DAB: Experimental Results


Operation with $\frac{V}{V_g} \neq n$ and $\frac{V}{V_g} \neq 1$

- E.g. Decrease $M_n < 1$ 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 $V_{out}$

Design Trajectory Example: Operation
Design Trajectory Example: Operation

Example:

- $j_t$
- $m_p$
- $P_{int}$
- $M_S$
- $t$

$\theta_p$

$\dot{\theta}_p$

$\ddot{\theta}_p$

$\theta_p$

$t$

$t$
Application Example: Automotive

Alternate Modulation Schemes

*F. Krismer, J.W. Kolar, “Closed Form Solution for Minimum Conduction Loss Modulation of DAB Converters”*
Efficiency Results

Fig. 12. (Solid lines) Predicted efficiencies and (□) measured efficiencies for different operating conditions. The efficiencies are calculated with the improved DAB loss model which includes all methods discussed in Section IV.

Transformer Saturation

\[ \lambda_1 \neq \lambda_2 \]
\[ \langle \lambda_2 \rangle \geq L_T \neq 0 \]
\[ \langle \lambda_{im} \rangle = \emptyset \]
Next: SRC

Series Resonant Converter

\[
\frac{1}{\sqrt{L_c c_r}} \geq f_s
\]

Magnetics Losses
Magneics Winding Loss (DC)

- DC Resistance given by
  \[ R_{DC} = \rho \frac{l_b}{A_w} \]
- At room temp, \( \rho = 1.724 \times 10^{-6} \, \Omega \text{-cm} \)
- At 100°C, \( \rho = 2.3 \times 10^{-6} \, \Omega \text{-cm} \)
- Losses due to DC current:
  \[ P_{cu,DC} = I_{L, rms}^2 R_{DC} \]

Skin Effect in Copper Wire

- Current profile at high frequency is exponential function of distance from center with characteristic length \( \delta \)
Skin Depth

\[ \delta = \sqrt{\frac{\rho}{\pi \mu f}} \]

Fig. 13.23 Penetration depth \( \delta \) as a function of frequency \( f \), for copper wire.

Skin Depth Calculations
Example Calculation

10/2/2016

1 A DC, 1 A ph square curve current
1 m long
1 MHz = f_s

• In foil conductor closely spaced with $h \gg \delta$, flux between layers generates additional current according to Lentz’s law.

\[ P_1 = I_{L,rms}^2 R_{ac} \]

• Power loss in layer 2:

\[ P_2 = I_{L,rms}^2 R_{ac} + (2I_{L,rms})^2 R_{ac} \]

\[ P_2 = 5P_1 \]

Proximity Effect

See Fundamentals of Power Electronics, Section 13.
Simulation Example

- AWG#30 copper wire
  - Diameter \( d = 0.294 \) mm
  - \( d = \delta \) at around 50 kHz
- 1:1 transformer
  - Primary and secondary are the same, 30 turns in 3 layers
- Sinusoidal currents,
  \[ I_{1\text{rms}} = I_{2\text{rms}} = 1 \text{ A} \]

Numerical field and current density solutions using FEMM (Finite Element Method Magnetics), a free 2D solver, http://www.femm.info/wiki/HomePage

Flux density magnitude

Current density magnitude
Frequency: 1 kHz

Flux density

Current Density

Frequency: 100 kHz

Flux density

Current Density

Total copper losses 1.8 larger than at 1 kHz
Frequency: 1 MHz

Flux density

Current Density

Total copper losses 20 times larger than at 1 kHz

Frequency: 10 MHz

Flux density

Current Density

Very significant proximity effect
Total copper losses = 65 times larger than at 1 kHz
Fringing

• Near air gap, flux may bow out significantly, causing additional eddy current losses in nearby conductors

Finite Element Simulation

\[ P_{\text{cond}} = 330 \text{ W} \]

\[ |J| \text{ [A/mm}^2\text{]} \]

http://www.femm.info/wiki/HomePage
Removing Copper From Fringing Field

\[ P_{\text{cond}} = 180 \text{ W} \]

\[ |J| \text{ [A/mm}^2\text{]} \]