Christian-Albrechts-Universität zu Kiel

IEEE PELS Webinar 2021

IEEE POWER ELECTRONICS SOCIETY

Opportunities and Challenges of Multiwinding Transformer-Based DC-DC Converter

March 2021

Prof. Marco Liserre

Thiago Pereira

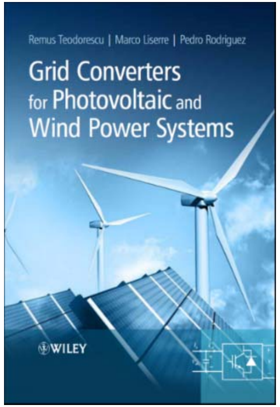
Chair of Power Electronics
Christian-Albrechts-Universität zu Kiel
Kaiserstraße 2
24143 Kiel

A short summary about me . . .

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

CAU
Christian-Albrechts-Universität zu Kiel

Head of Chair
Prof. Marco Liserre

Technician

Secretary

IEEE PELS WEBINAR

Table of Content

Christian-Albrechts-Universität zu Kiel

T. Pereira, F. Hoffmann, R. Zhu and M. Liserre, "A Comprehensive Assessment of Multiwinding Transformer-Based DC-DC Converters," IEEE Trans. on Power Electr., 2021 (accepted for publication for publication in February of 2021).

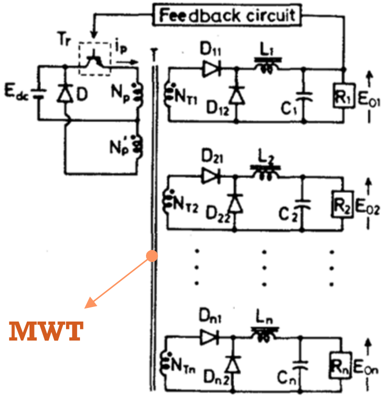
HISTORY OF MTB DC-DC CONVERTERS

History of MTB DC-DC Converters

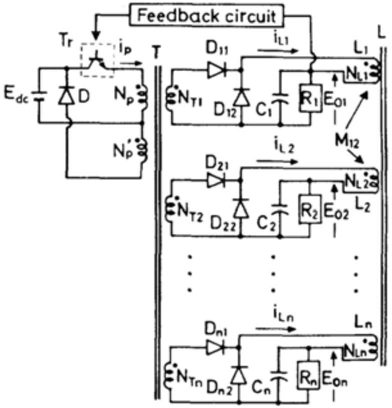
C | A | U
Christian-Albrechts-Universität zu Kiel

- In the literature, the **MWT was first introduced** as the key element of a multiple-output DC-DC converter by **[1]** in **1970s**.
- In this converter, the concept **based on the cross-regulation (proposed in [2])** was used to ensure the adjustment of the output voltages through the **magnetic coupling.**
- Afterwards, **in 1990s by [3],** the same concept employing also MWT was extended to a multiple input DC-DC converter, whereas the first electrical model of MWT was being developed by **[4].**

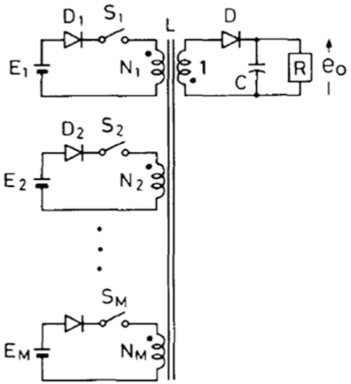
1970s **Timeline** **1990s**



Multiple-output DC-DC converter



Cross-regulation by using the magnetic coupling



Multiple-input DC-DC converter

[1] H. Matsuo and K. Harada, "New energy-storage dc-dc converter with multiple outputs," IEEE Trans. Mag., vol. 14, no. 5, pp. 1005–1007, 1978.

[2] T. G. Wilson, "Cross regulation in an energy-storage dc-to-dc converter with two regulated outputs," in 1977 IEEE Power Electr. Spec. Conf., 1977, pp. 190–199.

[3] H. Matsuo, T. Shigemizu, F. Kurokawa, and N. Watanabe, "Characteristics of the multiple-input dc-dc converter," in Proc. of IEEE Power Electr. Spec. Conf.- PESC '93, 1993, pp. 115–120.

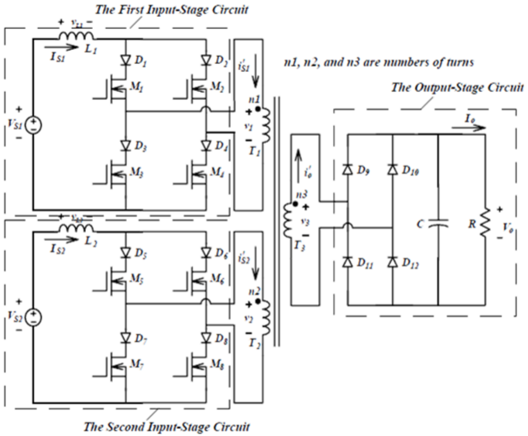
[4] Q. Chen, F. Lee, Jian Zhong Jiang, and M. M. Jovanovic, "A new model for multiple-winding transformer," in Proc. of 1994 Power Electr. Spec. Conf.- PESC'94, vol. 2, 1994, pp. 864–871.

History of MTB DC-DC Converters

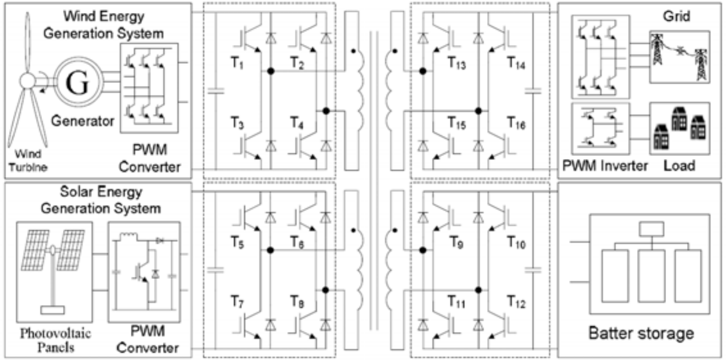
- **Years later, in 2000s**, to overcome the control limitations of the prior topologies, an **unidirectional three-ports** DC-DC converter using a **three-winding transformer** was introduced by **[5]**.

- Then, based on this work, **a bidirectional four-ports version** employing a **four-winding transformer** were proposed by **[6]**.

2000s **Timeline** **2010s**



Unidirectional Three-Port DC-DC Converter



Bidirectional Four-Port DC-DC Converter

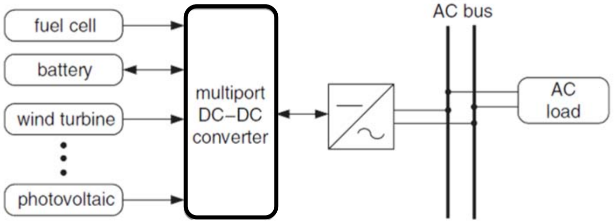
[5] Y. M. Chen, Y. C. Liu, and F. Y. Wu, "Multi-input dc/dc converter based on the multiwinding transformer for renewable energy applications," IEEE Trans. Ind. Appl., vol. 38, no. 4, pp. 1096–1104, 2002.

[6] M. Qiang, W. Wei-yang, and X. Zhen-lin, "A multi-directional power converter for a hybrid renewable ener. distributed generation system with battery storage," in 2006 CES/IEEE 5th Conf., vol. 3, 2006, pp. 1–5.

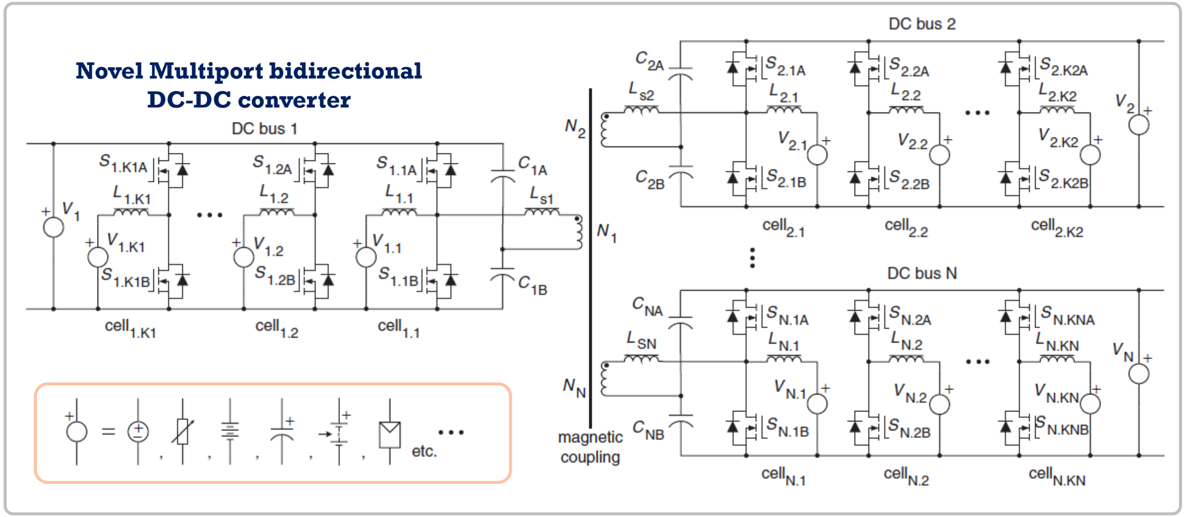
History of MTB DC-DC Converters

- **In 2010s**, a family of **multiport bidirectional DC-DC converters** were proposed by **[7]**.

- Derived from the **DAB**, in **[8]–[10]**, the **TAB** was introduced with the same aim of **integrating simultaneously multiple DC sources and loads.**



2000s **Timeline** **2010s**



[7] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, "Family of multiport bidirectional dc-dc converters," IEEE Proc. - Electric Power Appl., vol. 153, no. 3, pp. 451–458, 2006.

[8] J. L. Duarte, M. Hendrix, and M. G. Simoes, "Three-port bidirectional converter for hybrid fuel cell systems," IEEE Trans. Power Electr., vol. 22, no. 2, pp. 480–487, 2007.

[9] S. Inoue and H. Akagi, "A bidi. isolated dc–dc converter as a core circuit of the next-generation MV power conversion system," IEEE Trans. Power Electr., vol. 22, no. 2, pp. 535–542, 2007.

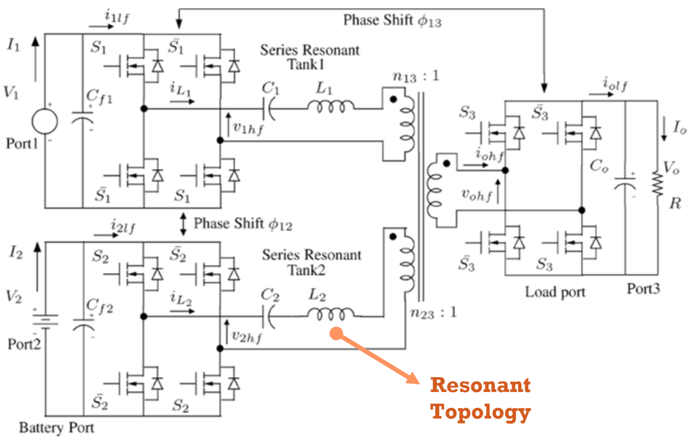
[10] C. Zhao, S. D. Round, and J. W. Kolar, "An isolated three-port bidirectional dc-dc converter with decoupled power flow management," IEEE Trans. Power Electr., vol. 23, no. 5, pp. 2443–2453, 2008.

History of MTB DC-DC Converters

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

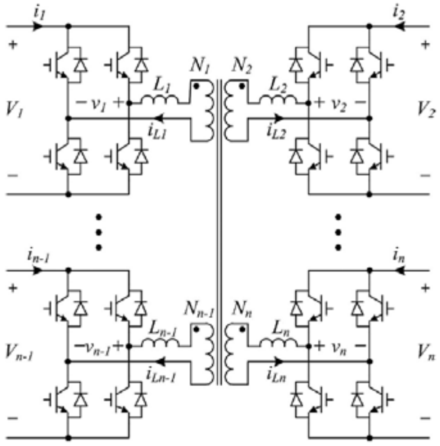
- ❑ Concurrently, a three-port version of the series-resonant (SR) converter was introduced by **[11]**.
- ❑ However, only in **[12]**, **[13]**, the TAB and QAB converters were generalized for an arbitrary number of coupled cells with the called **multiple-active-bridge (MAB).**
- ❑ Finally, **other papers** have gradually arisen in the literature to further investigate these converters in several **application fields**.

2010s **Timeline** **2020s**



Resonant Topology

Three-port bidirectional DC-DC converter



Multiple Active Bridge DC-DC Converter

[11] H. Krishnaswami and N. Mohan, "Three-port series-resonant dc–dc converter to interface renewable energy sources with bidirectional load and energy storage ports," IEEE Trans. Power Electr., vol. 24, no. 10, pp. 2289–2297, 2009.

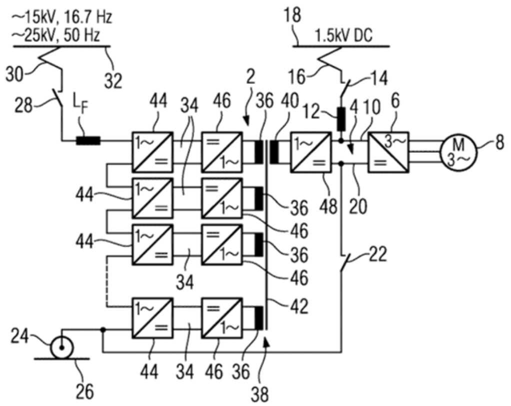
[12] S. Falcones, X. Mao, and R. Ayyanar, "Topology comparison for solid state transformer implementation," in IEEE PES Meet., 2010, pp. 1–8.

[13] S. Falcones, R. Ayyanar, and X. Mao, "A dc–dc multiport-converter based solid-state transformer integrating distributed generation and storage," IEEE Trans. on Power Electr., vol. 28, no. 5, pp. 2192–2203, 2013.

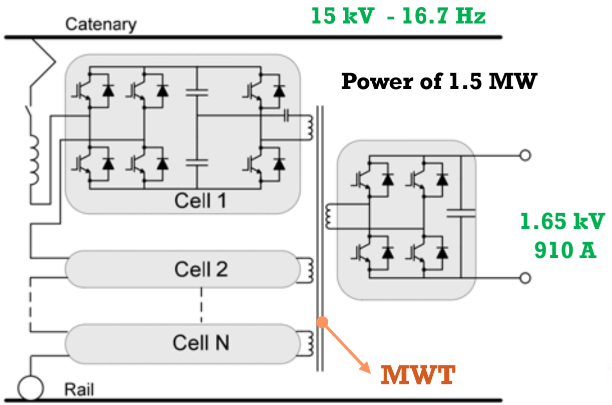
History of MTB DC-DC Converters

Christian-Albrechts-Universität zu Kiel

▶ Power Electronics Transformer for Traction – Alstom/Siemens

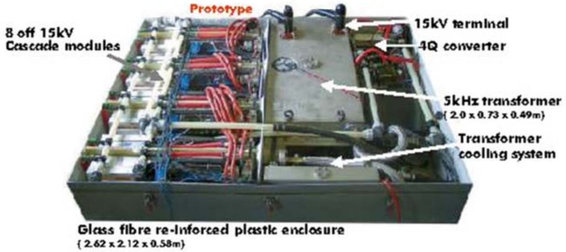


Patent: WO2012025254A1 (2012) [14]



Concept of the System based on the AMTB DC-DC Converter (2007) [15]-[16]

Feature	Value
Input voltage	15 kV
Input frequency	16.7 Hz
Output voltage	1.65 kV DC
Rating power	1500 kVA
Maximum power	2250 kVA (30 s)
Efficiency	94%
Transformer frequency	5 kHz
Transformer + electronic weight	2830 kg
Output LC filter weight	385 kg
Heat exchanger weight	255 kg
Overall weight	<3600 kg
Power density	0.42 kVA/kg
Total number of IGBTs	52
Cooling system	Forced oil circulation



Multi-system Traction Power Converter – **Alstom/Siemens**

[14] D. Dujic, F. Kieferndorf, F. Canales and U. Drofenik, "Power electronic traction transformer technology," Proceedings of The 7th International Power Electronics and Motion Control Conference, Harbin, China, 2012, pp. 636-642, 2012.

