PEMC Webinar 2021 – Electric Technologies for Green Airport

Opportunities and Challenges of Smart Transformer Architectures for More Sustainable Airport

April 2021

Prof. Marco Liserre

Thiago Pereira, Yongjong Ko and Kanga Wang

Chair of Power Electronics
Christian-Albrechts-Universität zu Kiel
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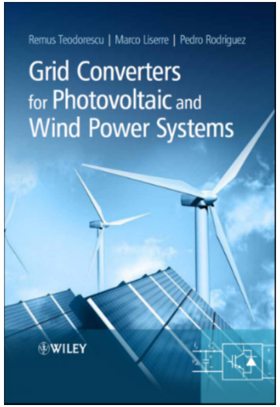
24143 Kiel

A short summary about me . . .

C | A | U
Christian-Albrechts-Universität zu Kiel

- ► 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 World's Most Influential Minds from 2014
- 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.)
- Reserch Centres and Laboratories with companies
- Smart Grid (20 years) and WBG-devices and reliability (last 10 years)



Team at the Chair of Power Electronics

C | A | U
Christian-Albrechts-Universität zu Kiel

Head of Chair
Prof. Marco Liserre

Technician

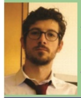
 

Secretary

Senior Staff



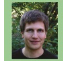
Dr.-Ing. Sante Pugliese
- PhD from Politecnico di Bari (Italy)
- Chair Teaching Assistant
- Responsible of Control Group

Mr. Marius Langwasser (Chair assistant)
- **PhD** Hybrid grid control & protection
- Responsible of Grid Group

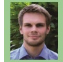
Team Members

Modell., Control & Reliability

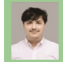
- **PostDoc** (PhD from Pusan National Uni.)
- Modulation and PHIL testing of MV-converter
- National Funding



- **PhD** MMC for MV applications
- Regional Funding



- **PhD** Reliability and Active thermal control in hybrid grids
- Chair Funding



- **PhD** Digital twin of WBG converter
- Industrial PhD

- **PhD** AI-based control of hybrid-Sic NPC-based high speed drives
- EU Funding

- **PhD** Sub-synchronous Resonance damping based on large wind farm system
- EU Funding

- **PhD** Robust Control for Hybrid ac and dc grids
- National Funding

Power Converters & Batteries

- **PostDoc** (PhD from Université Paris-Saclay, France)
- Company Funding

- **PostDoc** (PhD from Lorestan Uni., Iran)
- Passive Components & Batteries
- Regional/Company Funding

- **PhD** Fault-tolerant MMC
- National Funding

- **PhD** Die-level active thermal control
- Regional Funding

- **PhD** GaN-based wireless power & data transfer
- Chair Funding

- **PhD** GaN-based Power Converter
- Chair Funding

- **PhD** PV Architecture
- Industrial PhD

Electric Grid

- **PhD** Modeling & stability of power electronics-based grid
- Scholarship

- **PhD** Grid inertia support based on large wind farm system
- EU Funding

- **PhD** PHIL-based analysis of power converter for high power application
- National Funding

- **PhD** Ancillary service provision in distribution grids with PE & storage
- National Funding

- **PhD** PHIL-based evaluation of PE based close couplings in distribution grids
- National Funding

- **PhD** Grid-integration issues of PV systems
- Industrial PhD

University of Nottingham
UK | CHINA | MALAYSIA

PEMC Webinar: Electric Technologies for Green Airport

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Motivation for More Sustainable Airport

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► Aircraft — Ground support Electrical Supplies — General Requirements

- **Airplane Electrical Systems** cannot be connected directly to the distribution network (50 Hz or 60 Hz), since they employ **400 Hz Electrical Systems** [1].
- In this context, **ISO 6858:2017** specifies the electrical output characteristics and interface requirements between an Aircraft and ground support electrical supplies. This includes all external electric power generation facilities, such as **Ground Power Unit (GPU).**
- A **GPU** is a key component that deliveries power to grounded aircraft without wasting fuel. As a result, the **auxiliary power unit (APU)** of the Airplane can be disabled in order to reduce air contamination, noise, maintenance revision of the APU, or inclusive engine starting [1] – [3].
- An aircraft ground power unit delivers specified power (current, frequency, voltage) to an aircraft through either the use of a **3-Phase Electrical System** or a **Large Battery System** or **Gasoline/Diesel**.
- According to **ISO 6858:2017**, the voltage supply standard is **115/230V 400 Hz**, three-phase four wires **galvanic isolated** or/and **28 V DC**. The power range of one unit may be up to 180 kVA.

[1] R. A. Mastromauro, S. Stasi, F. Gervasio and M. Liserre, "**A ground power unit based on paralleled interleaved inverters for a More-Electric-Aircraft**," 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, 2014, pp. 216-221.

[2] M. Rivera, D. Faundez, J. Kolar, P. Wheeler, F. Besoain and J. A. Riveros, "**A New Ground Power Unit (GPU) Supply for Aircraft Applications**," 2018 IEEE Biennial Congress of Argentina (ARGENCON), 2018, pp. 1-6.

[3] M. Rivera, D. Faundez, J. Kolar, P. Wheeler, J. A. Riveros and S. Toledo, "**An Integral Design of Ground Power Unit Supply for Aircraft Applications**," 2018 IEEE International Conference on ESARS-ITEC, 2018, pp. 1-6.

More Sustainable Airport and Integration

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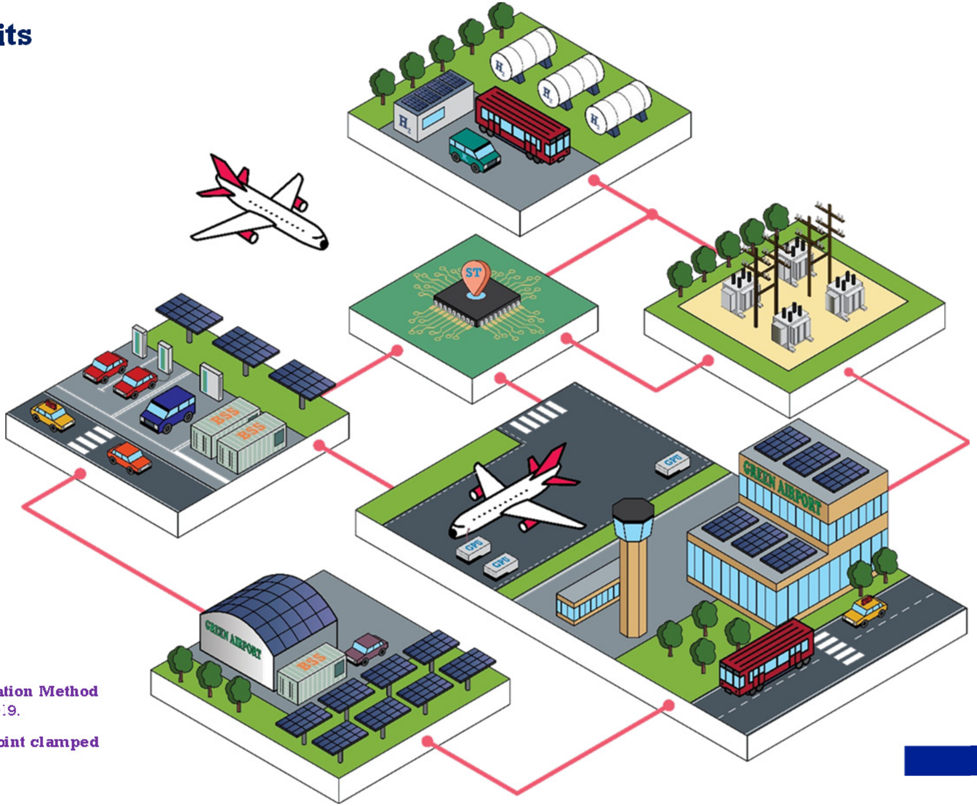
▶ Challenges and Opportunities for Ground Power Units

- **GPUs** have both been implemented as rotating motor–generator systems and as **solid-state converters**.
- However, the **solid-state solution** has been accepted as a standard due to low maintenance, lower price, high reliability and high efficiency [4].
- In this scenario, due to the low-ratio between the grid frequency (50/60 Hz) and the fundamental frequency of the Airplane system (400 Hz)**, the conventional solution based on the multipulse rectifier difficult to achieve high waveform quality** [5].
- The control of **these converters is complex**, having a slow dynamic response to load steps [2].
- Therefore, the **Smart Transformer** might be a promising opportunity to ensure the operation with highly nonlinear loads and at the same time allows the **integration of renewable sources** (PV System, Fuel Cell and Battery Storage System).



[4] M. Abarzadeh and K. Al-Haddad, "**An Improved Active-Neutral-Point-Clamped Converter With New Modulation Method for Ground Power Unit Application**," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 1, pp. 203-214, Jan. 2019.

[5] M. Abarzadeh, H. M. Kojabadi and L. Chang, "**A modified static ground power unit based on active natural point clamped converter**," *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015, pp. 3508-3514.

More Sustainable Airport and Integration

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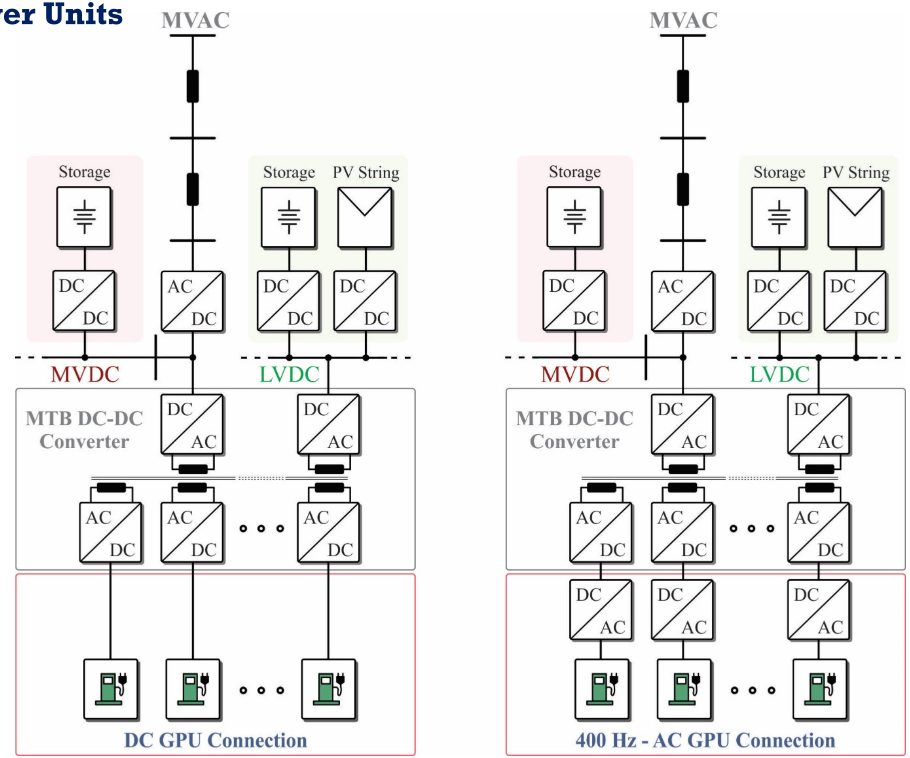
► Smart Transformer enabling multiple Ground Power Units

- In this scenario, **Smart Transformer** based system might offer the optimal trade-off between multi-source integration and minimal effects for the electrical network.
- The **Smart Transformer** provides new functionalities for reducing the effects on the electrical grid, leading sometimes to concepts like Power-to-Grid.
- Intensive research has been performed to **provide integration of more systems into the distribution network** while ensuring higher efficiency, and low infrastructure with low maintenance.
- For **GPUs**, the **Smart Transformer** arises as an interesting solution to integrate different sources (PV system, Storage, and MVAC grid) while providing **multiples DC and/or 400 Hz AC outputs**, which can be used to supply directly the Airplane Electrical System.
- Depending on the power level, the **outputs can also be connected in parallel** in order to assure a higher power demand.

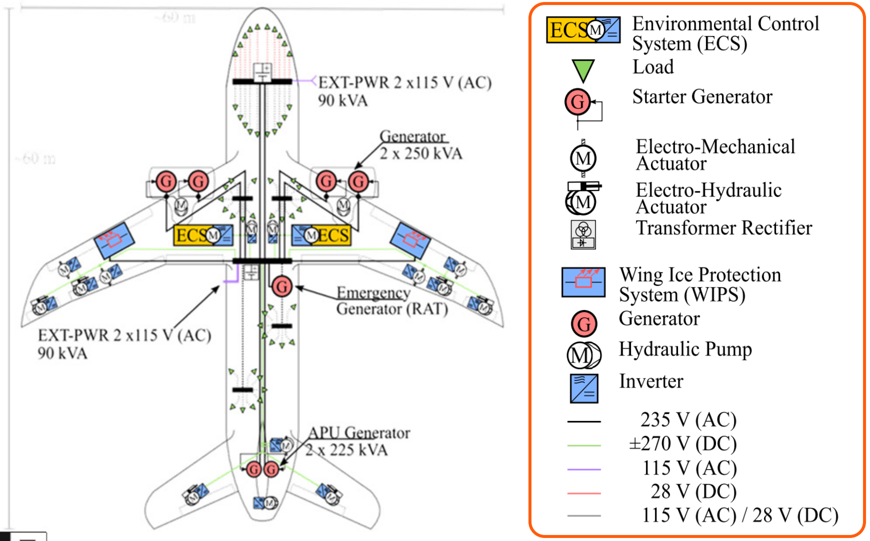


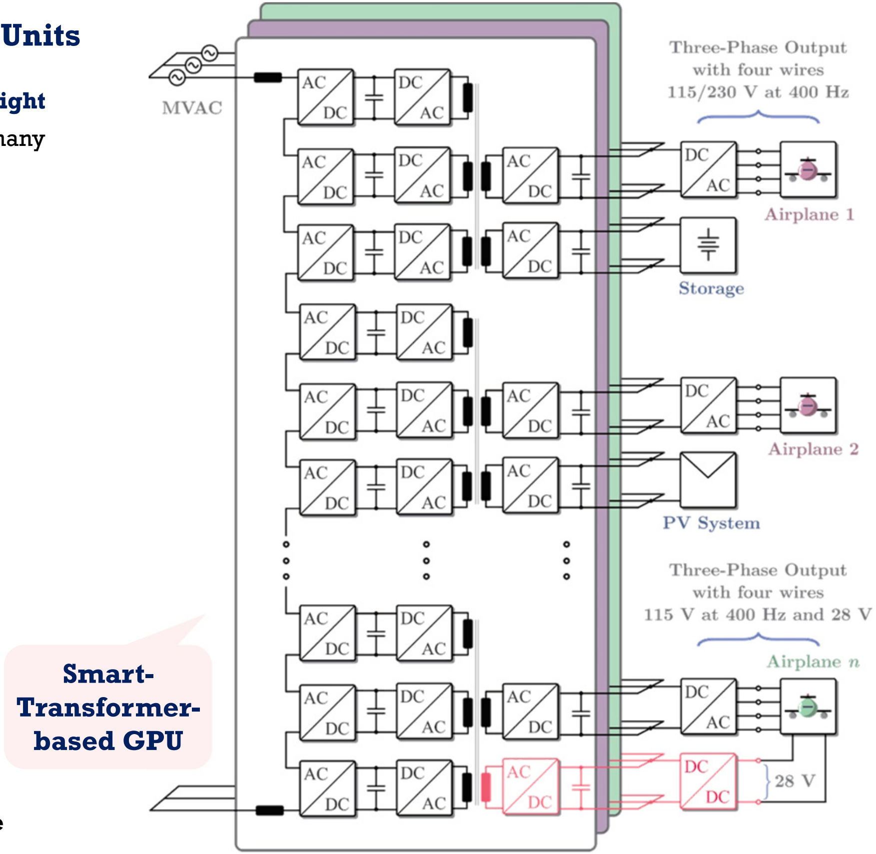
More Sustainable Airport and Integration

▶ Smart Transformer enabling multiple Ground Power Units

- ❑ For compatibility reasons, **the voltage level 115/230 V AC and 28 V DC might provide**, since many components are designed for this voltage level and many airports provide this external power supply.

