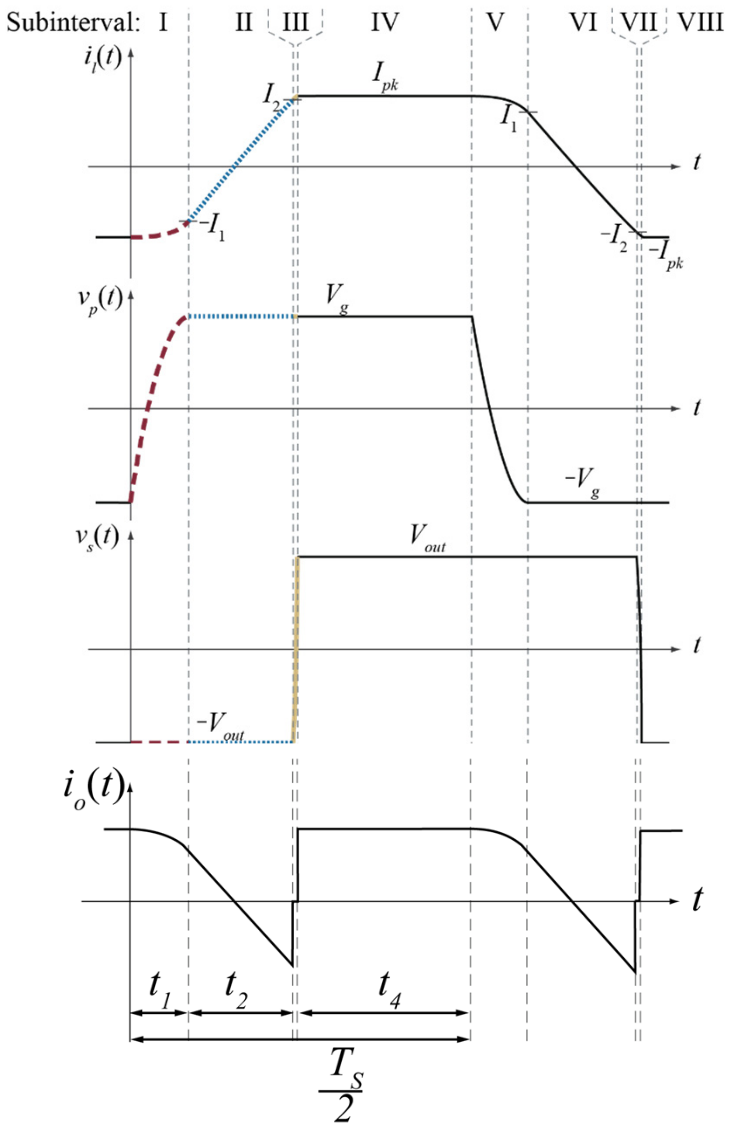
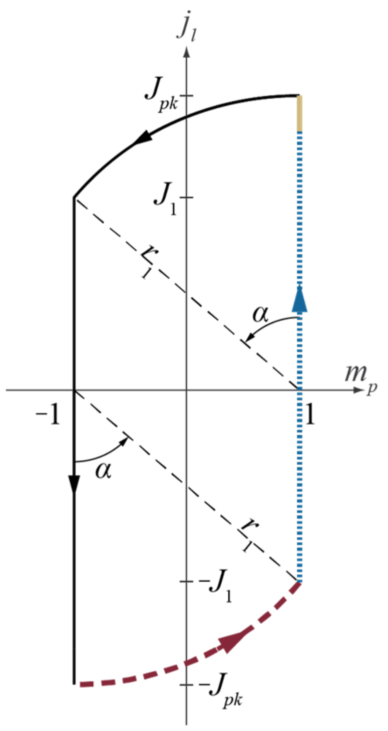
State Plane Analysis of DAB Converter

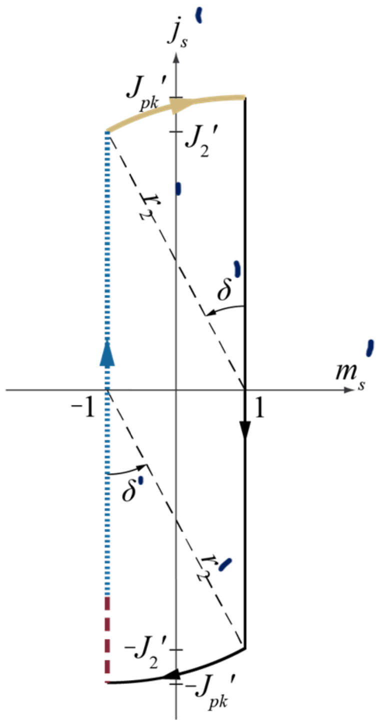


Primary



$$I_{base} = V_g\sqrt{\frac{C_p}{L_l}}$$

Secondary



$$I'_{base} = V_g\sqrt{\frac{C_s}{n_t^2 L_l}}$$

State Plane Solution

$V_{base} = V_g$

I $\quad r_1^2 = \boxed{J_{pk}^2 = J_1^2 + 4}$

$$\alpha = \tan^{-1}\left(\frac{2}{J_1}\right)$$

II $\quad \frac{V_g + \frac{V}{n}}{L_\ell} t_2 = I_2 + I_1 \qquad$ Here $M = n$, $\frac{V}{n} = V_g$

$$2\frac{R_o}{L_\ell} t_2 = \boxed{J_2 + J_1 = 2\theta_2}$$

III $\quad r_2'^2 = \boxed{(J_{pk}')^2 = (J_2')^2 + 4}$

$$\delta' = \tan^{-1}\left(\frac{2}{J_2'}\right) \longrightarrow \frac{\delta'}{\omega_0'} = t_\delta = \frac{\delta}{\omega_0}$$