[15] J. Taufiq, "Power Electronics Technologies for Railway Vehicles," 2007 Power Conversion Conference - Nagoya, Nagoya, Japan, 2007, pp. 1388-1393, 2007.

[16] Patent: WO2012025254A1, "Multi-system traction power converter," 2012.

IEEE

IEEE POWER ELECTRONICS SOCIETY

Architecture and Operation Principle

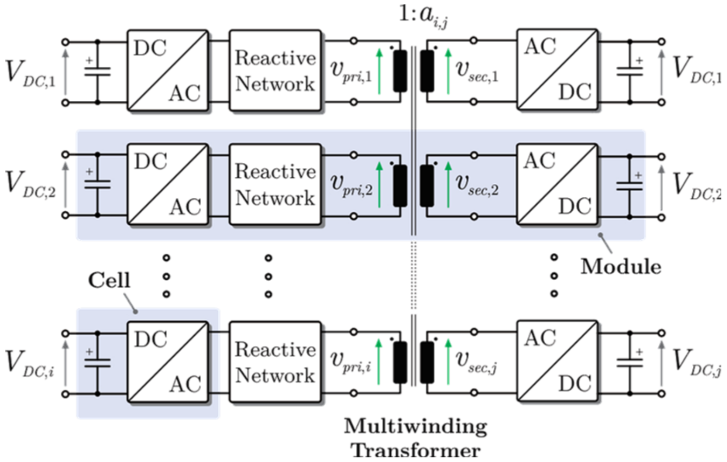
Architecture and Operation Principle

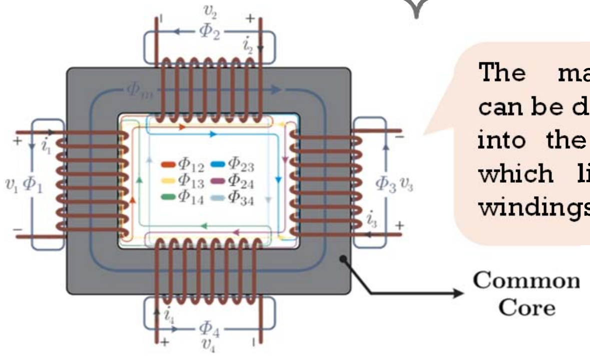
Christian-Albrechts-Universität zu Kiel

► 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.

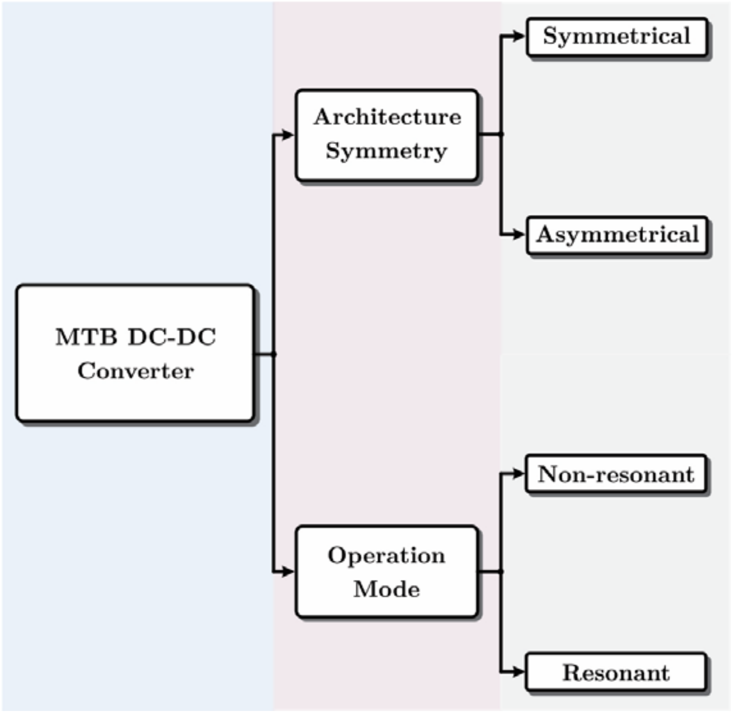


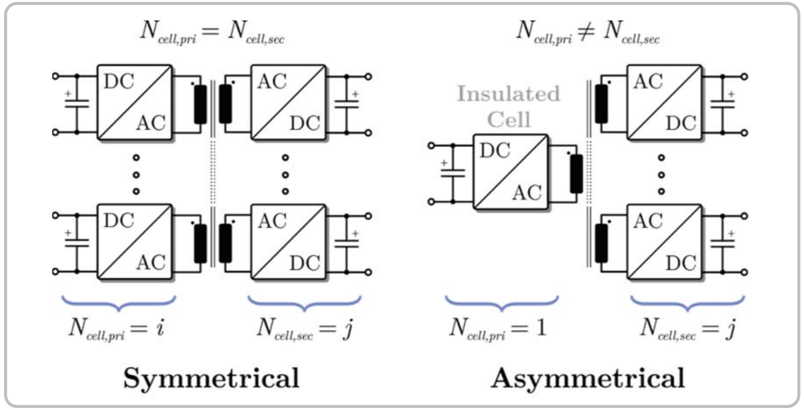


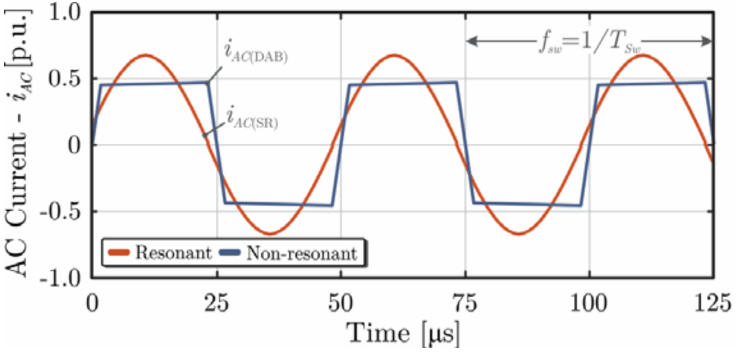
The magnetic flux can be decomposed into the **main flux**, which links all the windings.

Architecture and Operation Principle

▶ **Classification of the MTB Topologies**



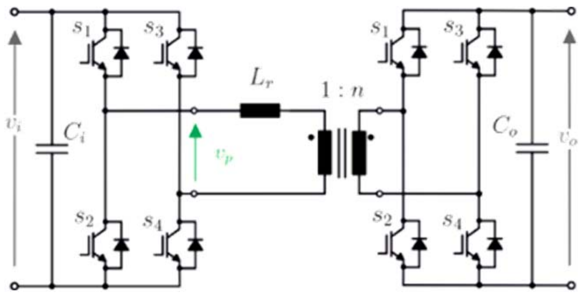




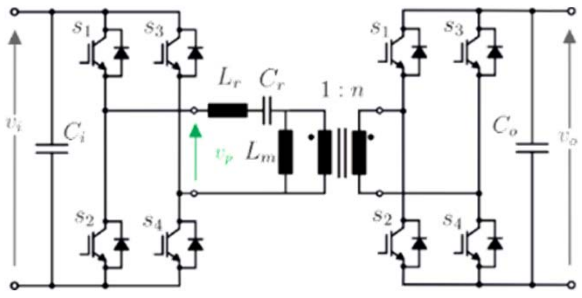
Architecture and Operation Principle

Christian-Albrechts-Universität zu Kiel

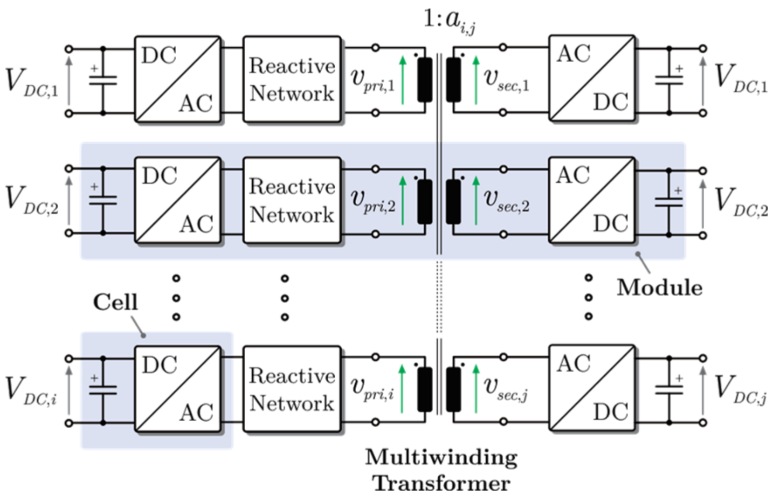
▶ Operation Principle of the MTB Topologies



Dual-Active-Bridge (DAB)



SR and LLC Converter



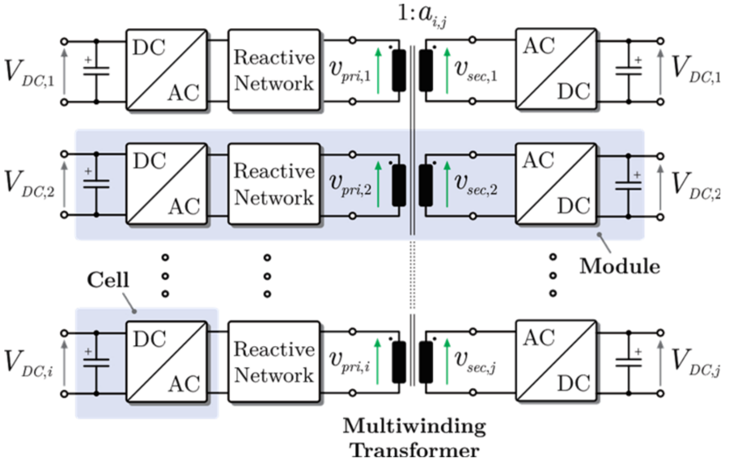
Resonant x Non-Resonant MTB DC-DC Converter

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

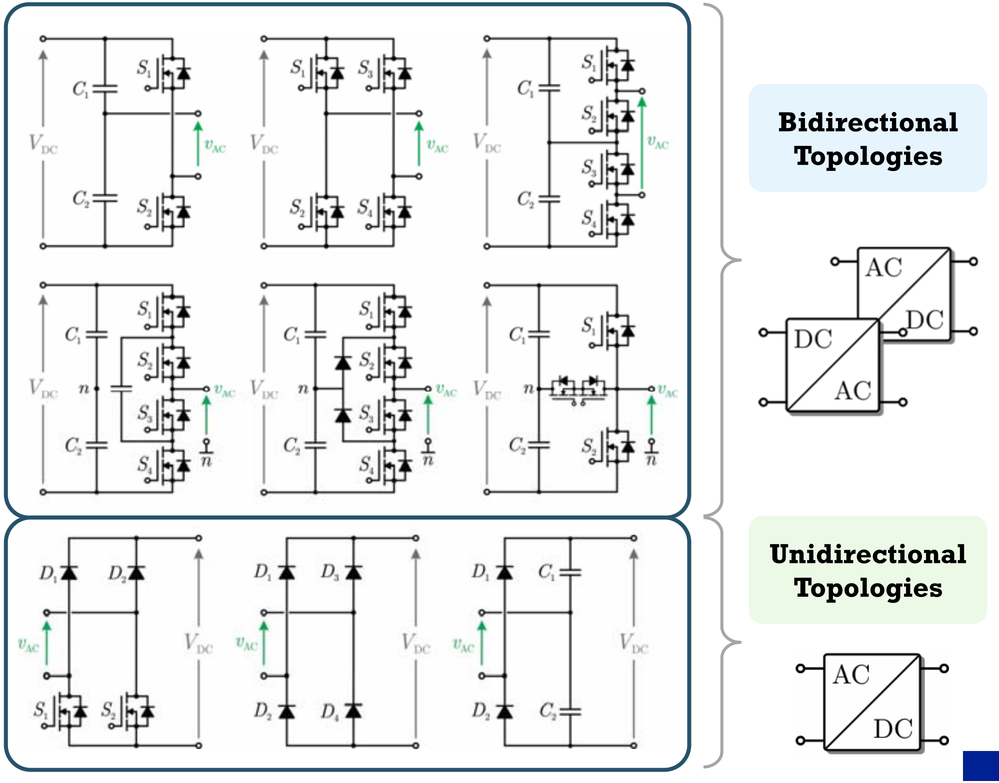
Architecture and Operation Principle

Christian-Albrechts-Universität zu Kiel

▶ Overview of the MTB DC-DC Topologies



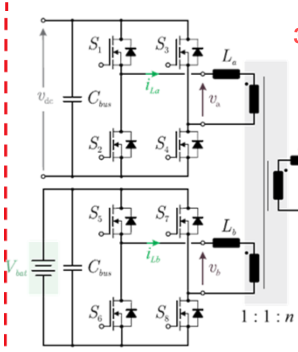
Depending on the power requirements, the conversion stages (cell) can be implemented by using different **active**, **semi-active** (hybrid), and **passive topologies**.



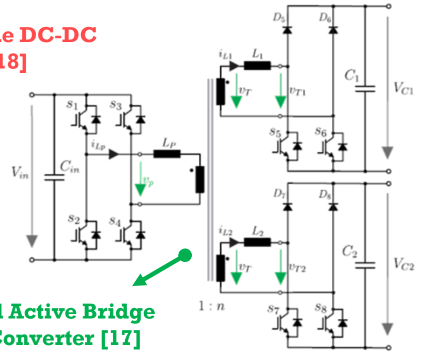
Architecture and Operation Principle

Christian-Albrechts-Universität zu Kiel

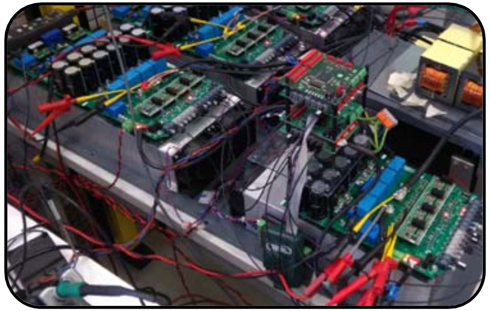
▶ Overview of the MTB DC-DC Topologies

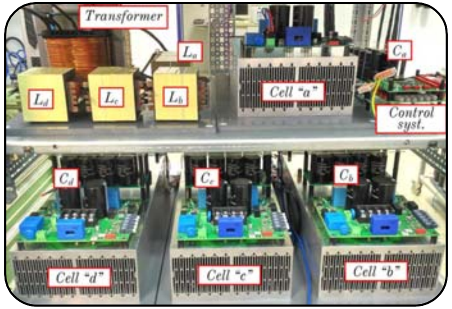


3-Ports Multi-Mode DC-DC Converter [18]

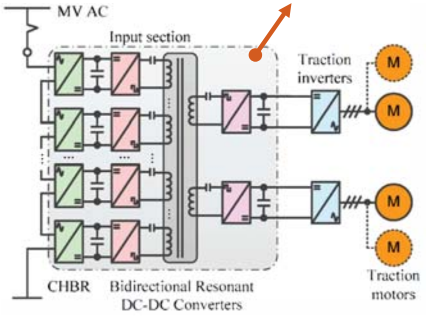


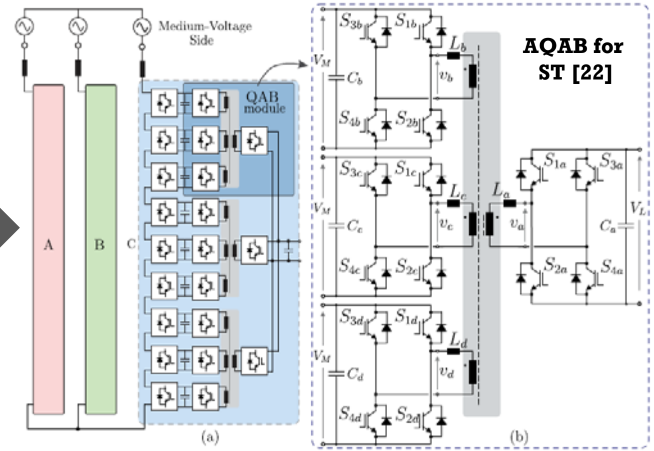
Semi-Dual Active Bridge DC-DC Converter [17]





12-Ports SR DC-DC Converter [27]



