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

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A short summary about me . . .

► **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)
IEEE PELS Webinar
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  • Overview of the Main Topologies presented in the literature

► Assessment and Comparative Analysis of the MTB DC-DC Converters:
  • Potential of the MTB Topologies (Power Density, Cost-benefit, and Fault Tolerant Capability);
  • Challenges of the MWT in MTB Topologies (Operation mode realization, Stray Component Deviation, Unwanted coupling, and Max number of windings).

► Interconnection and operation modes issues of MTB DC/DC Converters.

► Quantitative analysis and comparison of MTB DC/DC converters in relation to the application.

► Conclusion & Outlook.

HISTORY OF MTB DC-DC CONVERTERS
History of MTB DC-DC Converters

- 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].

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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].

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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.


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.


History of MTB DC-DC Converters

Power Electronics Transformer for Traction – Alstom/Siemens


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

Multi-system Traction Power Converter – Alstom/Siemens


ARCHITECTURE AND OPERATION PRINCIPLE
**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.
Classification of the MTB Topologies

MTB DC-DC Converter

- Architecture Symmetry
  - Symmetrical
  - Asymmetrical

- Operation Mode
  - Non-resonant
  - Resonant

- Classification of MTB Topologies:
  1. Symmetrical: $N_{cell,pri} = N_{cell,sec}$
  2. Asymmetrical: $N_{cell,sec} = j$

- Resonant vs. Non-resonant AC Currents:
  - Resonant
  - Non-resonant

- Parameters:
  - $f_w = 1/T_w$
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) Non-Resonant

SR and LLC Converter 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.
Architecture and Operation Principle

► 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**
- **Penta-Active Bridge (PAB)**
- **Interphase Multiple-Active-Bridge for ST**

[Diagram showing the architecture and operation principle of the MTB DC-DC Topologies]
Architecture and Operation Principle

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

Characteristics:
- 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

Extension of SR Converter

Magnetizing Inductance

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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

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

HBB - Hybrid Half-bridge;
FB - Full-bridge;
SABR - Semi-active bridge rectifier;
FWR - Full-wave rectifier.
ASSESSMENT AND COMPARATIVE ANALYSIS
Assessment and Comparative Analyses

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.

<table>
<thead>
<tr>
<th>Magnetic Core Geometry</th>
<th>U-U</th>
<th>U-I</th>
<th>E-E</th>
<th>ETD-ETD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Material Reduction</td>
<td>10%</td>
<td>15%</td>
<td>12%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Core Material Reduction By Using The MWT (U-cores).
Assessment and Comparative Analyses

▶ 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.

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

\[
\frac{V_{\text{MWT}}}{V_{\text{2WT}}} \mid_{\text{asy}} = \frac{1}{k_{\text{Vol}}N_{\text{2WT}}} \left( \frac{N_{\text{cell, pri}} + 1}{2} \right)^{0.75}
\]

\(k_{\text{Vol}}\) is the ratio between the core size of the 2WT and MWT \((0 < k_{\text{Vol}} < 1)\).
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 have its volume varying according to the total power processed:

\[ V_{o,cell} = k_{v,cell} V_{o,cell} \text{ \ \ \ \ where \ \ \ \ } k_{v,cell} = (N_{cell,i,j})^{1.5} \]
Assessment and Comparative Analyses

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.

<table>
<thead>
<tr>
<th>$N_{\text{cells,pri}}$</th>
<th>Cost Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cells</td>
<td>15.60 %</td>
</tr>
<tr>
<td>3 cells</td>
<td>21.43 %</td>
</tr>
<tr>
<td>4 cells</td>
<td>25.00 %</td>
</tr>
<tr>
<td>5 cells</td>
<td>21.43 %</td>
</tr>
<tr>
<td>6 cells</td>
<td>8.33 %</td>
</tr>
</tbody>
</table>
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
Assessment and Comparative Analyses

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.

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**Power Routing applied to the MTB DC-DC Converters**

\[ P_{\text{sys}} = P_{\text{cell,1}} + P_{\text{cell,2}} + \ldots + P_{\text{cell,i,j}} \]


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Assessment and Comparative Analyses

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

INTERCONNECTION AND OPERATION MODE ISSUES
Possible Configurations used to interconnect the modules in the MTB DC-DC Topologies

- Input-series Output-series
- Input-series Output-paralle;
- 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