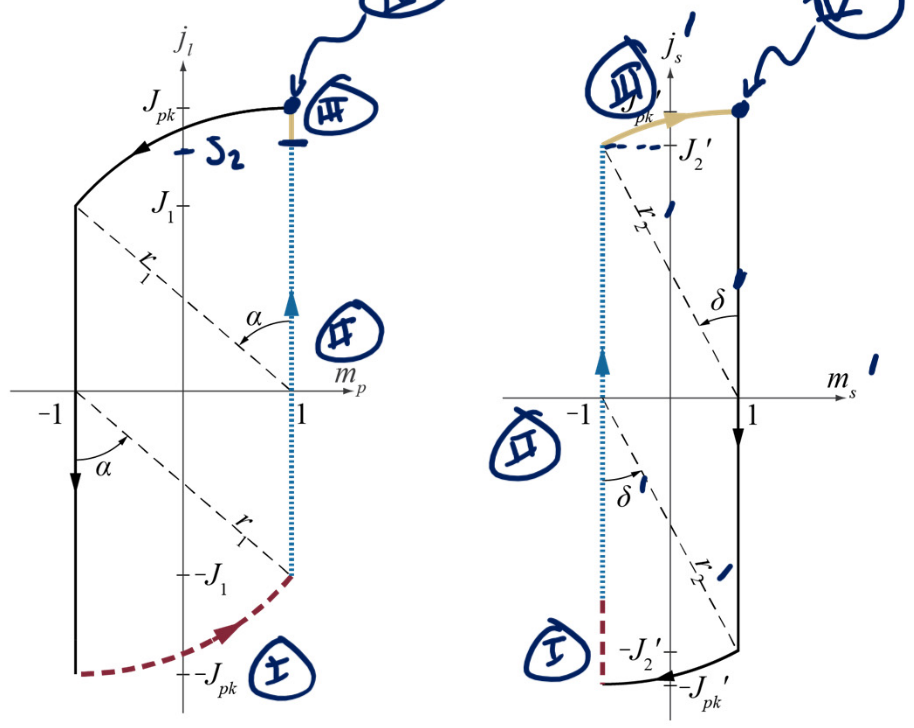
$$\delta = \frac{\omega_0}{\omega_0'}\delta'$$

IV $\rightarrow$ Nothing from waveforms

$$\frac{T_s}{2} = t_\alpha + t_2 + t_\delta + t_4$$

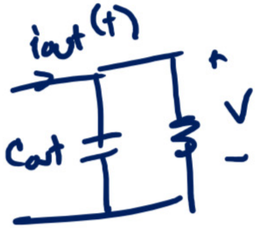
$$\frac{\pi}{F} = \alpha + \theta_2 + \delta + \theta_4$$

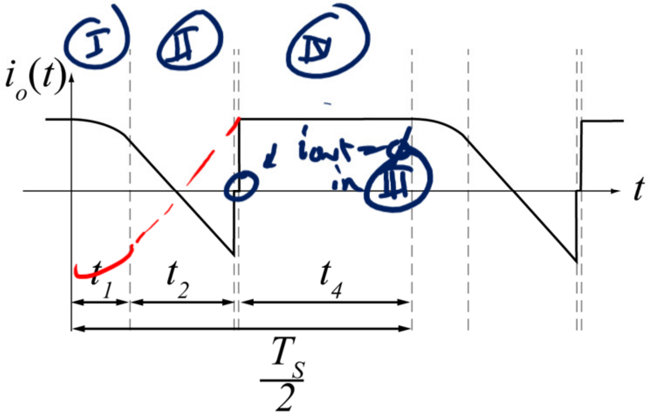
Primary $\qquad$ Secondary

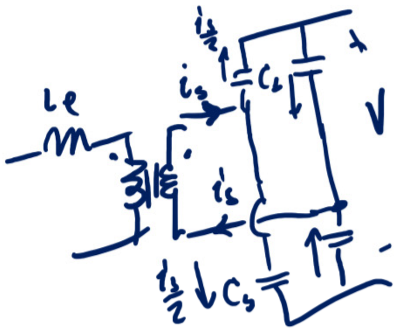


$$I_{base} = V_g\sqrt{\frac{C_p}{L_l}} \qquad I_{base}' = V_g\sqrt{\frac{C_s}{n_t^2 L_l}}$$

Averaging Step (fix)