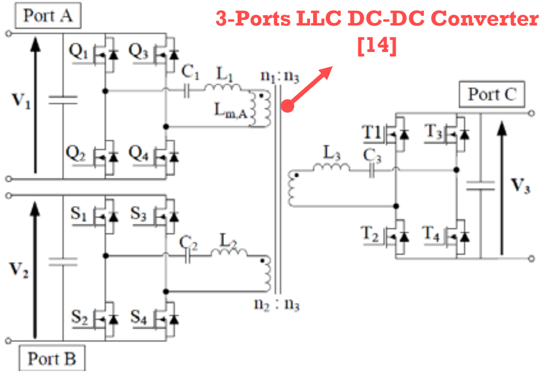


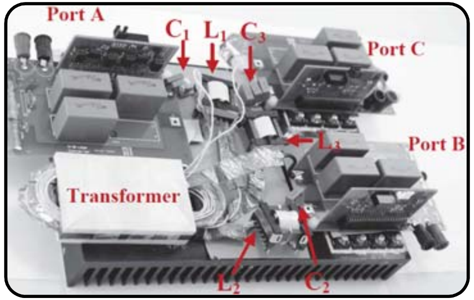
AQAB for ST [22]

Architecture and Operation Principle

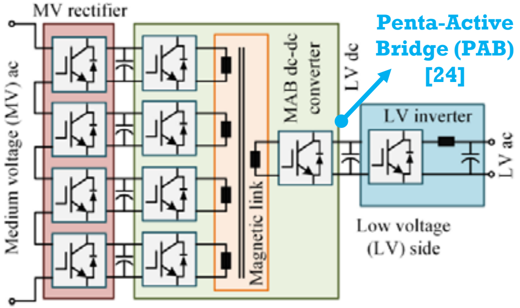
▶ Overview of the MTB DC-DC Topologies

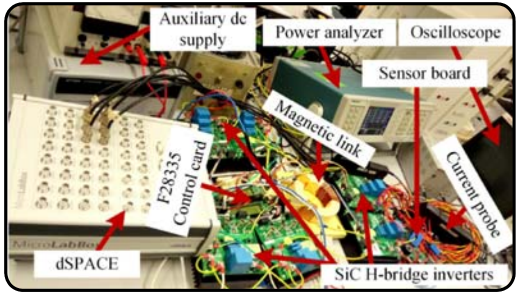
3-Ports LLC DC-DC Converter [14]

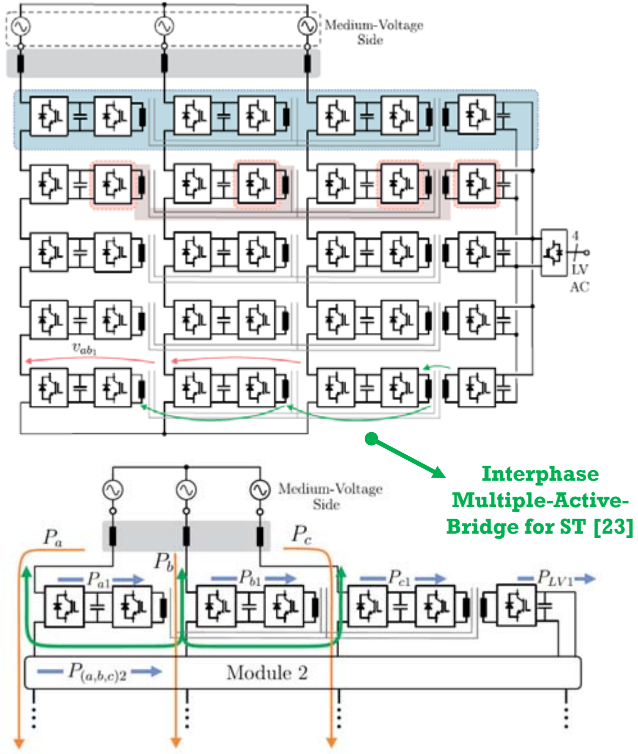




Penta-Active Bridge (PAB) [24]



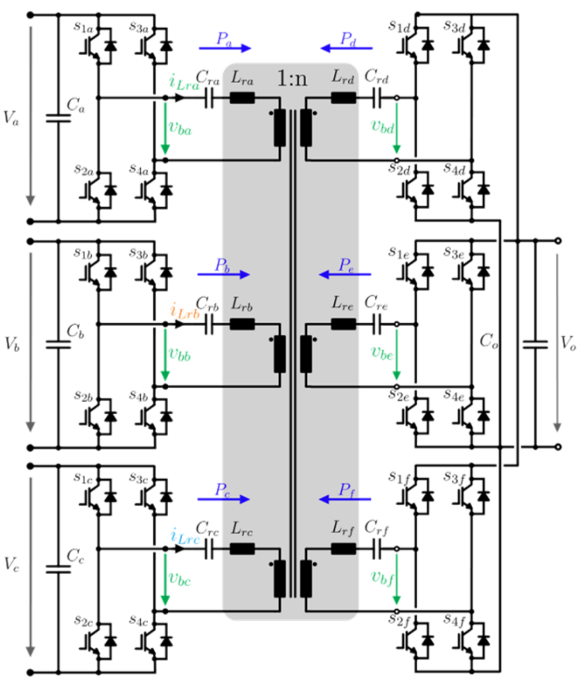


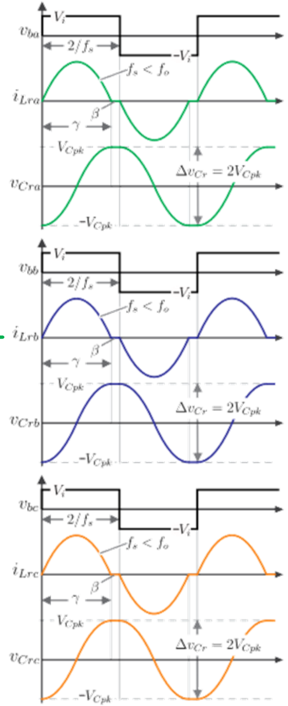


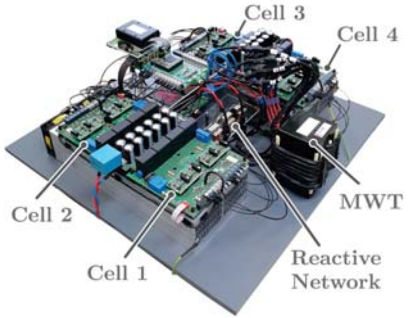
Interphase Multiple-Active-Bridge for ST [23]

Architecture and Operation Principle

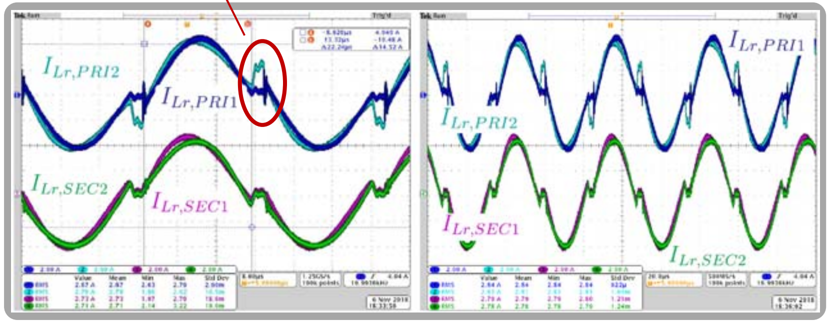
► Overview of the MTB DC-DC Topologies – Four-Port Series-Resonant Converter







Magnetizing Inductance



Extension of SR Converter

Characterisitcs:

- ❑ 50 % duty cycle
- ❑ Open-loop stability
- ❑ Soft switching→High efficiency (ZVS/ZCS)
- ❑ One magnetic core
- ❑ Integration of storage in floating port

Main Challenges

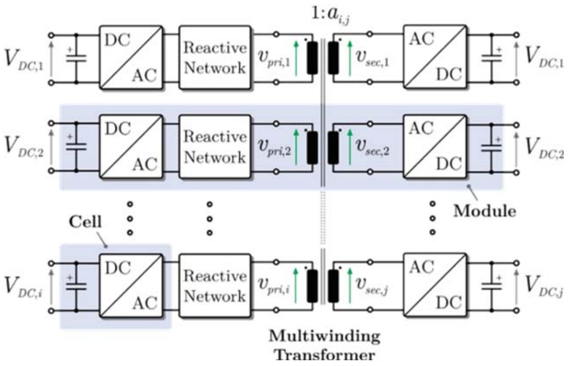
- ❑ Accurate determination of multi-winding transformer parasitics
- ❑ Accurate tuning of the resonant tanks to ensure good **power balance** in open-loop

Architecture and Operation Principle

Christian-Albrechts-Universität zu Kiel

▶ Overview of the MTB DC-DC Topologies

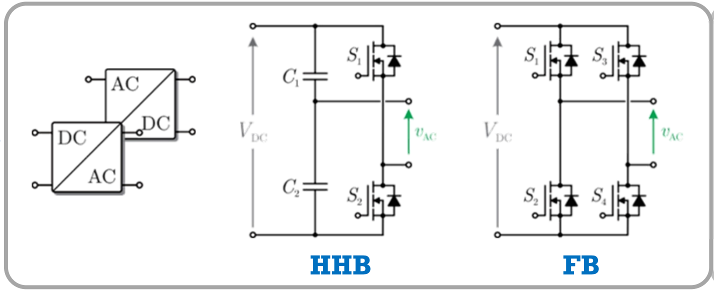
Assuming the Power Flow from the primary-side to the secondary side

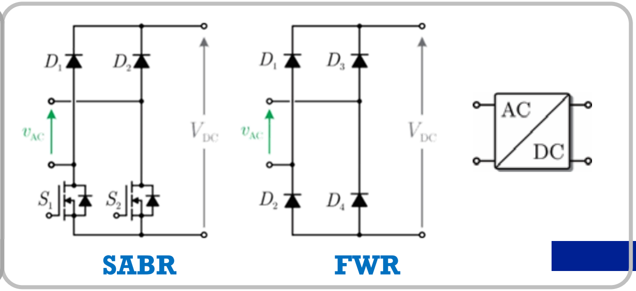


Main topologies presented in the Literature

MTB DC-DC Converter	Architecture Symmetry	Nº of Cells Pri : Sec	Operation Mode	Power Flow Pri ↔ Sec	Input/Output Cell	References
Triple-Active-Bridge (TAB)	Asymmetric	1 : 2	Non-resonant	Unidirectional	FB-SABR	[17]
					FB-FWR	[18]
				Bidirectional	FB-FB	[8]-[11], [19]-[20]
Quadruple-Active-Bridge (QAB)	Asymmetric	3 : 1	Non-resonant	Bidirectional	FB-FB	[22]-[23]
	Symmetric	2 : 2				[21]
					FB-FB/FWR	[22]
Penta-Active-Bridge (PAB)	Asymmetric	4 : 1	Non-resonant	Bidirectional	FB-FB	[23]
Multiple-Active-Bridge (MAB)	Symmetric	6 : 6	Non-resonant	Bidirectional	FB-FB	[24]
Three-Port LLC Converter	Asymmetric	1 : 2	Resonant	Bidirectional	HHB-FB	[25]
					FB-FB	[26]
Multiport LLC Converter	Symmetric	6 : 6	Resonant	Bidirectional	HHB/FB-FB	[27]
Three-Port SR Converter	Asymmetric	1 : 2	Resonant	Bidirectional	FB-FB	[26]

HHB - Hybrid Half-bridge;
FB - Full-bridge;
SABR - Semi-active bridge rectifier;
FWR - Full-wave rectifier.



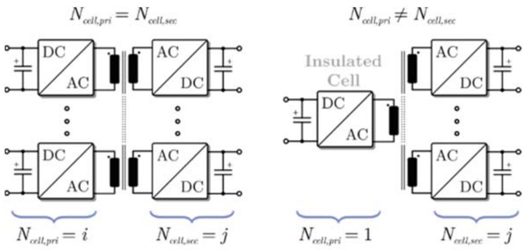


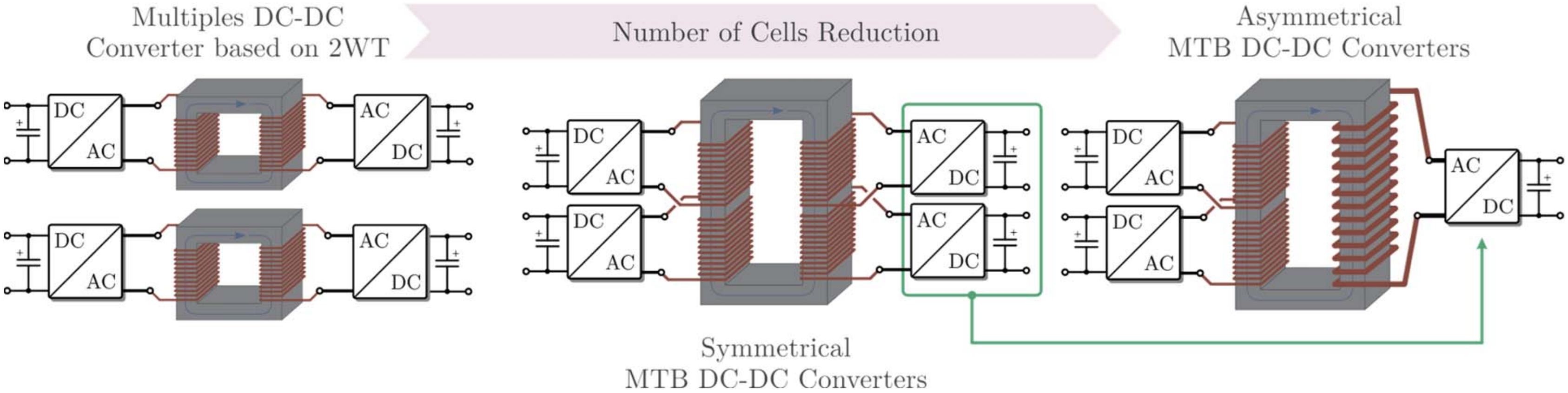
IEEE POWER ELECTRONICS SOCIETY

Assessment and Comparative Analysis

▶ 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





Assessment and Comparative Analyses

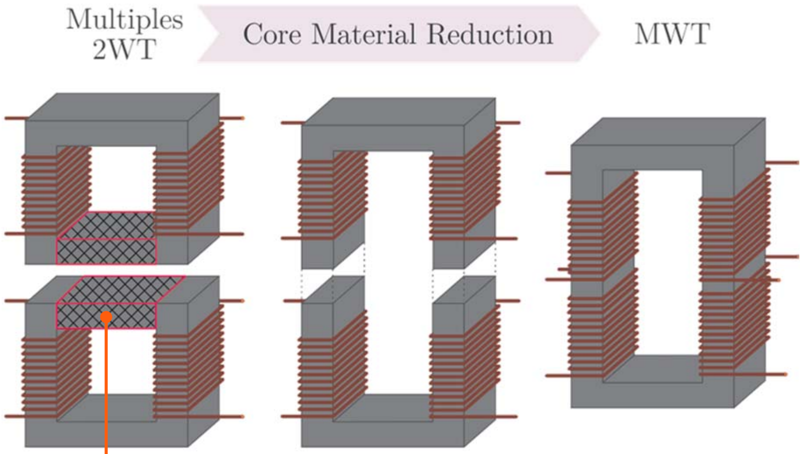
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

- 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).