Typical distributed Electrical Power System in an Aircraft [6]

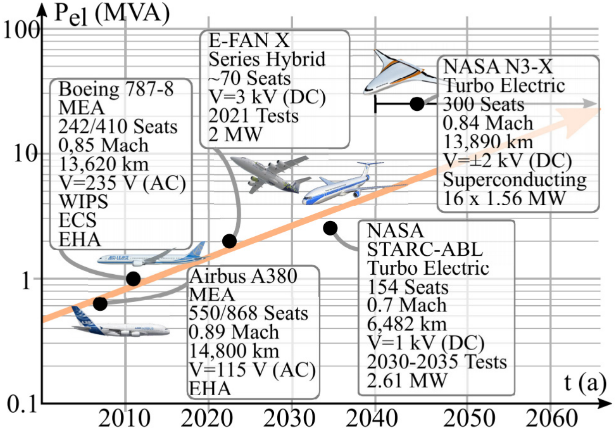




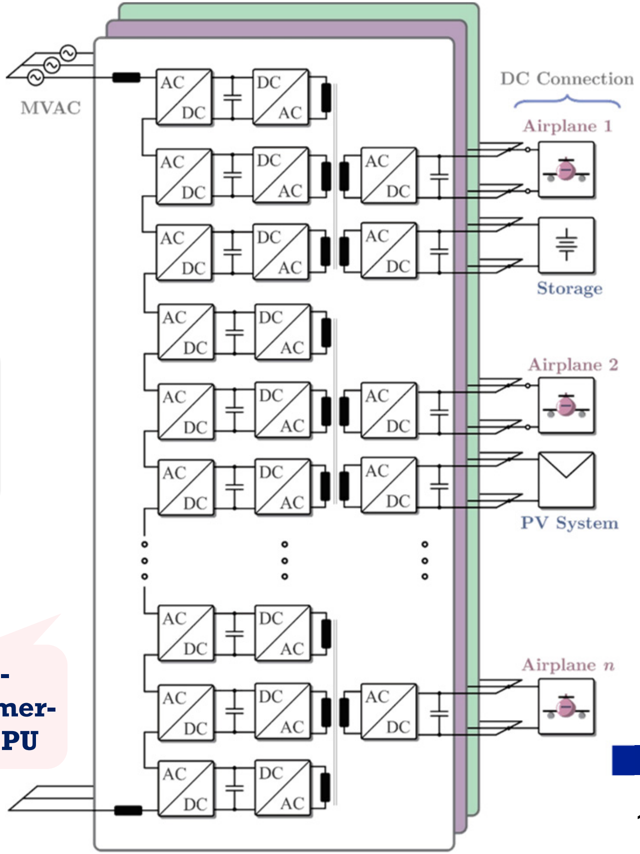
More Sustainable Airport and Integration

▶ Trend of Electrification in Aircraft Applications

- Following the **trends and the predicted development of electrification** in commercial aviation **[6]**, the research effort is focusing on increase the **DC voltage of the electrical power supply system in the range of kV** and hence eliminate the **conventional AC connection of 115/230 V at 400 Hz.**



Therefore, a new supply grid voltage for future aircraft will be needed, so that **DC grid structures** are highly considered for this application **(e.g. using MMC instead of CHB)**



Smart-Transformer-based GPU

[6] H. Schefer, L. Fauth, T. H. Kopp, R. Mallwitz, J. Friebe and M. Kurrat, "**Discussion on Electric Power Supply Systems for All Electric Aircraft**," in *IEEE Access*, vol. 8, pp. 84188-84216, 2020.

Smart Transformer for More Sustainable Airports

Smart Transformer for More Sustainable Airports

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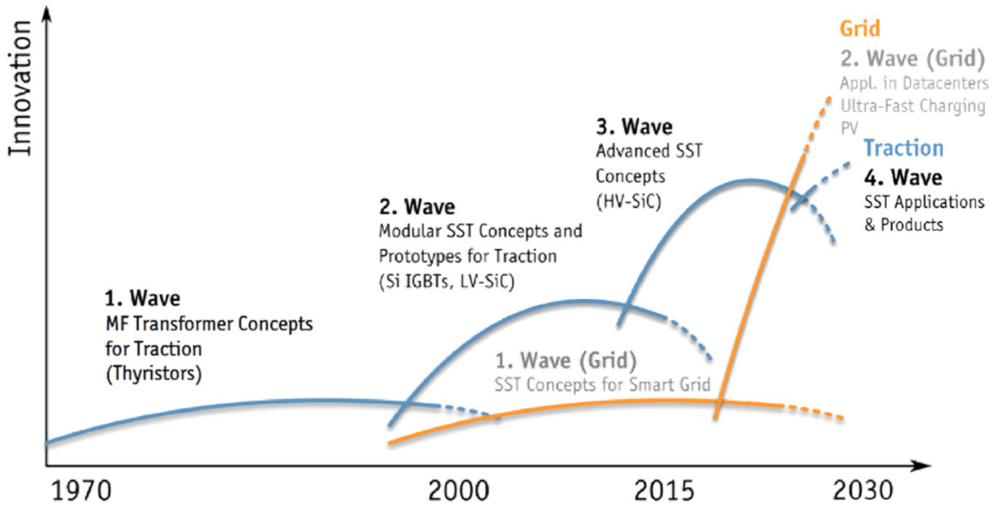
► Solid State Transformer Development Cycles

- ❑ 1968, McMurray, SST Concept
- ❑ 1980, Brook, Patent on HF ac/ac
- ❑ 1990, Application for transaction
- ❑ The potential to use SST as the enabling technology for smart grid functionality is much higher.



[ref] Johann W. Kolar, "**Solid-State-Transformer Applications – A Glimpse Into the Future**",SGRE 2019, Nov. 19, 2019

Smart Transformer for More Sustainable Airports

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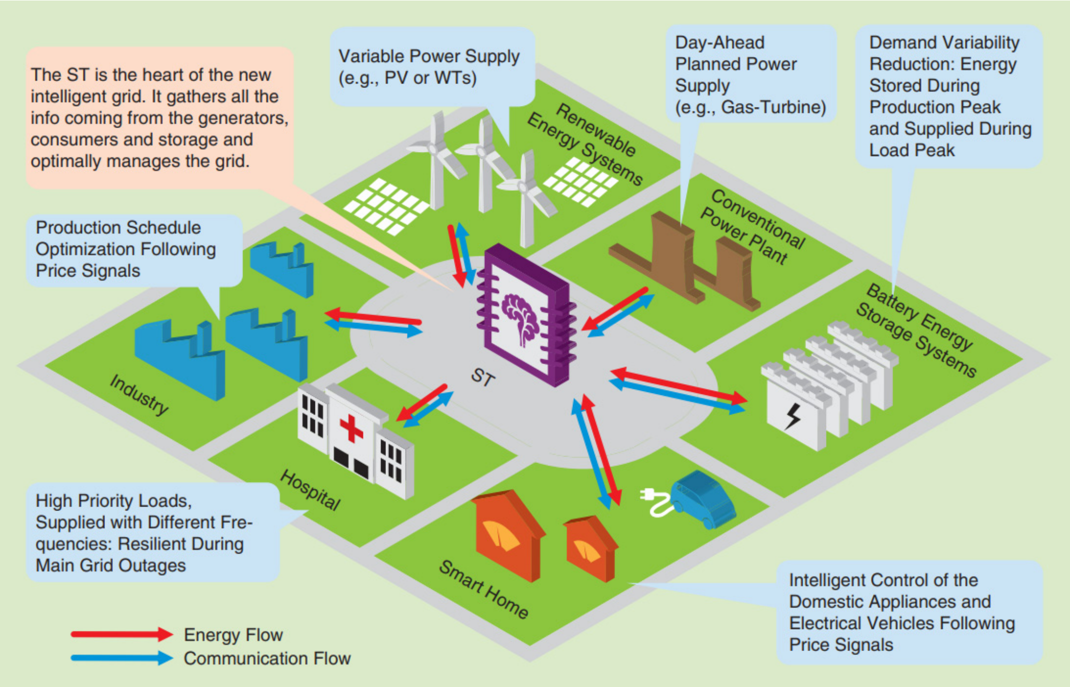
▶ Key Characteristics of Smart Transformer

- **Higher host capability of DGs**
  - Bidirectional power flow control;
  - Reactive power compensation;
  - Interface to DC grid.
- **Reduced footprint of system**
  - Medium/High-Frequency Isolation.



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

Architectures and Operation Principle of the Smart Transformer

Architecture and Operation Principle of the Smart Transfomers

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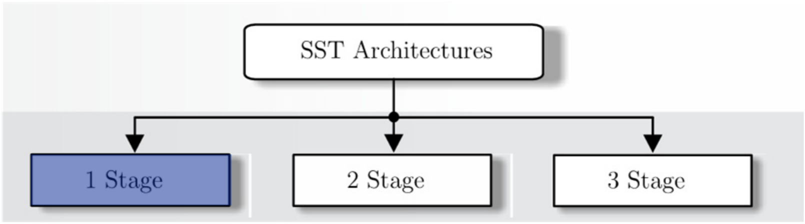
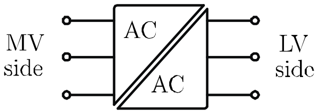
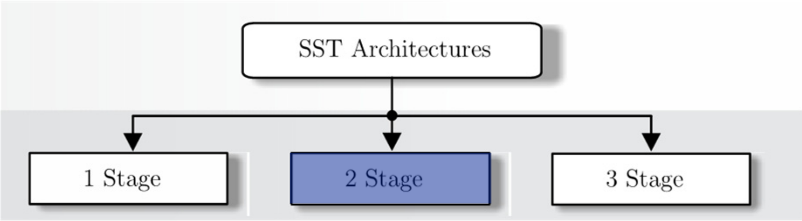
▶ ST Architecture Classfication: By Number of Power Stages

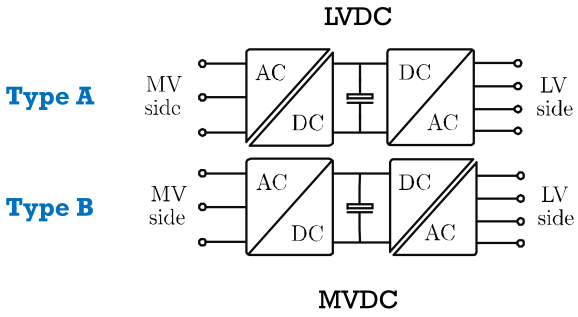




- **Features**
  - Direct AC-AC conversion with galvanic isolation;
- **Pros**
  - Simple structure;
  - Less number of power components;
- **Cons**
  - No DC grid connectivity;
  - Strongly coupled between MV/LV side;

▶ ST Architecture Classfication: By Number of Power Stages

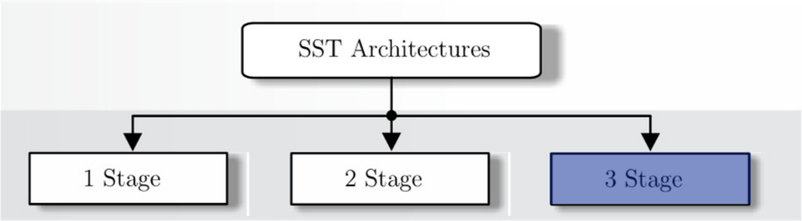


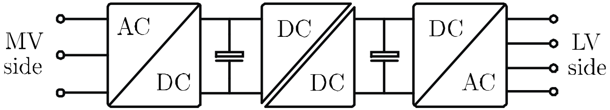


- **Features**
  - Galvanic isolation in either MV side or LV side.
- **Pros**
  - DC grid connectivity (either MVDC or LVDC).
- **Cons**
  - **Type A** - Low efficiency of MV side converter;
  - **Type A** - Limited application of multilevel topology for MV side;
  - **Type B** - No LVDC grid connectivity.

Architecture and Operation Principle of the Smart Transfomers

▶ **ST Architecture Classfication: By Number of Power Stages**





- **Features**
  - Galvanic isolation by MVDC-LVDC stage
- **Pros**
  - MVDC and LVDC grid connectivity
  - Completely decoupled between MVAC and LVAC grid
  - Flexible topology option for each stage
- **Cons**
  - More number of power components (switching device, capacitor, inductor,...)

Architecture and Operation Principle of the Smart Transfomers

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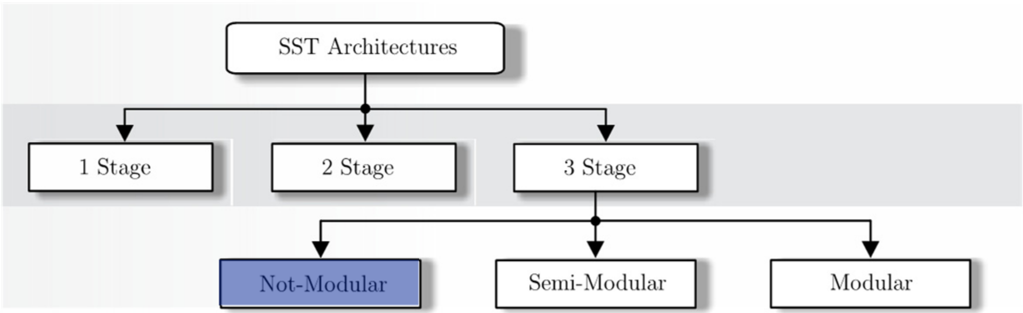
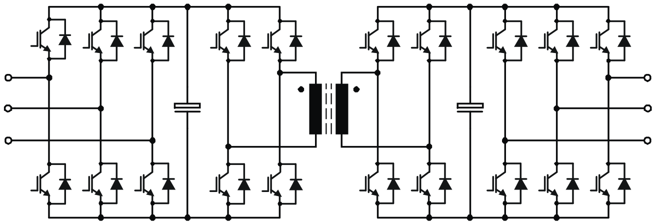
► ST Architecture Classfication: By Modularity





- **Features**
  - Simple structure
- **Pros**
  - Less number of power components
- **Cons**
  - No scalability in power and voltage
  - High EMI noises (high dv/dt and/or di/dt)
  - Low reliability (very limited to fault tolerant operation and maintenance)

Architecture and Operation Principle of the Smart Transfomers

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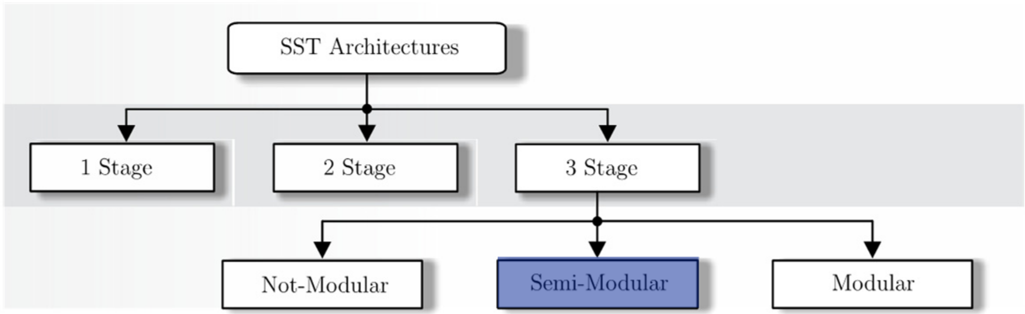
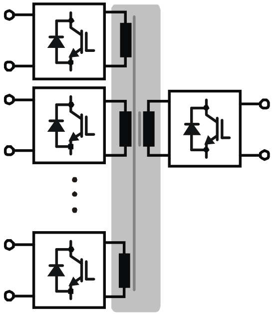
▶ ST Architecture Classfication: By Modularity





- **Features**
  - Based on a multiport transformer
- **Pros**
  - Cell level modularity
  - low EMI noise (low dv/dt and/or di/dt)
- **Cons**
  - Limited scalability in power and voltage
  - Limited fault tolerant operation