Small Ripple Approx on C_{out}

$$\frac{V}{R} = I_{out} = \frac{1}{T_s}\int_0^{T_s} i_{out}(t)\,dt$$

$$n\langle i_{out}\rangle = \frac{2}{T_s}\int_0^{T_s/2} n\, i_{out}(t)\,dt \quad , \quad n\, i_{out}(t) = \begin{cases} -i_L(t), & \text{I, II} \\ +i_L(t), & \text{IV} \\ \phi, & \text{III} \end{cases}$$

$$= \frac{2}{T_s}\left[q_1 + q_2 + \overset{\phi}{\cancel{q_3}} + q_4 \right]$$

$$q_1 = C_p(2V_g)$$

$$q_2 = \frac{I_2 - I_1}{2} t_2$$

$$q_4 = I_{ph} t_4$$

$$n\langle i_{out}\rangle = \frac{2}{T_s}\left[2V_g C_p + \frac{I_2 - I_1}{2} t_2 + I_{ph} t_4 \right]$$

$$J = n J_{out} = \frac{2}{T_s}\left[2C_p R_0 + \frac{J_2 - J_1}{2} t_2 + J_{ph} t_4 \right] \left(\frac{\omega_0}{\omega_0}\right)$$

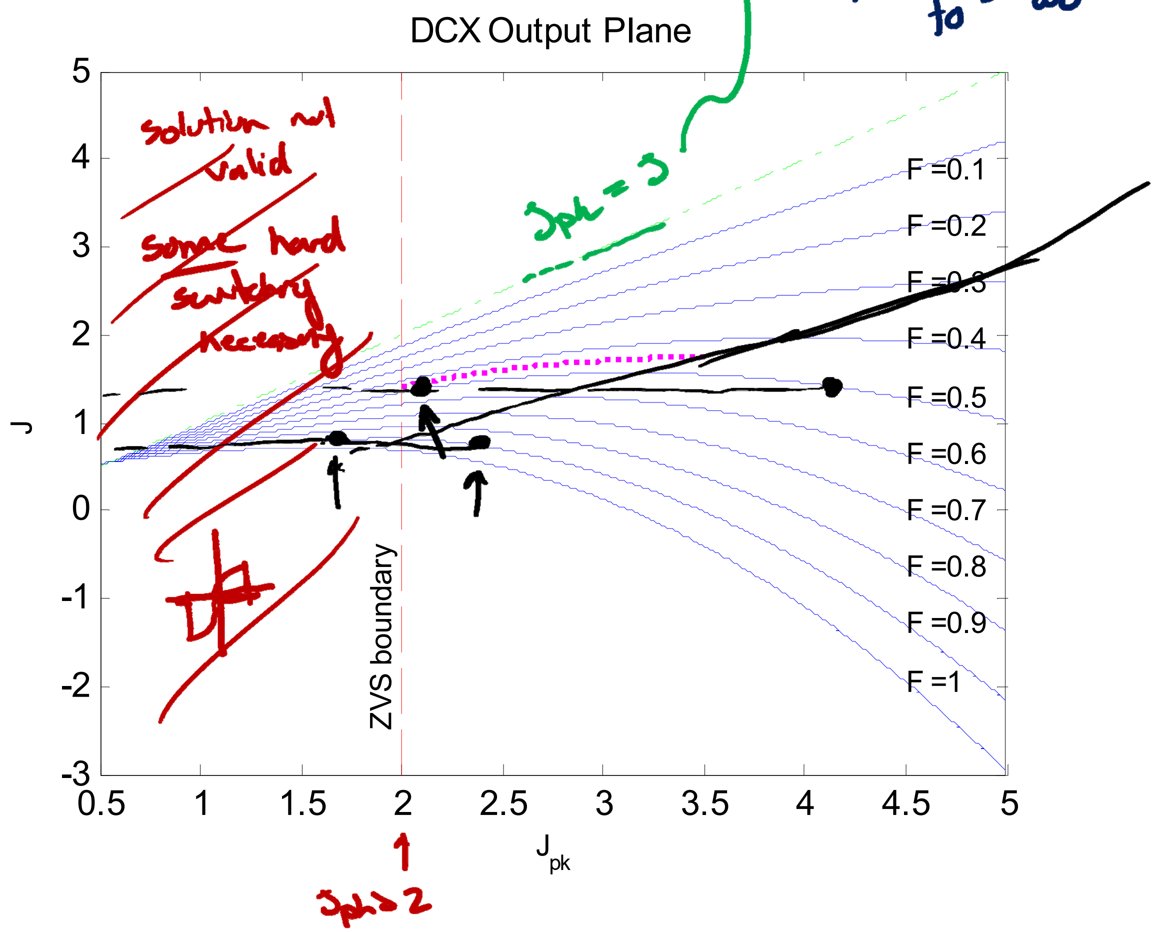
$$\boxed{J = n J_{out} = \frac{F}{\pi}\left[2 + -(J_2 - J_1)\frac{\theta_2}{2} + J_{ph}\theta_4 \right]}$$

Output Plane

$$J = \frac{n\langle i_{out}\rangle}{I_{base}} = \frac{F}{\pi}\left[2 + \frac{1}{4}\left(J_1^{\,2} - J_2^{\,2}\right) + J_p\left(\frac{\pi}{F} - \alpha - \overset{\theta_2}{\cancel{\beta}} - \delta\right)\right]$$