Assessment and Comparative Analyses

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

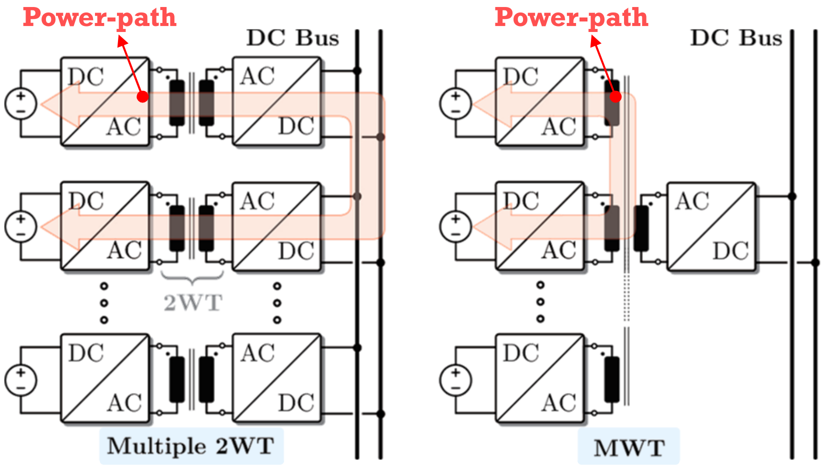
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

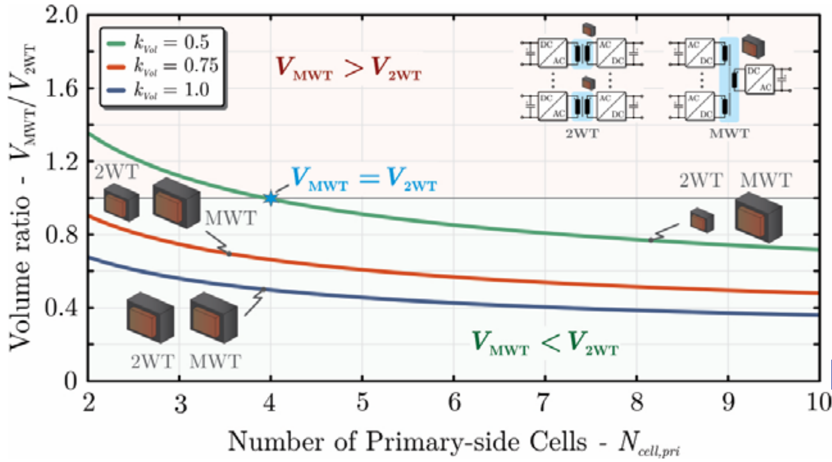
The **power-paths** can be shortened when the MWT is adopted, due to its inherent magnetic link. As a result, since the structure uses less cells, the **power density** of the MTB topologies can be increased when the MWT is adopted.

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

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

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:

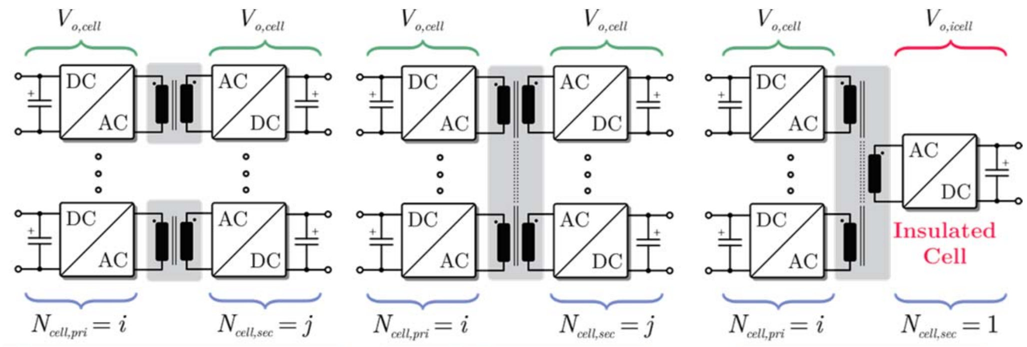
$$V_{o,icell} = k_{v,cell} V_{o,cell} \quad \text{where} \quad k_{v,cell} = (N_{cell,i,j})^{1.5}$$

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

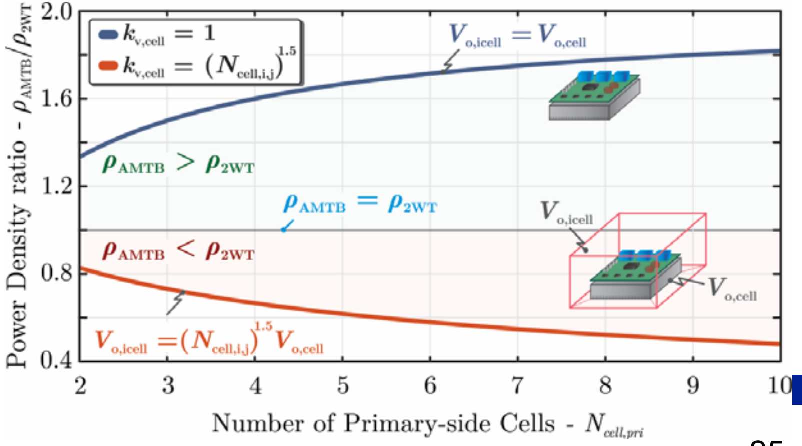
$$V_{\mathrm{Total,SMTB}} = 2N_{cell,i,j} V_{o,cell} + V_{\mathrm{MWT}}$$

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

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



Multiple 2WT-based Topology | SMTB Topology | AMTB Topology



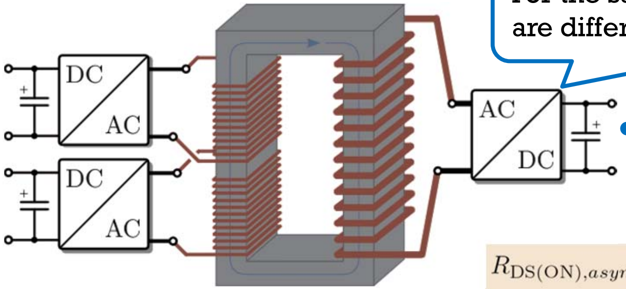
Assessment and Comparative Analyses

Christian-Albrechts-Universität zu Kiel

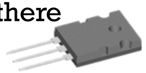
▶ Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault Tolerant Capability

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**.

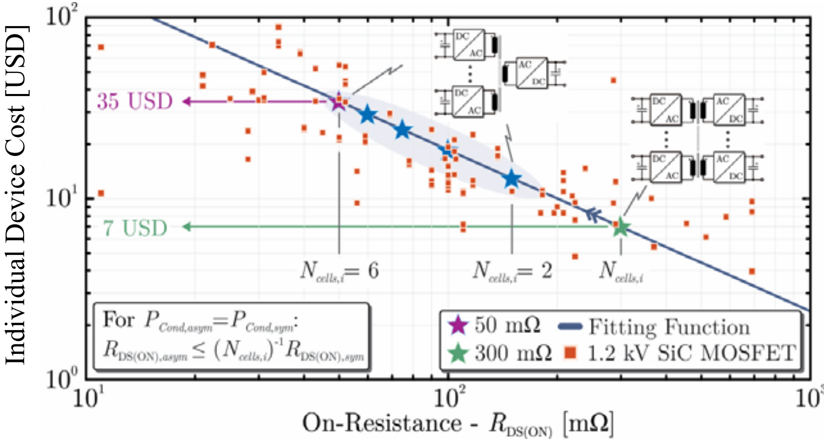


For the same Package, there are different devices.



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 %

Assessment and Comparative Analyses

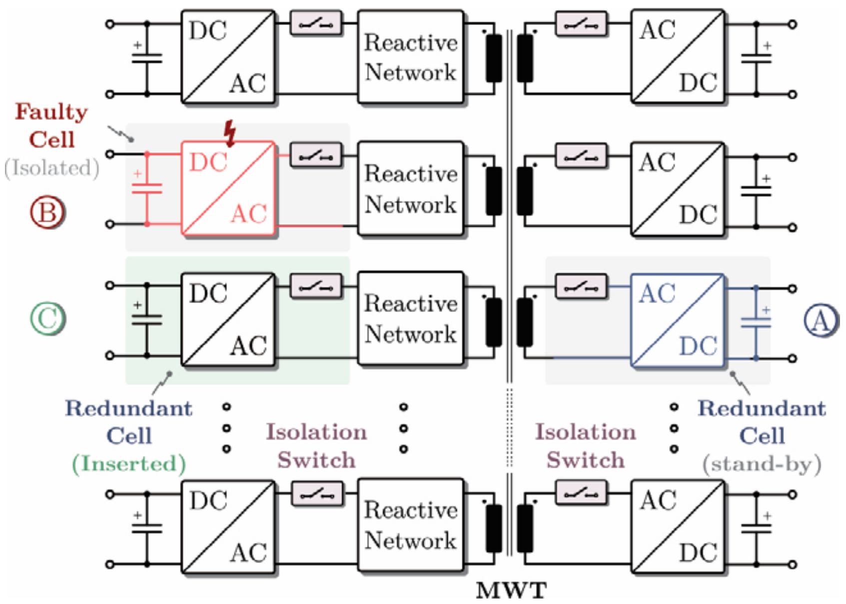
► Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault-Tolerant Capability

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.

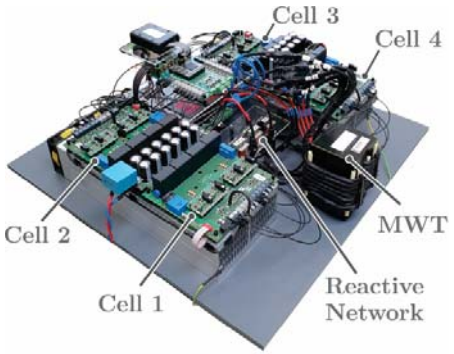
A. Normal operation with redundant cells in **stand-by mode** and others in **power-sharing mode** (as part of the MTB DC-DC converter);

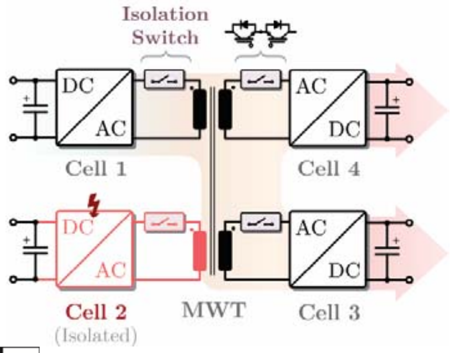
B. **Reconfiguration** example after a fault by means of the isolation switches to disconnect the faulty cell.

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



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

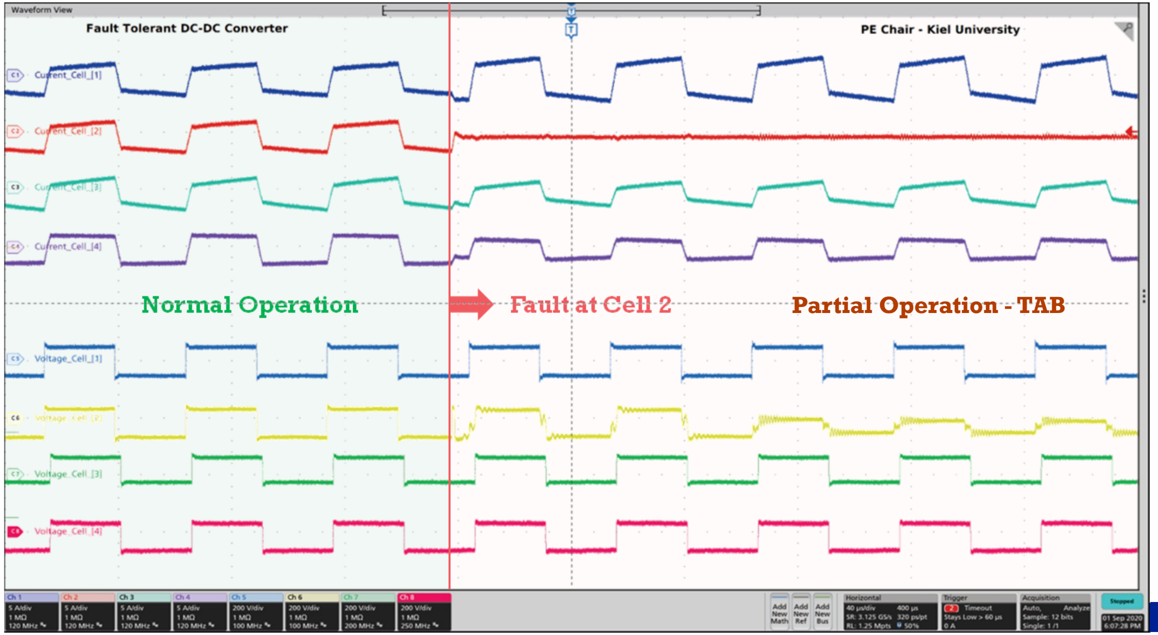




Symmetrical Quadruple-Active-Bridge (SQAB) DC-DC Converter

Current Waveforms

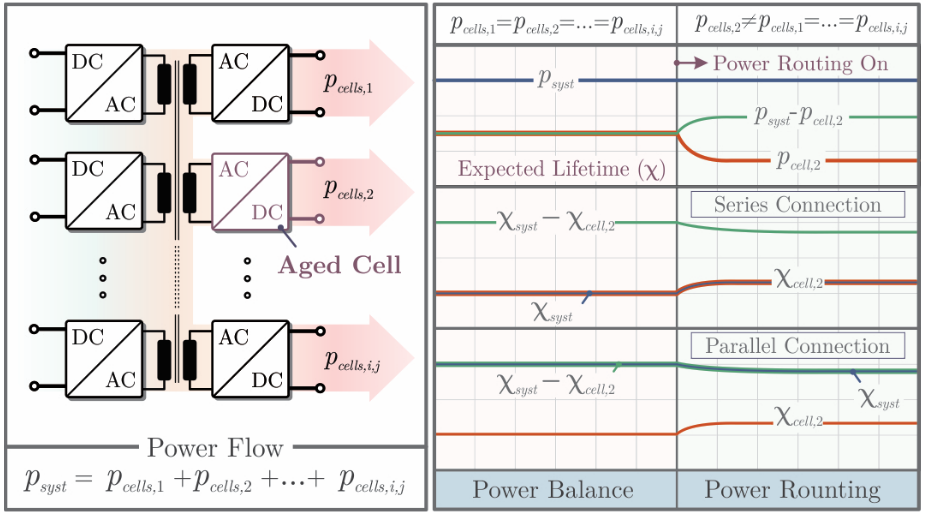
Voltage Waveforms



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

- 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.

Power Routing applied to the MTB DC-DC Converters



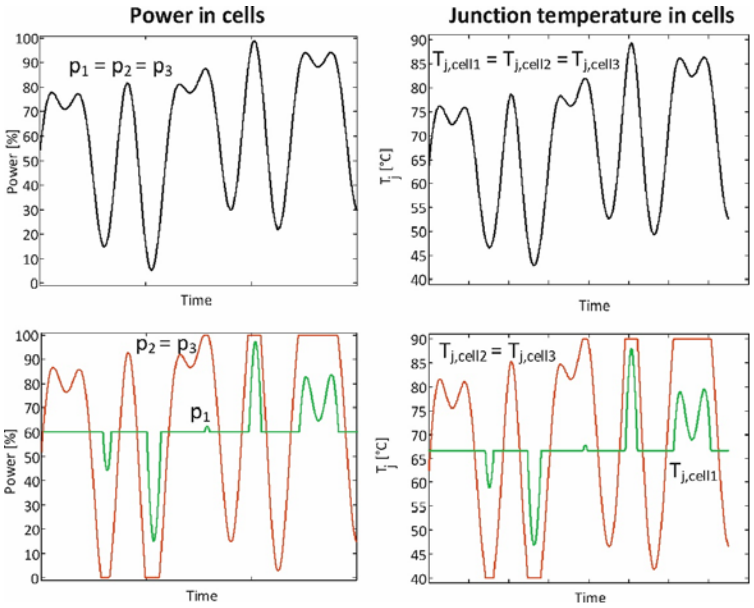
M. Liserre, M. Andresen, L. Costa and G. Buticchi, "Power Routing in Modular Smart Transformers: Active Thermal Control Through Uneven Loading of Cells," in IEEE Industrial Electronics Magazine, vol. 10, no. 3, pp. 43-53, Sept. 2016.

