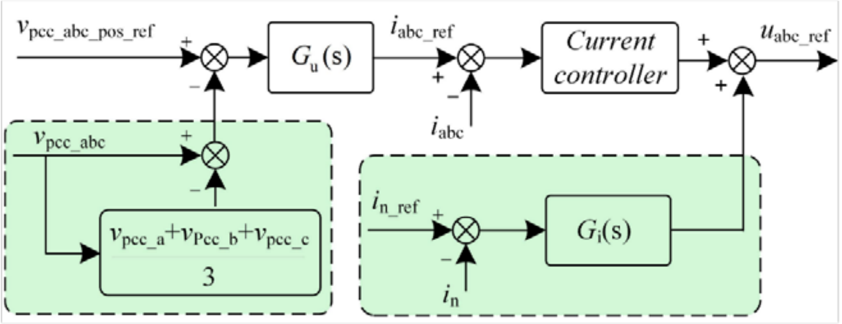


CM current caused by deadtime

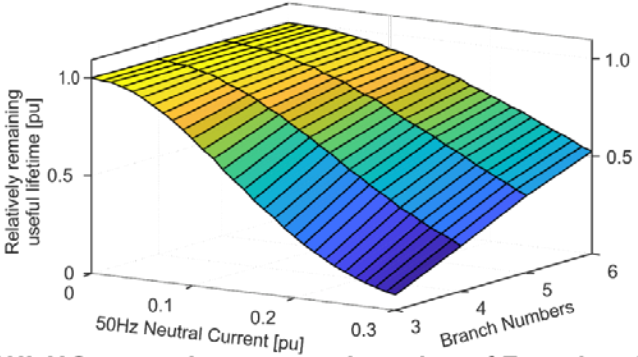


CM current caused by switching frequecy

Solution 2: Neutral current control-based suppression (CM current caused by unbalanced loads)



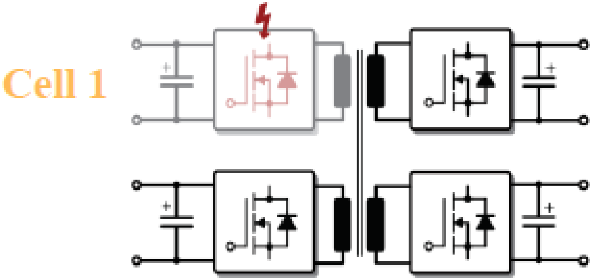
Block Diagram of Neutral current Control

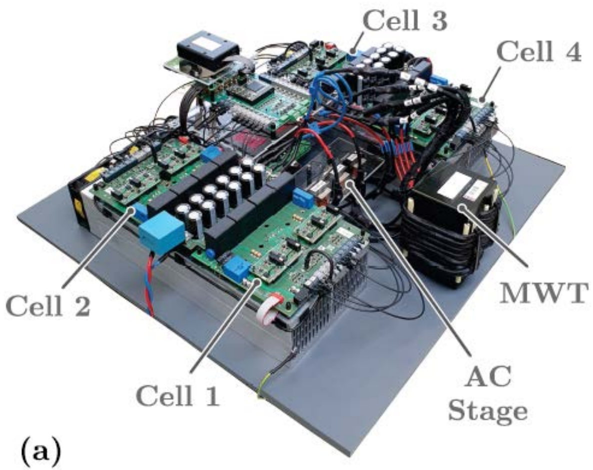


RUL V.S. neutral current and number of Ecap. brach

Handling faults . .

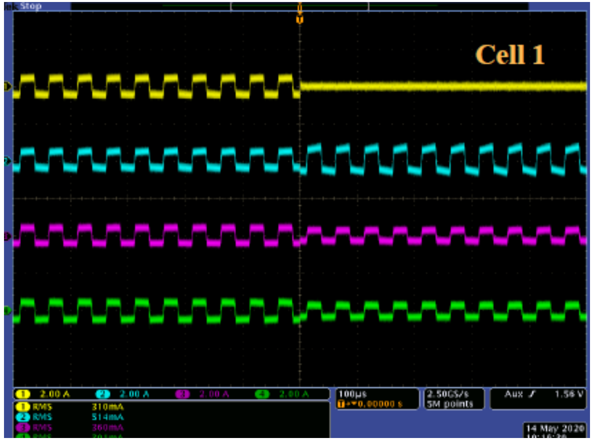
U-Heart: Fault tolerant DC/DC converter



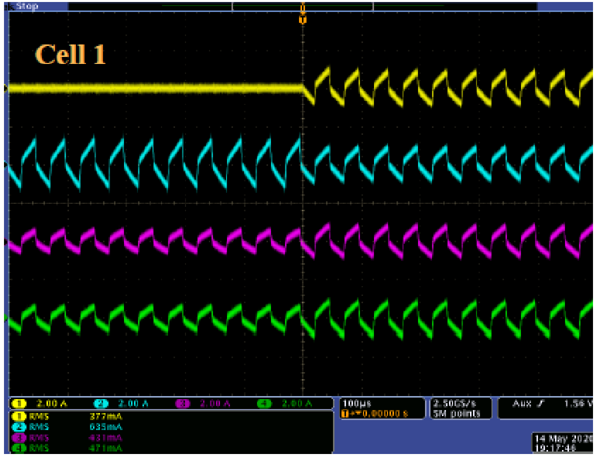


(a)

Fault detection and isolation



Fault clearance and possible reconfiguration



Fault problems in a ST-based grid

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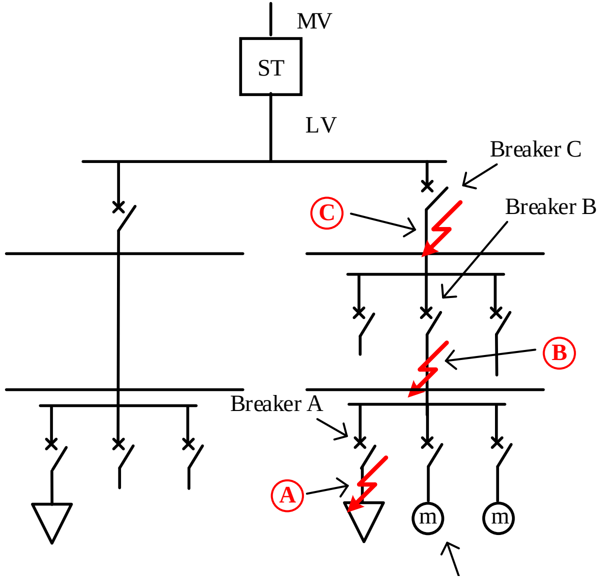
Faults in ST-fed grids:

- high short circuit currents
  - the ST behaves as constant voltage source after the fault due to the energy stored in passive components (e.g., capacitor filter);
- limited overload capability
  - the converter protect itself opening the circuit far before the breaker relays see the fault → vertical selectivity difficult to handle;



G. De Carne, M. Langwasser, R. Zhu and M. Liserre, "Smart Transformer-Based Single Phase-To-Neutral Fault Management," in IEEE Transactions on Power Delivery, vol. 34, no. 3, pp. 1049-1059, June 2019.

R. Zhu, M. Liserre, "Control of Smart Transformer under Single-Phase to Ground Fault Condition" IEEE Transactions on Power Electronics.