~ min conduction loss operation

$F = \frac{f_s}{f_0} = \frac{\omega_s}{\omega_0}$

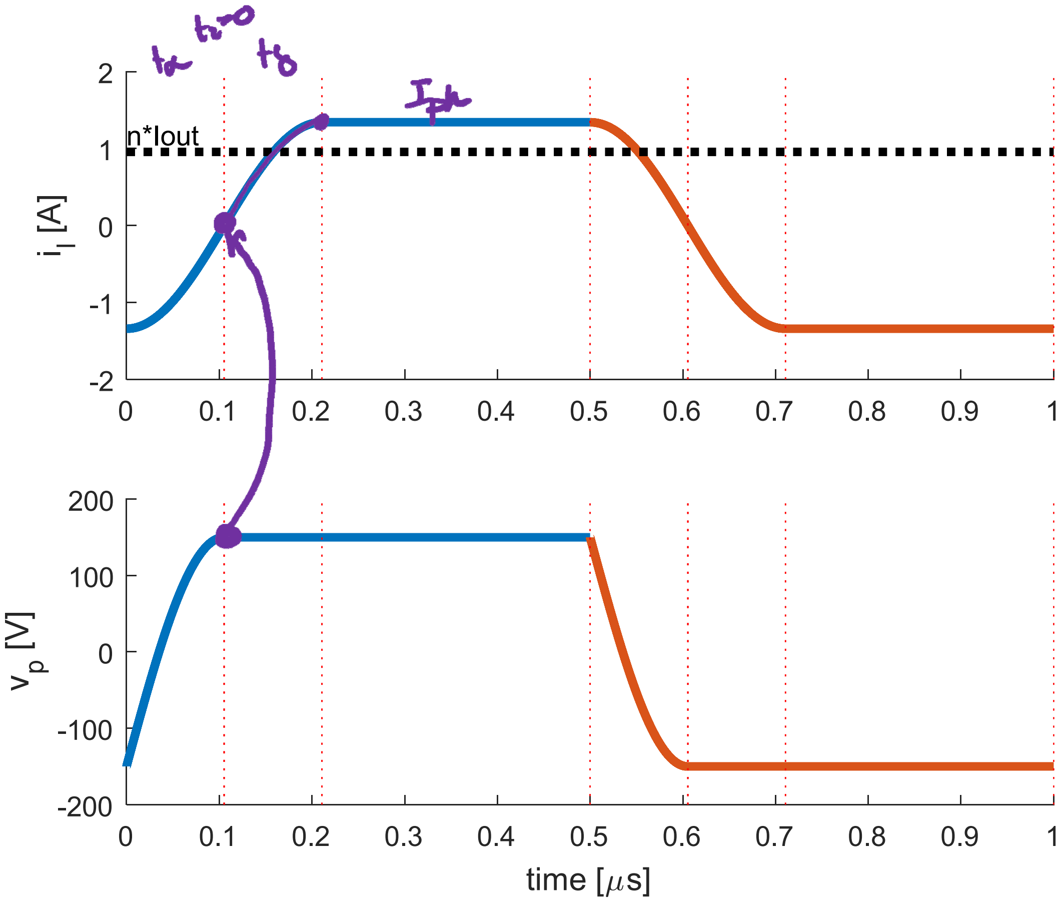


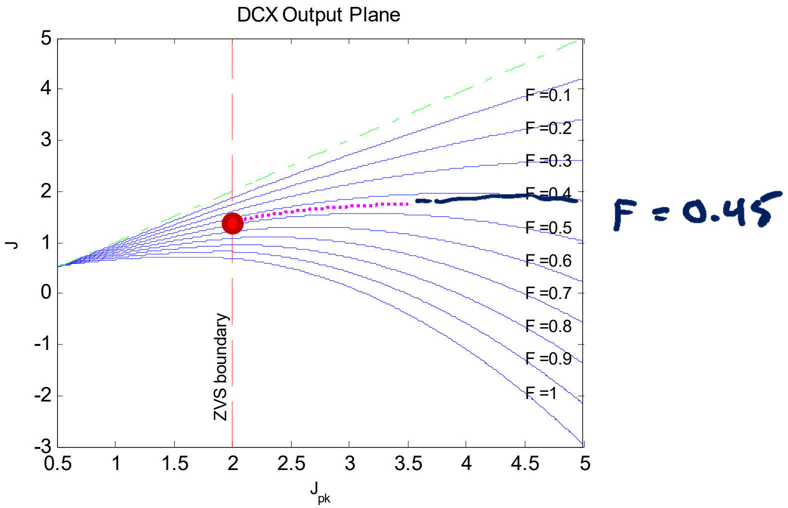
usually operate with $(t_d + t_2 + t_\delta) \lesssim \frac{T_s}{4}$