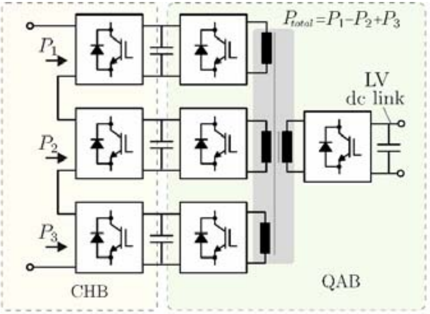
Assessment and Comparative Analyses

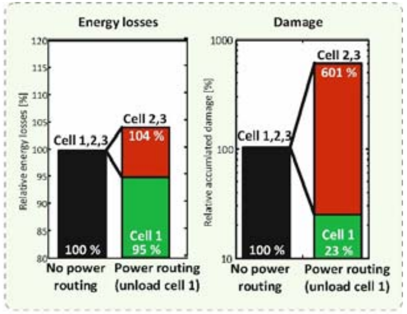
► Potential of the MTB DC-DC Topologies - Power Density, Cost-benefit, and Fault-Tolerant Capability

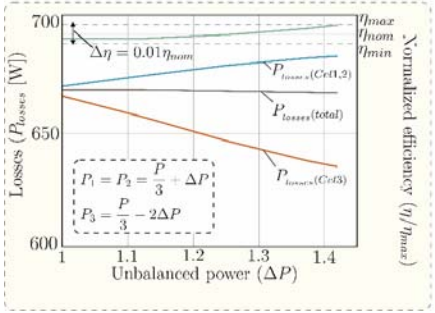
Without Power Routing

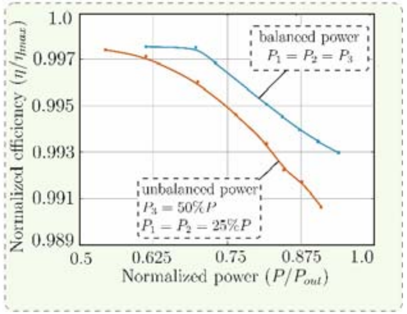
With Power Routing (Unload Cell 1)











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.

Christian-Albrechts-Universität zu Kiel

IEEE POWER ELECTRONICS SOCIETY

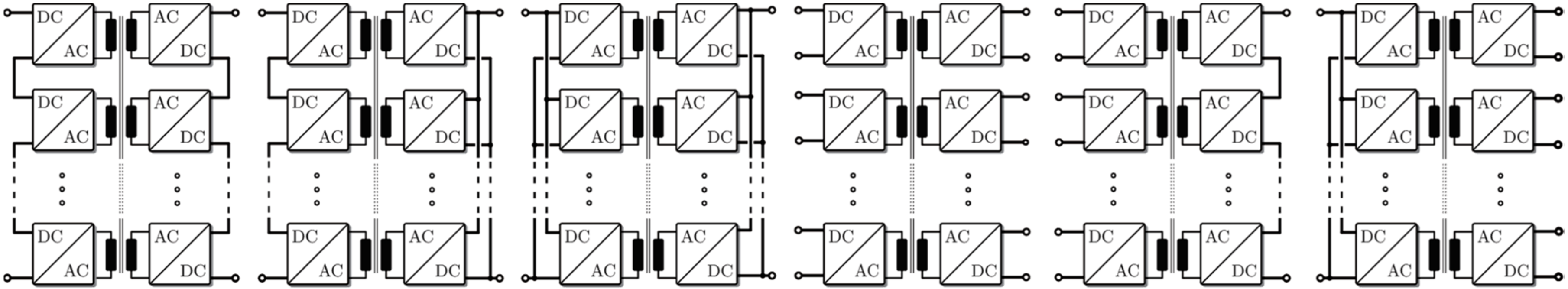
INTERCONNECTION AND OPERATION MODE ISSUES

Interconnection and Operation Issues

Christian-Albrechts-Universität zu Kiel

▶ **Possible Configurations used to interconnect the modules in the MTB DC-DC Topologies**

Input-series Output-series	Input-series Output-parallel	Input-parallel Output-series	Input-independent Output-independent	Input-series Output-independent	Input-parallel Output-independent



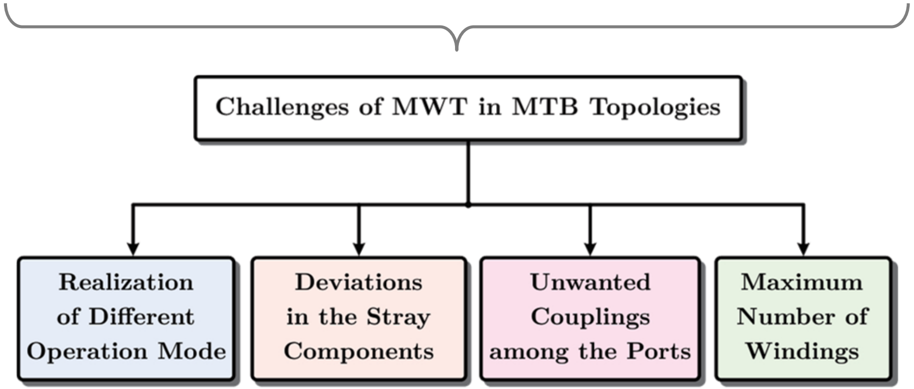
Assuming the Power Flow from the primary-side to the secondary side

Ports	ISOS	ISOP	IPOS	IPOP	IIOI	IIOS	ISOI	IIOP	IPOI
Input [I]	Series	Series	Parallel	Parallel	Independently	Independently	Series	Independently	Parallel
Output [O]	Series	Parallel	Series	Parallel	Independently	Series	Independently	Parallel	Independently

Interconnection and Operation Issues

▶ Challenges of the MTB DC-DC Topologies

The advantages of the common magnetic core come at the expense of specific challenges related to the operation of MTB Topologies



- ❑ In the **Resonant MTB topologies,** limiting factors arise from the practical requirement for **splitting the resonant tank** on the different reactive networks;
- ❑ The MWT topologies are susceptible to deviations of the **stray elements** of the MWT. Deviations in the stray elements can lead to **unequal power transfers** among the cells.
- ❑ Although the cells are isolated from each other, through the common magnetic core, the load change of one port might affect the other cells by means of the **unwanted coupling**.
- ❑ The **maximum available number of windings** is limited by the commercial off-the-shelf available magnetic cores.

Interconnection and Operation Issues

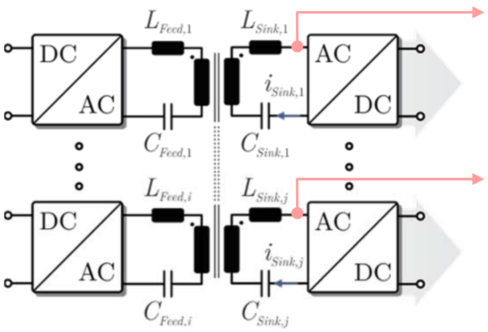
Christian-Albrechts-Universität zu Kiel

▶ Challenges of the MTB DC-DC Topologies: Deviations in the Stray Elements of the MWT

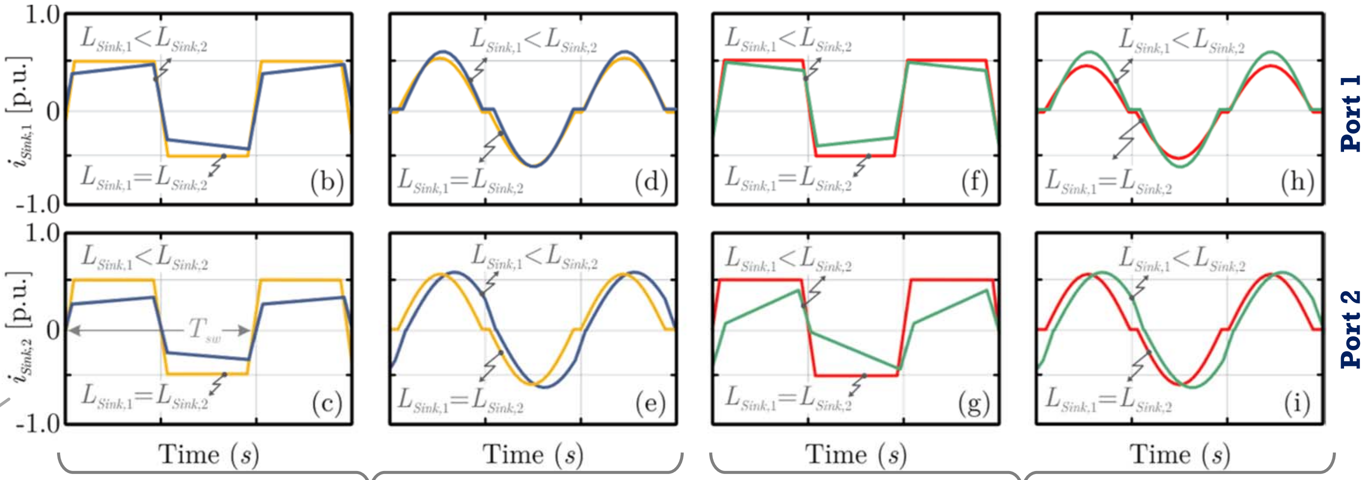
Effects of **parameter variations** in the reactive network of the MTB DC-DC converter

Parallel interconnection in **non-resonant** MTB Converter	Parallel interconnection in **resonant** MTB Converter	Independent interconnection in **non-resonant** MTB Converter	Independent interconnection in **resonant** MTB Converter

Assuming that $L_{Sink,1} < L_{Sink,2}$



Current Waveforms on the Sinking Inductance



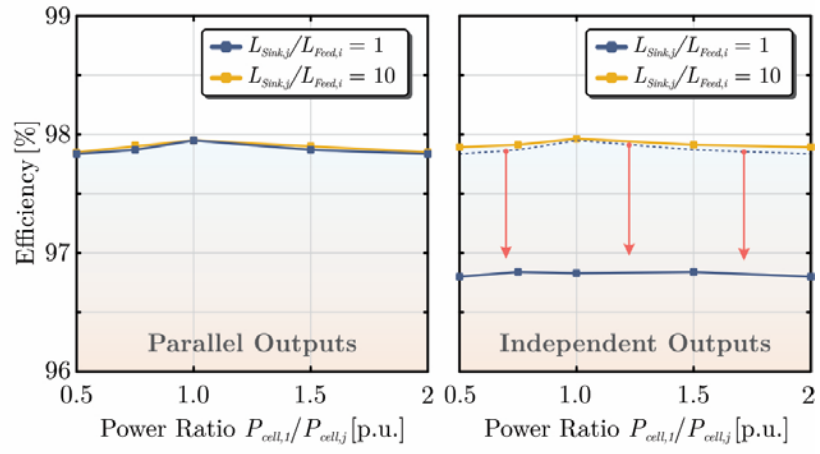
Parallel interconnection | **Independent interconnection**

Interconnection and Operation Issues

▶ Challenges of the MTB DC-DC Topologies: Unwanted Coupling among the Ports

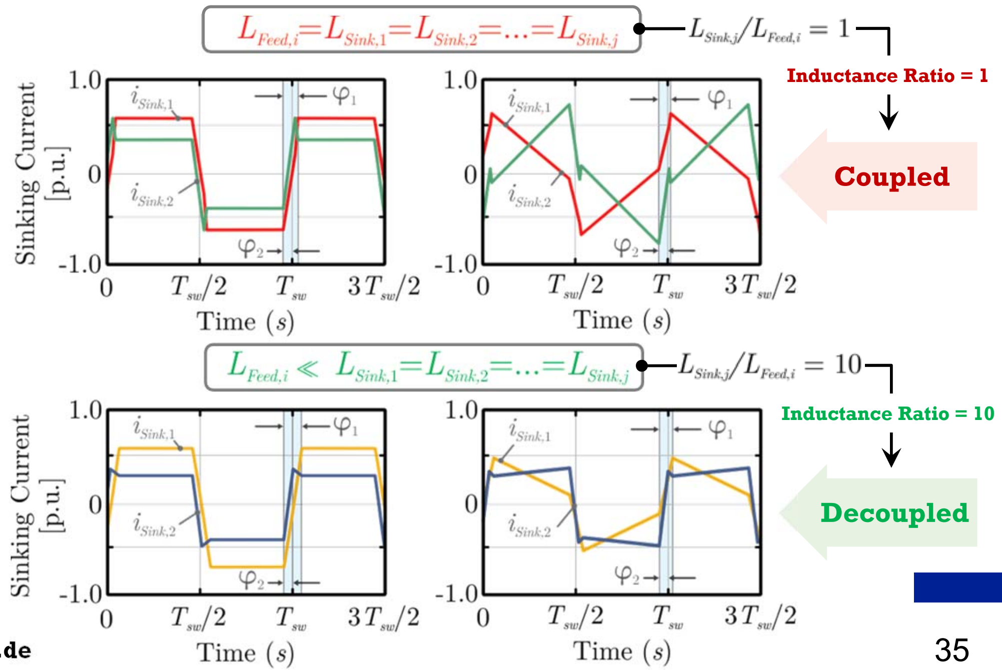
Effects of **cross couplings** due to a load variation in one output port in dependency of the output configuration for different **inductance ratio** ($L_{Sink,j}/L_{Feed,i}$).

Effiencincy of the DC-DC Converter for each case



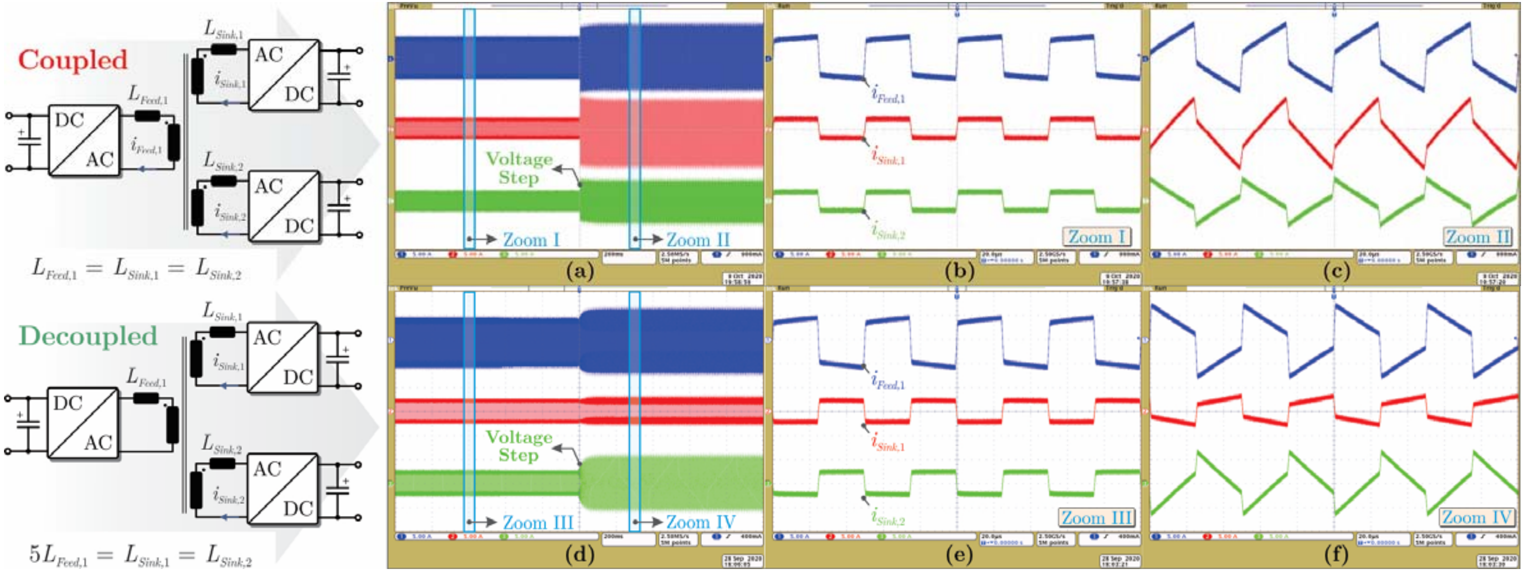
Parallel interconnection

Independent interconnection



▶ Challenges of the MTB DC-DC Topologies: Unwanted Coupling among the Ports

Effects of **cross-couplings** in TAB converter with one feeding-port and two sinking-ports, considering **Independent Interconnection** among the ports for different inductance ratio.