Operations with a faulty-phase

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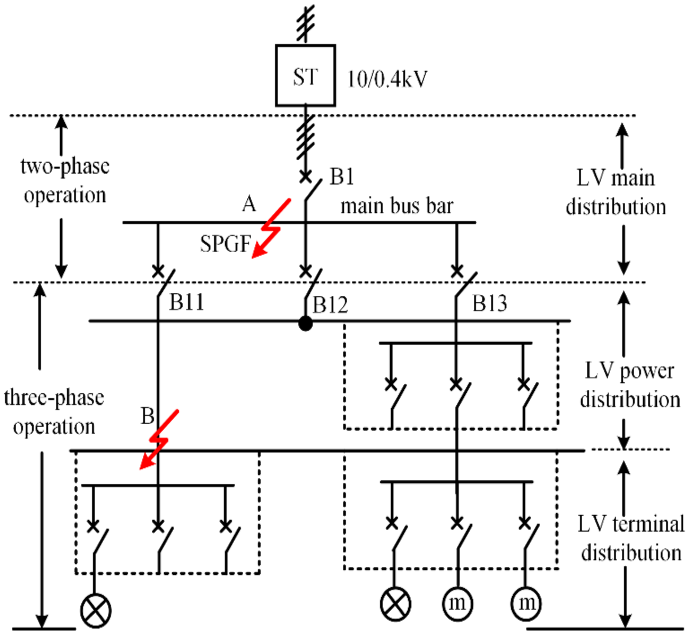
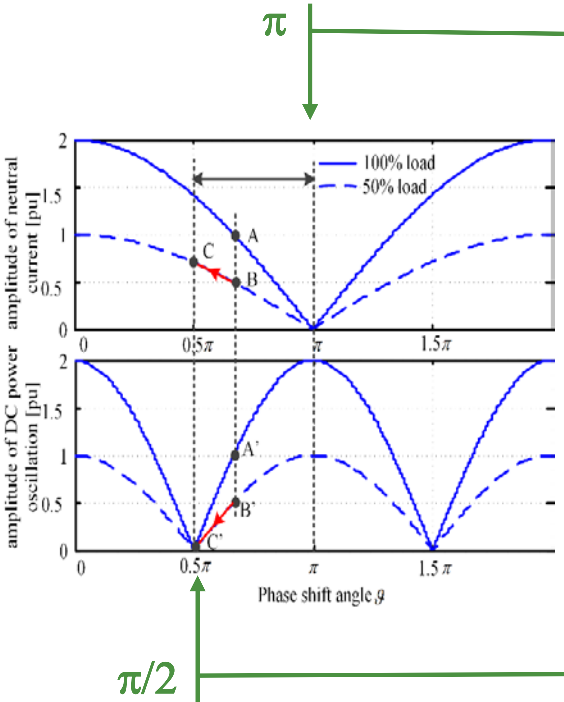
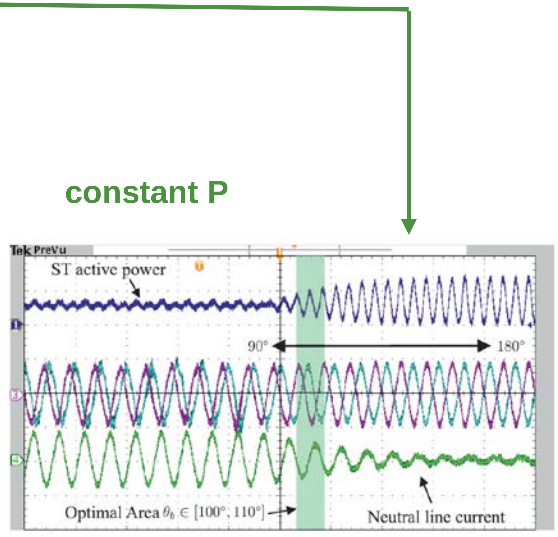
Reduce the impacts of Single-phase faults on the healthy phases as much as possible.

Neutral line current control under different load conditions





constant P



minimal neutral current

ST-overloadcurrent Control

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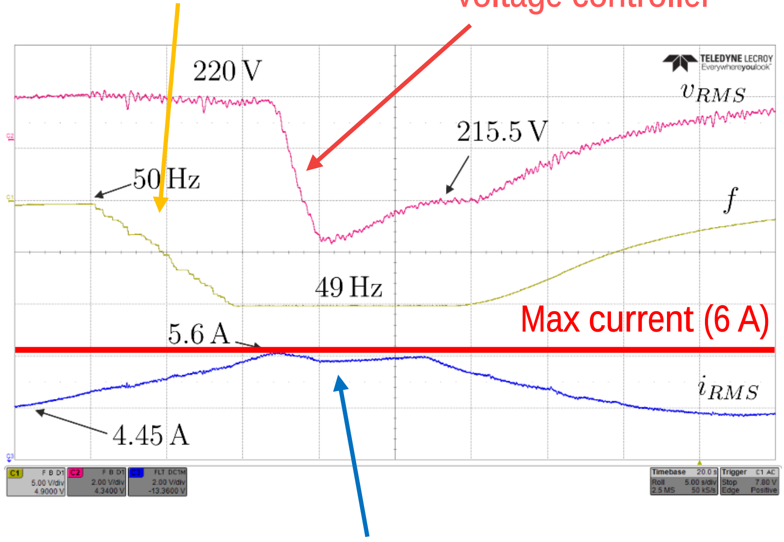
X The semiconductor devices have limited overload capability:

- High current → High temperature → components fault.

✓ The ST can:

- Vary the voltage → interacts with voltage-dependent loads
- Vary the frequency → interacts with generators droop controller
- Change the waveform → square-wave
- Regulate the voltage to reduce the current



G. De Carne, R. Zhu, M. Liserre, "Method for controlling a grid-forming converter, computer program and grid forming converter", 5979-008 EP-1.

. . . and the challenge of reliability/availability . . .

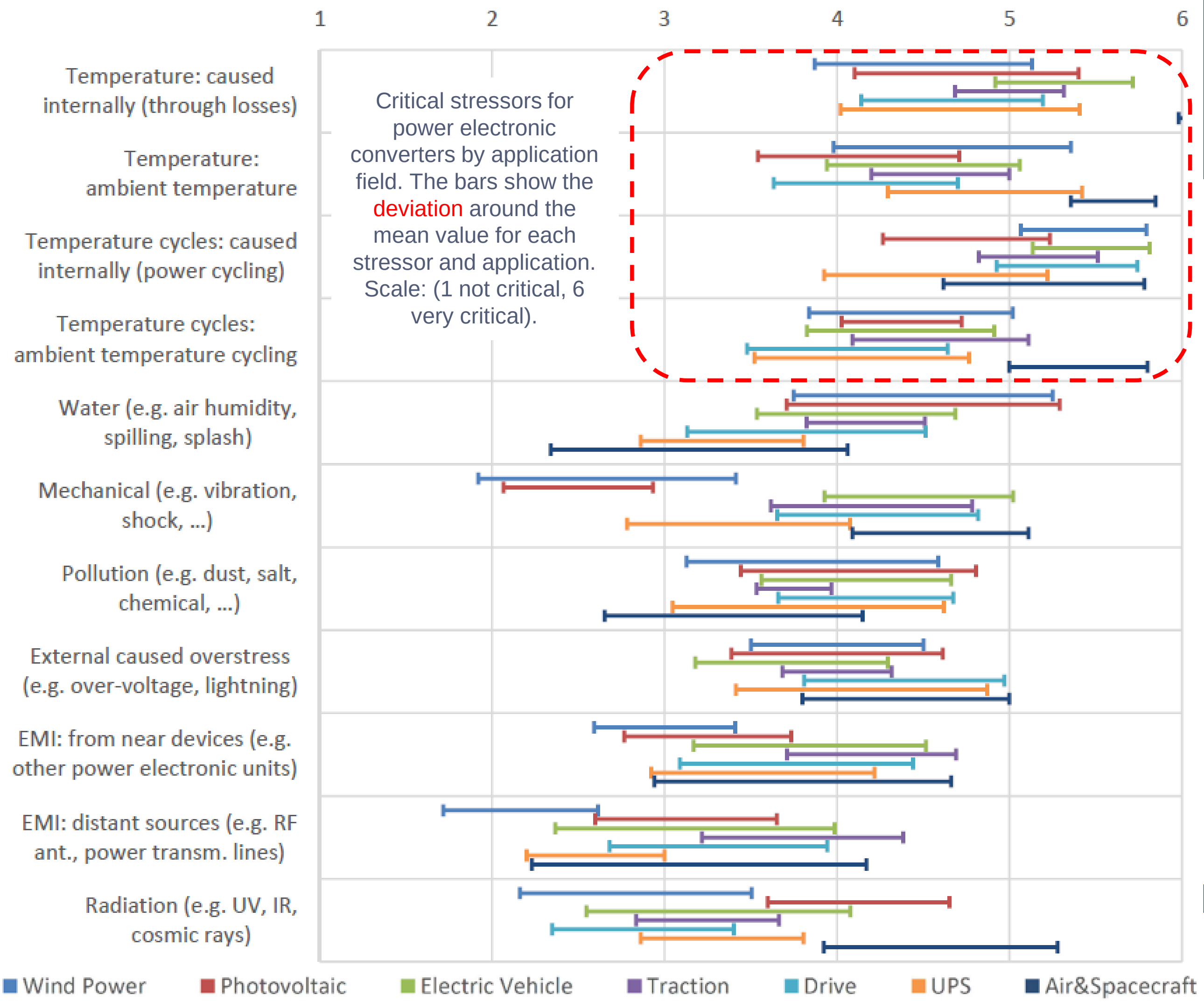
Maintenance of Traditional vs Smart Transformer