Architecture and Operation Principle of the Smart Transfomers

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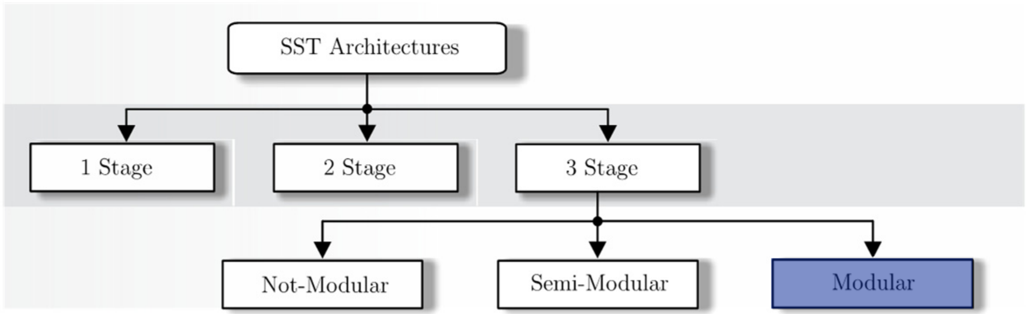
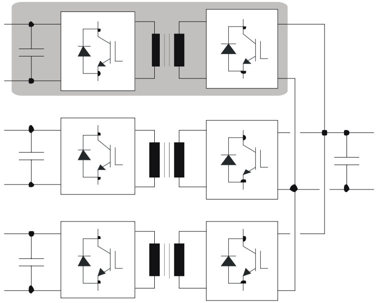
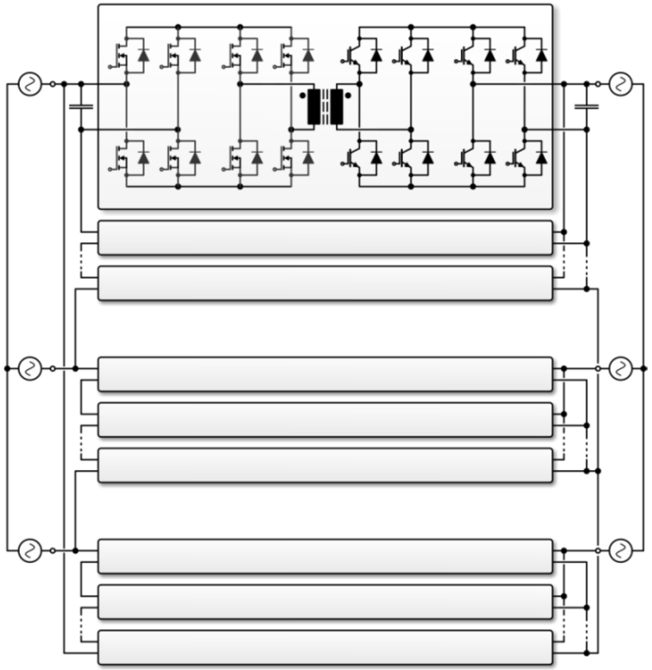
▶ ST Architecture Classfication: By Modularity





- **Features**
  - Based on multi-transformers
- **Pros**
  - Full modularity
  - Scalability in power/voltage
  - low EMI noise (low dv/dt and/or di/dt)
  - High reliability (flexible fault tolerant operation and maintenance)
- **Cons**
  - More number of power components

▶ GE Global Research (Mrinal K. Das, 2011)



- **Architecture**
  - Single power conversion stage
  - Full modularity
- **Features**
  - 10 kV SiC MOSFET
  - 1 MVA @ f_{sw}= 20 kHz
  - Efficiency: 97 % @ 885 kVA

[ref] N. Hugo, P. Stefanutti, M. Pellerin and A. Akdag, "**Power electronics traction transformer**," 2007 European Conference on Power Electronics and Applications, Aalborg, 2007, pp. 1-10.

Industrial and Academic Demonstrators

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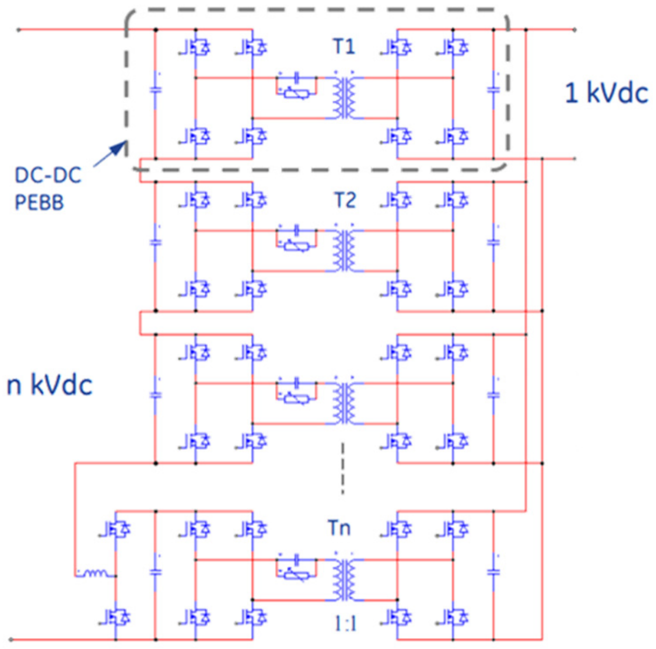
▶ GE Global Research (Ravisekhar Raju, 2017)



- **Architecture**
  - Three power conversion stages
  - Full modularity
- **Features**
  - 1.7 kV SiC Mosfet
  - 150 kVA @ fsw=40 kHz
  - Efficiency: max. 99.2 % @ approx. 50 kW

[ref] R. Raju, M. Dame and R. Steigerwald, "**Solid-state transformers using silicon carbide-based modular building blocks,**" 2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS), Honolulu, HI, 2017, pp. 1-7.

Industrial and Academic Demonstrators

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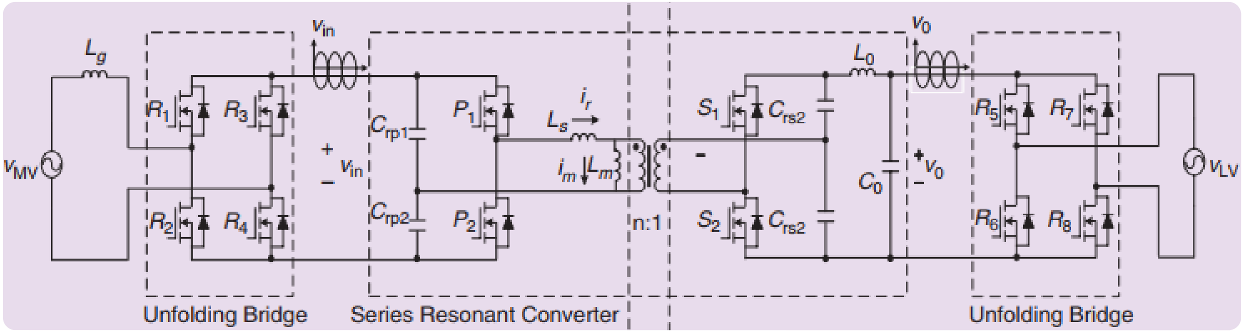
▶ **FREEDM (Alex Q. Huang, 2015)**



❑ Architecture

- single power conversion stage
- non-modularity

❑ Features

- 15 kV SiC Mosfet
- 10 kVA @ fsw=40 kHz
- Efficiency: >97 %

[ref] Q. Zhu, L. Wang, D. Chen, L. Zhang and A. Q. Huang, "**Design and implementation of a 7.2kV single stage AC-AC solid state transformer based on current source series resonant converter and 15 kV SiC MOSFET,**" 2017 IEEE ECCE, Cincinnati, OH, 2017, pp. 1288-1295.

Industrial and Academic Demonstrators

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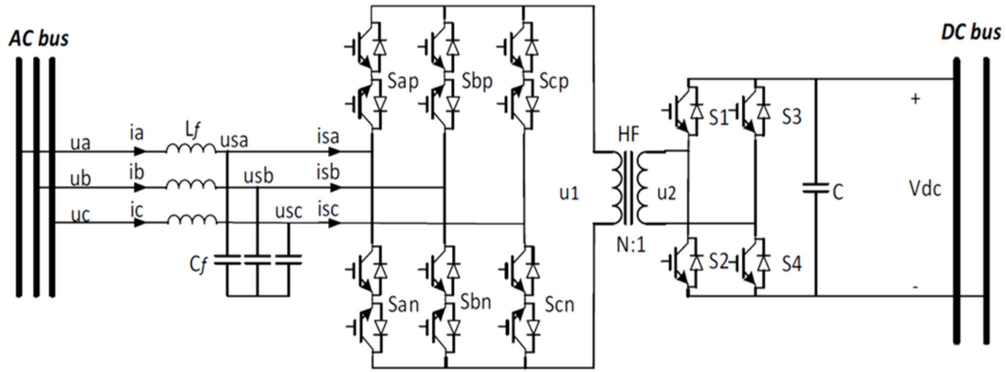
▶ **University of Alberta (Yun Wei Li, 2017)**



- Architecture
  - two power conversion stages
  - non-modularity

[ref] F. Fang and Y. W. Li, "**Modulation and control method for bidirectional isolated AC/DC matrix based converter in hybrid AC/DC microgrid,**" 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 37-43.

Industrial and Academic Demonstrators

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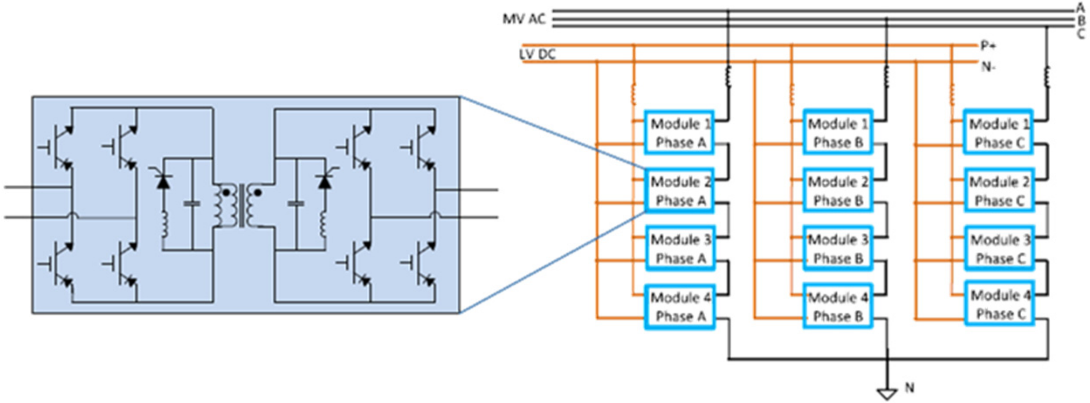
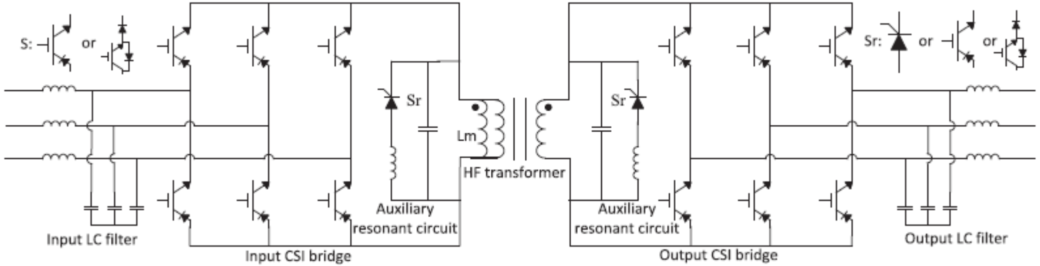
▶ **Georgia Institute of Technology (Deepak Divan, 2018)**





- Architecture
  - Two power conversion stages
  - Full modularity
- Features
  - Efficiency: 97.4 % @ 50 kVA
  - Soft-switching current source converter

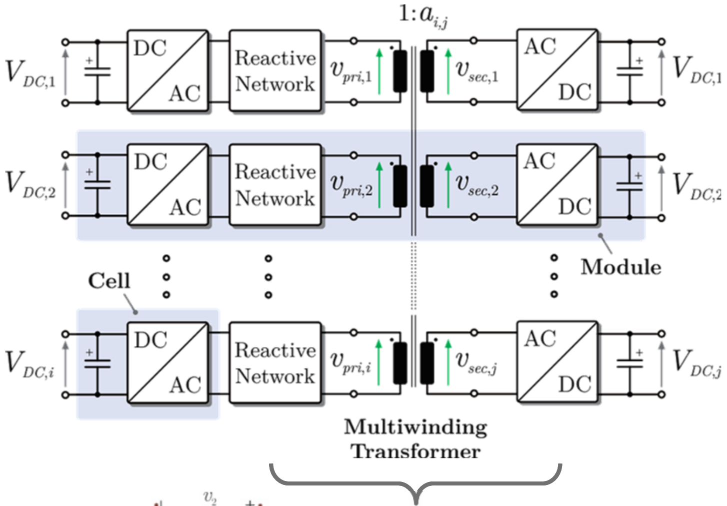
[ref] H. Chen and D. Divan, "**Soft-Switching Solid-State Transformer (S4T),**" in IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 2933-2947, April 2018.

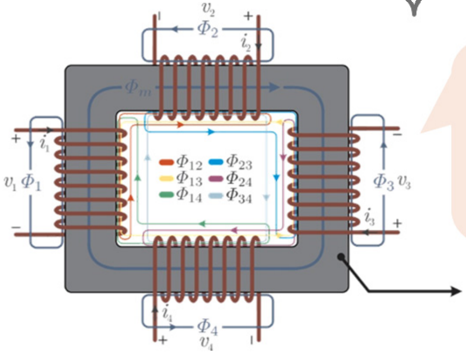
MTB DC-DC Converter for Multi-source Integration

► Generic Scheme of the MTB DC-DC Converters

- ❑ Several cells connected to the same **MWT**;
- ❑ MWT performs an important role establishing the magnetic coupling between the **Cells** and consequently composing the **Modules** and the overall power converter;
- ❑ The architecture of the MTB DC-DC converter can be generically defined by combining of: *i* primary-side cells; *i* reactive networks; and *j* secondary-side cells.
- ❑ **Reactive Network** provides either the **resonant** or **non-resonant** behavior for the DC-DC converter.

- ❑ Extension of the conventional converters with multiple ports;
- ❑ Interconnection Flexibility;
- ❑ Fault-tolerant Capability.





The magnetic flux can be decomposed into the **main flux**, which links all the windings.

MTB DC-DC Converters for Multi-source Integration

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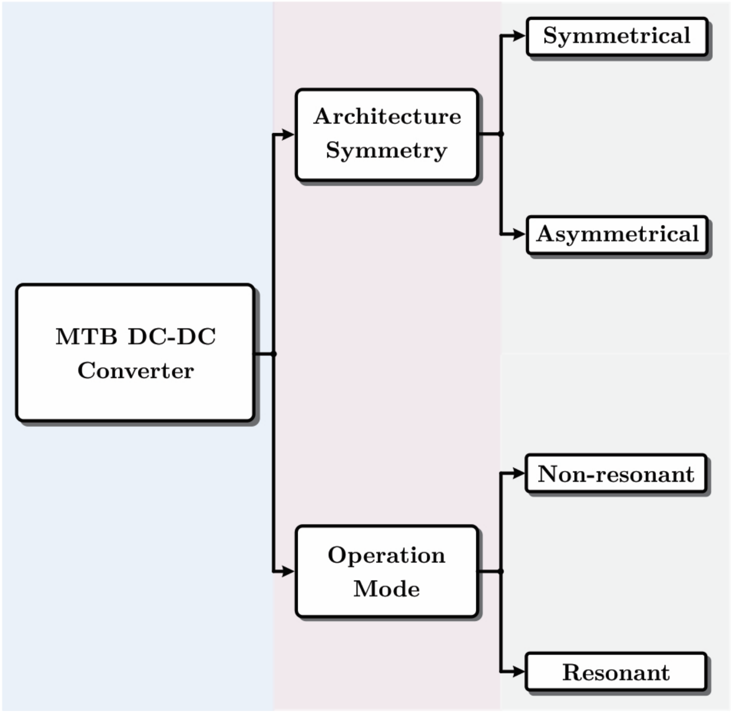
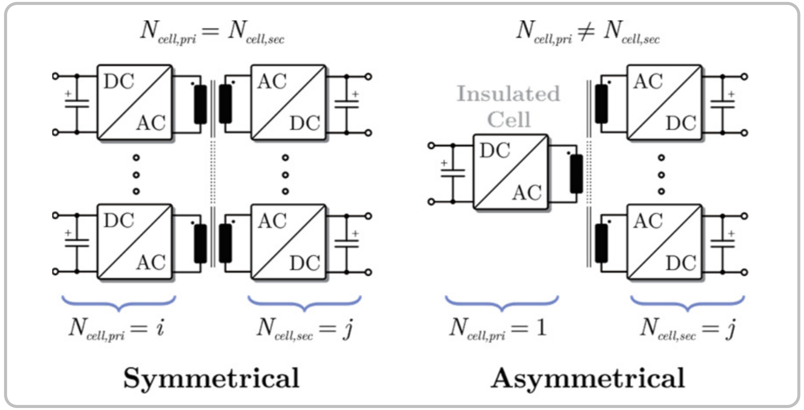
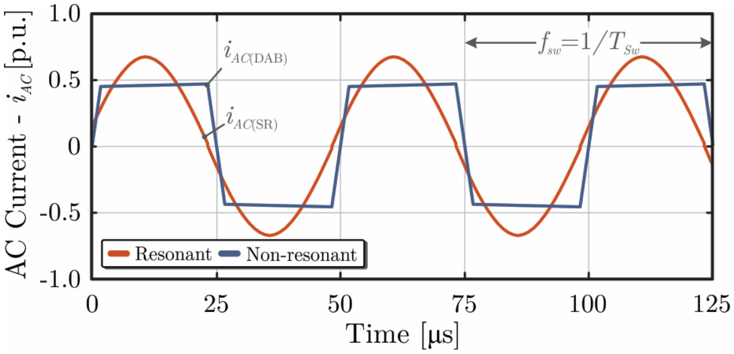
▶ Classification of the MTB Topologies

