State Plane Solution

Primary

\[ I_{\text{base}} = V_g \sqrt{\frac{C_p}{L_i}} \]

Secondary

\[ I_{\text{base}} = V_g \sqrt{\frac{C_s}{n_i^2 L_i}} \]
Averaging Step
\[ J = \frac{n(i_{out})}{I_{base}} = \frac{F}{\pi} \left[ 2 + \frac{1}{4} (J_1^2 - J_2^2) + J_p \left( \frac{\pi}{F} - \alpha - \theta_2 - \delta \right) \right] \]
Example Waveforms

- Waveform 1: Voltage $V_p$ over time $t$.
- Waveform 2: Current $i$ over time $t$.

DCX Output Plane

- ZVS boundary
- $F = 0.1$ to $F = 1$
Example Waveforms
Example Waveforms

Waveforms:

- $i_{out}$ [A]
- $v_{p}$ [V]

Time [μs]:

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Graph showing $i_{out}$ and $v_{p}$ over time.

DCX Output Plane:

- Various curves indicating different F values.
- ZVS boundary highlighted.

Graph showing the DCX Output Plane with different curves and the ZVS boundary.
Example Waveforms

- **Waveform 1:**
  - Axis: $i_1$ [A]
  - Time: 0 to 1 [μs]
  - Values: $-4$ to 4 A

- **Waveform 2:**
  - Axis: $n*I_{out}$
  - Time: 0 to 1 [μs]
  - Values: $-200$ to 200

- **Graph 1:**
  - DCX Output Plane
  - Axes: $J_{pk}$ vs. $J$
  - ZVS Boundary
  - Values: $F = 0.1$ to $F = 1$

- **Graph 2:**
  - Axes: $J_{pk}$ vs. $J$
  - ZVS Boundary
  - Values: $F = 0.1$ to $F = 1$
Example Waveforms
Output Current Vs. Inductance

\[ L_l = 5 \mu\text{H} \]
\[ L_l = 15 \mu\text{H} \]
\[ L_l = 25 \mu\text{H} \]
Output Current Vs. Inductance

Normalized Output Current

- $L_l = 5\mu H$
- $L_l = 15\mu H$
- $L_l = 25\mu H$

Time $t \text{ [\mu s]}$

Tank Inductance $L_l \text{ [\mu H]}$

Normalized Current

- $I_{o,rms}$
- $I_{o,avg}$
- $I_{o,pk}$
Constraints on Inductance

Tank Inductance \( L_t \) [\( \mu \text{H} \)]

Normalized Current

- \( I_{o,\text{avg}} \)
- \( I_{o,\text{rms}} \)
- \( I_{o,pk} \)
- \( I_{o,ZVSmin} \)

Non-ZVS
DAB: Experimental Results

Operation with $V \neq nV_g$

- **E.g.** Decrease to $M_N < 1$
  
  by decreasing output voltage

- **Current now ramping,** causing more energy available for primary ZVS, but higher RMS currents

- Can use behavior to extend ZVS range of one bridge
Soft Switching Range with Varying $V_{out}$

Application Example: Automotive

Fig. 1. Converter operating voltage ranges required for automotive application.

Fig. 3. Automotive DAB converter (273 × 90 × 53 mm).

Alternate Modulation Schemes

Florian Krismer; Johann W. Kolar, “Closed Form Solution for Minimum Conduction Loss Modulation of DAB Converters”
DAB: Transformer Saturation
Series Resonant Converter