Example Waveforms

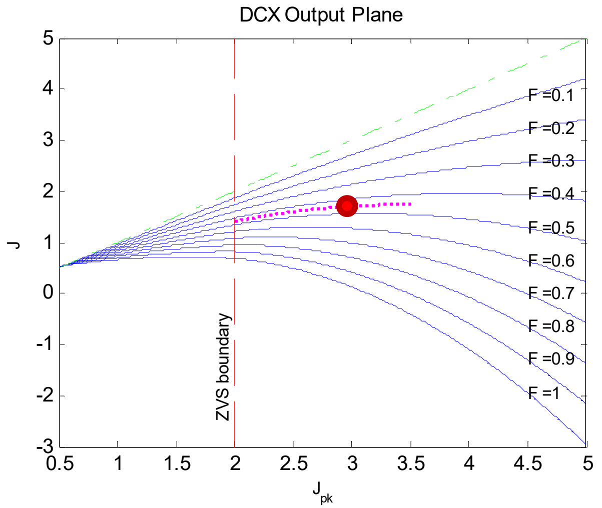
$f_0 = 1MHz$ $V_g = 150V$ $V = 12V$

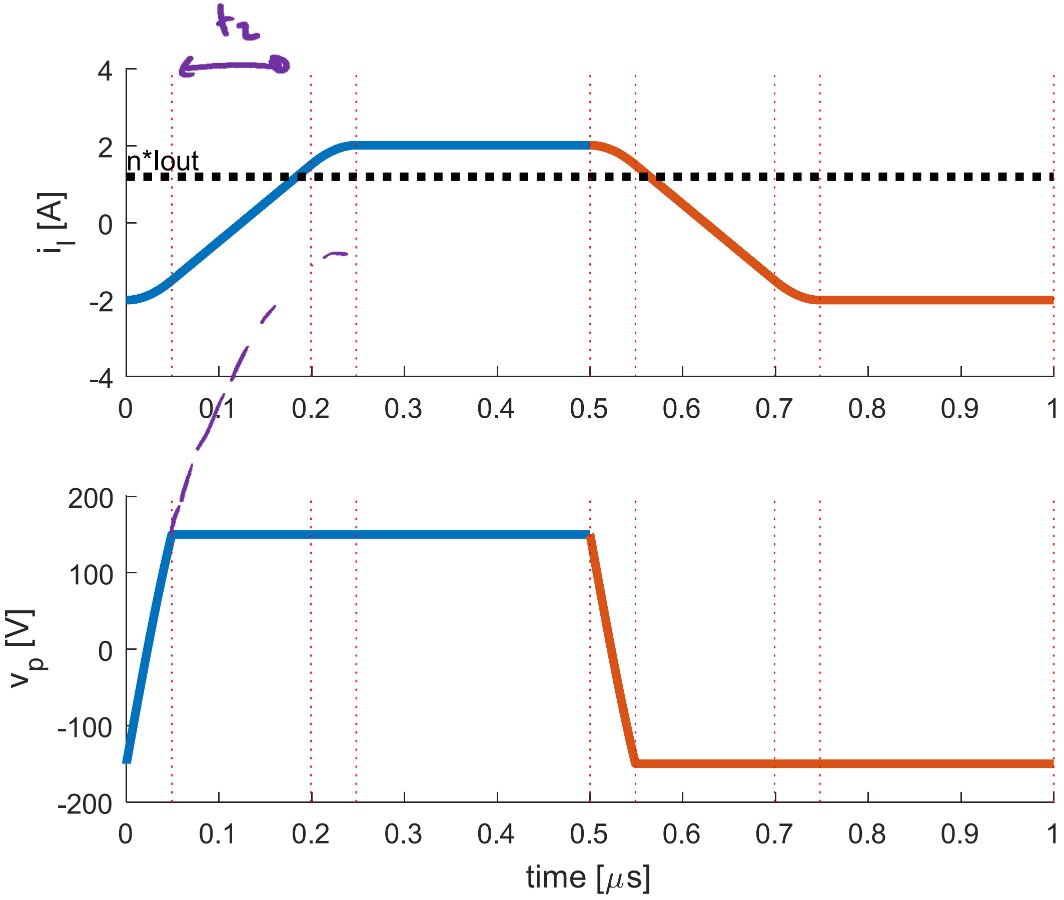
$L_r = 15\mu H$ $C_p = 300pF$ $C_s = \frac{C_p}{n^2}$



