Introduction to Scalable Multi-Port Converters
Modeling and control of an arbitrary number of power ports

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June 14, 2016
Trends in power electronics: multi-port converters

- **Traditional power converters**
  - One input, one output
  - Unidirectional power flow
  - Stages for ac-dc and dc-dc

- **Recent developments**
  - Multi-port
  - Bidirectional power flow
  - Combined dc-dc and ac-dc conversion
Example application

- **bi-directional multi-port converter**

- **Household equipment**
  - Photovoltaics
  - Mains grid
  - Stationary battery

- **Electric vehicle**
Topology concept

- Active bridge (AB) as building block
- Number of active bridges is variable
Topography concept

- Properties:
  - Modular and scalable structure
  - Bi-directional power flow
  - Galvanically isolated ports
  - Little passive components
Modeling

• Fourier-based modeling approach
  - Steady-state solutions
  - Low computational effort

• Allows analysis of
  - Power transfer
  - Voltage and current waveforms
  - Switching transients
  - Conduction losses
Modeling

- Steps to obtain model using Fourier-series
  1. Describe switched-node voltages by
     \[ u'(t) = \sum_{k=1}^{\infty} Ua'(k) \cos((2k - 1)\omega_{sw}t) + \]
     \[ Ub'(k) \sin((2k - 1)\omega_{sw}t) \]

  2. Calculate coefficients of current through inductor
     \[ i'(t) = \frac{\int u'(t) \, dt}{L_\sigma} = \sum_{k=1}^{\infty} -Ub'(k) \frac{\cos((2k - 1)\omega_{sw}t)}{(2k - 1)\omega_{sw}L_\sigma} \]
     \[ + \sum_{k=1}^{\infty} Ua'(k) \frac{\sin((2k - 1)\omega_{sw}t)}{(2k - 1)\omega_{sw}L_\sigma} \]

  3. Calculate power transfer using voltage and current
     \[ P'(k) = 0.5i'_{\sigma a}(k) Ua'(k) + 0.5i'_{\sigma b}(k) Ub'(k) \]
Modeling accuracy

(a) Fourier-based model, truncated at 25 harmonics

(b) Plexim PLECS simulation
Evaluating soft-switching properties

- Steps to analyze soft-switching

1. Determine transient instants

\[
\begin{align*}
t_{s,0H} &= \frac{-\Phi - 0.5\pi d}{\omega_{sw}} \\
t_{s,H0} &= \frac{-\Phi + 0.5\pi d}{\omega_{sw}}
\end{align*}
\]

2. Calculate current at these instants (truncation!)

\[
\begin{align*}
i'_{\sigma,s,0H} &= \sum_{k=1}^{\infty} I'_{\sigma a}(k) \cos((2k-1)\omega_{sw}t_{s,0H}) + I'_{\sigma b}(k) \sin((2k-1)\omega_{sw}t_{s,0H}) \\
i'_{\sigma,s,H0} &= \sum_{k=1}^{\infty} I'_{\sigma a}(k) \cos((2k-1)\omega_{sw}t_{s,H0}) + I'_{\sigma b}(k) \sin((2k-1)\omega_{sw}t_{s,H0})
\end{align*}
\]

etc…

3. Check if sufficient current to charge parasitics within dead-time
Modeling accuracy

(a) Truncation of harmonics vs duty cycle and accuracy (fixed phase shift)

(b) Accuracy of first-harmonic approximation for all operating points
Model truncation

- First-harmonic approximation \((k_{max} = 1)\) for
  - Invertible power flow equations
  - Performance optimization

- Large number of harmonics \((k_{max} \gg 1)\) for
  - Accurate power flow estimations
  - Waveform analysis
  - Soft-switching analysis
  - Losses analysis
Modulation scheme

• Use first-harmonic approximation in Newton optimization
  - Cost function contains circulating current (i.e. conduction losses)
  - Lagrange operator to include power constraints (i.e. reference tracking)

• Results in duty-cycle at given phase shift with minimum circulating current

\[
\begin{align*}
\text{minimize} \quad & H = W + \lambda (\Gamma - 2\alpha^2) \\
\text{where} \quad & \Gamma = \left\| \Phi \times (1^T) - \left( \Phi \times (1^T)^T \right)^T \right\|_2 \\
\end{align*}
\]

\[
v' \cdot \chi = \frac{\sqrt{\|P'\|} \pi^2 \omega \sin \sigma}{\sqrt{8 \sin (\alpha)}}
\]
Modulation scheme

- Multiple strategies possible
- E.g. phase-shift that results in:
  - Minimum conduction losses, or
  - Lowest thermal stress, or
  - Combination of both

First-harmonic phasor diagram

Varying circulating current with fixed port output power
Modulation scheme

(a) Optimized modulation, minimum circulating current

(b) Phase-shift modulation, no optimization
Quad Active-Bridge and Neutral-Voltage Lift
Prototype

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum output power</td>
<td>20 kW</td>
</tr>
<tr>
<td>Power ports</td>
<td>4 (“QAB”)</td>
</tr>
<tr>
<td>Neutral-voltage lift</td>
<td>✔️</td>
</tr>
<tr>
<td>Semiconductor material</td>
<td>SiC</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>45 kHz</td>
</tr>
<tr>
<td>Cooling</td>
<td>Forced air</td>
</tr>
</tbody>
</table>
Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains voltage</td>
<td>230 V rms</td>
</tr>
<tr>
<td>Mains current</td>
<td>20,7 A rms</td>
</tr>
<tr>
<td>Mains power</td>
<td>14,2 kW</td>
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<tr>
<td>Power factor</td>
<td>0,997</td>
</tr>
<tr>
<td>THD of current</td>
<td>4,5 %</td>
</tr>
<tr>
<td>DC voltage</td>
<td>502 V</td>
</tr>
<tr>
<td>DC current</td>
<td>26,2 A</td>
</tr>
<tr>
<td>DC power</td>
<td>13,1 kW</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Mains power</td>
<td>5 kW → -5 kW</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Vertical:** U: 150V/div, I: 5A/div
- **Horizontal:** 20 ms/div

- **Vertical:** U: 300V/div, I: 5A/div
- **Horizontal:** 20 ms/div
Measurements

- Converter start-up behavior
### Measurements

<table>
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<tr>
<th>Parameter</th>
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</tr>
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<tbody>
<tr>
<td>Mains voltage</td>
<td>230 V rms</td>
</tr>
<tr>
<td>DC voltage</td>
<td>500 V</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Inverter</td>
</tr>
</tbody>
</table>

![Graph showing efficiency vs. input power]
Conclusion

• Framework for multi-port converters
  − Topology concept
  − Modeling
  − Modulation scheme
  − Neutral-voltage lift for ac-connections

• Experimental verification on 20 kW prototype in ac-dc application

• Multi-port converters are a competitive solution in a wide range of applications