The sinking-port 2 is also affected

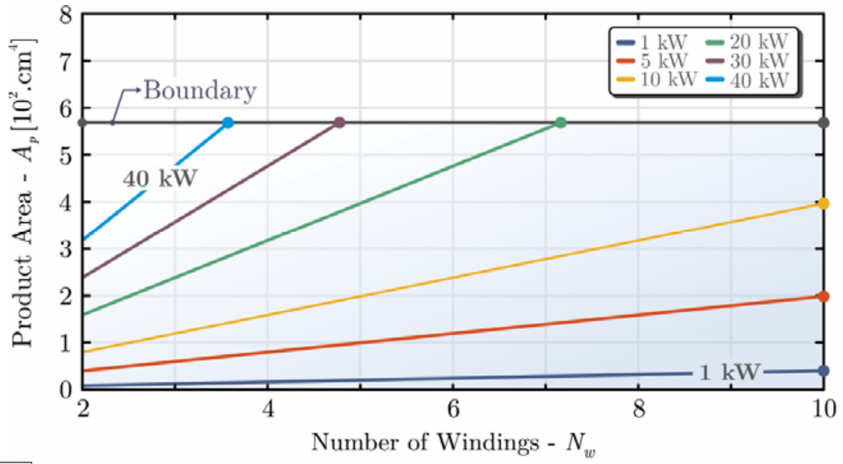
The sinking-port 2 is not also affected

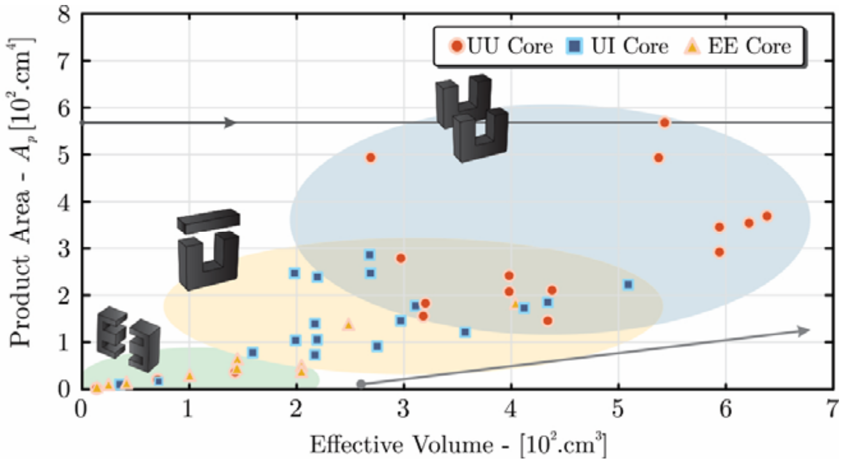
Interconnection and Operation Issues

▶ **Challenges of the MTB DC-DC Topologies: Maximum Number of Windings**

The larger the number of windings, the larger will be the required window area of the magnetic core. Thus, the maximum available **number of windings** is limited by the **commercial off-the-shelf available magnetic cores.**

Considering the largest available core **U126/91/20** (UU cores) from magnetics with the product area **(Ap = 572 cm^4)**, the power processed by the MWT is limited to **PMWT = 143 kW**.

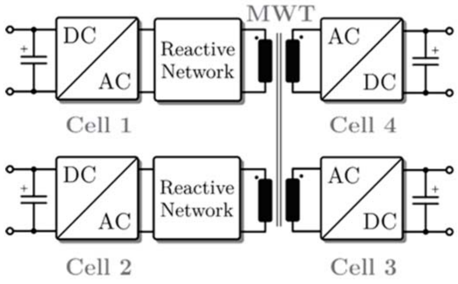




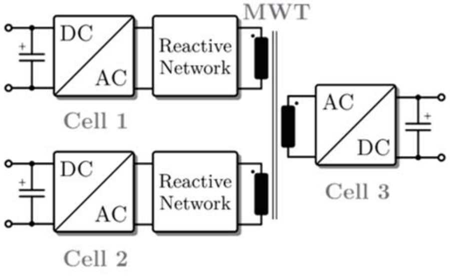
Quantitative Analyses and Applications

Quantitative Analyses and Applications

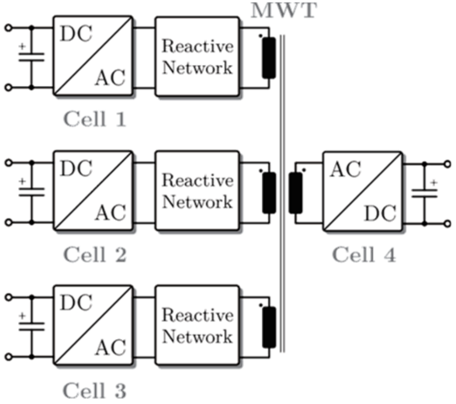
▶ MTB DC-DC Converters used in the Quantitative Analyses



Symmetrical 4-Port Converter



Asymmetrical 3-Port Converter

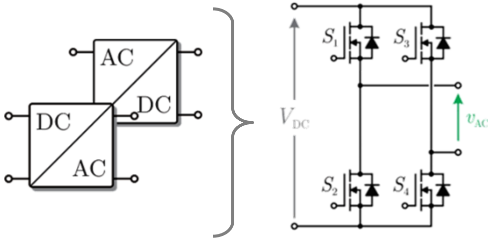


Asymmetrical 4-Port Converter

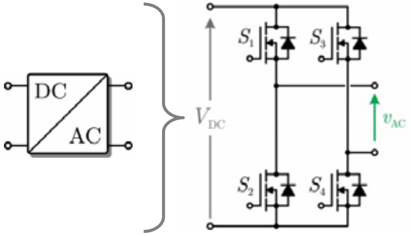
Electrical Specifications

Rated Power	10 kW
DC-Link Voltage	400 V
Switching Frequency	20 kHz
Turn-ratio	1:1:1:1

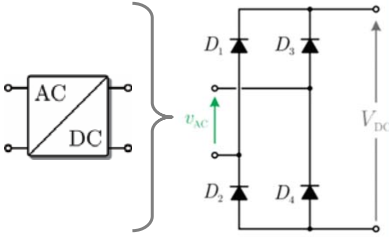
Bidirectional



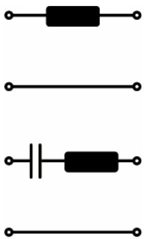
Unidirectional



&



Reative Network



Non-resonant

Resonant

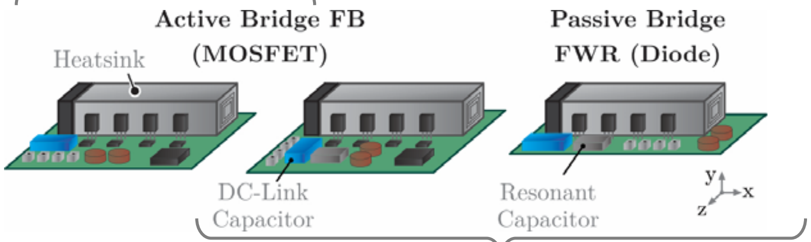
▶ Quantitative Analyses among different MTB DC-DC Topologies

Higher Efficiency | Higher Power Density

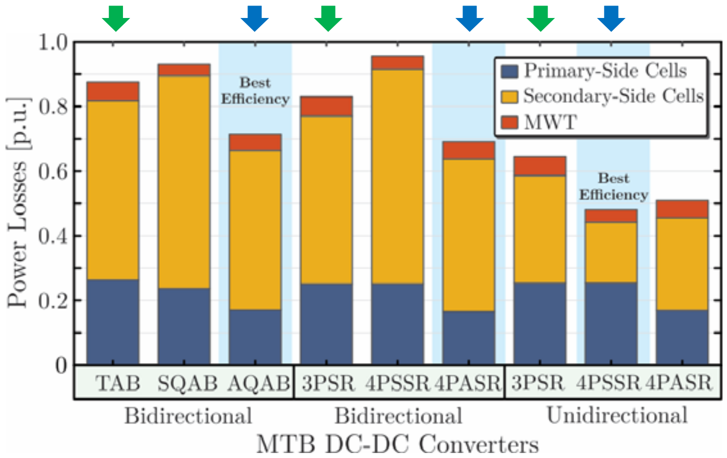
MTB DC-DC Topologies	Non-Resonant & Bidirectional Active Bridge			Resonant & Bidirectional Series-Resonant			Resonant & Unidirectional Series-Resonant		
	TAB	SQAB	AQAB	3P-SR	4P-SSR	4P-ASR	3P-SR	4P-SSR	4P-ASR
Architecture Symmetry (primary : secondary)	3-Ports (2 : 1)	4-Ports (2 : 2)	4-Ports (3 : 1)	3-Ports (2 : 1)	4-Ports (2 : 2)	4-Ports (3 : 1)	3-Ports (2 : 1)	4-Ports (2 : 2)	4-Ports (3 : 1)
Efficiency [%]	98.27	98.15	98.48	98.36	98.11	98.54	98.73	99.05	98.90
Power Density [W/cm^3]	3.79	3.24	3.02	3.58	3.06	2.85	4.39	3.91	3.33

For the MWT, it was assumed the same magnetic core **(E80/38/20)** and the same wires on the primary-side windings for all topologies.

Cell used in the Non-Resonant MTB Converters
150 x 30 x 150 mm

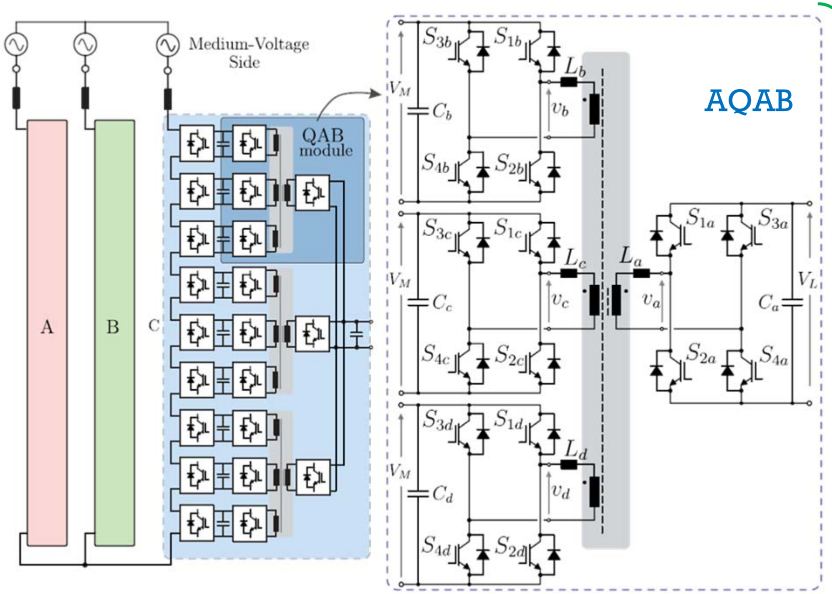


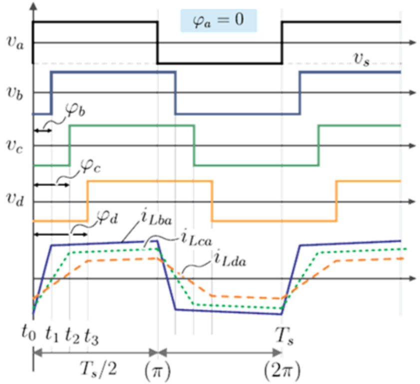
Cell used in the Resonant MTB Converters
150 x 30 x 160 mm and 150 x 30 x 75 mm

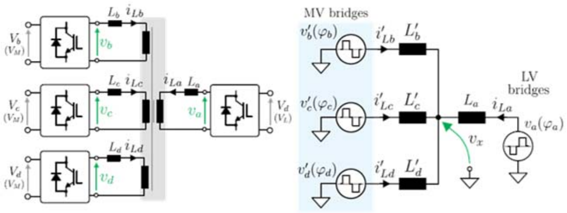


Quantitative Analyses and Applications

▶ Non-Resonant MTB DC-DC Topologies – AQAB Converter for Smart-Transfomer







Extension of DAB Converter

Characteristics:

- ❑ Higher controllability
- ❑ Higher control complexity
- ❑ Soft-switching → High efficiency (ZVS);
- ❑ One magnetic core;
- ❑ Integration of storage in floating port;

Main Challenges

- ❑ Accurate determination of multi-winding transformer parasitic
- ❑ Reactive power circulation;

Electrical Specifications

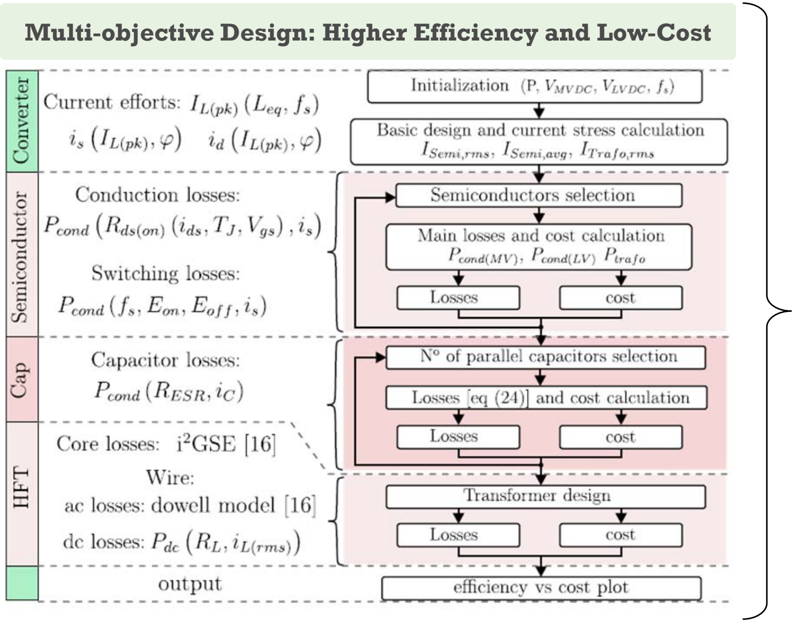
Rated Power	MVAC	LVAC	Grid frequency
500 kVA	10 kV	400 V	50 Hz
QAB Converter Specification			
Rated Power	Input Voltage	Output Voltage	Switching freq.
20 kW	800 V	700 V	20 kHz

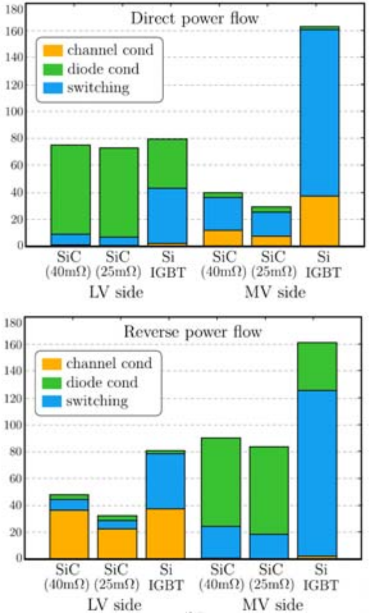
L. F. Costa, G. Buticchi and M. Liserre, "Optimum Design of a Multiple-Active-Bridge DC–DC Converter for Smart Transformer," in IEEE Transactions on Power Electronics, vol. 33, no. 12, pp. 10112-10121, Dec. 2018.