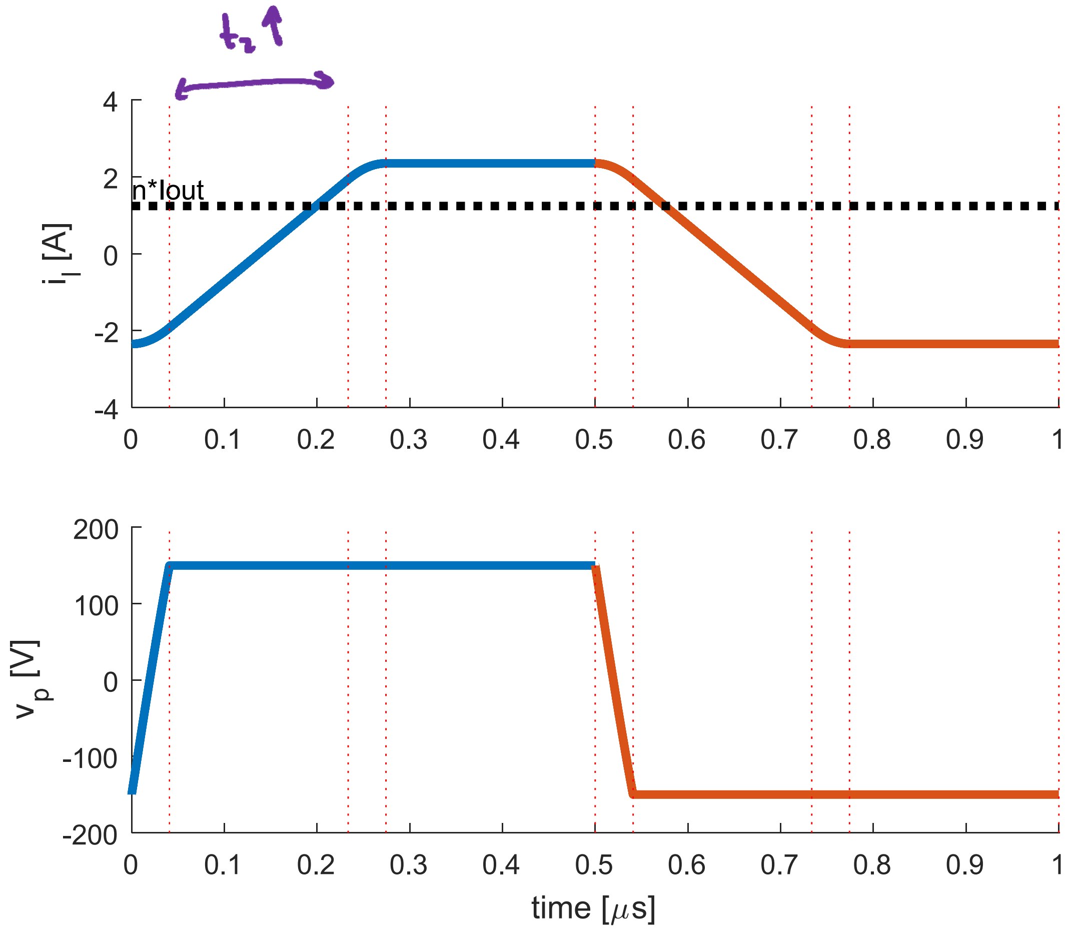


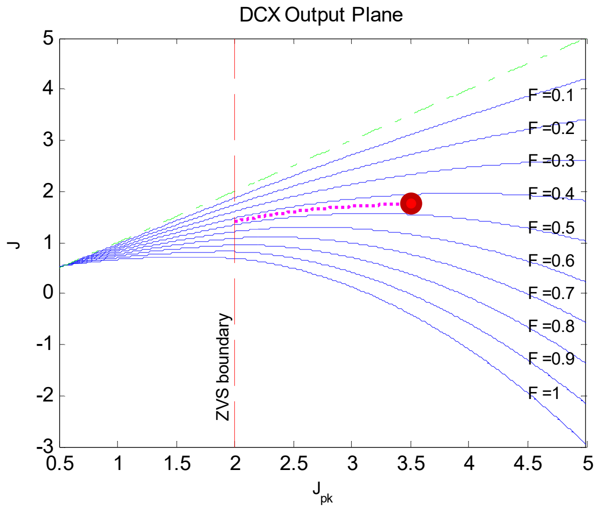
Example Waveforms



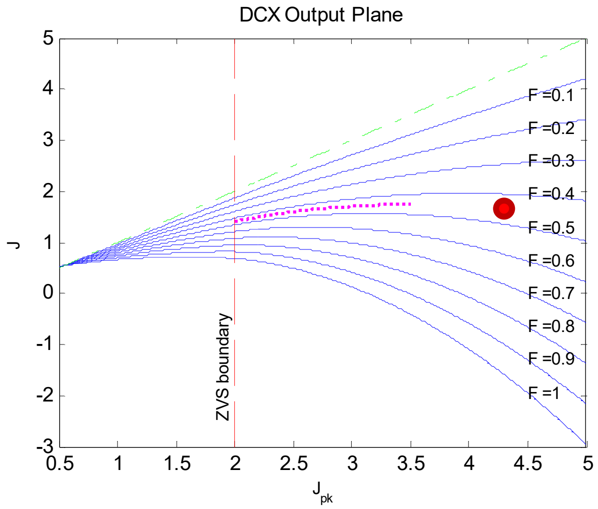


