Power Flow Control in Multi-Active-Bridge Converters: Theories and Applications

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Multiport Power Conversion Applications

- Solar energy system
- Battery system
- Smart home
- Electric vehicle
Multiport Architecture

- **Dc coupled**
  - Decoupled control
  - Low efficiency

- **Ac coupled**
  - Higher efficiency & power density
  - Coupled control
Multi-Active-Bridge Converter

- Ac coupled: single magnetic core
- One “dc-ac-dc” stage between two arbitrary ports
- Control the power flow by changing the phase-shift

\[
P = \frac{1}{2\pi f_s} \frac{V_{in}V_o}{N_{in}N_o L} \Phi \left(1 - \frac{|\Phi|}{\pi}\right)
\]

- MAB converter
- Full-bridge output voltage and current
Power Flow Control and Voltage Regulation

- Power flow control:
  - Energy price
  - Power fluctuation

- Voltage regulation:
  - Different load
Power Flow Control and Voltage Regulation of the MAB Converter

- Phase-shift

- Time-sharing

- Hybrid

• How do we control the power flow of multiple ports?
• How do we regulate the voltage of multiple ports?
• How do we achieve high efficiency across wide operation range?
Principles of Phase-Shift Control

• Large signal model for power flow

\[
P_i = \frac{1}{2\pi f_s} \sum_{j \neq i} \frac{V_i V_j}{N_i N_j L_{ij}} (\Phi_i - \Phi_j) \left(1 - \frac{|\Phi_i - \Phi_j|}{\pi}\right)
\]

\[
V_i = \frac{R_i}{2\pi f_s} \sum_{j \neq i} \frac{V_j}{N_i N_j L_{ij}} (\Phi_i - \Phi_j) \left(1 - \frac{|\Phi_i - \Phi_j|}{\pi}\right)
\]

• Small signal model for stability

\[
\hat{v}_i = \left(K_{\Phi i} \hat{\Phi}_i + \sum_{j \neq i} (K_{\Phi ij} \hat{\Phi}_j)\right) Z_i
\]

Port voltage control loop
**Principles of Time-Sharing Control**

- Low efficiency with **PS** control in light load
- Fixed phase-shift $\Phi_i$
- $T_m \gg T_s$

- Audible noise
- Higher voltage ripple

Decoupled PI control of $D$

$$D_2 + D_3 + D_4 \leq 1$$
Hybrid Phase-Shift & Time-sharing Control

- Low transformer utilization, higher voltage ripple with TS control
- $D_2 + D_3 + D_4 \neq 1$

- Two control parameters:
  - Duty ratio $D$
  - Phase-shift $\Phi$

- No audible noise
- Lower voltage ripple than TS
Simplified Hybrid Control

- $D_2 + D_3 + D_4 = 1$
- Fixed $D$ + changing $\Phi$ or Fixed $\Phi$ + changing $D$

- No audible noise
- Lower voltage ripple than TS

Decoupled PI control of $D$ and $\Phi$
# Summary of Control Methods

<table>
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<tr>
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<th>Phase-shift</th>
<th>Time-sharing</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Loops</strong></td>
<td>coupled</td>
<td>uncoupled</td>
<td>partially coupled</td>
</tr>
<tr>
<td><strong>Power Capability</strong></td>
<td>high</td>
<td>lowest</td>
<td>medium</td>
</tr>
<tr>
<td><strong>Light Load Efficiency</strong></td>
<td>low</td>
<td>high</td>
<td>??</td>
</tr>
<tr>
<td><strong>Voltage Ripple</strong></td>
<td>low</td>
<td>high</td>
<td>medium</td>
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Prototype Specifications

- DC power delivery architecture for smart home

- 400V: PV, PFC to grid
- 48V: battery, high power appliances
- 15V & 5V: consumer electronics
Hardware

- PCB layout
- Cross section view of transformer
  - Ferroxcube E38/8/25, 3F36
  - $N_1 = 80$, $N_2 = 10$, $N_3 = 3$, $N_4 = 1$
  - All GaN switches: 650 V/30 A & 100 V/90 A
Simulation Results

- Phase-shift

- Time-sharing

- Hybrid

\[ \Phi_1, \Phi_3 \]
\[ \Phi_2, \Phi_4 \]
\[ D_1, D_3 \]
\[ D_2, D_4 \]
\[ \Phi_i \ and \ D_i \]
Phase-Shift Control

400V input

48V/300W

15V/70W

5V/35W

400V input

48V/300W

15V/70W

5V/35W

DC
AC

DC
AC

DC
AC

DC
AC

\[ \Phi_1 = 0 \]

\[ \Phi_2 \]

\[ \Phi_3 \]

\[ \Phi_4 \]

\[ V_{#1} \]

\[ I_{L1} \]

\[ I_{L2} \]

\[ I_{L3} \]

\[ I_{L4} \]