- **Traditional Transformer:**
  - Less prone to failure (expected yearly or biannual inspections)
  - Spare parts are available and maintenance can be executed relatively easily
- **Solid-state Transformer:**
  - Semiconductors and capacitors are more prone to failure
  - Spare parts can not be easily substituted
- **Smart Transformer:**
  - Prognostic and Maintenance (sensors, soft-computing and power routing)
  - Fault-handling capability

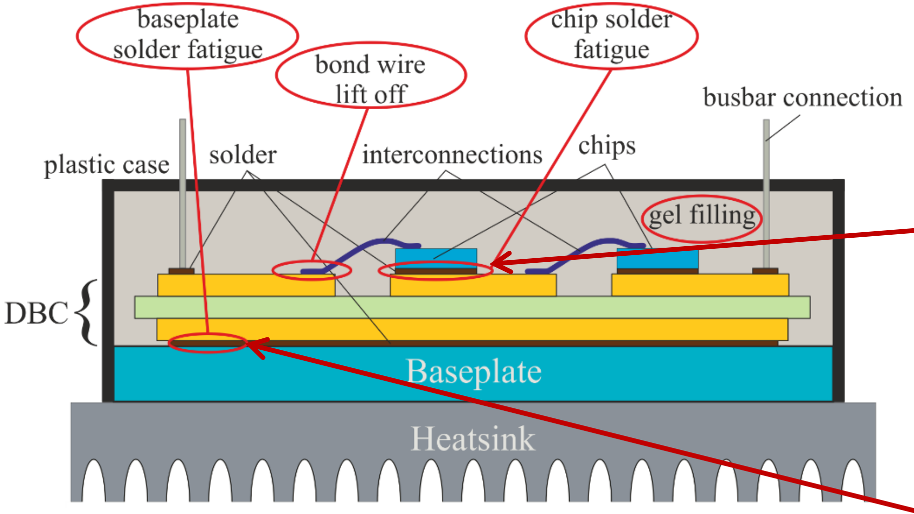
Stressors identified in the survey

Temperature is still considered the most critical stressor

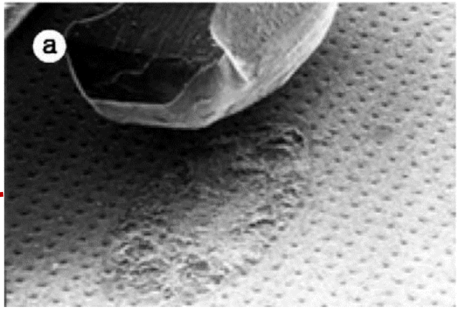
J. Falck, C. Felgemacher, A. Rojko, M. Liserre and P. Zacharias, "Reliability of Power Electronic Systems: An Industry Perspective," in IEEE Industrial Electronics Magazine, vol. 12, no. 2, pp. 24-35, June 2018.



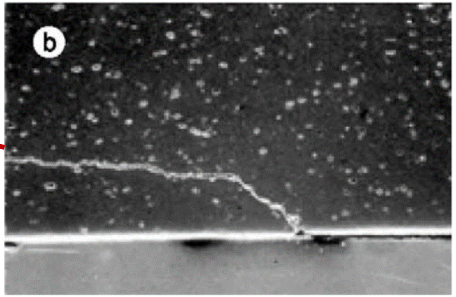
An example of major wear-out failures in IGBT module



Break down of a typical IGBT module.



Bond wire lift-off



Soldering cracks

Stress: Thermal cycling
Strength: Cycles to failure
Failures: Dislocation of joints
Symptom: Increase of Vce, thermal impedance, etc.

Prognostics & maintenance

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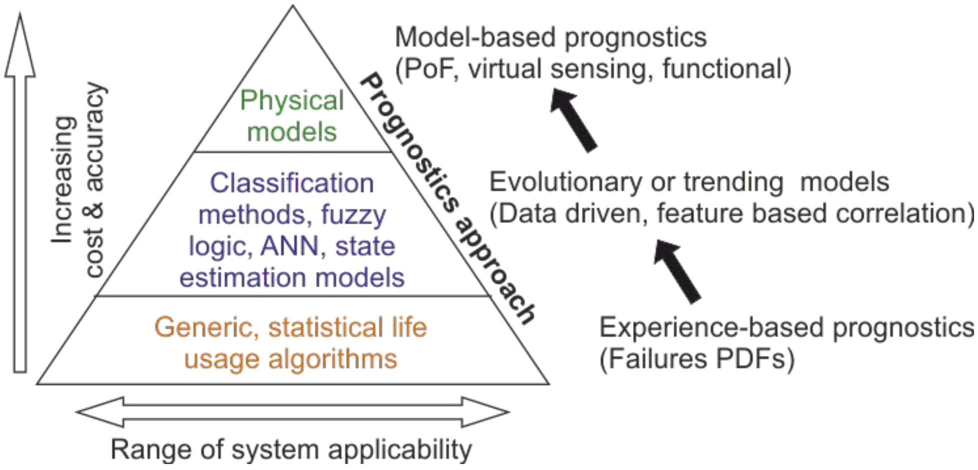
- Shift from experience based prognostics to model-based and AI based methods
- Condition monitoring enable detection of health deterioration



- Condition Based Maintenance relies on PoF models or data driven methods to estimate RUL and thereby optimally scheduling maintenance

Data source: C. S. Byington, M. J. Roemer and T. Galie, "Prognostic enhancements to diagnostic systems for improved condition-based maintenance [military aircraft]," Proceedings, IEEE Aerospace Conference, Big Sky, MT, USA, 2002, pp. 6-6.

Prognostics & maintenance

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Semiconductor characterization

Assess dynamic range, accuracy, and coherence of estimated FRF data; execute additional experiments, if necessary

Design and apply loss (heat) injection signals strategically having certain frequency content

$Q = Q_{cond} + Q_{sw}$

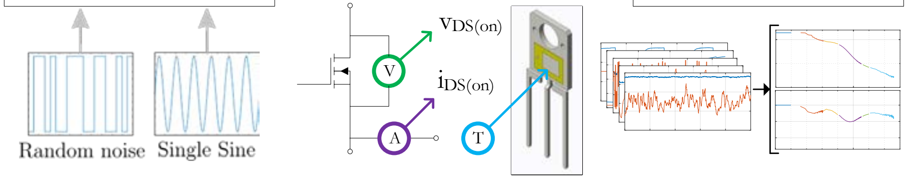
Estimate thermal response via TSEP

$T = f\,(TSEP, i_{load})$

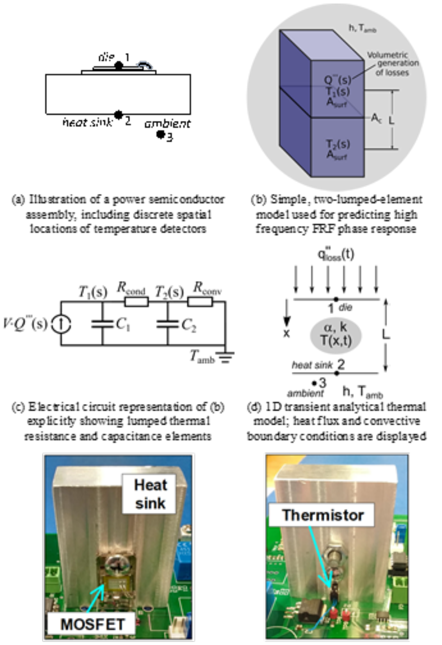
Compute frequency response function (FRF) data for each system identification experiment

