Bidirectional Shared-Switch DC-DC Converter for Electric Vehicle Applications

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FREEDM Symposium
April 3, 2024
• Energy from the main battery pack is consumed by:
  – Traction drive system
  – Accessory loads via low voltage subsystem, such as lighting, climate control, radio, etc.

• DC-DC converter connects high and low voltage systems with galvanic isolation
  – Typical size:
    • 2-3 kW (passenger)
    • 5-10 kW + (heavy duty)
Research Motivation

- Increase efficiency - improves battery life, reduces cooling needs
- Increase density - less mass, easier packaging
- Reduce cost - improved value for manufacturer and consumer

*The proposed “Shared-Switch Converter” can achieve all 3*
  - One set of switches performs functions for two converter stages
  - Lower parts count means lower size, cost, and losses
• Benefits:
  – Reduced parts count – smaller, lighter, cheaper
  – Fewer switches to generate switching losses
  – More direct current path reduces conduction loss

• Challenges, gaps in prior art:
  – Gating generation to ensure proper operation of both converters under all conditions – unique to the specific topology
  – Modeling for shared-switch topologies, especially if converters operate in different modes (CCM vs. DCM, etc.)
  – Hardware design: component sizing, minimization of parasitic effects
Literature Review

• Numerous examples of integrated topologies in literature

• Boost + Series Resonant Converter:

  - Allows resonant stage to operate in efficient DCX mode across varying input voltage from photovoltaic array
  - Number of active switches reduced by 50% vs. two stage converter
  - Minimum 96.8% efficiency across voltage range vs. 90% for series resonant only

Literature Review

• Examples from literature show:
  – Improved efficiency across varying operating conditions
  – Successful reduction of active switch and filter element requirements
  – Lower cost and higher power density vs. traditional topologies

• Research objectives:
  – Increased power capability for heavy vehicle applications
  – Broader range of voltage conversion ratios to account for changing battery state of charge
  – Ability to maintain high efficiency at conversion ratio extremes
  – Straightforward method for modelling and controller development
  – Simplified control without coupling of controlled variables or nonlinear behavior
Proposed Topology

- **EV DC-DC converter requirements:**
  - Bidirectional power: LV battery bank can support HV bus under transients
  - Galvanically isolated
  - Wide voltage conversion ratio range $3:1 \left(\frac{HV_{\text{max}}}{LV_{\text{min}}} : \frac{HV_{\text{min}}}{LV_{\text{max}}}\right)$ due to changing battery state of charge

- **Series-connected DAB and Interleaved Buck**
  - DAB offers isolation, bidirectional power control
  - Interleaved buck adapts to changing voltage conversion ratio, allowing DAB to maintain ideal ratio for DCX operation\(^1\)

\[ (1) \quad V_{\text{Cint}} = \frac{1}{2} V_{HV} \frac{N_2}{N_1} \]
Proposed Topology

• DCX operation of DAB minimizes RMS winding currents, losses

  Primary Current for equal power throughput and input voltage:
  Sec. voltage matched \( V_{C_{int}} = V_{HV} \frac{N_2}{N_1} \)

  Sec. voltage mismatch \( V_{C_{int}} \neq V_{HV} \frac{N_2}{N_1} \)

• Applying integration concept reduces switch count 40%, reduces switching and conduction losses
Efficiency Comparison

DAB

DAB + Buck

Integrated DAB + Buck
Efficiency Comparison

Loss Breakdown for 600V - 28V, 3.75 kW Operation

- Integrated DAB + Buck (Proposed)
- Series DAB + Buck
- DAB
• Conventional DAB modulation: fixed 50% duty, variable phase
  – Single, Double, or Triple Phase Shift used to control power flow
  – HV bridge to LV bridge phase, phase between each full bridge leg
Modulator Challenges

- Fundamental differences for proposed topology vs. traditional DAB:
  - LV Duty ≠ 50% - variable according to buck converter requirements – not DAB
  - HV half bridge cannot enforce $V_{pri} = 0$ when $I_{pri} \neq 0$
- DAB and Buck interaction causes control difficulty
• Phase shift between LV legs provides magnetizing current reset once per period for any duty.
Decoupled Control