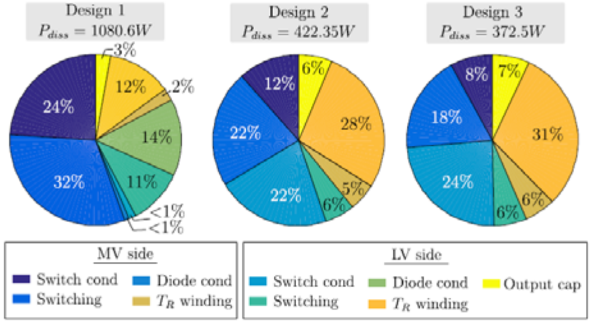
Quantitative Analyses and Applications

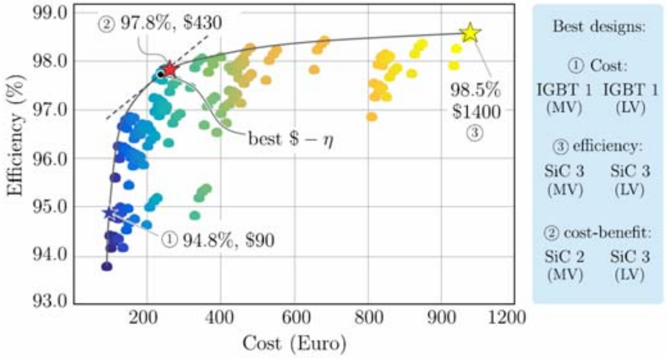
Christian-Albrechts-Universität zu Kiel

► Non-Resonant MTB DC-DC Topologies – AQAB for Smart-Transfomer





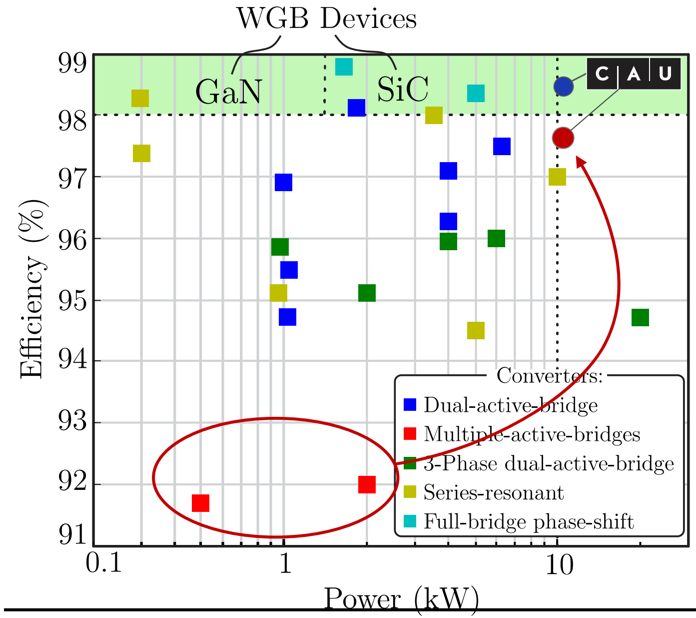


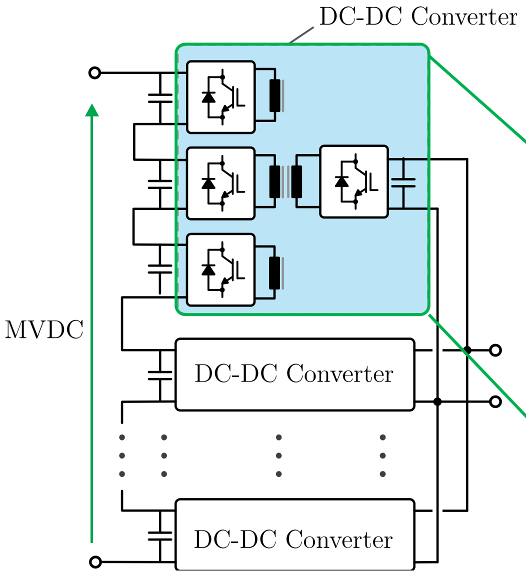


L. F. Costa, G. Buticchi and M. Liserre, "Optimum Design of a Multiple-Active-Bridge DC–DC Converter for Smart Transformer," in IEEE Transactions on Power Electronics, vol. 33, no. 12, pp. 10112-10121, Dec. 2018.

Quantitative Analyses and Applications

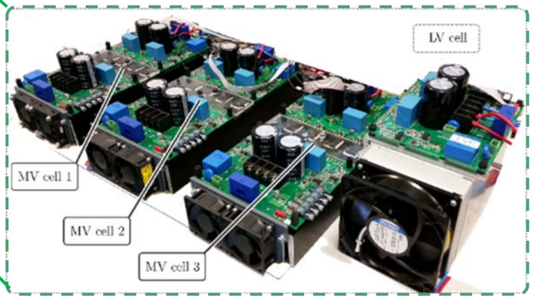
▶ Non-Resonant MTB DC-DC Topologies – AQAB Converter for Smart-Transfomer





CAU Kiel DC-DC converter

Max Eff = 97.5% (SiC)



Highest efficiency of a MAB converter

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.

Quantitative Analyses and Applications

Christian-Albrechts-Universität zu Kiel

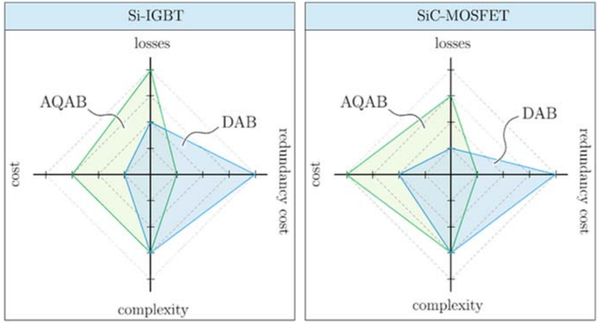
► Non-Resonant MTB DC-DC Topologies – AQAB for Smart-Transfomer

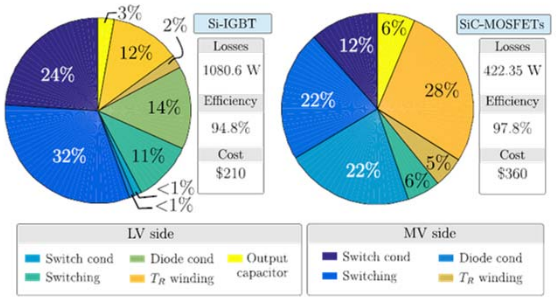
SPECIFICATION OF THE PROTOTYPE

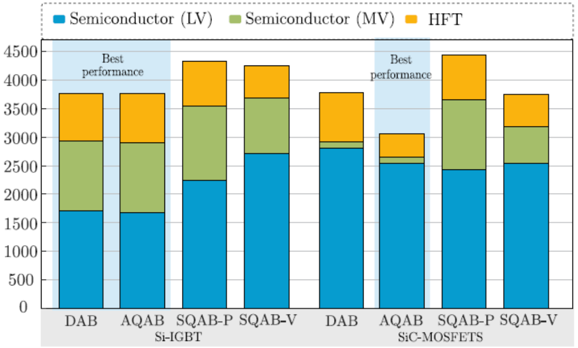
Nominal power of the unit	$P_o = 20$ kW
Nominal ac voltage	$V_{ac} = 1.4$ kVrms / 50 Hz
Individual MVdc link	$V_{MV} = 800$ V
LVdc link	$V_{LVDC} = 700$ V
Switching frequency	$f_s = 20$ kHz

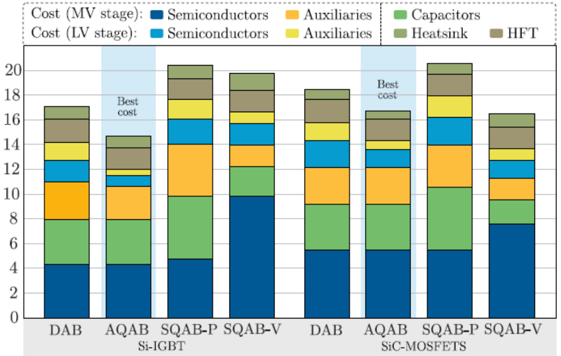
Comparative Analysis of MAB Converters in Modular Smart Transformer

AQAB x DAB









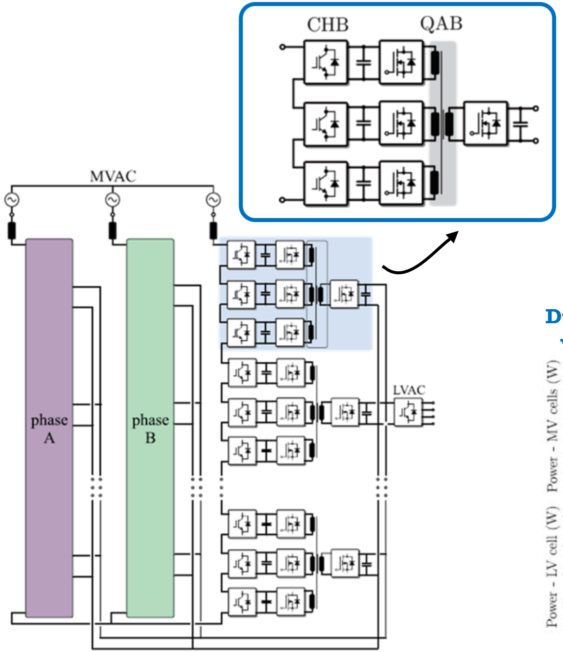
L. F. Costa, F. Hoffmann, G. Buticchi and M. Liserre, "Comparative Analysis of Multiple Active Bridge Converters Configurations in Modular Smart Transformer," in IEEE Transactions on Industrial Electronics, vol. 66, no. 1, pp. 191-202, Jan. 2019.

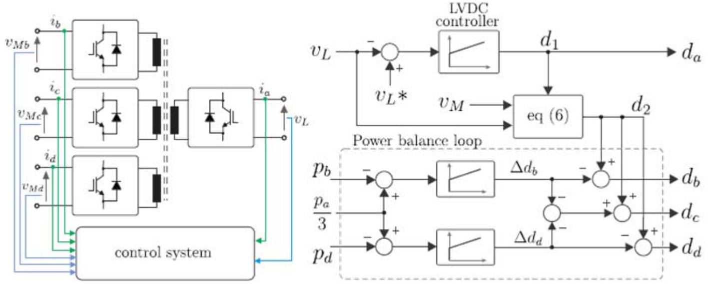
▶ Non-Resonant MTB DC-DC Topologies – AQAB Converter for MV Modular Inverters

To ensure soft switching for the entire operation range of the QAB converter, the **Triangular Current-mode Modulation (TCM)** strategy is applied to the **AQAB** converter.

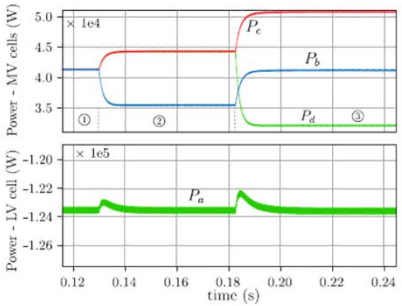
Advantages: **leakage inductance deviation has no influence on the soft-switching operation** of the AQAB converter, but only a small influence on the transferred power.

The Power processed by the cells of the **CHB** can be **balanced** by using the AQAB + TCM.

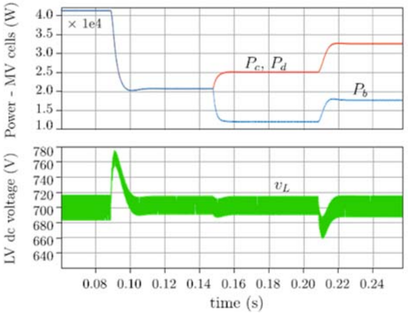




Dynamic operation of the AQAB showing variation on the power in the MV cells

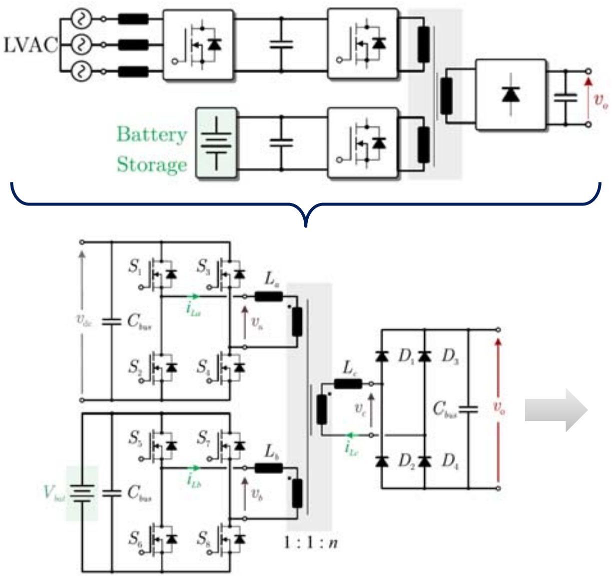


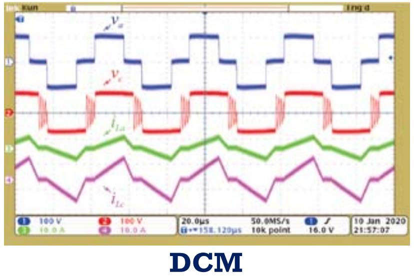
Dynamic behavior for load variation.

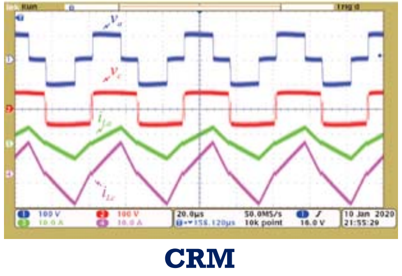


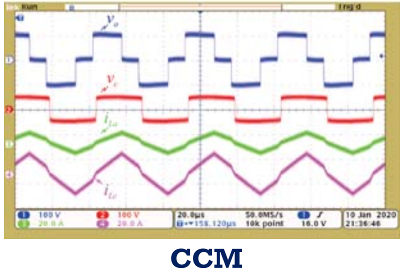
L. F. Costa, G. Buticchi and M. Liserre, "Quad-Active-Bridge DC–DC Converter as Cross-Link for Medium-Voltage Modular Inverters," in IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1243-1253, March-April 2017, doi: 10.1109/TIA.2016.2633539.

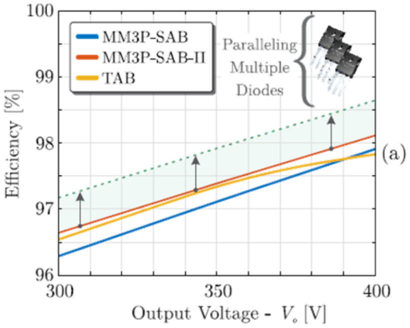
▶ Non-Resonant MTB DC-DC Topologies – Multimode 3-Ports Converters

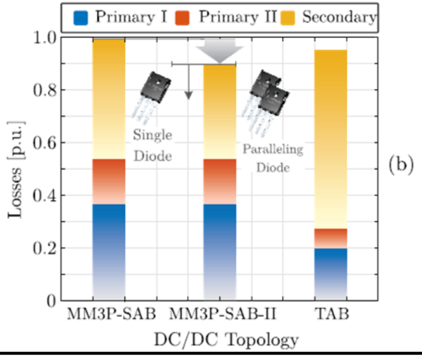


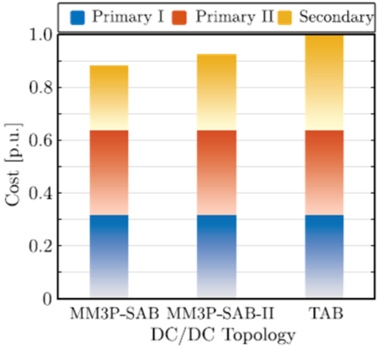












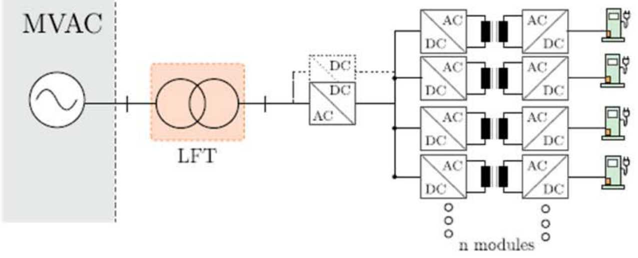
F. Hoffmann, T. Pereira and M. Liserre, "Isolated DC/DC Multimode Converter with Energy Storage Integration for Charging Stations," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020, pp. 633-640, 2020.

Quantitative Analyses and Applications

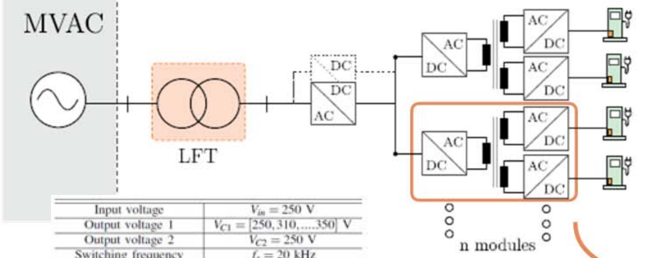
Christian-Albrechts-Universität zu Kiel

▶ Non-Resonant MTB DC-DC Topologies - Semi-DAB Converter (Hybrid Topologies)

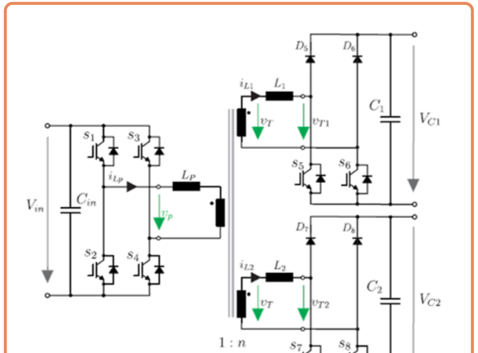
Conventional Solution of FCS Architecture



Proposed Solution of FCS Architecture

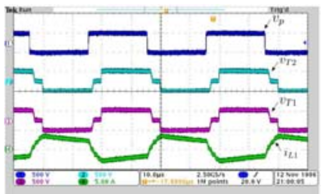


Input voltage	$V_{in} = 250$ V
Output voltage 1	$V_{C1} = \boxed{250, 310, ..., 350}$ V
Output voltage 2	$V_{C2} = 250$ V
Switching frequency	$f_s = 20$ kHz
Nominal PS angle	$\varphi_{nom} = 30°$
Transformer turns ratio	$n = 1$
Primary side switches	C2M0025120D
Secondary side switches	C2M0040120D
Secodary side diodes	C4D40120D

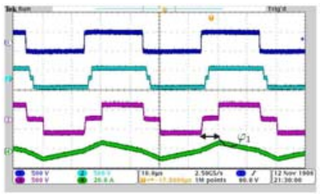


Semi-DAB

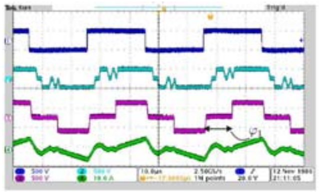
- ❑ The **Semi-DAB** features the same positive characteristics like the DAB in terms of soft switching and high efficiency operation.
- ❑ At the same time the **Semi-DAB** reduces the cost and the driver circuit complexity on the secondary side. Thus, **the semi-DAB is an excellent candidate as a building block for the dc-dc stage in FCS**.