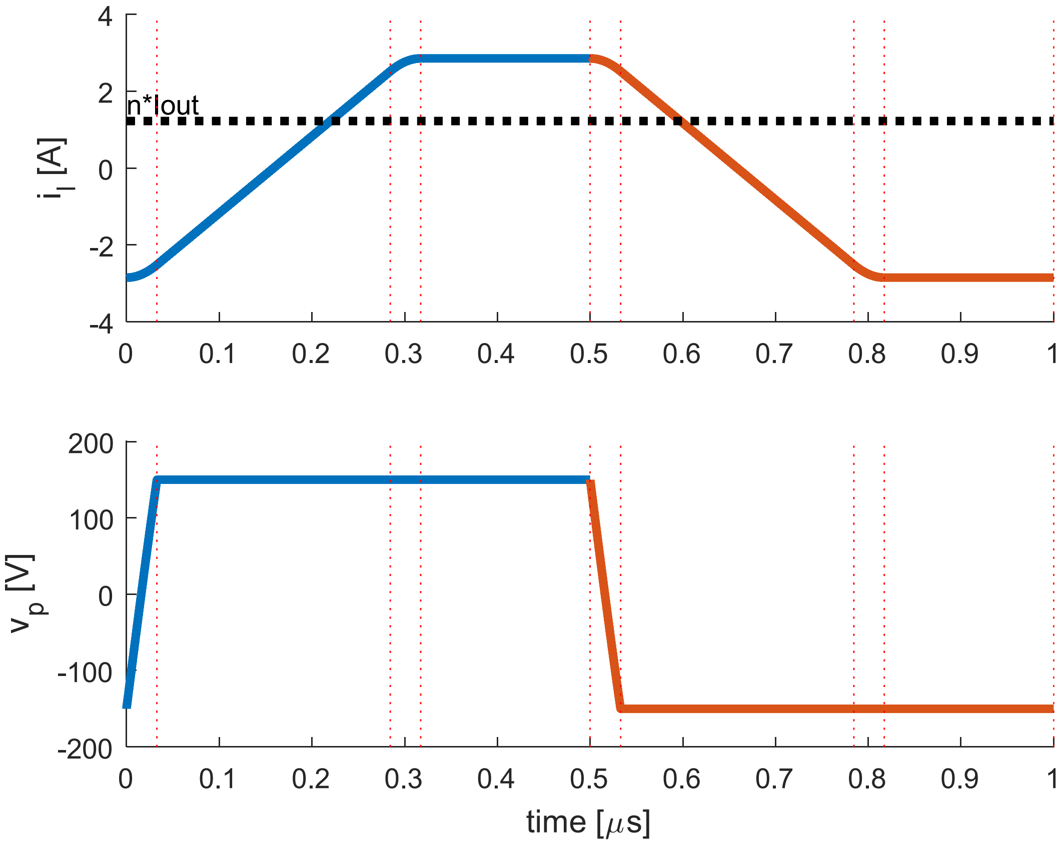
Example Waveforms



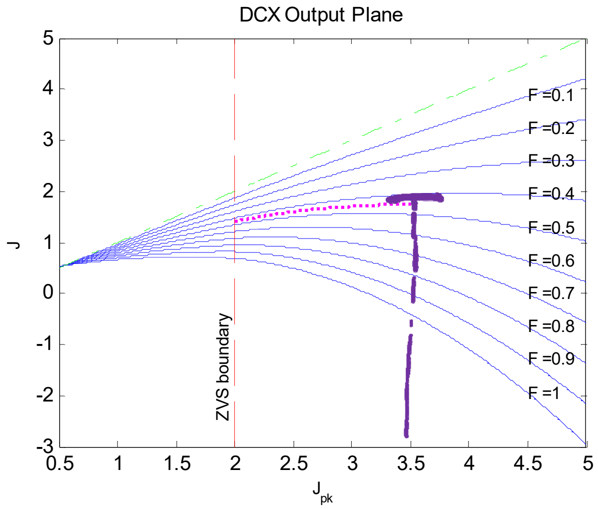


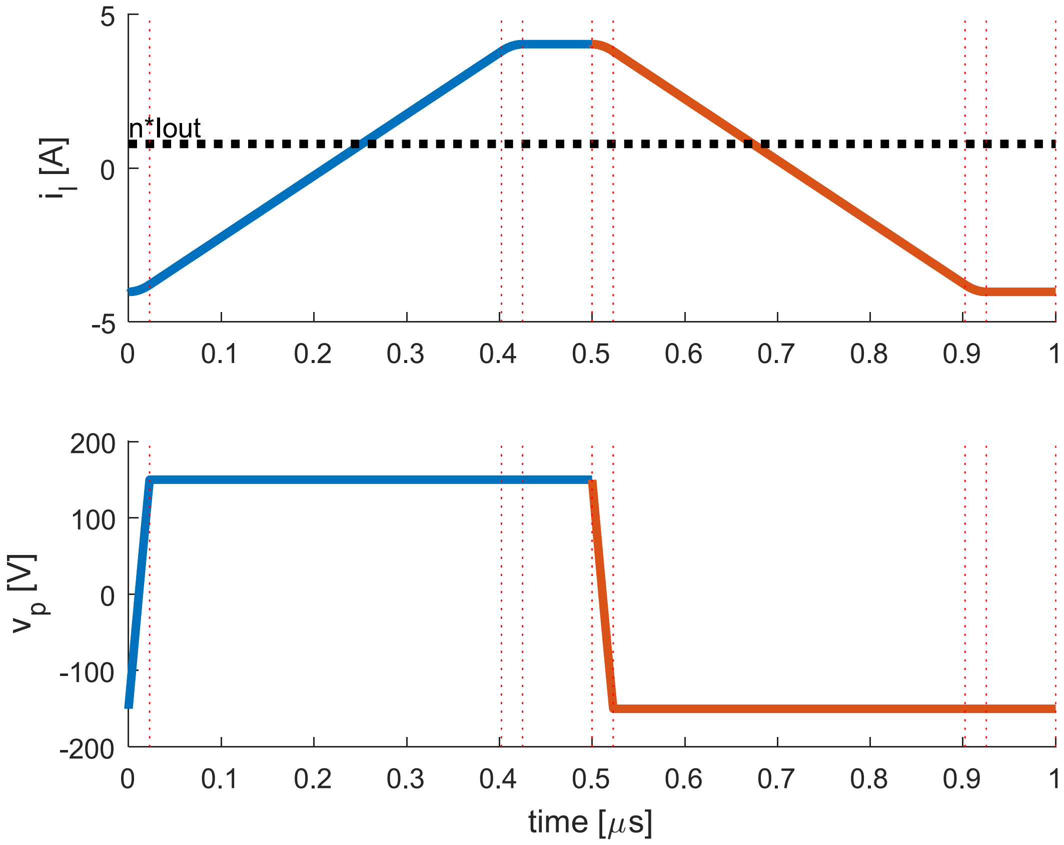