<table>
<thead>
<tr>
<th>Ports</th>
<th>ISOS</th>
<th>ISOP</th>
<th>IPOS</th>
<th>IPOP</th>
<th>IIOI</th>
<th>IIOS</th>
<th>ISOI</th>
<th>IIOP</th>
<th>IPOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input [I]</td>
<td>Series</td>
<td>Series</td>
<td>Parallel</td>
<td>Parallel</td>
<td>Independently</td>
<td>Independently</td>
<td>Series</td>
<td>Independently</td>
<td>Parallel</td>
</tr>
<tr>
<td>Output [O]</td>
<td>Series</td>
<td>Parallel</td>
<td>Series</td>
<td>Parallel</td>
<td>Independently</td>
<td>Independently</td>
<td>Series</td>
<td>Independently</td>
<td>Independently</td>
</tr>
</tbody>
</table>
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

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 $L_{\text{Sink},1} < L_{\text{Sink},2}$

Current Waveforms on the Sinking Inductance

Parallel interconnection

Independent interconnection

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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 \((L_{\text{Sink}}/L_{\text{Feed}})\).

Efficiency of the DC-DC Converter for each case

![Efficiency Graphs]

- **Parallel interconnection**
  - Inductance Ratio = 1
  - Coupled

- **Independent interconnection**
  - Inductance Ratio = 10
  - Decoupled

Efficiency of the DC-DC Converter for each case:

- Parallel Outputs
- Independent Outputs
Interconnection and Operation Issues

► 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.
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 \(A_p = 572 \text{ cm}^4\), the power processed by the MWT is limited to \(P_{MWT} = 143 \text{ kW}\).
QUANTITATIVE ANALYSES AND APPLICATIONS
Quantitative Analyses and Applications

MTB DC-DC Converters used in the Quantitative Analyses

Symmetrical 4-Port Converter

Bidirectional

Unidirectional

Asymmetrical 3-Port Converter

Asymmetrical 4-Port Converter

Electrical Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>10 kW</td>
</tr>
<tr>
<td>DC-Link Voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Turn-ratio</td>
<td>1:1:1:1</td>
</tr>
</tbody>
</table>

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Quantitative Analyses and Applications

► Quantitative Analyses among different MTB DC-DC Topologies

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 |
Non-Resonant MTB DC-DC Topologies – AQAB Converter for Smart-Transformer

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

<table>
<thead>
<tr>
<th>Rated Power</th>
<th>MVAC</th>
<th>LVAC</th>
<th>Grid frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kVA</td>
<td>10 kV</td>
<td>400 V</td>
<td>50 Hz</td>
</tr>
<tr>
<td>QAB Converter Specification</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rated Power</th>
<th>Input Voltage</th>
<th>Output Voltage</th>
<th>Switching freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 kW</td>
<td>880 V</td>
<td>700 V</td>
<td>20 kHz</td>
</tr>
</tbody>
</table>

Quantitative Analyses and Applications

Non-Resonant MTB DC-DC Topologies – AQAB for Smart-Transformer

Multi-objective Design: Higher Efficiency and Low-Cost

Current efforts: $I_{L(pk)}$ ($I_{eq}$, $f_s$) $i_s$ ($I_{L(pk)}$, $\varphi$) $i_d$ ($I_{L(pk)}$, $\varphi$) 

Initialization ($P_{V_{MSDC}}$, $V_{LDC}$, $f_s$) 

Basic design and current stress calculation $I_{S_{max}}$, $V_{S_{max}}$, $I_{V_{fmax}}$ 

Conduction losses: $P_{cond}$ ($R_{ds(on)}$, $I_{ds}$, $T_J$, $V_{gs}$, $i_s$) 

Switching losses: $P_{cond}$ ($f_s$, $E_{on}$, $E_{off}$, $i_s$) 

Capacitor losses: $P_{cond}$ ($R_{ESR}$, $i_C$) 

Core losses: $i_2$GSE [16] 

Wire: ac losses: dowell model [16] 

dc losses: $P_{dc}$ ($R_z$, $I_{L(rms)}$) 

Transformer design 

Efficiency vs cost plot 

Quantitative Analyses and Applications

- **Non-Resonant MTB DC-DC Topologies – AQAB Converter for Smart-Transformer**

  ![Graph showing efficiency vs. power for different converter types.](image)

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

  **CAU Kiel DC-DC converter**

  **Highest efficiency of a MAB converter**

Quantitative Analyses and Applications

Non-Resonant MTB DC-DC Topologies – **AQAB for Smart-Transformer**

**Comparative Analysis of MAB Converters in Modular Smart Transformer**

**AQAB x DAB**

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.

Quantitative Analyses and Applications

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

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

- 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.

Quantitative Analyses and Applications

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

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

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.

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


References


References


THANK YOU!

FOR MORE DETAILS, PLEASE VISIT OUR SOCIAL MEDIAS AND HOME-PAGE - https://www.pe.tf.uni-kiel.de/en
Opportunities and Challenges of Multiwinding Transformer-Based DC-DC Converter

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