- DAB output is proportional to new control input “Vm”

\[
P_{DAB} = I_{DAB}V_{LV}
\]

\[
I_{DAB} = \frac{2 \times (A_1 + A_2)}{N_2}
\]

\[
A_1 = D_e T_s \frac{\phi T_s V_{HV}}{2L_{\text{leak}}}
\]

\[
A_2 = 0 \text{ for } V_{\text{Cint}} = \frac{1}{2} V_{HV} \frac{N_2}{N_1}
\]

Define: \[\varphi = f^{-1}(D_e) * Vm\]

Result: \[P_{DAB} \propto Vm\]
Decoupled Control

- DAB output current is fully decoupled from LV Duty
- DAB output current is directly proportional to control input Vm
Virtual Converter Model

- Integrated converter analysis can be difficult due to interaction between stages at the shared components.
- Virtual Converter Modeling (VCM) splits an integrated converter into separate “virtual converters” which can be analyzed by traditional methods.
Application of VCM

- Bidirectional Shared-Switch DC-DC Converter is modelled as separate DAB and Interleaved Buck
  - Additional constraint: LV bridge gates are driven in unison
Model Derivation

- Large signal model is combination of standard DAB and buck models
  - DAB model derived by integrating transformer current (1)
  - Different operating modes (DCM vs. CCM) not an issue

\[ I_{DAB} = \frac{2 \ast (A_1 + A_2) N_1}{T_s} \frac{N_2}{N_2} \quad (1) \]

Large signal model and corresponding state space equations

\[
\begin{bmatrix}
V_{C_{int}}
\
i_{out}
\end{bmatrix}
= \begin{bmatrix}
\frac{I_{DAB}}{C_{int}} & -\frac{dV_{out}}{C_{int}} \\
\frac{2dV_{C_{int}}}{L_{buck}} & -\frac{2V_{LV}}{L_{buck}}
\end{bmatrix}
\]

- Small signal model can be derived from large signal state space equations

\[
\begin{bmatrix}
V_{C_{int}}
\
i_{out}
\end{bmatrix}
= \begin{bmatrix}
\frac{\partial}{\partial V_{C_{int}}} & I_{DAB} & -\frac{d}{V_{C_{int}}}
\\
2d & \frac{V_{LV}}{L_{buck}} & 0
\end{bmatrix}
\begin{bmatrix}
V_{C_{int}}
\
i_{out}
\end{bmatrix}
+ \begin{bmatrix}
\frac{\partial}{\partial \phi} & I_{DAB} & \frac{dV_{out}}{C_{int}}
\\
0 & \frac{2V_{LV}}{L_{buck}} & 2d
\end{bmatrix}
\begin{bmatrix}
\phi
\
\bar{d}
\end{bmatrix}
\]
Hardware Design

- 600V to 28V DC-DC for military vehicles
- 4x parallel converters per module, 15kW total

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>3750 W</td>
</tr>
<tr>
<td>$V_{HV}$</td>
<td>565 – 635 V</td>
</tr>
<tr>
<td>$V_{LV}$</td>
<td>20 – 32 V</td>
</tr>
<tr>
<td>Switching Freq.</td>
<td>200 kHz</td>
</tr>
<tr>
<td>$N_1:N_2$</td>
<td>11:2</td>
</tr>
<tr>
<td>HV Switches</td>
<td>SiC, 1200 V, 31 A</td>
</tr>
<tr>
<td>LV Switches</td>
<td>GaN, 100 V, 101 A (2p top, 4p bottom)</td>
</tr>
</tbody>
</table>
Summary

• Shared-Switch converter topologies offer the benefits of a multi-stage converter with a reduced switch count
  • Lowered size, cost, and losses vs. independent stages
• A series connected DAB and Buck converter is well suited for heavy-duty electric vehicle applications
  • DAB provides isolation and bidirectional power control
  • Buck ensures DAB operates at maximum efficiency for all conditions
  • Proposed shared-switch configuration reduces switch count by 40%
• An innovative modulation method ensures linear power control and decoupling between stages
• Virtual Converter Modeling alleviates the difficulty of analyzing a shared-switch converter as a single circuit by superimposing simpler converter models
Thank you!