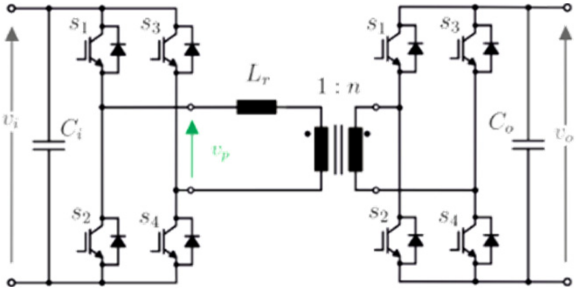




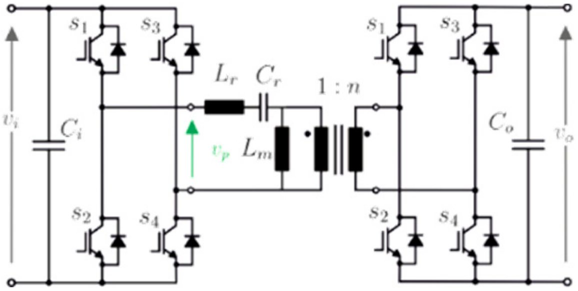


MTB DC-DC Converters for Multi-source Integration

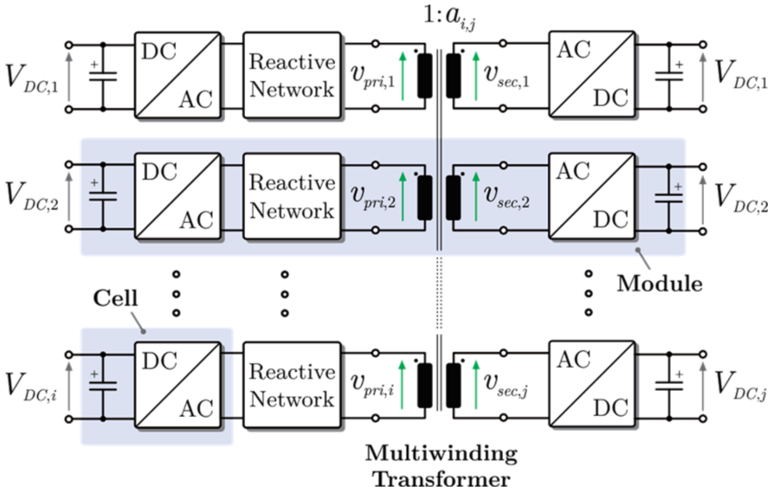
▶ Operation Principle of the MTB Topologies



Dual-Active-Bridge (DAB)



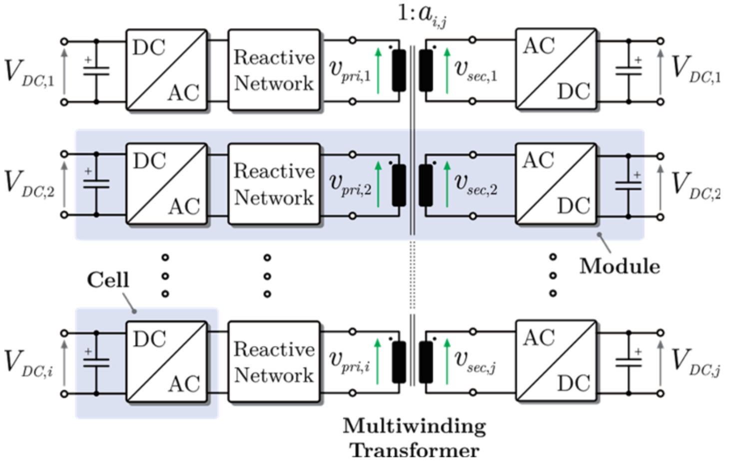
SR and LLC Converter



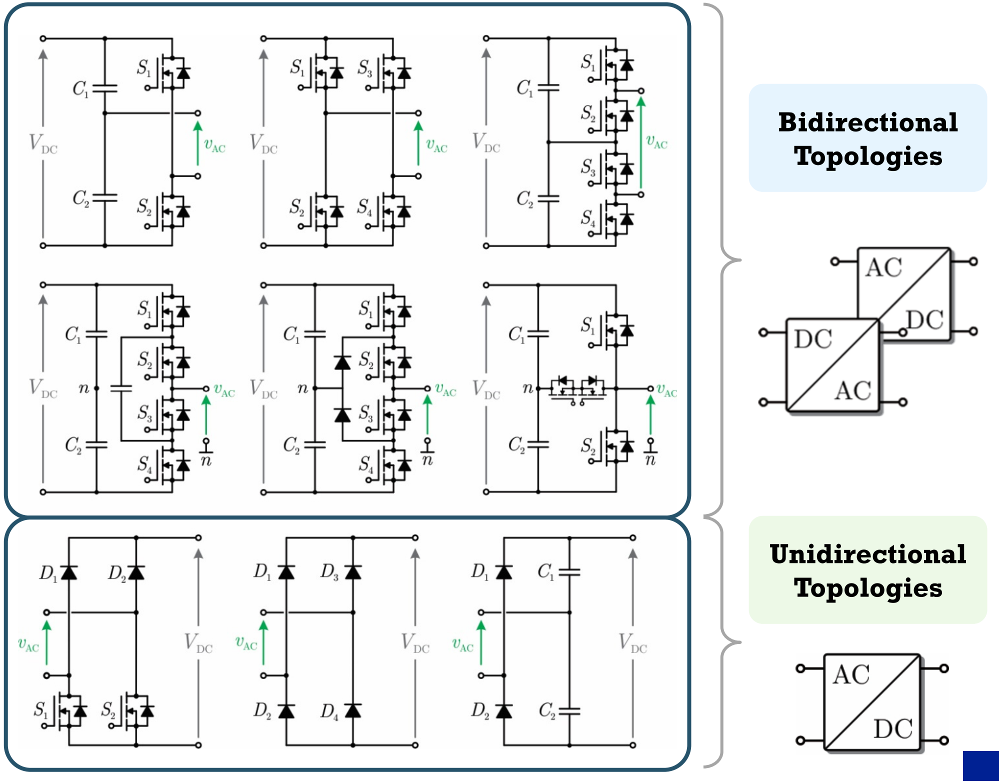
Resonant x Non-Resonant MTB DC-DC Converter

Dual-Active-Bridge (DAB)	SR and LLC Converter
Non-Resonant	Resonant

▶ Overview of the MTB DC-DC Topologies



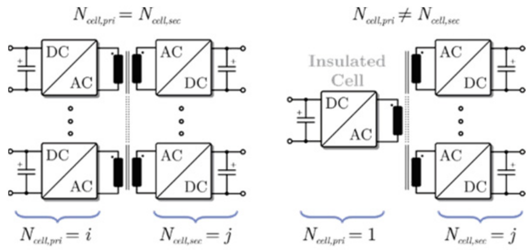
Depending on the power requirements, the conversion stages (cell) can be implemented by using different **active**, **semi-active** (hybrid), and **passive topologies**.

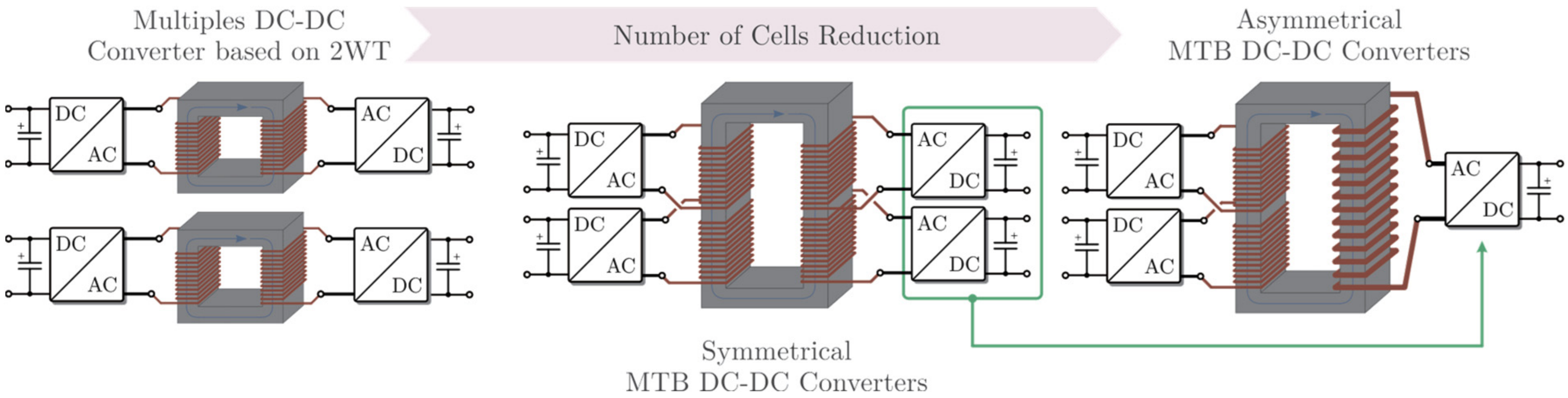


MTB DC-DC Converters for Multi-source Integration

▶ **Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability**

By means of the **magnetic coupling**, the **Symmetrical MTB (SMTB)** topologies can be designed to merge its secondary side cells in only one single cell, yielding then the **Asymmetrical MTB (AMTB)** topologies and enabling also the reduction of cells





MTB DC-DC Converters for Multi-source Integration

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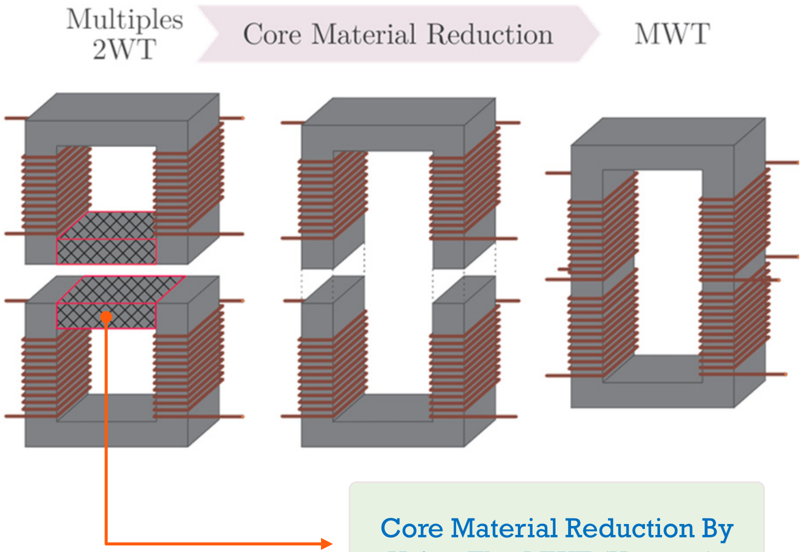
▶ **Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability**

- Due to the magnetic coupling among the cells, the MWT presents a clear advantage regarding the **material reduction** compared to multiple 2WTs.

- As can be seen, some core material can be saved when the **2WT** is replaced by the **MWT**.

Core Material Reduction by Using The MWT.

Magnetic Core Geometry	U-U	U-I	E-E	ETD-ETD
Core Material Reduction	10 %	15 %	12 %	2 %



Core Material Reduction By Using The MWT (U-cores).

MTB DC-DC Converters for Multi-source Integration

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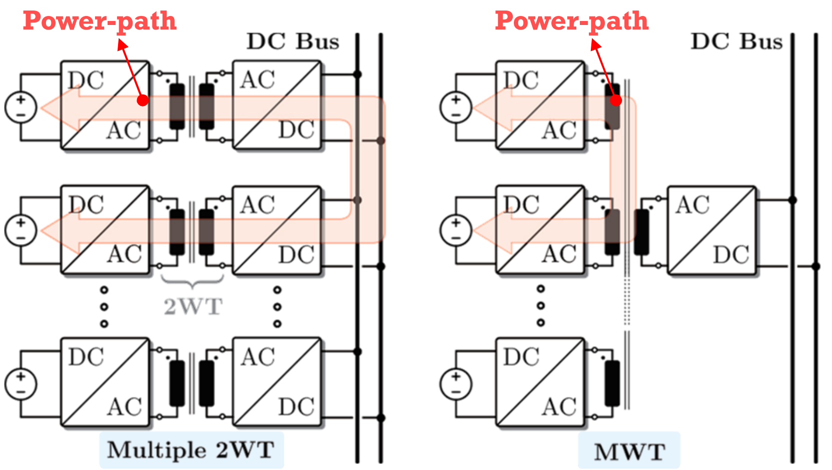
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

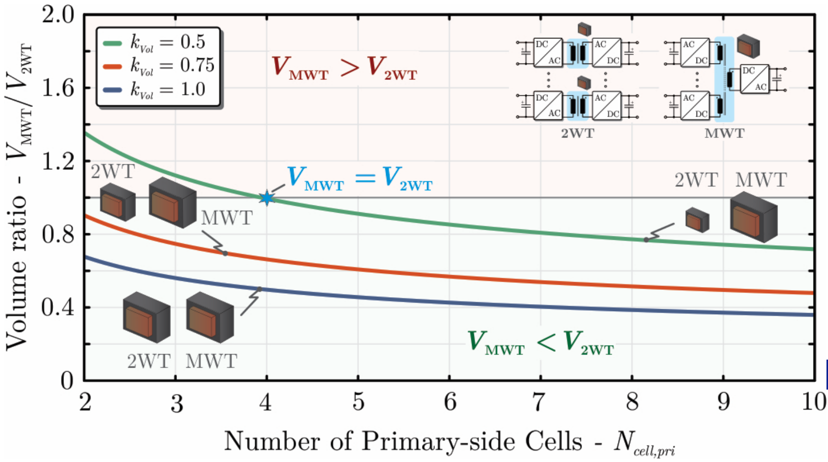
The **power-paths** can be shortened when the MWT is adopted, due to its inherent magnetic link. As a result, since the structure uses less cells, the **power density** of the MTB topologies can be increased when the MWT is adopted.

Base on the **Product Area**, the **total MWT volume** scales with the number of cells compared to multiple 2WTs for the same processed power.

$$\left.\frac{V_{MWT}}{V_{2WT}}\right|_{asym} = \frac{1}{k_{Vol}N_{2WT}}\left(\frac{N_{cell,pri}+1}{2}\right)^{0.75}$$

k_{Vol} is the ratio between the core size of the **2WT** and **MWT** ($0 < k_{Vol} < 1$).





▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

Whereas the **SMTB** and **2WT-based topologies** can be fully composed by **identical cells** with the **same volume**, the **AMTB topologies** is composed by **the same primary-side cells** and only one **insulated cell** which might has its **volume** varying according to the total power processed:

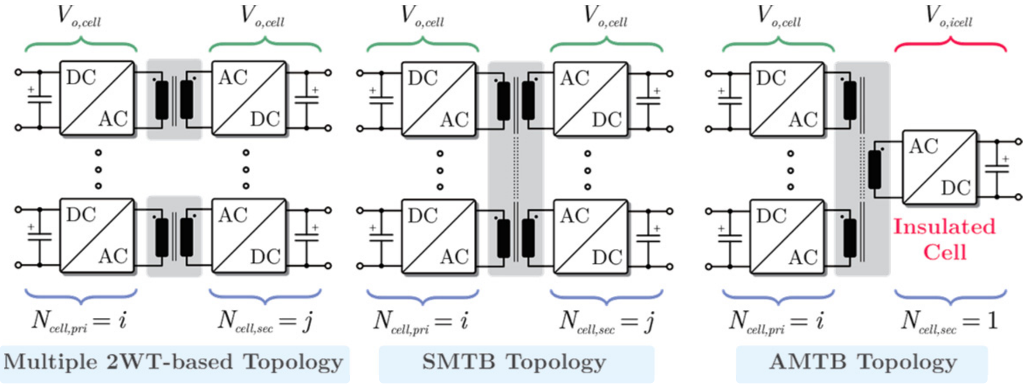
$$V_{o,icell} = k_{v,cell} V_{o,cell} \quad \text{where} \quad k_{v,cell} = (N_{cell,i,j})^{1.5}$$

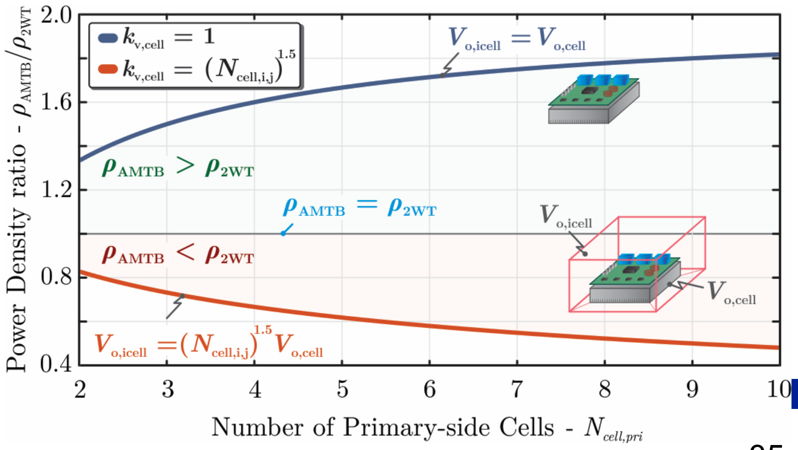
$$V_{\text{Total,2WT}} = 2N_{cell,i,j} V_{o,cell} + N_{cell,i,j} V_{\text{2WT}}$$

$$V_{\text{Total,SMTB}} = 2N_{cell,i,j} V_{o,cell} + V_{\text{MWT}}$$

$$V_{\text{Total,AMTB}} = (N_{cell,i,j} + k_{v,cell}) V_{o,cell} + V_{\text{MWT}}$$

$$\frac{\rho_{\text{AMTB}}}{\rho_{\text{2WT}}} = \frac{2N_{cell,i,j} V_{o,cell} + N_{cell,i,j} V_{\text{2WT}}}{(N_{cell,i,j} + k_{v,cell}) V_{o,cell} + V_{\text{MWT}}}$$



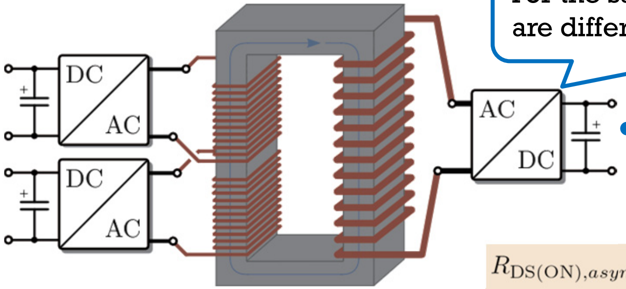


MTB DC-DC Converters for Multi-source Integration

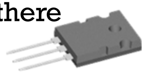
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

Thanks to the **core material** and **number of cells reduction**, the MTB topologies, in particular the **AMTB** ones might be **more advantageous** in terms of **cost**. Further, with a reduction of the number of cells, the **cost-benefit** can also be extended to the **power semiconductor devices.**

Although higher-current rating devices **(with lower on-resistance)** are required to implement the **insulated cell**, the increased price of the individual device does not impact further the **total cost**.

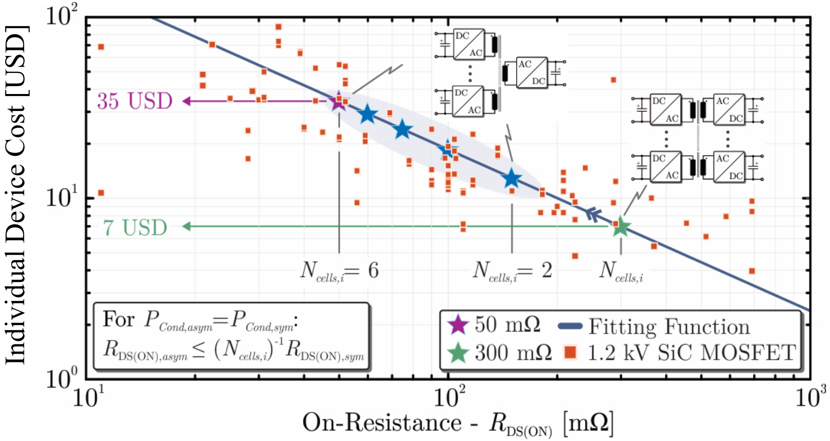


For the same Package, there are different devices.



Condition for ensure the Cost-benefit

$$R_{DS(ON),asym} \leq (N_{cells,pri})^{-1} \cdot R_{DS(ON),sym}$$



$N_{cells,pri}$	2 cells	3 cells	4 cells	5 cells	6 cells
Cost Reduction	15.60 %	21.43 %	25.00 %	21.43 %	8.33 %

MTB DC-DC Converters for Multi-source Integration

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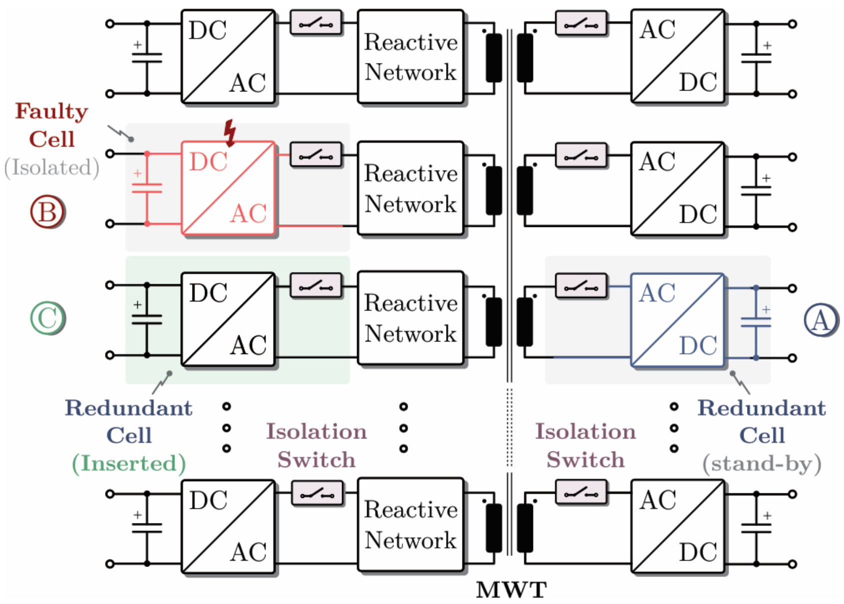
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault-Tolerant Capability

Another advantage and potential of the MWT is related to the redundant power path, which provides **Fault-Tolerant Capability** by means of the **magnetic coupling** among the cells.

A. Normal operation with redundant cells in **stand-by mode** and others in **power-sharing mode** (as part of the MTB DC-DC converter);

B. **Reconfiguration** example after a fault by means of the isolation switches to disconnect the faulty cell.

C. **Connection** of the redundant cell previously in stand-by or just **routes** the power by the healthy ones.



MTB DC-DC Converters for Multi-source Integration

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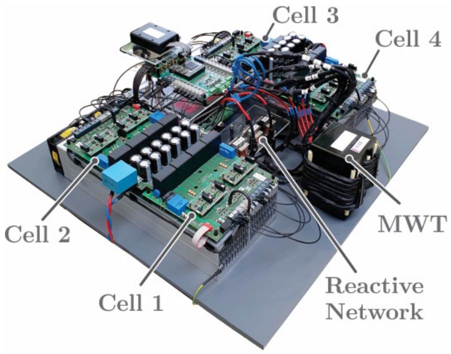
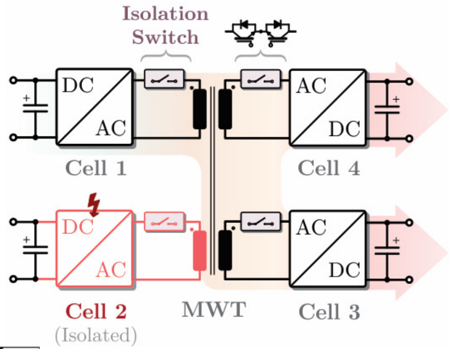
▶ **Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault-Tolerant Capability**

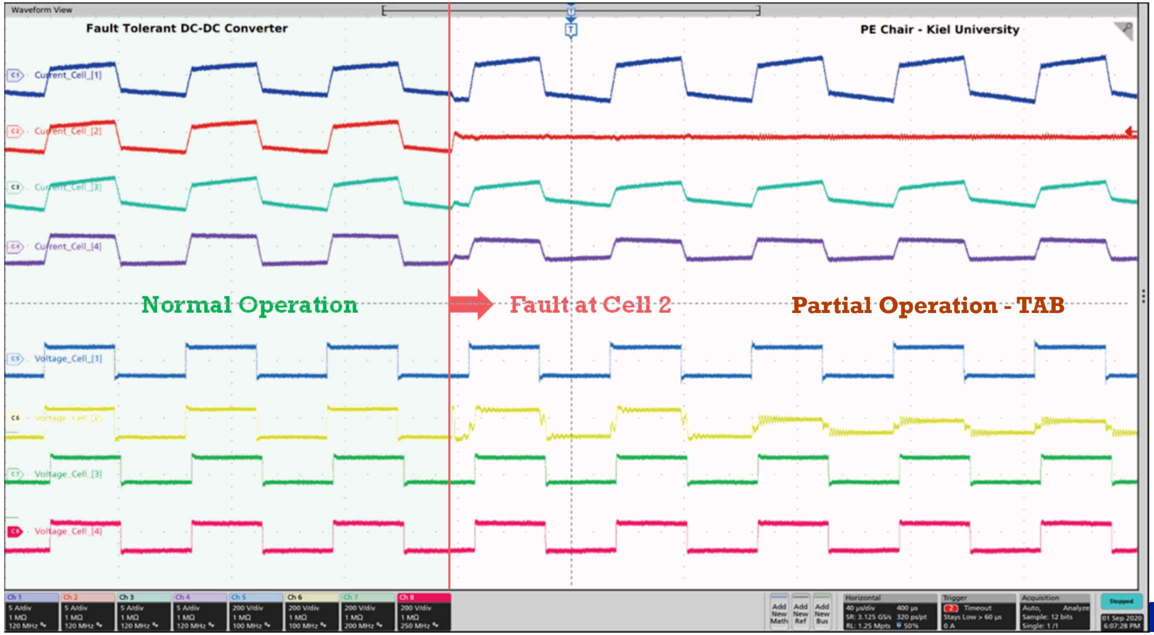




Symmetrical Quadruple-Active-Bridge (SQAB) DC-DC Converter

Current Waveforms

Voltage Waveforms



GRID INTERFACE BY USING CASCADE H-BRIDGE (CHB) MULTILEVEL CONVERTER

Grid Intercace by using CHB Converter

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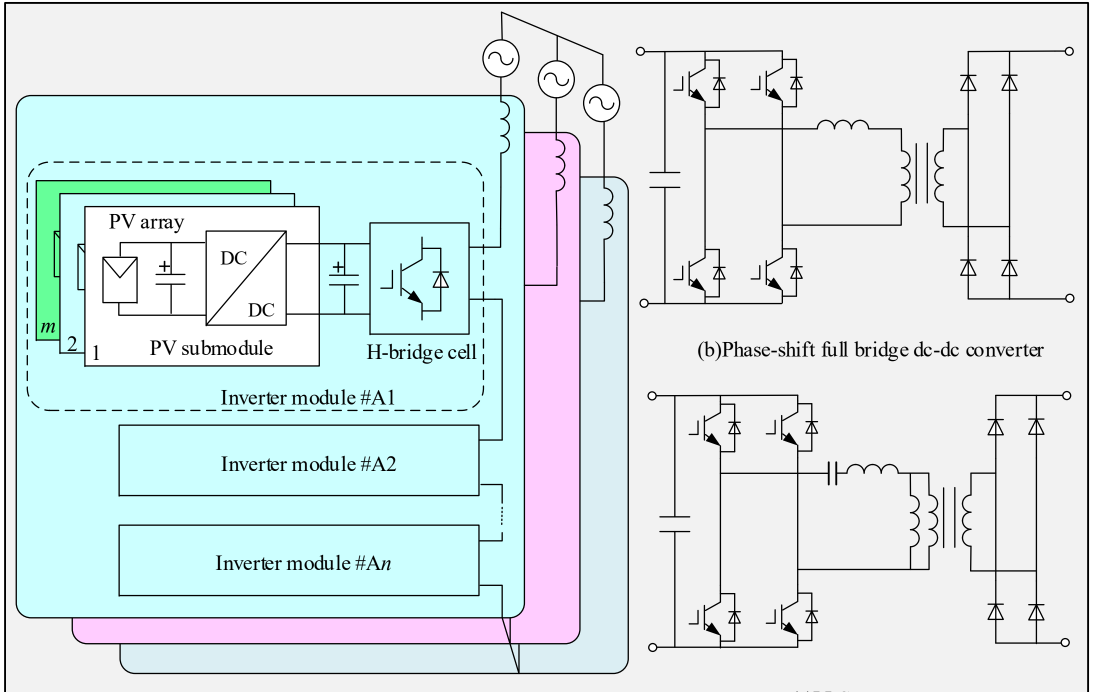
▶ Conventional System Architecture for Grid Interface by Using CHB Converter



(a)Circuit configuration of conventional CHB PV system with dc-dc converters

(c)LLC resonant converter

Advantages:

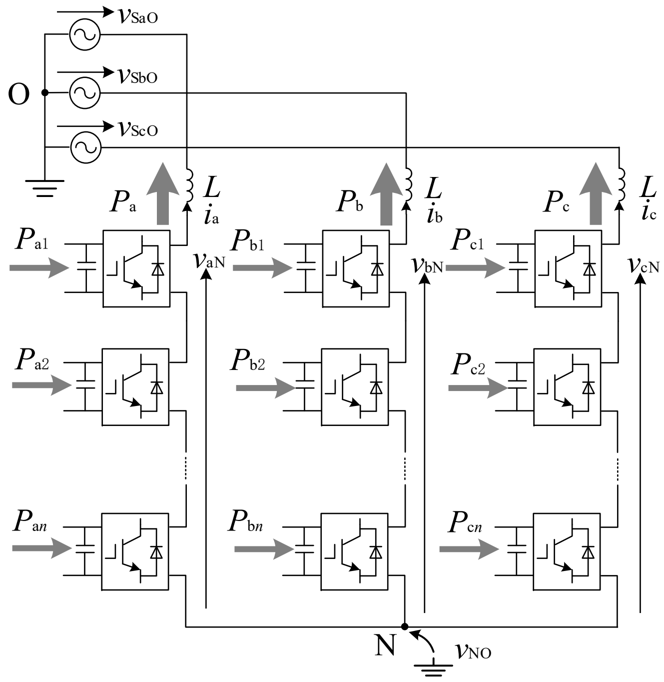
- ❑ Without low-frequency transformer;
- ❑ Modularity and scalability;
- ❑ Individual MPPT
- ❑ Available ports for PV and BESS

Challenages:

- ❑ Isolated DC/DC converters with high performances
- ❑ **Inter-module and inter-phase power imbalance**
- ❑ Control systems with multi-objectives