Q(t), T(t)→ Q(s), T(s)

Combine FRF data segments; estimate & interpret transfer function model(s)



$$\frac{T(s,x)}{Q(s)} = \exp\left(-\left(s\cdot\tau_{diff}(x)\right)^{\sigma}\right)\sum_{i=1}^{n_{poles}}\frac{R_i}{\tau_i\, s+1}$$



(a) Illustration of a power semiconductor assembly, including discrete spatial locations of temperature detectors
(b) Simple, two-lumped-element model used for predicting high frequency FRF phase response
(c) Electrical circuit representation of (b) explicitly showing lumped thermal resistance and capacitance elements
(d) 1D transient analytical thermal model; heat flux and convective boundary conditions are displayed
(e) Decapsulated TO-247 MOSFET assembly mounted to an aluminum block heat sink before application of black paint
(f) Thermistor mounted to the reverse side of the heat sink to sense its temperature

Fig 3. Thermal system models and experimental hardware

T.A. Polom, M. Andresen, M. Liserre and R. D. Lorenz, "Frequency Domain Electrothermal Impedance Spectroscopy of an Actively Switching Power Semiconductor Converter„, IEEE Transactions on Industry Applications

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Prognostics & maintenance

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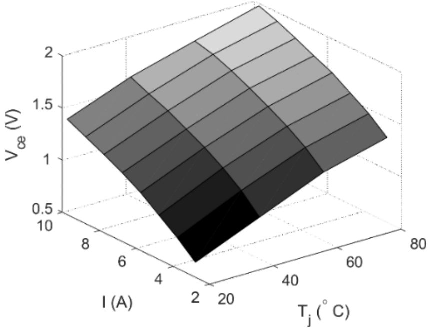
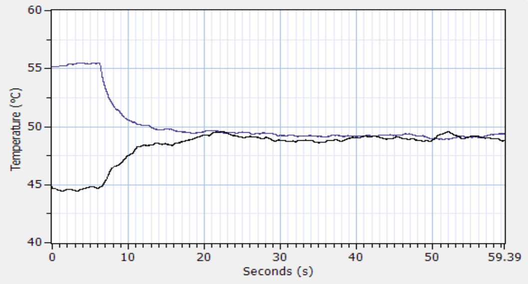
Semiconductor temperature mesur.





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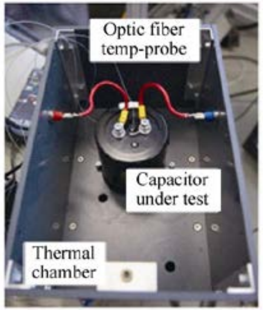
7 DE SETEMBRO DE 1927
UFMG

Capacitor temperature mesur.



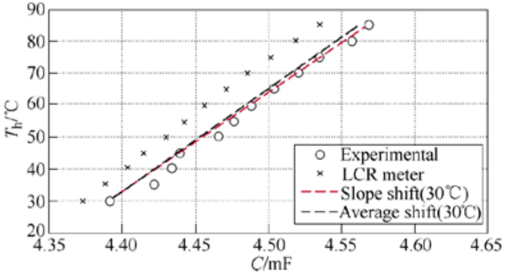


Fig.5 Experimental demonstration of capacitor hotspot temperature estimation on basis of electrical capacitance measurement[22]

H. Jedtberg, G. Buticchi, M. Liserre and H. Wang, "A method for hotspot temperature estimation of aluminum electrolytic capacitors," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 3235-3241.

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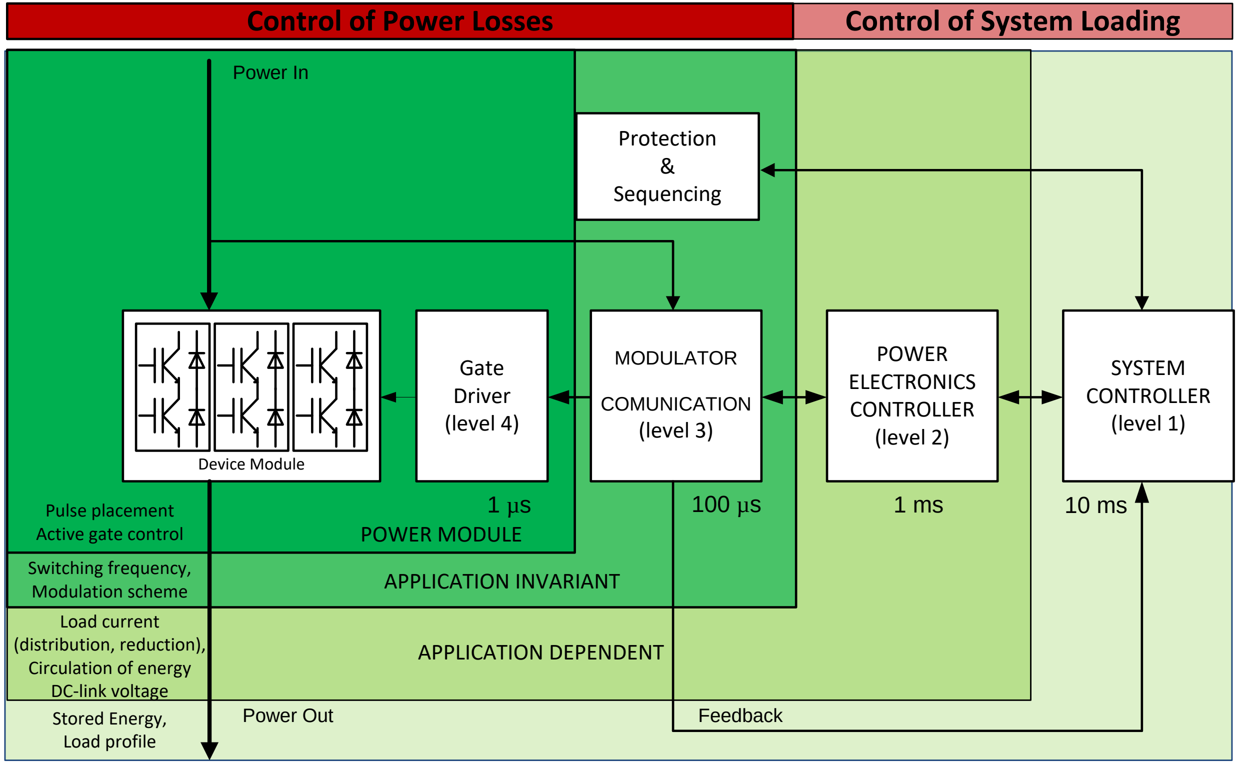
. . . by means of power routing

Active Thermal Control



M. Andresen, K. Ma, G. Buticchi, J. Falck, M. Liserre, F. Blaabjerg, "Junction Temperature Control for More Reliable Power Electronics" in IEEE Transactions on Power Electronics, vol. 33, no. 1, pp. 765-776, Jan. 2018.