10\mu s

2\mu s

500V/div

2A/div

10A/div

20A/div

500V/35W

48V/300W

400V input
Experiment Results

- **Time-sharing**

  - DC/AC
  - 400V in
  - 48V/60W
  - 5V/10W

  - DC/AC
  - 15V/10W

  - DC/AC
  - AC/DC
  - 15V/10W

- **Simplified hybrid**

  - DC/AC
  - 400V in
  - 48V/60W
  - 5V/10W

  - DC/AC
  - 15V/10W

  - DC/AC
  - AC/DC
  - 15V/10W

  - DC/AC
  - AC/DC
  - 48V/60W

  - DC/AC
  - 5V/10W

  - DC/AC
  - 48V/60W

  - DC/AC
  - 5V/10W

  - DC/AC
  - 48V/60W

  - DC/AC
  - 5V/10W
Single-Input Single-Output Efficiency

![Diagram showing AC/DC conversions and efficiency graph]

- **Efficiency**
- **400V-48V**
  - Phase-shift
  - Burst
MAB Efficiency

- **Phase-shift**
  - 400V: DC/AC
  - 48V: DC/AC

- **Time-sharing**
  - 400V: DC/AC
  - 48V: DC/AC

Total Output Power (W)

- DC
- AC

Efficiency

- 100%
- 95%
- 90%
- 85%
- 80%
- 75%
- 70%

- 400V: 15V/10W
- 48V: 5V/10W

- 15% increase in efficiency between Phase-shift and Time-sharing.
Power Flow Control: 2 Input 2 Output

Input 1 (PV) 400V/100W 400V/20W
Input 2 (battery) 48V/20W 48V/100W

DC AC DC AC
DC AC DC AC
AC DC AC DC

15V/75W 5V/45W

Input 2
Input 1

1s
Conclusion

• Design and validate three control methods

• Optimize efficiency:
  – Time-sharing with low power
  – Phase-shift with high power

• Future work:
  – Optimize hybrid control

Thank you!
PI Control of Phase-Shift

- Single port voltage control loop

\[
\frac{v_i(s)}{v_{\text{ref}}(s)} = \frac{G_{PL_i}(s)K_{\phi_i}(s)Z_i(s)}{1 + H_i(s)G_{PL_i}(s)K_{\phi_i}(s)Z_i(s)}
\]

\[
\frac{v_i(s)}{\phi_j(s)} = \frac{K_{\phi ji}(s)Z_i(s)}{1 + H_i(s)G_{PL_i}(s)K_{\phi i}(s)Z_i(s)}
\]

\[
G_{PSi}(s) = H_i(s)K_{\phi i}(s)Z_i(s)
\]

Same loop gain function

- Increase system stability and immunity to disturbance of \( \phi_j \)
- Slower dynamic response
Prototype Design

- Maximum flux density
  \[ B_{\text{max}} = \frac{V_1 T_s}{4 N_1 A_e} \]
- Power rating
  \[ P_{\text{imax}} \approx \frac{V_a^2}{8 f_s} \sum_{j \neq i} \frac{1}{L_{ij}} \]
- Voltage ripple
  \[ \Delta v_i \leq \frac{P_{\text{imax}} T_m}{4 C_i V_i} \]

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<th>Parameters</th>
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<tr>
<td>Switching Frequency: ( f_s )</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Port #1 Switches</td>
<td>GS66508T 650 V/30 A/50 m( \Omega )</td>
</tr>
<tr>
<td>Port #2–#4 Switches</td>
<td>GS61008P 100 V/90 A/7 m( \Omega )</td>
</tr>
<tr>
<td>Transformer</td>
<td>Ferroxcube E38/8/25, 3F36 80:10:3:1, 4 \times 4-layer PCB</td>
</tr>
<tr>
<td>Leakage Inductance: ( L_{ik1} - L_{ik4} )</td>
<td>18.2 ( \mu )H, 0.81 ( \mu )H, 84.1 nH, 26.4 nH</td>
</tr>
<tr>
<td>External Inductors: ( L_{ext1} - L_{ext4} )</td>
<td>0, 4.2 ( \mu )H, 200 nH, 100 nH</td>
</tr>
<tr>
<td>Bus Capacitors: ( C_1 - C_4 )</td>
<td>120 ( \mu )F, 2 mF, 20 mF, 40 mF</td>
</tr>
<tr>
<td>DC Blocking Capacitors: ( C_{b1} - C_{b4} )</td>
<td>10 ( \mu )F, 20 ( \mu )F, 134 ( \mu )F, 154 ( \mu )F</td>
</tr>
</tbody>
</table>
MAB Efficiency: PS Control

Efficiency vs. Total Output Power (W)

- DC 15V/10W
- AC 5V/35W
- AC 48V
- DC 400V

- DC 15V/70W
- AC 5V/35W
- AC 48V
- DC 400V

Efficiency Graph:
0% 70% 75% 80% 85% 90% 95% 100%

Total Output Power (W):
0 50 100 150 200 250 300 350 400 450