Grid Intercace by using CHB Converter

▶ **Power imbalance in CHB-based PV Systems**



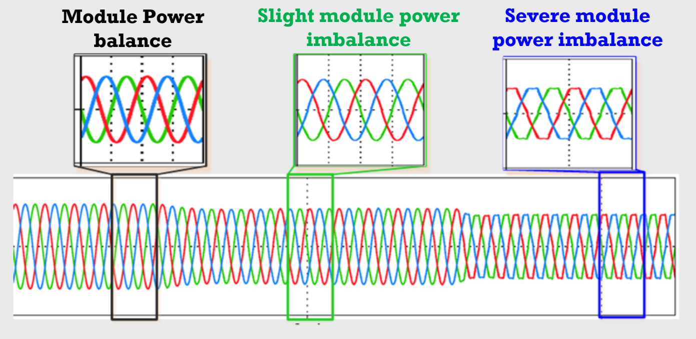
Power imbalance

↓

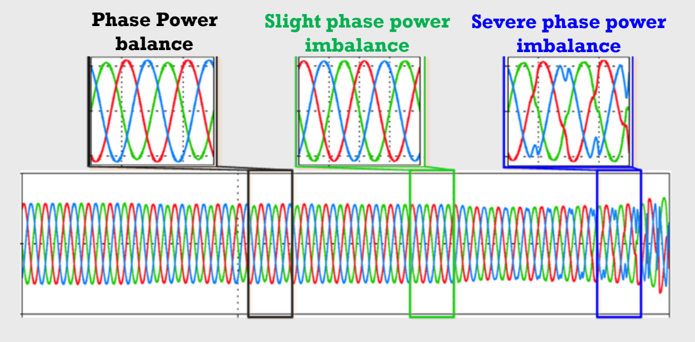
Over-modulation

↓

Current Distortion



Current Waveforms in case of inter-module power imbalance



Current Waveforms in case of inter-phase power imbalance

Grid Intercace by using CHB Converter

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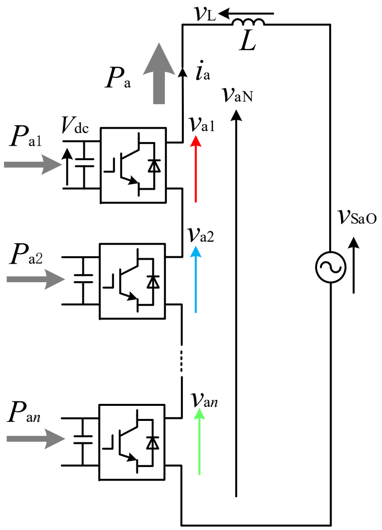
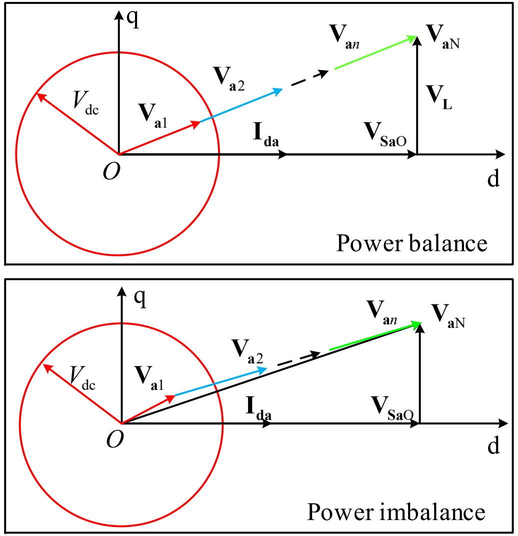
▶ Operation Range Limited by Inter-module Power Imbalance





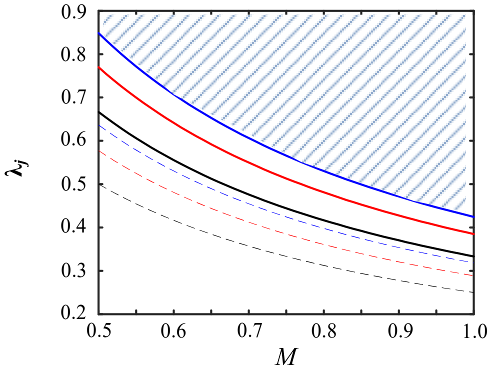
The derivation of operation range using sinusoidal modulation with different amplitudes:

$$\lambda_{ai} = \frac{P_{ai}}{P_a}$$

$$|\mathbf{V}_{aj}| \leq V_{dc} \quad \Rightarrow \quad \sqrt{(\lambda_{ai}\frac{V_{aO}}{V_{dc}})^2 + (\frac{2\omega L P_a}{n V_{dc} V_{aO}})^2} \leq 1$$

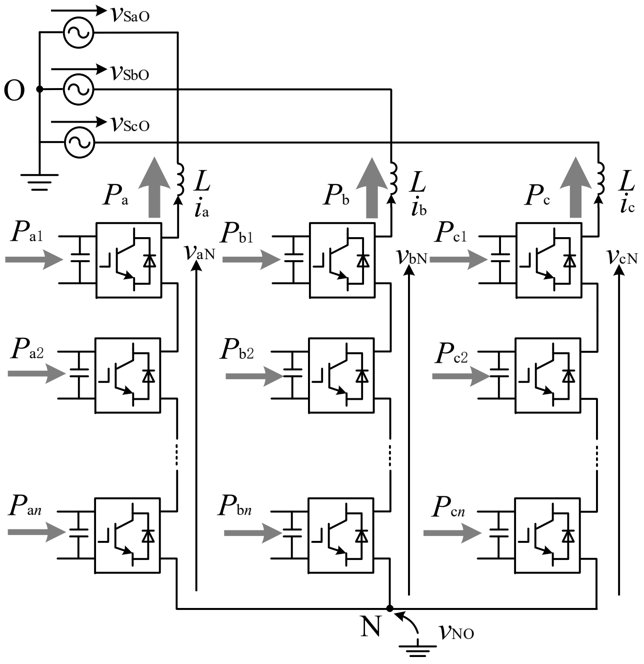
Some control methods are applied to extend the operation range limited by inter-module power imbalance

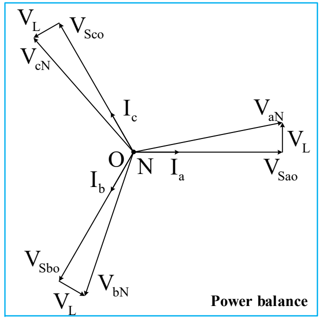
- Sinusoidal with different amplititudes (**Black**)
- Multi-frequency control method (**Red**)
- Discontinuous modulation method (**Blue**)

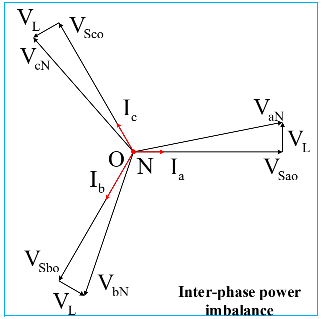


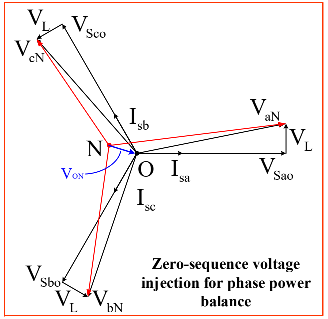
The control methods can not ensure the system stable operation!

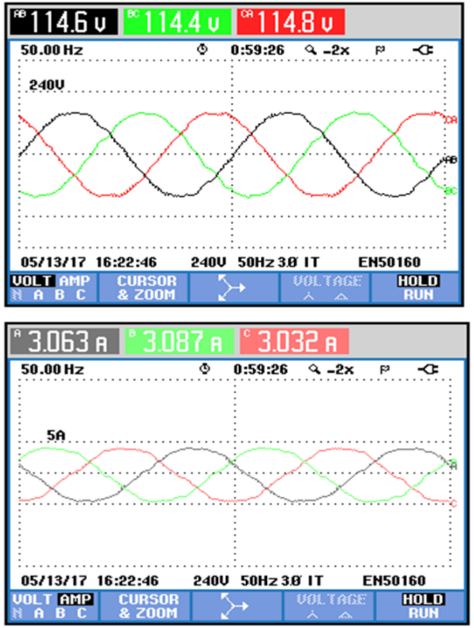
▶ Operation Range Limited by Inter-phase Power Imbalance











Experimental waveforms with zero-sequence voltage Injection in the case of P_a=0.75P_b=0.75P_c

Grid Intercace by using CHB Converter

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▶ Operation Range Limited by Inter-module Power Imbalance

Some control methods are used to extend the operation range limited by inter-phase power imbalance:

- Sinusoidal Injection
- Square-wave Injection
- Minimum-maximum Injection
- Double Third-harmonic Injection
- Optimum Zero-sequence Injection

The derivation of operation range using sinnsoidal zero-sequence voltage injection:

$$\gamma_a = \frac{P_a}{P_a},\quad \gamma_b = \frac{P_b}{P_a},\quad \gamma_c = \frac{P_c}{P_a}\ (P_a \geq P_b \geq P_c)$$

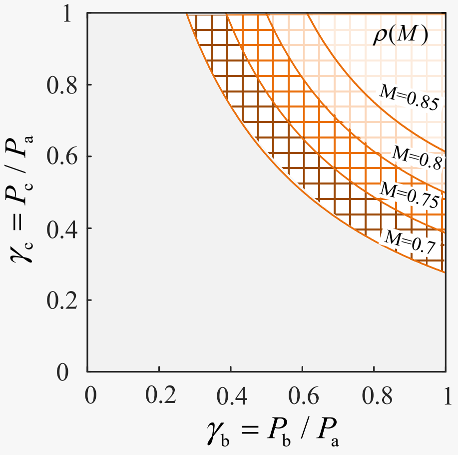
$$\hat{v}_{invA} = \sqrt{3}V_s \frac{\sqrt{3+(\gamma_B-\gamma_C)^2}}{1+\gamma_B+\gamma_C}$$

The constrain condition:

$$\max\{|V_{aN}|,|V_{bN}|,|V_{cN}|\} \leq nV_{dc}$$

The derivate condition:

$$\frac{\sqrt{3+(\gamma_b-\gamma_c)^2}}{1+\gamma_b+\gamma_c} < \frac{1}{\sqrt{3}M}$$

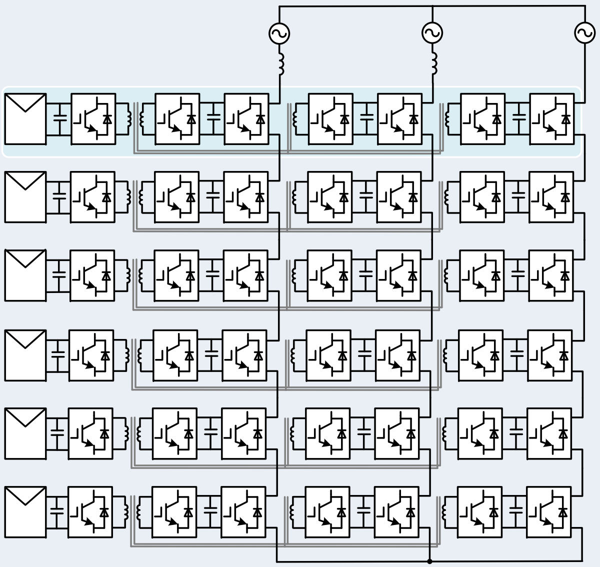


Operation range with Sinusoidal Zero-sequence voltage injection

The Power Balancing Capacity of Control Methods is Finite!

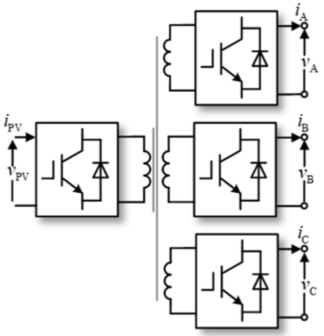
Grid Intercace by using CHB Converter

► Several Architectures with Power Balancing Capacity: CHB+QAB



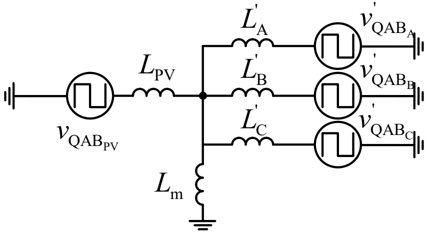
Characteristics:

- ❑ Each module is composed of one **QAB converter** and three **H-bridge cells** that belong to Phase A, B and C, separately.
- ❑ The dc-link of the active bridge in the PV side is connected to PV arrays while the active bridges in the MV sides are connected to the dc links of the H-bridge cells, **which can ensure the inter-phase power balance**.



Control methods used for the power transmission:

- Single Phase Shift (SPS)
- Dual Phase Shift (DPS)
- Extended Phase Shift (EPS)
- Triple Phase Shift (TPS)



$$L_A = L_B = L_C = \alpha L_{PV} \ll L_m$$

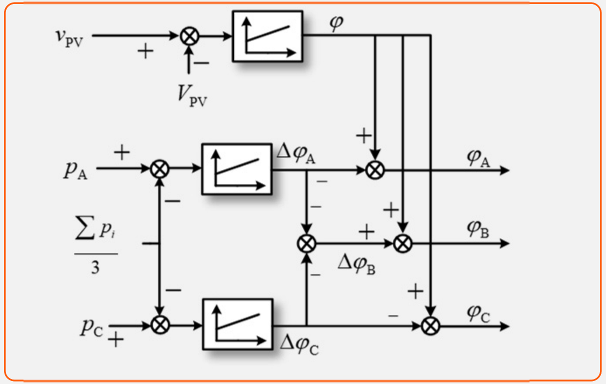
$$N_A = N_B = N_C = \beta N_{PV}$$

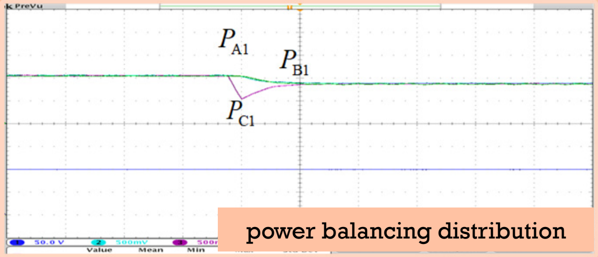
$$P_{PVi} = \frac{V_{PV} V_i}{2\pi f_s L_{PV}} \cdot \frac{\beta}{3\beta^2 + \alpha} \varphi_{PVi} \left(1 - \frac{|\varphi_{PVi}|}{\pi}\right)$$

Grid Intercace by using CHB Converter

▶ Control and Design of Asymmetrical Quadruple-Active-Bridge (AQAB)

Control of Power Distribution





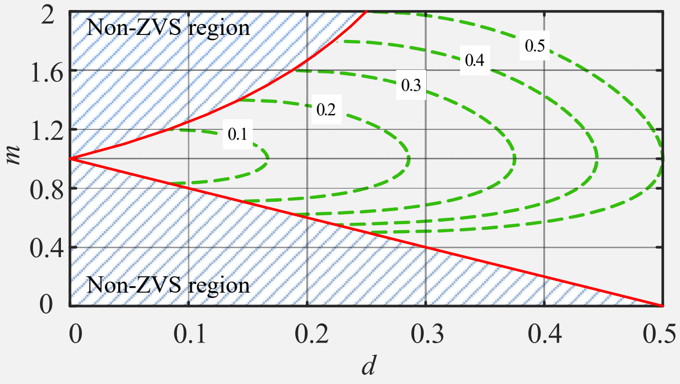
power balancing distribution

Optimized Design:

ZVS Analysis

Reactive Current Analysis

$$m=\frac{V_i}{\beta v_{PV}},\quad d=\frac{\varphi_{PVi}}{\pi}$$



In the *d*-*m* plane, non-ZVS region (shadow region) and the contour line of reactive current ratio γ (green line) are marked. In order to reduce γ and ensure the converter work in the ZVS region, $V_i/(\beta V_{base})\approx 1$ is preferred.