M Andresen, G Buticchi, M Liserre, "Study of reliability-efficiency tradeoff of active thermal control for power electronic systems" in Microelectronics Reliability, 2016 - Elsevier

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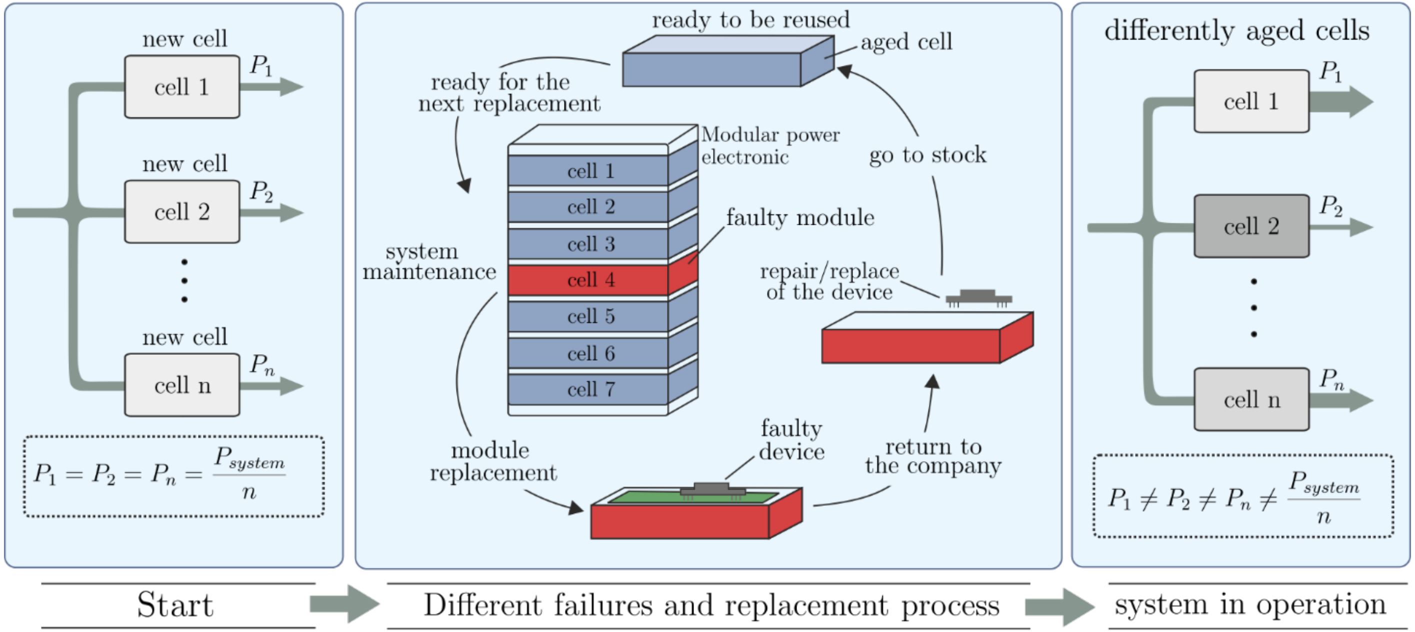
Reliability Enhancement by Uneven Loading of Cells



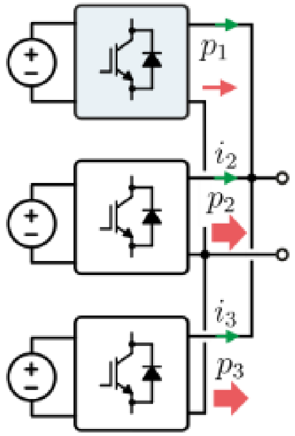
M. Liserre, M. Andresen, L. Costa and G. Buticchi, "Power Routing in Modular Smart Transformers: Active Thermal Control Through Uneven Loading of Cells," in IEEE Industrial Electronics Magazine, vol. 10, no. 3, pp. 43-53, Sept. 2016.

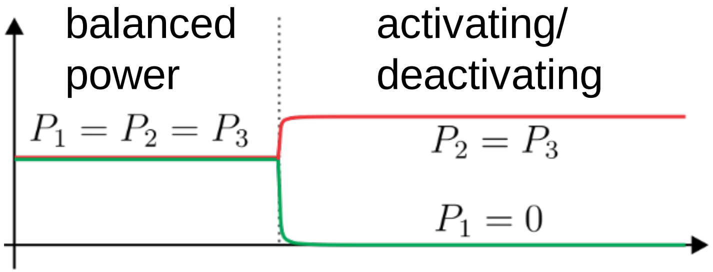
Power routing concept

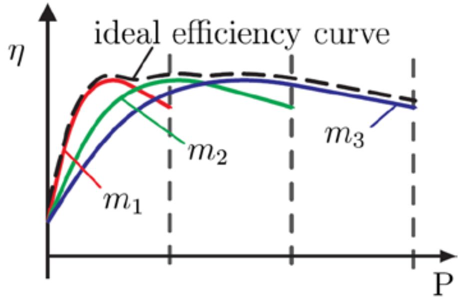
On/off control for parallel power converters (State of the art)

<u>Improve the efficiency</u>: activate/de-activate parallel power paths to work on the maximum efficiency point, mainly in light power.

Only the components in the <u>activated power paths are stressed</u>, while the <u>power quality is affected</u>



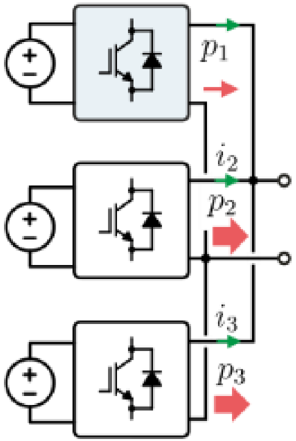


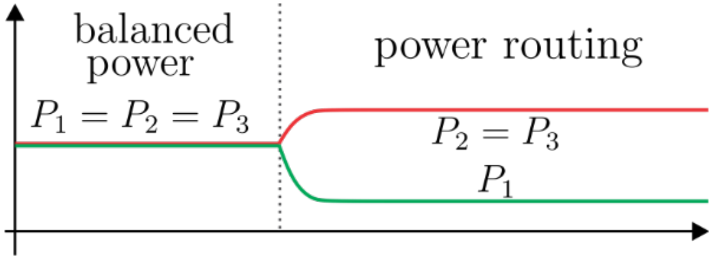


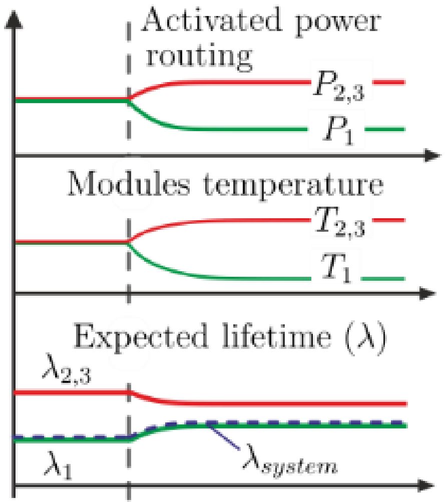
m_1: one module activated
m_2: two module activated
m_3: three module activated
light load η improvement

Power routing for parallel power converters (Innovation)

Control the lifetime: Identify aged IGBTs and reduce the power processed by them, until the repair or replacement of the module. Consequently, optimize remaining useful lifetime and efficiency



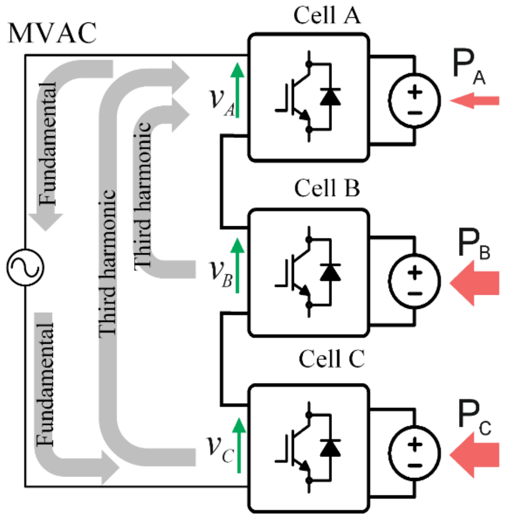




Power Routing in cascaded H-bridges

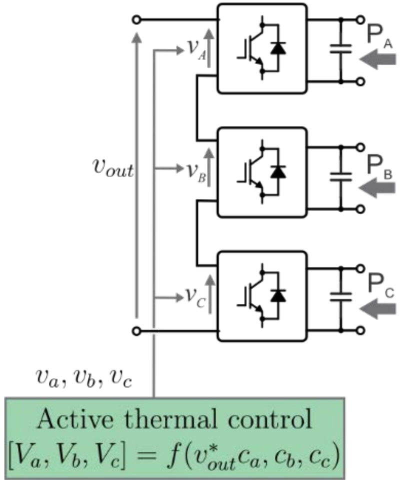
Series connected building blocks can share the power unequally:

