An Innovative Bidirectional Isolated Multi-Port Converter with Multi-Phase AC-Ports and DC-Ports

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Motivation

- **Power Electronics for Future Energy Systems**
  - Coupling of different AC/DC Energy Sources with AC/DC Grids
  - Full Controllability of Power Flows (e.g. Reactive Power Compensation)

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**50 Hz Transformer**

**Solid-State Transformers (SST)**

- AC Grid 1
- AC Grid 2
- DC Grid
- DC Storage
State-of-the-Art Approaches

- **Conventional Three-Stage Approach**
  - AC-DC Rectifier
  - DC-DC Converter
  - Isolation & Voltage Adaptation
  - DC-AC Inverter

- **Topologies for AC-DC & DC-AC Conversion**
  - Active-/Diode-Clamped Multilevel Converter
  - Flying-Capacitor Multilevel Converter
  - Modular Multilevel Converter (M2C)
  - Cascaded H-Bridge Converter (CHB)

- **Topologies for DC-DC Conversion**
  - Dual-Active-(Full-)Bridge (DAB) Converter
  - Dual-Half-Bridge (DHB) Converter

- **Other Topologies**
  - AC-AC Matrix Converter (non-isolated)
  - AC-DC 3-by-2 Cycloconverter (isolated)
Multi-Port Converter with AC and DC Ports

- **Multi-Port Converter**
  - Direct coupling AC-DC-AC with Isolation
  - Multi-Phase AC Ports & DC Ports
  - Stackable (Ports in series/parallel)
  - Suitable for HV/MV Applications

- **Field of Application**
  - Wind Energy Generation Systems
  - Solid State Transformers (SST)
  - Charging Systems (e.g. Electric Mobility)
  - Grid Energy Storage Systems
  - PV Inverter
Examples of Bidirectional Isolated DC-DC Converter with Phase-Shift Operation
- Dual-Active-(Full-)Bridge (DAB) Converter
- Dual-Half-Bridge (DHB) Converter
→ Two DC Ports

- Basic Equivalent Circuit
- Wave-Forms in Phase-Shift Operation

Leakage Inductance of Transformer
From a DC Port to a Multi-Phase AC Port
- Sum of absolute Phase Voltages nearly constant
  → Available for Control

Principle of Phase-Shift Operation
Converter Topology – Three-Phase AC-DC System

- Three-Phase AC Port
  - T-Type Switching Networks
  - Low-Frequency (LF) Side
    → AC-System Voltage
  - High-Frequency (HF) Side
    → Square-Wave Voltage with Clamping

- DC Port
  - Full-Bridge Switching Network
  - DC Voltage on DC Side
  - High-Frequency (HF) Side
    → Square-Wave Voltage with Clamping

- Port Coupling
  - 3 Two-Winding Transformers
  - Windings on DC Side in series
Operating Principle – Phase-Shift Control

- **Equivalent Converter Circuit**
  - HF Port Voltage Sources
  - Total Leakage Inductance (primary referred)

- **Time-Varying Phase-Shift Control**
  - Phase-Shifts change over AC System Period
  - Reference: HF Voltage on DC Side
  - Composition of Voltage Sum on AC Side
### Operating Principle – Phase-Shift Control

- **HF Fundamental Model**
  - Time-independent HF Voltage Sum Phasor → Constant Amplitude & Phase
  
  \[
  v_{p,s} = v_{p,a} + v_{p,b} + v_{p,c} = \hat{v}_{p,s} e^{j\phi_s} = \frac{3\hat{V}_{abc} \cos(\delta_{abc})}{\pi} e^{j\phi_s}
  \]

  **Average Power over Switching Cycle**

  \[
  p_a = \text{Re}\left\{ \frac{1}{2} v_{p,a} i_{L\sigma} \right\} = v_a \frac{\hat{i}_{L\sigma} \cos(\delta_{abc})}{\pi} \cos(\phi_a - \phi_i) \]

- **Control Functions for Phase-Shifts**

  \[
  \phi_a = \omega_{abc} t + \phi_s \\
  \phi_b = \omega_{abc} t - \frac{2\pi}{3} + \phi_s \\
  \phi_c = \omega_{abc} t - \frac{4\pi}{3} + \phi_s
  \]

  **Control Variables**
Prototype System

- AC Port Voltage $230 \text{ V}_{\text{rms}} / 50 \text{ Hz}$
- DC Port Voltage $400 \text{ V}_{\text{dc}}$
- Switching Frequency $20 \text{ kHz}$
- Total Leakage Inductance $9 \mu\text{H}$

Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC system voltage</td>
<td>$V_{abc}$</td>
<td>$230 \text{ V}_{\text{rms}}$</td>
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<tr>
<td>AC system frequency</td>
<td>$f_{abc}$</td>
<td>$50 \text{ Hz}$</td>
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<tr>
<td>DC port voltage</td>
<td>$V_{dc}$</td>
<td>$400 \text{ V}_{\text{dc}}$</td>
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<tr>
<td>Switching frequency</td>
<td>$f_s$</td>
<td>$20 \text{ kHz}$</td>
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<td>Transformer turns ratios</td>
<td>$n_{abc}$</td>
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<td>Transformer leakage inductances</td>
<td>$L_{\sigma,a}, L_{\sigma,b}, L_{\sigma,c}$</td>
<td>$3 \mu\text{H}$</td>
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<tr>
<td>Transformer magnetizing inductances</td>
<td>-</td>
<td>neglected</td>
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<tr>
<td>Total transformer leakage inductance</td>
<td>$L_{\sigma}$</td>
<td>$9 \mu\text{H}$</td>
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<tr>
<td>Inductors</td>
<td>$L_f$</td>
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<tr>
<td>Capacitors</td>
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<td>$10 \mu\text{F}$</td>
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<tr>
<td>Inductor</td>
<td>$L_{dc}$</td>
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</tr>
<tr>
<td>Capacitor</td>
<td>$C_{dc}$</td>
<td>$20 \mu\text{F}$</td>
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Prototype System – Simulation Results

Grid Voltages

AC Capacitor Voltages

AC Port Input Currents
Prototype System – Simulation Results

Transformer Leakage Inductance Current
Primary Side (blue)
Secondary Side (yellow)

HF Voltages applied to Primary Windings

HF Voltage applied to Secondary Windings (yellow)

HF Voltage Sum (blue)
Multi-Phase AC Ports
- Sum of absolute Phase Voltages nearly constant
  → Available for Control
- Requirement for Transformer Structure
  → HF Voltage Summation or Flux Summation

3 Two-Winding Transformers
- Secondary Windings in series
- HF Voltage Summation on DC Side
- Leakage Inductances in series

Four-Winding Transformer
- Single Secondary Winding
- Flux Summation on DC Side
Conclusion & Outlook

- **Concept of Multi-Port Converter**
  - Multi-Phase AC Ports
  - DC Ports
  - Isolation & Voltage Adaptation
  - Stackable (Inputs/Outputs in series/parallel)
  - Broad Field of Application

- **Modulation Strategy**
  - Based on HF Fundamental Model
  - Further Research on Modulation Schemes

- **Paper available on IEEE Xplore**
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Thank you for your Attention!