CCM



Boundary Mode



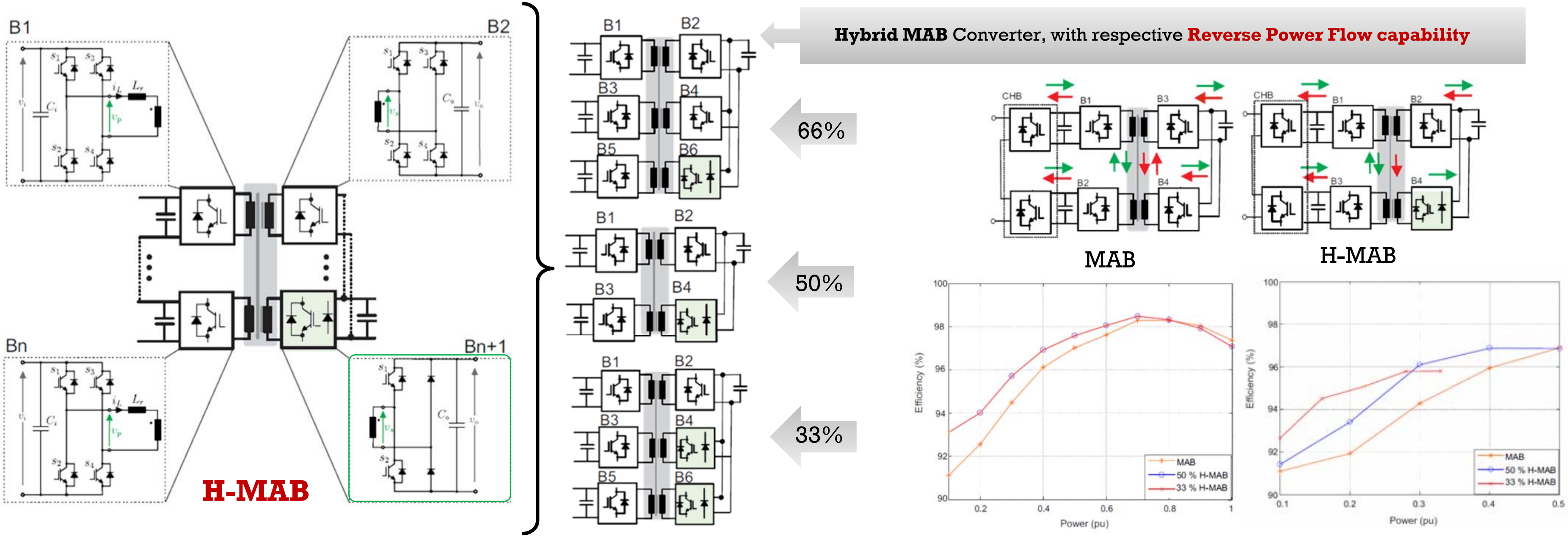
DCM

F. Hoffmann, J. -L. Lafrenz, M. Liserre and N. Vazquez, "Multiwinding based Semi-Dual Active Bridge Converter," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 2142-2149, 2020.

Quantitative Analyses and Applications

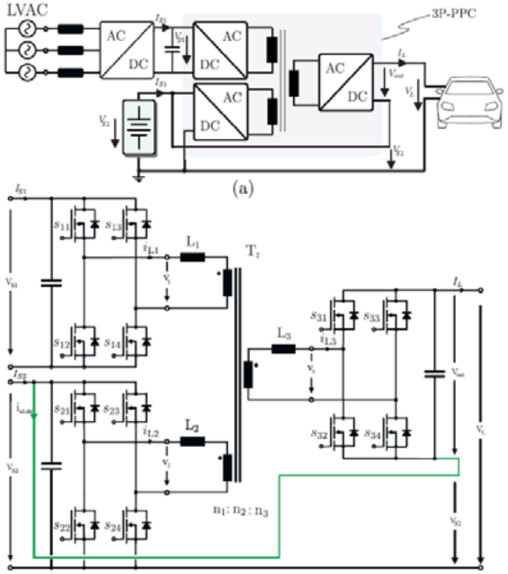
► Non-Resonant MTB DC-DC Topologies - Hybrid MAB (H-MAB)

Hybrid MAB Converter, with respective **Reverse Power Flow capability**

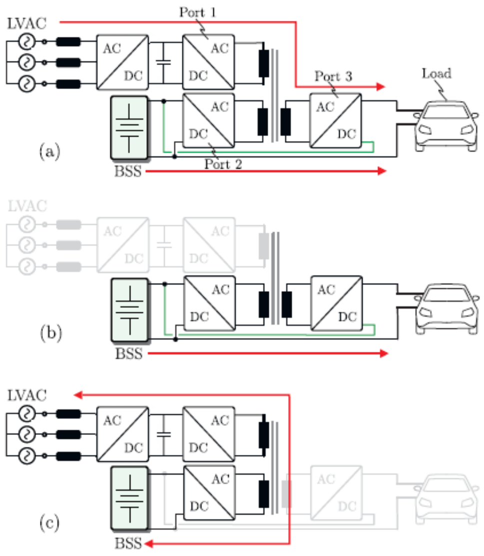


V. N. Ferreira, N. Vazquez, B. Cardoso and M. Liserre, "Hybrid Multiple-Active Bridge for Unequal Power Flow in Smart Transformers," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 5016-5021, 2019.

► Non-Resonant MTB DC-DC Topologies – Multiport Partial Power Processing Converter (PPPC) for BSS

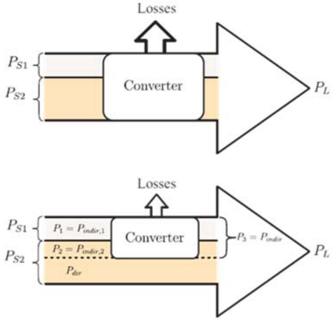


Operation Modes

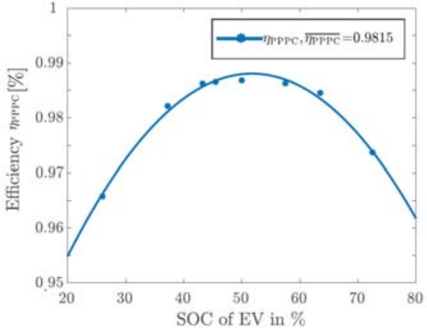


Advantages: The proposed three-port partial power processing converter (**3P-PPPC**) is derived from the TAB converter. The 3P-PPPC shows a **1.9% efficiency increase**, **resulting in 73% of loss reduction** and **25% cost reduction** compared to a conventionally used TAB converter.

Schematic of power sharing capability



Measured Efficiency



F. Hoffmann, J. Person, M. Andresen, M. Liserre, F. D. Freijedo and T. Wijekoon, "A multiport partial power processing converter with energy storage integration for EV stationary charging," (First Revision), 2020.

Conclusion & Outlook

Conclusion and Outlook

- **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.

- The **common magnetic core** and its **resulting** coupling might bring **specific challenges** depending on the **Number of Windings** and their arrangement. Thus, the impact of the **undesired cross-coupling** and the **parameter deviation** can be reduced by using a proper winding structure.

- In **several application fields**, such as EVs, fast charger station, uninterruptible power supply system (UPS), special medicine equipment, more-electric-aircraft (MEA), data processing (and data center), hybrid grids, solid-state transformer (SST) and others; **contain at least one DC-DC converter for adapting the voltage and/or control the power processed**.

REFERENCES

References

[1] H. Matsuo and K. Harada, "**New energy-storage dc-dc converter with multiple outputs**," IEEE Trans. Mag., vol. 14, no. 5, pp. 1005–1007, 1978.

[2] T. G. Wilson, "**Cross regulation in an energy-storage dc-to-dc converter with two regulated outputs**," in 1977 IEEE Power Electr. Spec. Conf., 1977, pp. 190–199, 1977.

[3] H. Matsuo, T. Shigemizu, F. Kurokawa, and N. Watanabe, "**Characteristics of the multiple-input dc-dc converter**," in Proc. of IEEE Power Electr. Spec. Conf.- PESC '93, 1993, pp. 115–120, 1993.

[4] Q. Chen, F. Lee, Jian Zhong Jiang, and M. M. Jovanovic, "**A new model for multiple-winding transformer**," in Proc. of 1994 Power Electr. Spec. Conf.- PESC'94, vol. 2, 1994, pp. 864–871, 1994.

[5] Y. M. Chen, Y. C. Liu, and F. Y. Wu, "**Multi-input dc/dc converter based on the multiwinding transformer for renewable energy applications**," IEEE Trans. Ind. Appl., vol. 38, no. 4, pp. 1096–1104, 2002.

[6] M. Qiang, W. Wei-yang, and X. Zhen-lin, "**A multi-directional power converter for a hybrid renewable ener. distributed generation system with battery storage**," in 2006 CES/IEEE 5th Conf., vol. 3, 2006, pp. 1–5, 2006.

[7] H. Tao, A. Kotsopoulos, J. L. Duarte, and M. A. M. Hendrix, "**Family of multiport bidirectional dc-dc converters**," IEEE Proc. - Electric Power Appl., vol. 153, no. 3, pp. 451–458, 2006.

[8] J. L. Duarte, M. Hendrix, and M. G. Simoes, "**Three-port bidirectional converter for hybrid fuel cell systems**," IEEE Trans. Power Electr., vol. 22, no. 2, pp. 480–487, 2007.

[9] S. Inoue and H. Akagi, "**A bidirectional isolated dc–dc converter as a core circuit of the next-generation MV power conversion system**," IEEE Trans. Power Electr., vol. 22, no. 2, pp. 535–542, 2007.

[10] C. Zhao, S. D. Round, and J. W. Kolar, "**An isolated three-port bidirectional dc-dc converter with decoupled power flow management**," IEEE Trans. Power Electr., vol. 23, no. 5, pp. 2443–2453, 2008.

[11] H. Krishnaswami and N. Mohan, "**Three-port series-resonant dc–dc converter to interface renewable energy sources with bidirectional load and energy storage ports**," IEEE Trans. Power Electr., vol. 24, no. 10, pp. 2289–2297, 2009.

References

[12] S. Falcones, X. Mao, and R. Ayyanar, "**Topology comparison for solid state transformer implementation**," in IEEE PES Meet., 2010, pp. 1–8, 2010.

[13] S. Falcones, R. Ayyanar, and X. Mao, "**A dc–dc multiport-converter based solid-state transformer integrating distributed generation and storage**," IEEE Trans. on Power Electr., vol. 28, no. 5, pp. 2192–2203, 2013.

[14] D. Dujic, F. Kieferndorf, F. Canales and U. Drofenik, "**Power electronic traction transformer technology**," Proceedings of The 7th International Power Electronics and Motion Control Conference, Harbin, China, 2012, pp. 636-642, 2012.

[15] J. Taufiq, "**Power Electronics Technologies for Railway Vehicles**," 2007 Power Conversion Conference - Nagoya, Nagoya, Japan, 2007, pp. 1388-1393, 2007.

[16] Patent: WO2012025254A1, "**Multi-system traction power converter**," 2012.

[17] F. Hoffmann, J. -L. Lafrenz, M. Liserre and N. Vazquez, "**Multiwinding based Semi-Dual Active Bridge Converter**," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 2142-2149, 2020.

[18] F. Hoffmann, T. Pereira, and M. Liserre, "**Isolated DC/DC Multimode Converter with Energy Storage Integration for Charging Stations**," IEEE Ener. Conver. Congr. and Exp., ECCE 2020, pp. 5016–5021, 2020.

[19] R. Liu, L. Xu, Y. Kang, Y. Hui, and Y. Li, "**Decoupled tab converter with energy storage system for HVDC power system of more electric aircraft**," The Journal of Engineering, vol. 2018, no. 13, pp. 593–602, 2018.

[20] R. Rai and N. R. Tummuru, "**Circulating and leakage power flow elimination technique between source ports in triple active bridge topology**," in 2020 IEEE Int. Conf. (PESGRE2020), 2020, pp. 1–6, 2020.

[21] M. A. Rahman, M. R. Islam, K. M. Muttaqi, and D. Sutanto, "**Data driven coordinated control of converters in a smart solid-state transformer for reliable and automated distribution grids**," IEEE Trans. Ind. Appl., vol. 56, pp. 4532–4542, 2020.

[22] L. F. Costa, G. Buticchi, and M. Liserre, "**Comparison of basic power cells for quad-active-bridge DC-DC converter in smart transformer**," 2015 17th European Conf. on Power Electr. and Appl., EPE-ECCE Europe 2015, vol. 1, 2015.

References

[23] L. F. Costa, G. Buticchi and M. Liserre, "**Modular Smart Transformer architectures: An overview and proposal of a interphase architecture**," 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Florianopolis, 2017, pp. 1-7, 2017.

[24] M. A. Rahman, M. R. Islam, K. M. Muttaqi, and D. Sutanto, "**Modeling and control of sic-based high-frequency magnetic linked converter for next generation solid state transformers**," IEEE Trans. Ener. Conver., vol. 35, pp. 549–559, 2020.

[25] C. Gu, Z. Zheng, L. Xu, K. Wang, and Y. Li, "**Modeling and control of a multiport power electronic transformer (pet) for electric traction applications**," IEEE Trans. Power Electr., vol. 31, no. 2, pp. 915–927, 2016.

[26] Y. Tran, D. Duji´c, and P. Barrade, "**Multiport resonant dc-dc converter**," in IECON 2015 - 41st Annu. Conf. of the IEEE Ind. Electr. Soc., 2015, pp. 003 839–003 844, 2015.

[27] K. Tomas-Manez, Z. Zhang, and Z. Ouyang, "**Multi-port isolated LLC resonant converter for distributed energy generation with energy storage**," in 2017 IEEE Ener. Conver. Congr. and Exp. (ECCE), 2017, pp. 2219–2226, 2017.

[28] Farnesi, Stefano et al. "**Solid-State Transformers in Locomotives Fed through AC Lines: A Review and Future Developments**." Energies 12 (2019): 4711, 2019.

[29] F. Hoffmann, J. Person, M. Andresen, M. Liserre, F. D. Freijedo and T. Wijekoon, "**A multiport partial power processing converter with energy storage integration for EV stationary charging**," (First Revision), 2020.

[30] 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.

[31] 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.

[32] L. F. Costa, G. Buticchi and M. Liserre, "**Quad-Active-Bridge DC–DC Converter as Cross-Link for Medium-Voltage Modular Inverters**," in IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1243-1253, March-April 2017.

[33] L. F. Costa, F. Hoffmann, G. Buticchi and M. Liserre, "**Comparative Analysis of Multiple Active Bridge Converters Configurations in Modular Smart Transformer,**" in IEEE Transactions on Industrial Electronics, vol. 66, no. 1, pp. 191-202, Jan. 2019.

Prof. Marco Liserre - Head of Chair
ml@tf.uni-kiel.de

THANK YOU!

FOR MORE DETAILS, PLEASE VISIT OUR SOCIAL MEDIAS AND HOME-PAGE - https://www.pe.tf.uni-kiel.de/en

Christian-Albrechts-Universität zu Kiel

IEEE PELS Webinar 2021

Opportunities and Challenges of Multiwinding Transformer-Based DC-DC Converter

Prof. Marco Liserre

Chair of Power Electronics
Christian-Albrechts-Universität zu Kiel
Kaiserstraße 2
24143 Kiel