- ✓ Unequal power P_a ,P_b and P_c is processed
- ✓ Different stress is affected for the devices connected to the cells
- ✓ The concept requires a sufficient margin of V_{grid}/V_{dc}
- ✓ The potential of the algorithm is mission profile dependent

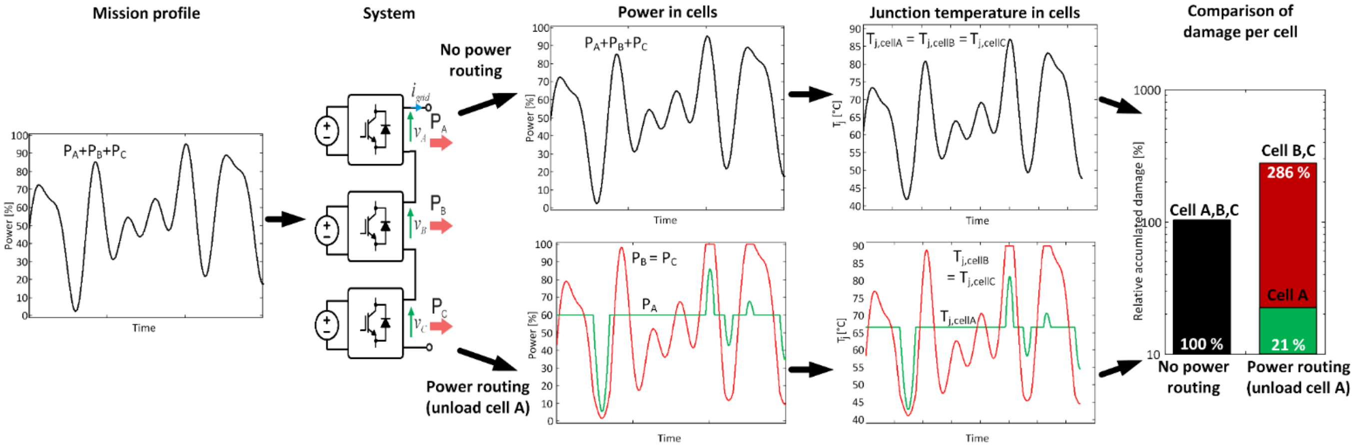


Concept of (multi-frequency) power routing for a seven level CHB-converter

Power Routing in cascaded H-bridges



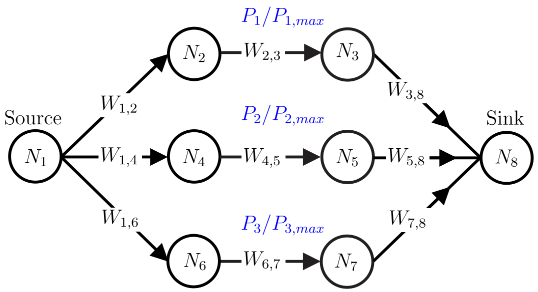
Control variables of the power routing for series-connected building blocks.

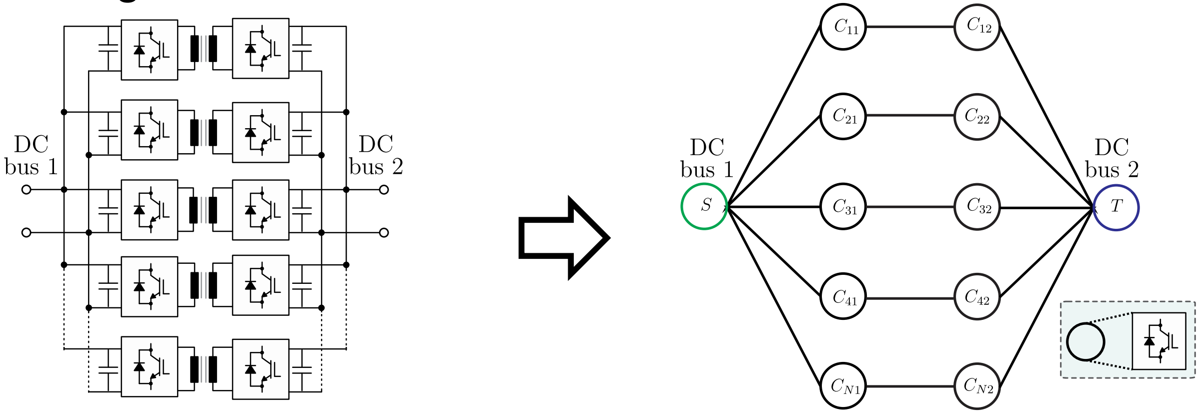


Demonstration of the concept for a highly varying mission profile with the resulting junction temperatures and accumulated damage for the power semiconductors in the cells.

Graph theory representation of modular converters

- Converters represented by Nodes N_1, N_2,...
- Power flow connections denoted by edges $W_{1,2}$, $W_{2,3}$,...
- Weights determine the power flow
- Power flow analogous to data flow





M. Liserre, V. Raveendran and M. Andresen "Graph Theory Based Modeling and Control for System level Optimization of Smart Transformers," in IEEE Transactions on Industrial Electronics.

Graph theory representation of modular converters

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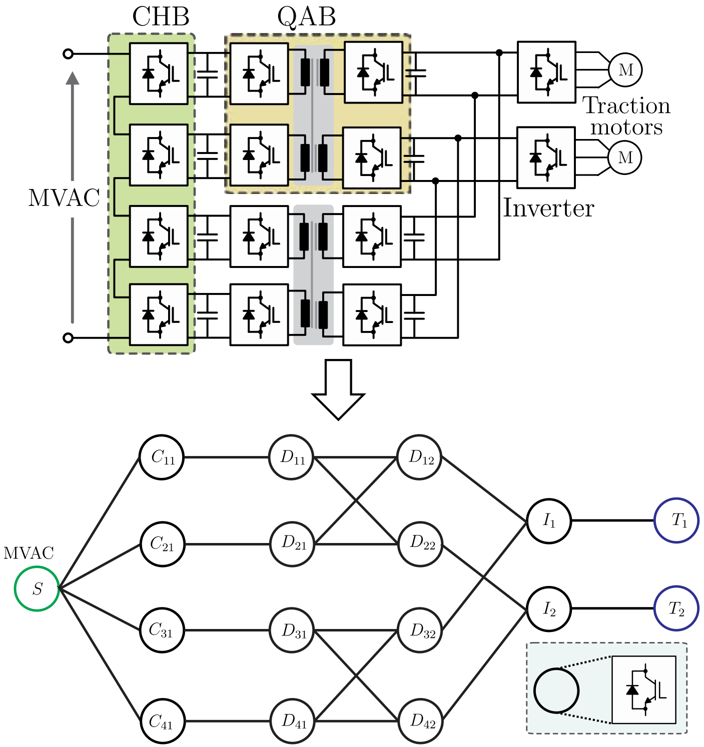
Modular power converter for traction