Grid Intercace by using CHB Converter

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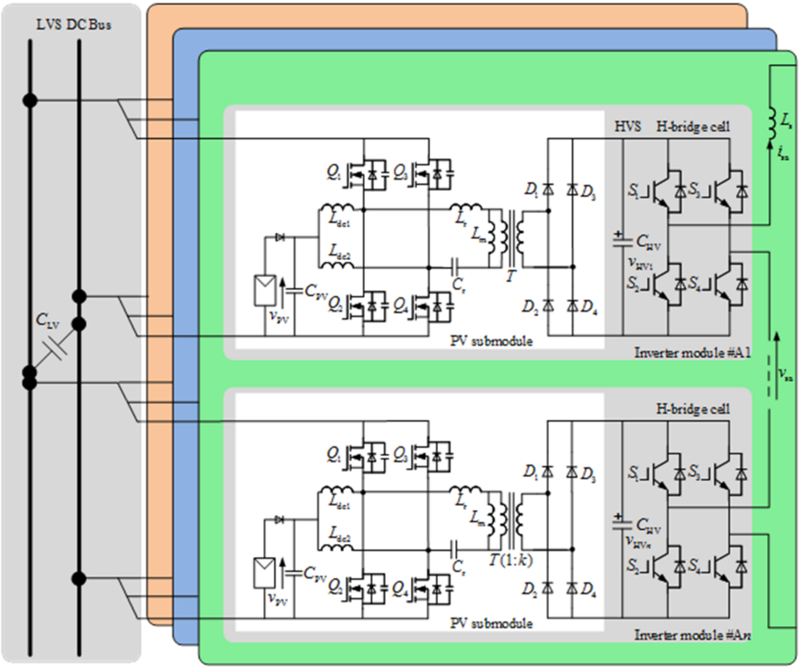
▶ Several Architectures with Power Balancing Capacity: CHB+IB-FBLLC

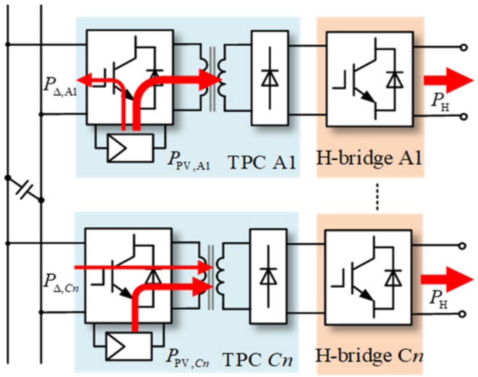
Circuit configuration of the CHB-based topology with IB-FBLLC dc-dc converters



Characteristics:

- In the first stage, instead of two-port dc-dc converters, each PV submodule includes PV arrays and one three-port dc-dc converter with high frequency transformer.
- The low voltage side (LVS) port of each IB-FBLLC converter is connected to a common dc bus, the input port is connected to PV arrays, and the high voltage side (HVS) port is connected to H-bridge dc-link.

Power balancing mechanism



The modules exchange the additional power through common dc bus.

Grid Intercace by using CHB Converter

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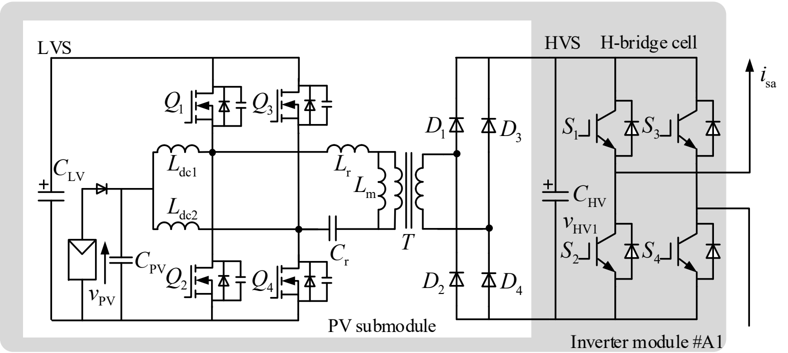
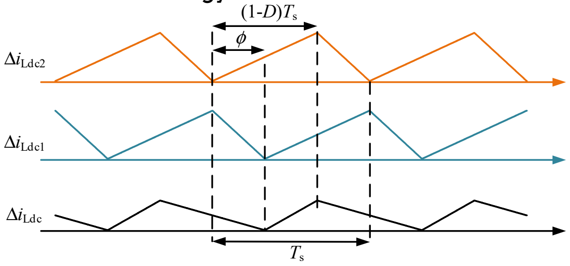
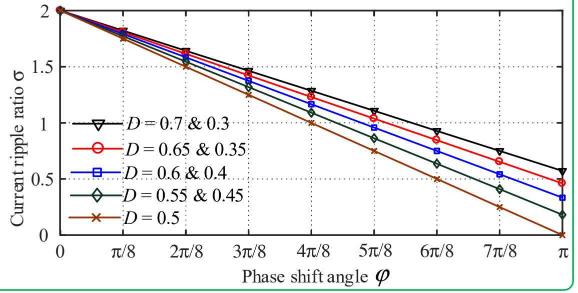
▶ The optimized design of IB-FBLLC converter:



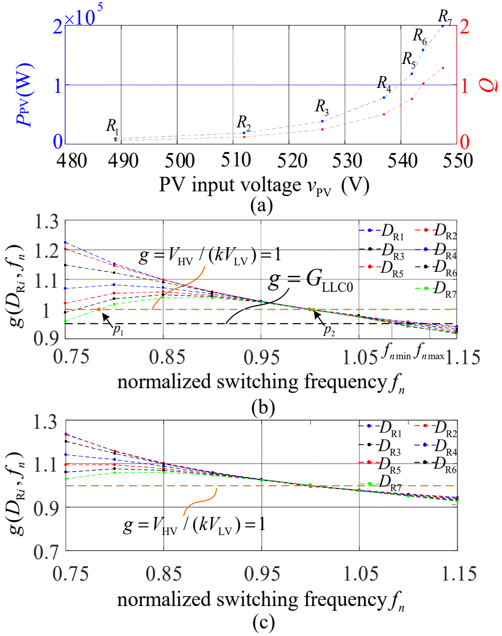
- ❑ Interleaved-structure to minimize the PV current ripple
- ❑ Boost-structure to extend the PV MPPT range
- ❑ ZVS and ZCS to reduce the switching power loss

In order to obtain less ripples, the phase shift angle is tuned as φ=π, which can be achieved by the modulation strategy.



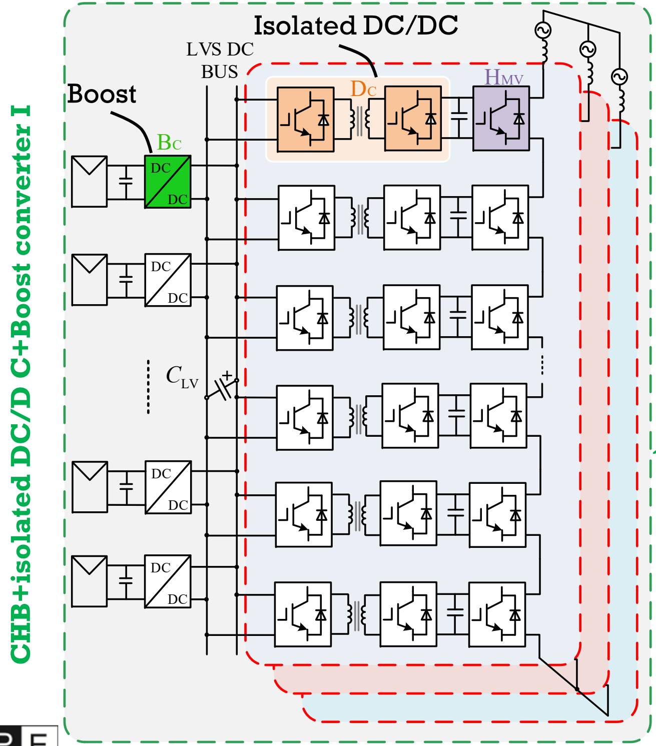


Through designing $V_{HV}/(kV_{LV})\approx 1$, the frequency range $[f_{nmin}, f_{nmax}]$ can be reduced and the operational switching frequency is near to constant frequency.



Grid Intercace by using CHB Converter

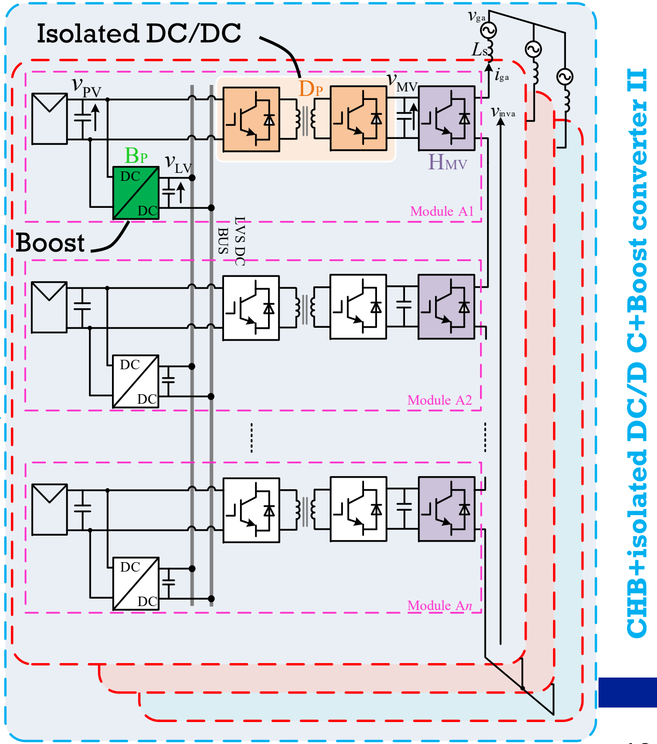
▶ Several Architectures with Power Balancing Capacity: CHB+isolated DC/DC+Boost converter I and II



Characteristics

In the architecture I, the system includes three-stage power conversation cells. The first stage is the PV stage, composing of PV arrays and boost converters Bc, where the boost converters implement MPPT and transfer the PV powerinto the LV dc bus. The second stage is the isolated dc-dc stage, composing of isolated dc-dc converters Dc. This stage is used for galvanic isolation between PV arrays and the MV grid. The third stage is the dc-ac stage, composing of the H-bridge cells.

Unlike the LV dc bus between the boost converters and the isolated dc-dc converters in the conventional architecture, the LV dc bus in the proposed architecture is only connected to the output ports of all boost converters Bp. The input ports of the boost converters are connected to the PV arrays, where the isolated dc-dc converters Dp are also connected to.



Grid Intercace by using CHB Converter

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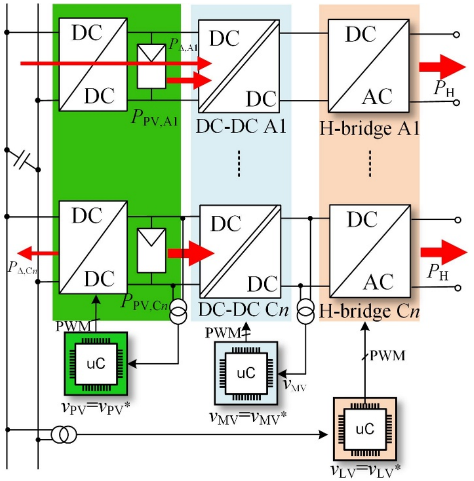
▶ Control and Performance Analysis

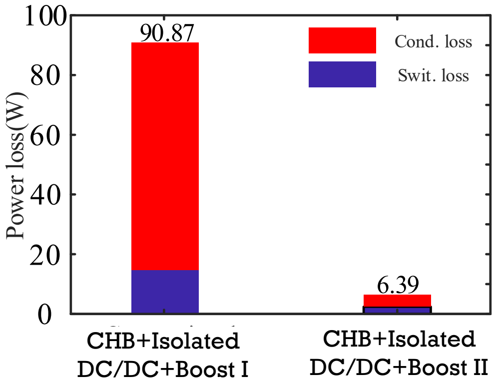
Control Structure for Architecture II



- For the architecture I, the Boost converter control the PV port voltage while the isolated DC/DC converter control the DC bus voltage and the CHB converter control the dc-link voltage of all H-bridge.
- For the architecture II, the Boost converter still control the PV port voltage while the isolated DC/DC converter control the dc-link voltages of all H-bridge cells and the CHB converter control the DC bus voltage.

Power Loss of Boost Converter

Parameters	Value
PV Power	30kW
PV Rated Voltage	550V
DC Bus Voltage	1100V
Switch Frequency	10kHz
SiC Mosfet	C2M0045170P



Reduced Power Loss in the Boost Converters!

Grid Intercace by using CHB Converter

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Qualitative Comparison of Several Architectures

Topology Architecture	Type of DC-DC Converters	Number of MPPT	Number of Isolated DC/DC Converters	Challenges	Operation Range
Conventional CHB-based Syetem Architecture	Two-port DC-DC Converter with Isolation	3n	3n	Inter-module and Inter-phase Power Imbalance	+
CHB+QAB	Four-port DC-DC Converter with Isolation	n	n	Inter-module Power Imbalance、Design of HFT	+++
CHB+IB-FBLLC	Three-port DC-DC Converter with Isolation Boost converter	3n	3n	Variable Switching Frequency 、Design of HFT	+++++
CHB+Isolated DC/DC+Boost I	Two-port DC-DC Converter with Isolation Boost converter	Arbitrarily	3n	Large number of DC/DC Converter、High Power Loss in Boost Stage	+++++
CHB+Isolated DC/DC+Boost II	Two-port DC-DC Converter with Isolation Boost converter	3n	3n	Large number of DC/DC Converter、Variable Input Voltage in Isolated DC/DC Stage	+++++

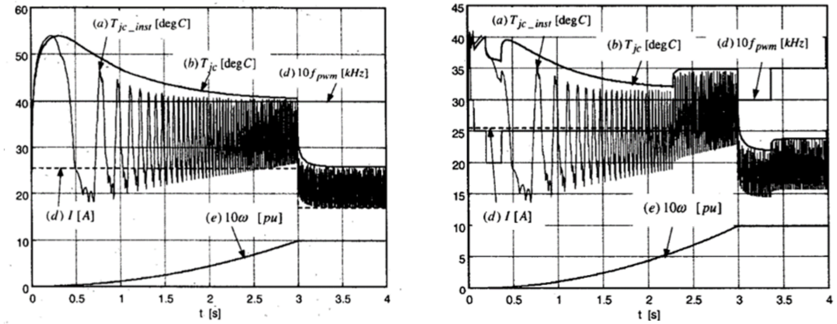
Power Routing for More Reliable ST

Control for Increased Reliability

▶ Online thermal management

- ❑ Rockwell automation published the first manuscript about active thermal control in 1999
- ❑ Motor drive application

[ref] V. Blasko, R. Lukaszewski and R. Sladky, "**On line thermal model and thermal management strategy of a three phase voltage source inverter,**" Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370), Phoenix, AZ, 1999, pp. 1423-1431 vol.2.

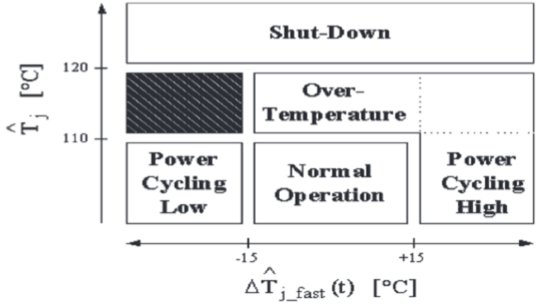


Junction temperature of the power semiconductors without/with active thermal control

▶ Region based controller

- ❑ First journal article published in 2006
- ❑ Motor drive application

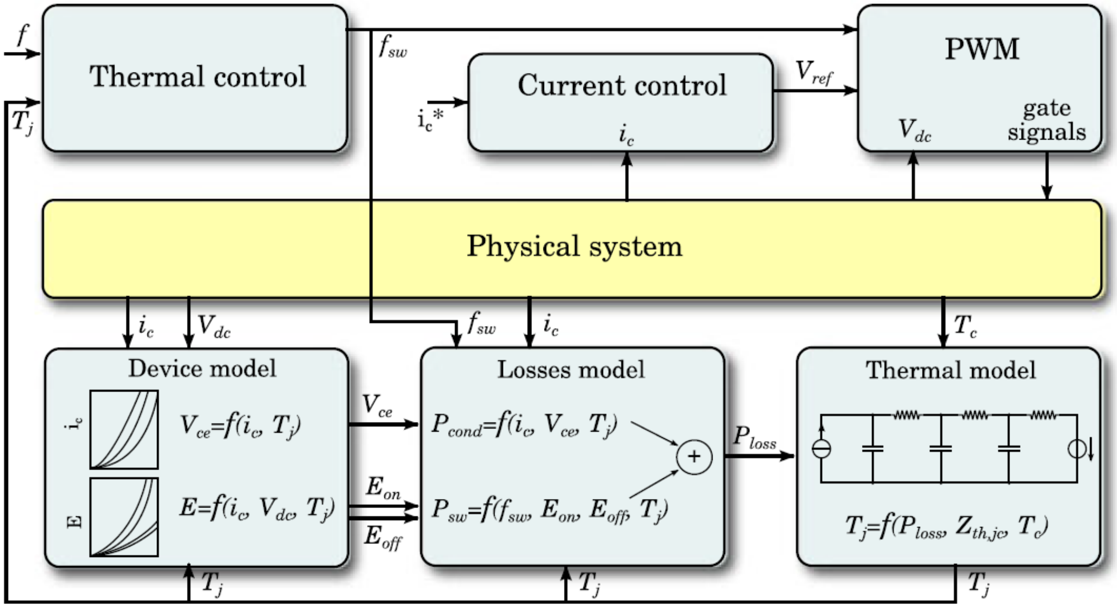
[ref] D. A. Murdock, J. E. R. Torres, J. J. Connors and R. D. Lorenz, "**Active thermal control of power electronic modules,**" in IEEE Transactions on Industry Applications, vol. 42, no. 2, pp. 552-558, March-April 2006.