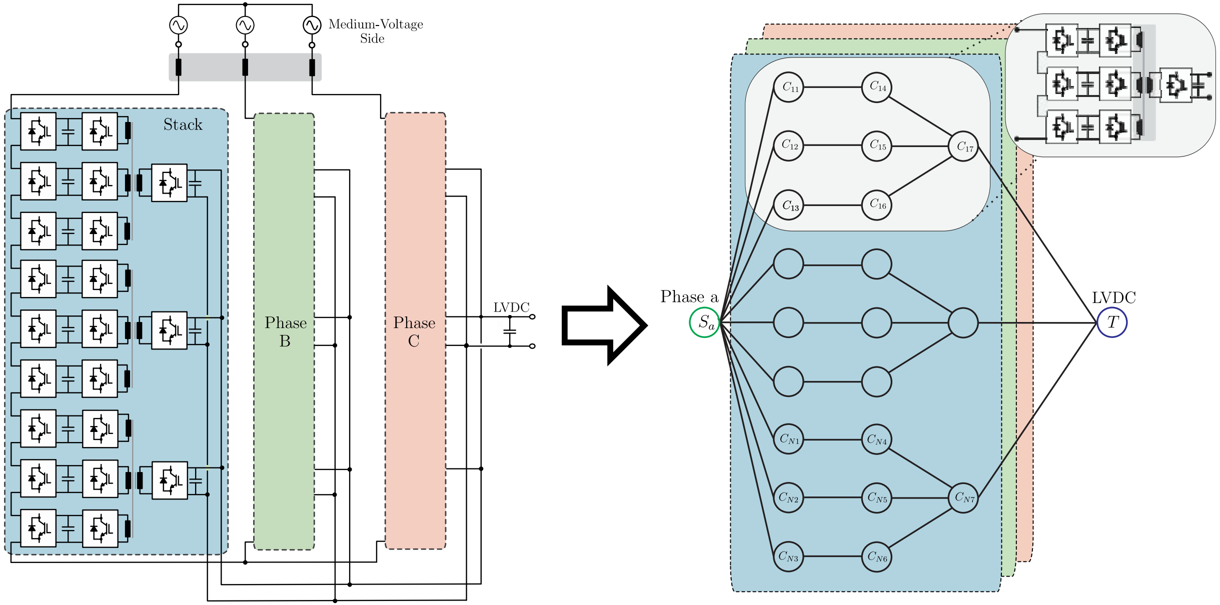
- Composed of Cascaded H bridge & Quadruple Active Bridges
- Multiple power flow paths from source to sink
- More opportunities for power routing



ST topologies: graph representation

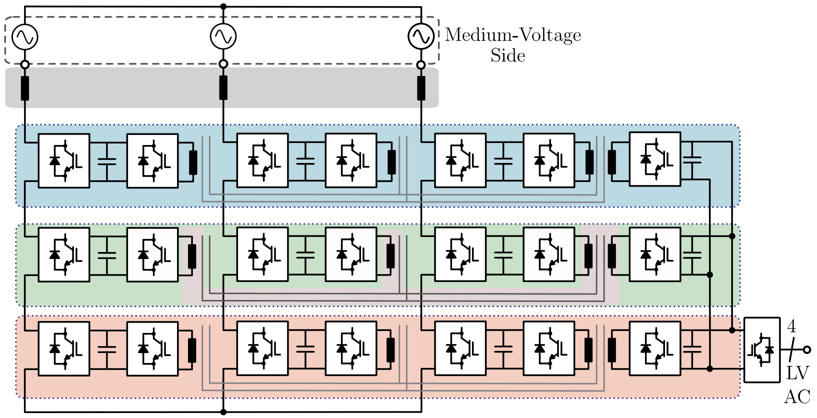
CHB-QAB based ST

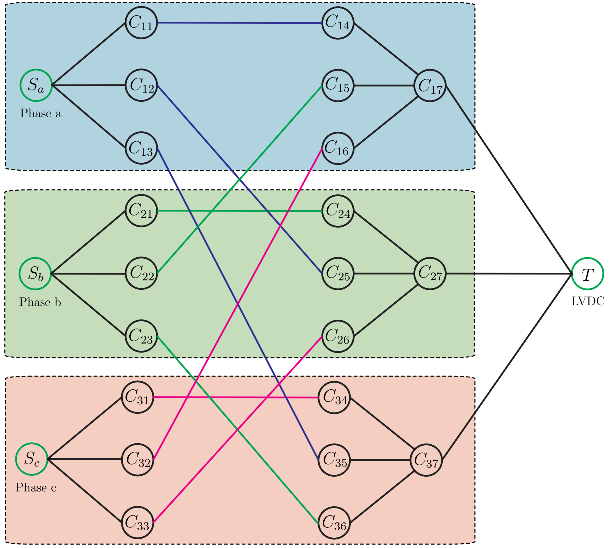
- Each H-bridge cell as node
- Power flow represented by edges
- Edges do not necessarily represent electrical connections



ST topologies: graph representation

CHB-QAB based Interphase ST





Complex modular architectures can be represented by graph theory

Graph Theory Optimization based power routing

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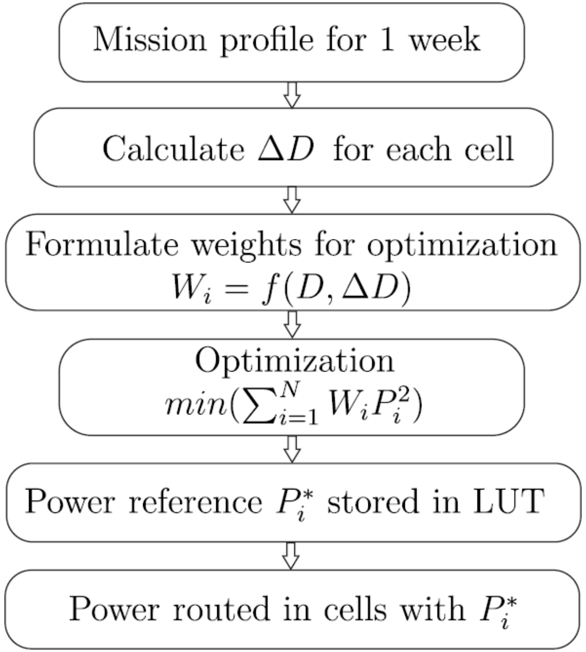
- All converters equipped with junction temperature sensing (V_{ce})
- Accumulated damage for a week calculated from sensed junction temperature profile
- Depending on damage of converter cell, weights change
- Optimization provides power reference for each converter depending on weights
- Power is routed according to aging of individual cell



Maintenance-driven control

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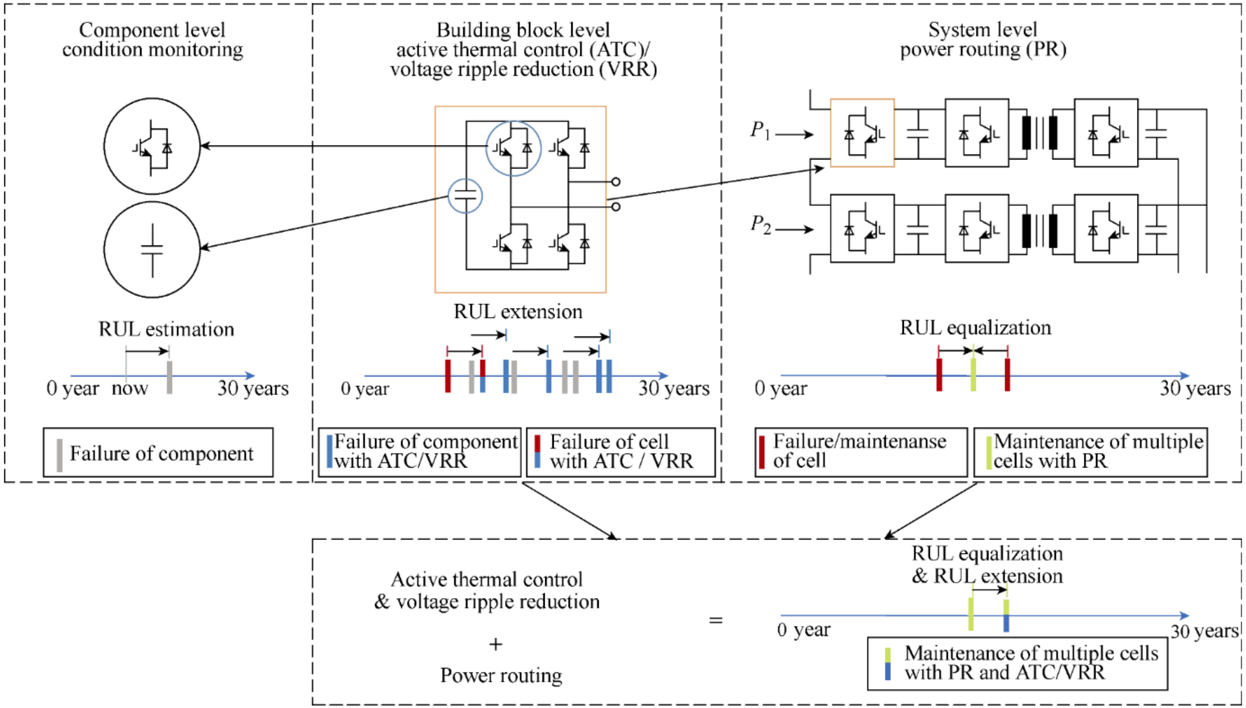
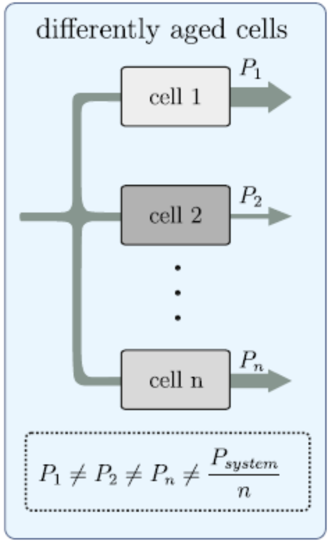
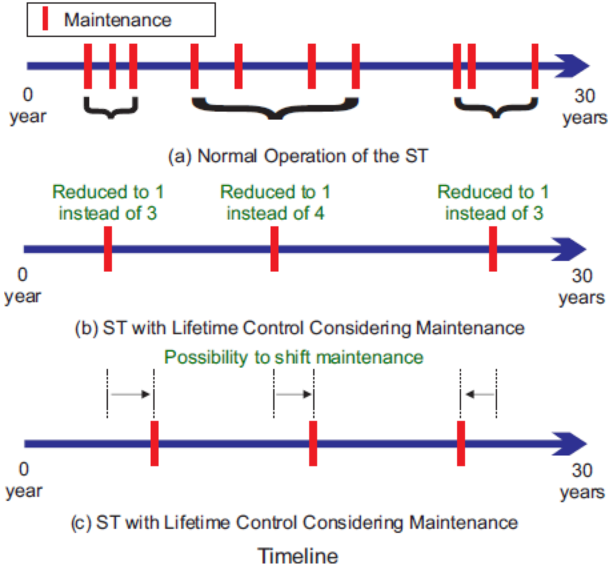


M. Andresen, J. Kuprat, V. Raveendran, J. Falck and M. Liserre, "Active thermal control for delaying maintenance of power electronics converters," in Chinese Journal of Electrical Engineering, vol. 4, no. 3, pp. 13-20, September 2018.

Maintenance-driven control





- Power is routed in the cells to achieve thermal stress based RUL control
- Possibility to reduce and control maintenance instances

V. Raveendran, M. Andresen and M. Liserre, "Lifetime Control of Modular Smart Transformers Considering the Maintenance Schedule," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 60-66.

Experimental implementation

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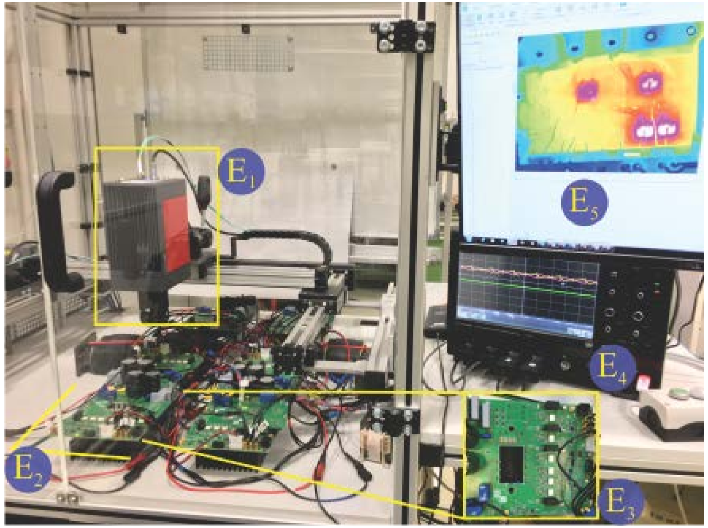
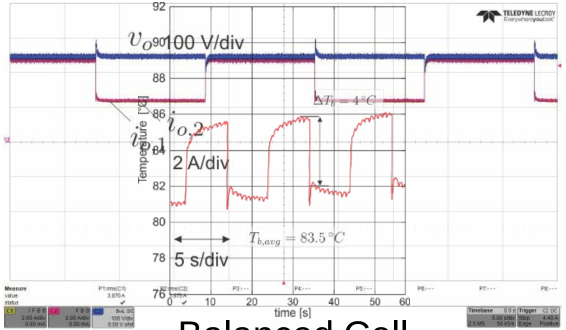


Experimental setup with 5-level CHB and DABs with Open Module and IR Camera

Without PR

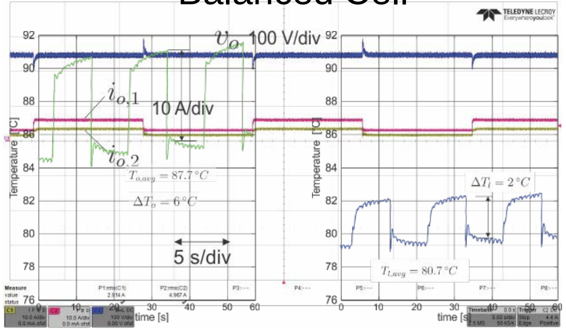
$P_{DAB1} = P_{DAB2}$



Balanced Cell

With PR

$P_{DAB1} = 1.7\, P_{DAB2}$



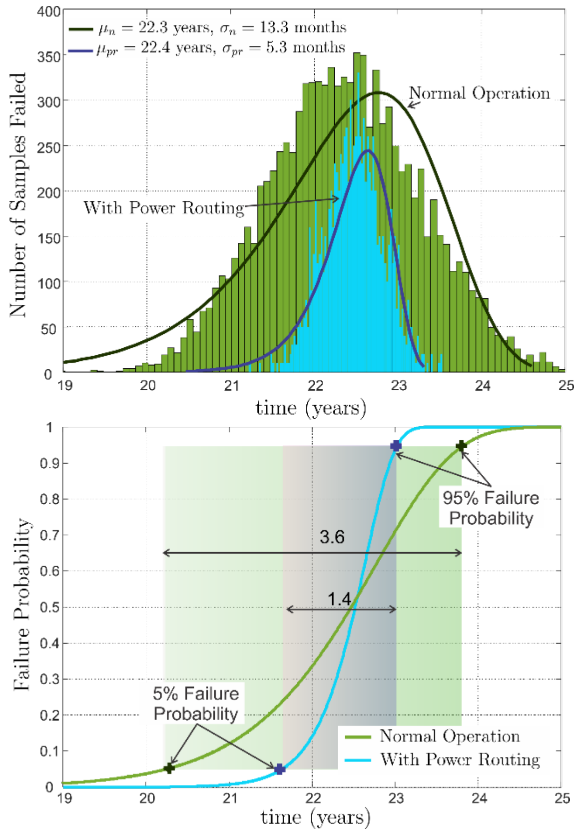
Overloaded Cell Unloaded Cell

Parameters of prototype

$V_g = 230\,V$	$L_g = 3.8\,mH$	$f_{sw,CHB} = 3\,kHz$	$n = 1:1$	$V_{DC} = 250\,V$	$V_o = 240\,V$	$f_{sw,DAB} = 12\,kHz$

Monte-Carlo simulation results

- Slightly different junction temperatures of the devices result in different lifetimes:
- With similar loading, the lifetime will have a high variance
- With power routing the variance of the lifetime is significantly reduced
- The time to a 5% failure probability is increased and mean lifetime is also slightly increased



Conclusions

- ✓ Smart Transformer can reduce the update of grid assets by means of:
  - ✓ Meshed and hybrid connections on MV- and LV-sides
  - ✓ Integrating storage, using the load dependent ΔP, controlling the P-flow
  - ✓ Regulating Q on MV- and LV-sides
  - ✓ Handling faults in active way
- ✓ Modular SST Topologies allow scalability and fault-tolerance but they may decrease reliability
- ✓ Power Routing allow handling stress of basic cell depending on its aging to increase availability and better schedule maintenance