Definition of different regions for the application of active thermal control

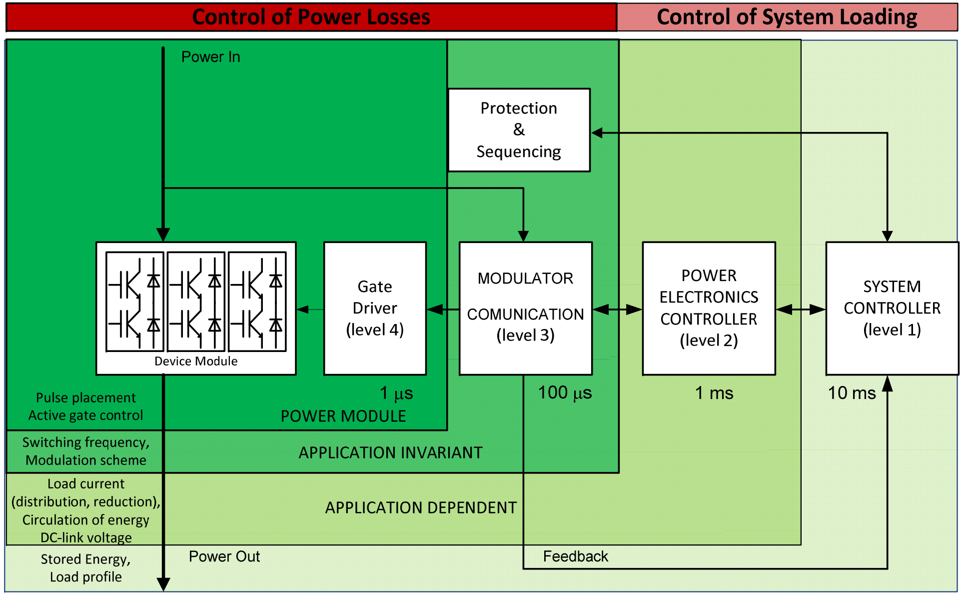
Active Thermal Control

▶ **Example of a model-based active temperature control scheme**



Active Thermal Control

▶ Active thermal control on different system levels



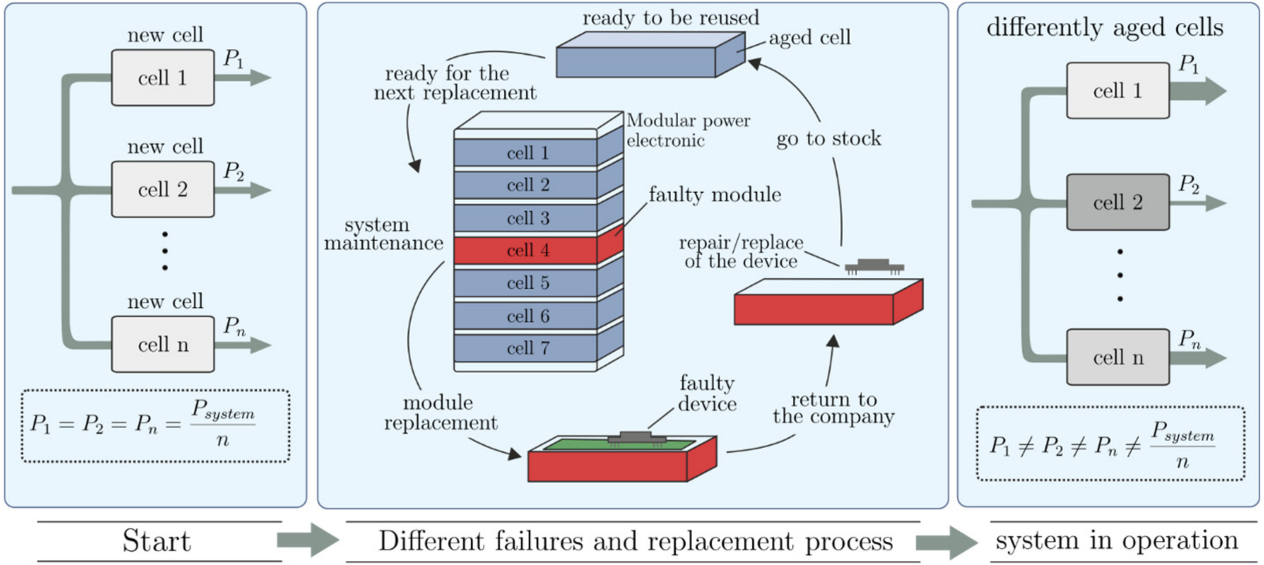
- ❑ Junction temperature control for reduction of thermal stress
- ❑ Thermal controller can address cycles with different time periods
- ❑ Different thermal controllers can be implemented in parallel

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

Power Routing for Modular ST

▶ Active thermal control on SYSTEM CONTROLLER LEVEL

- Power routing for modular converter as a repairable system composed by differently aged cells



[ref] 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 for Modular ST

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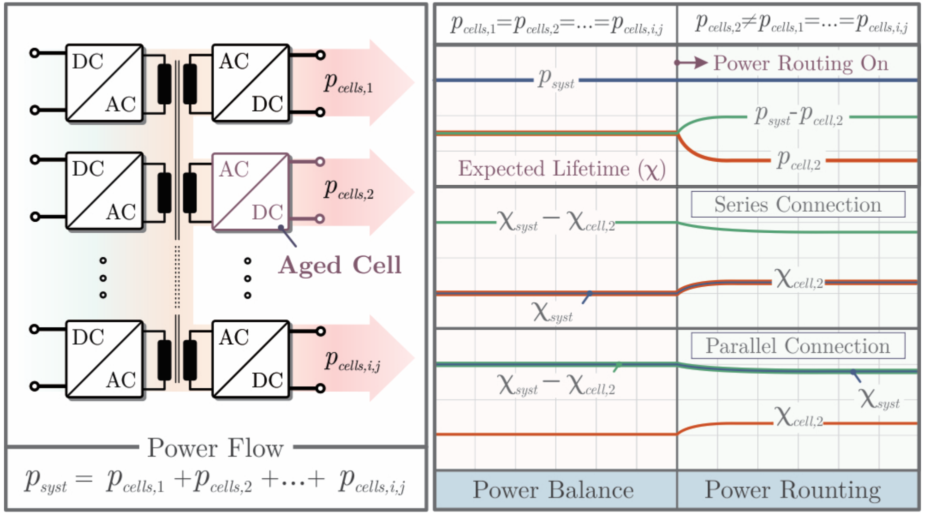
▶ Power routing for parallel connected building blocks

- Besides, from the maintenance point of view, a power sharing strategy among the cells, denoted **Power Routing**, can also be used with the aim of relieving the **thermal stress** from the **aged cells**.
- Thus, based on **uneven processing power**, the **Power Routing** can be used to optimize the lifetime of the aged cells and increase its reliability.
- As a result, **the failure** of these **aged cells** can be postpone and the **system maintenance scheduled**, so that the MTTF and the availability are expressively enhanced.



[ref] 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.

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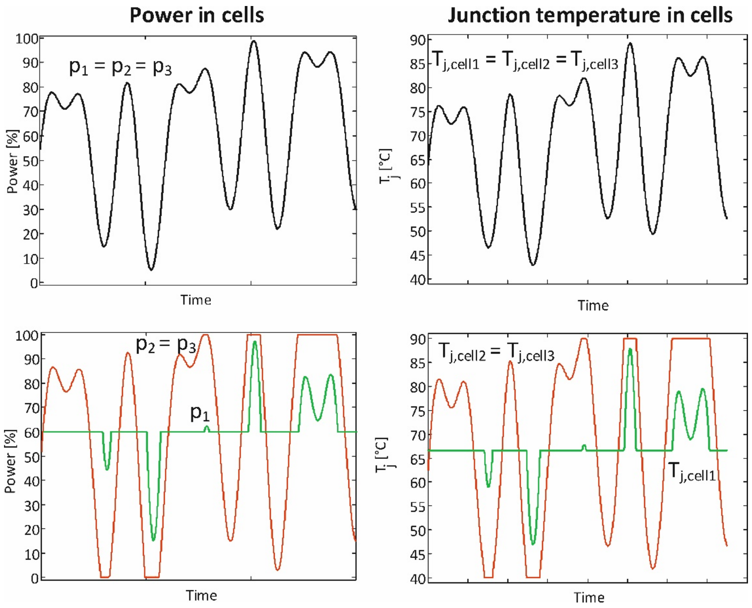
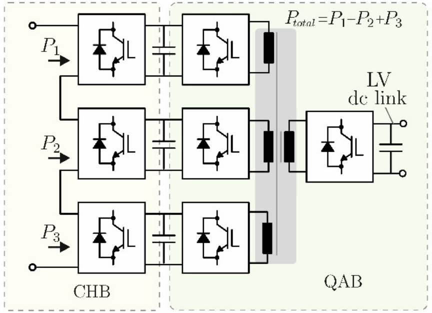
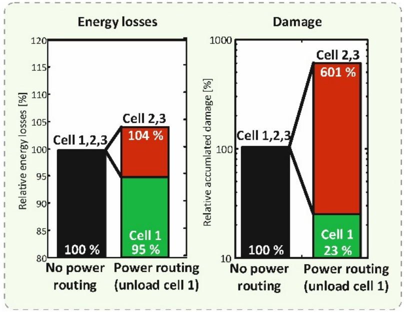
▶ Power routing for parallel connected building blocks

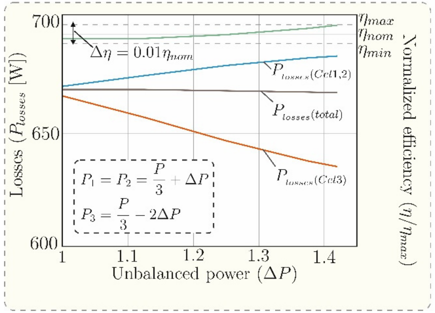
Without Power Routing

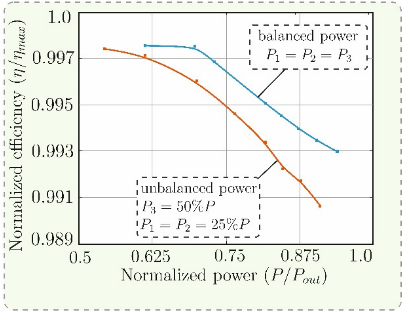
With Power Routing (Unload Cell 1)







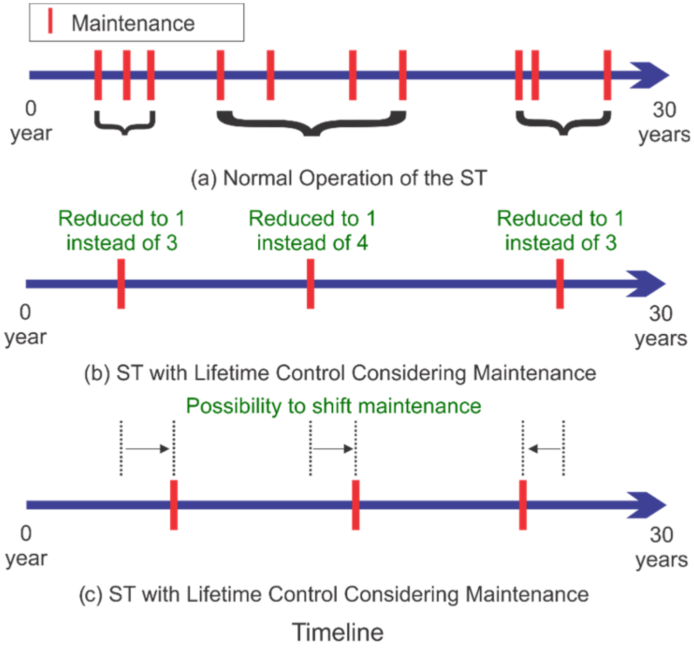




[ref] M. Liserre, M. Andresen, L. Costa and G. Buticchi, "**Power Routing in Modular Smart Transformers: Active Thermal Control Through Uneven Loading of Cells,**" in IEEE Industrial Electronics Magazine, vol. 10, no. 3, pp. 43-53, Sept. 2016.

Power Routing for Modular ST

▶ Power routing for maintenance scheduling



- ❑ Modular converters consist of many components, which will fail at different time instants (requiring maintenance)
- ❑ Active thermal control/power routing can be utilized to control the wear out and schedule maintenance
- ❑ Power routing can be used to delay maintenance

[ref] 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.

Power Routing for Modular ST

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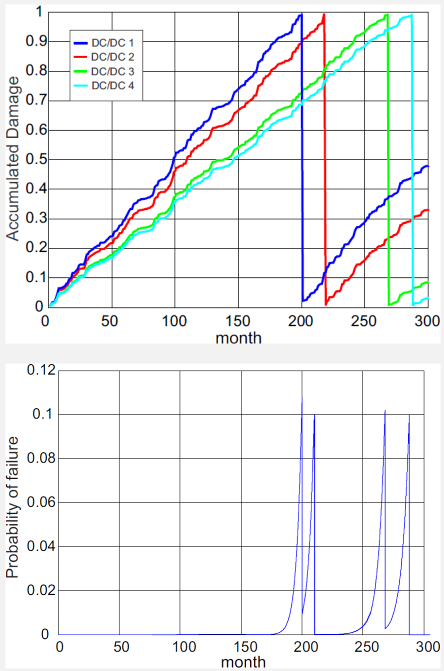
▶ Example of 4 parallel converters

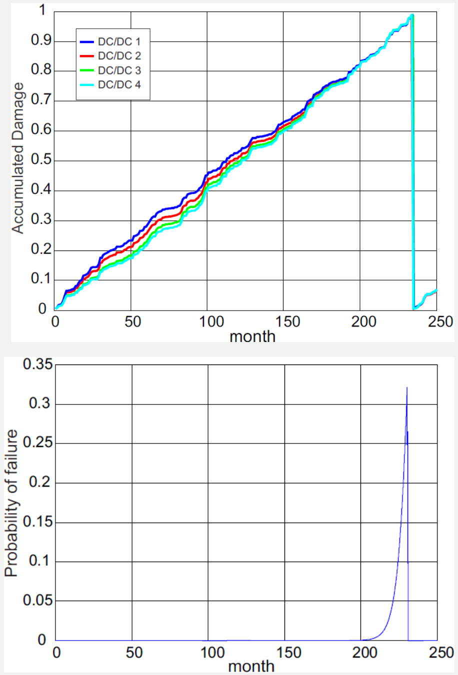
❑ Without Lifetime Control

- All the cells process equal power;
- Different failure time;
- Failure probability spread around 8 years;



❑ With Lifetime Control

- Cell loading varies
- Failures converge to the same instant
- Failure probability spread around 2 years;



Conclusion & Outlook

Conclusion and Outlook

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- **MTB topologies** can reduce the required **core material around 10%,** when the **MWT** is adopted. As a result, this leads to a **cost- and size reduction** when compared to the modular architectures based on the 2WT.
- Adopting the Asymmetrical MTB topologies instead of the conventional **2WT-based topologies** (e.g. multiple DAB and SR converters), the **power density** can be **enlarged by 30%** and the **semiconductor device's cost reduced at least by 15%.**
- From the availability perspective, the MTB topologies arise with another potential regarding the **inherent fault-tolerant capability**, which ensures the **continuous operation** of the system.
- **Smart Transformer** is a most promising technology for the future electric distribution, in particular for the Future Trends of Green Airports, by enabling the **Ground Power Units**.
- The different architectures for Smart transformer provides respective **pros** and **cons**;
- The CHB-based system architectures are promising topology choices for **grid-connection and PV integration**;
- For the issue of Power Imbalance, kinds of control methods can be used to extend the operation range, but they are unable to eliminate the Power Imbalance;
- Improved architectures are good solutions to ensure the **system power balance**, which needs special attentions to the topology choice, optimized design and engineering implementation of the MV high-power DC-DC converter with isolation (e.g. MTB DC-DC Converters).
- **Active thermal control** enables to reduce thermal stress and acts directly on the root cause of several failure mechanisms.

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THANK YOU!

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April 2021

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