Example Waveforms



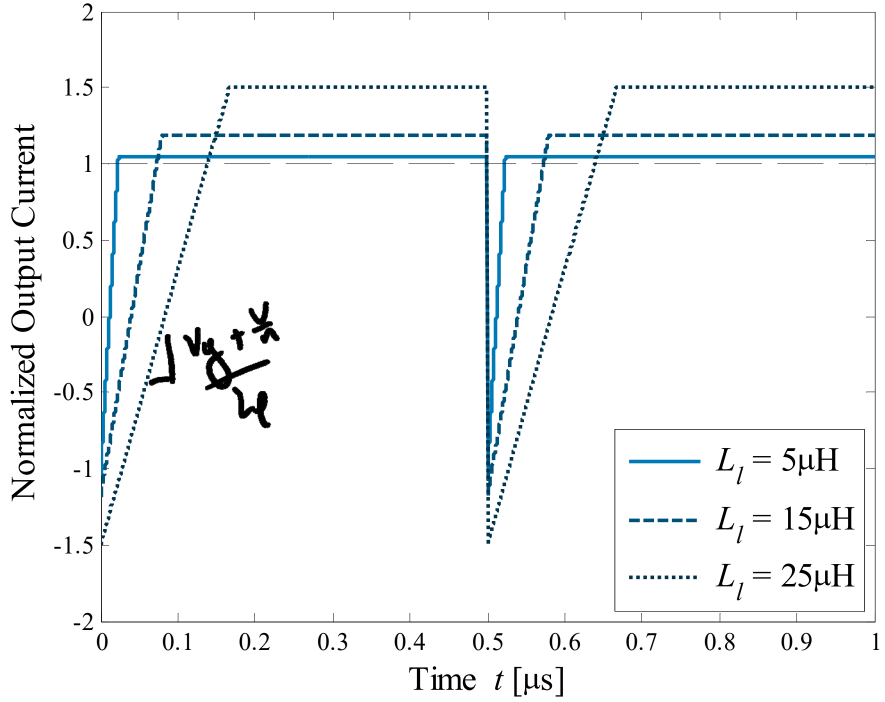


Example Waveforms





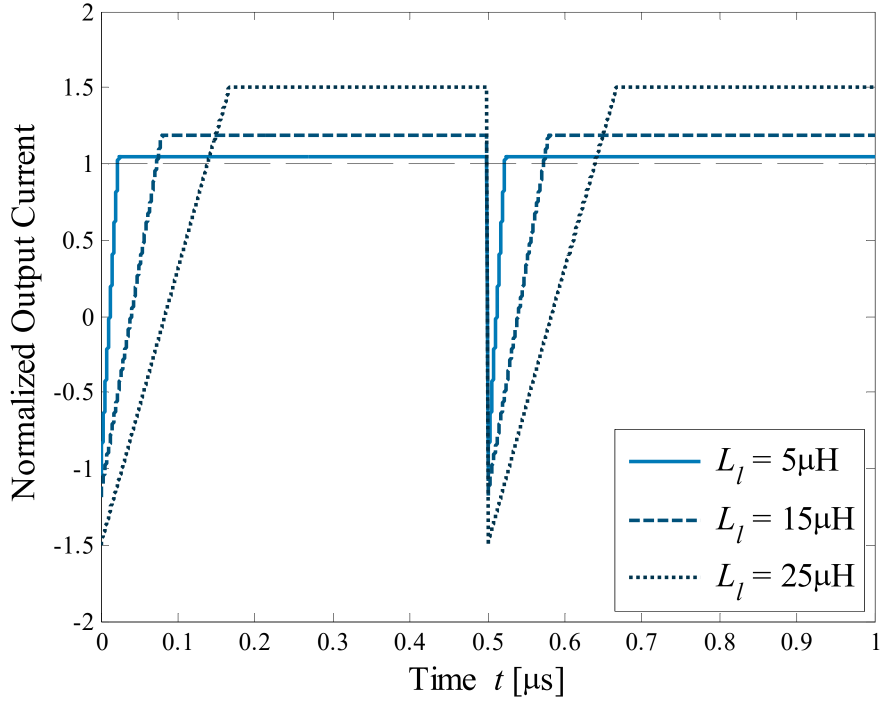
Output Current Vs. Inductance

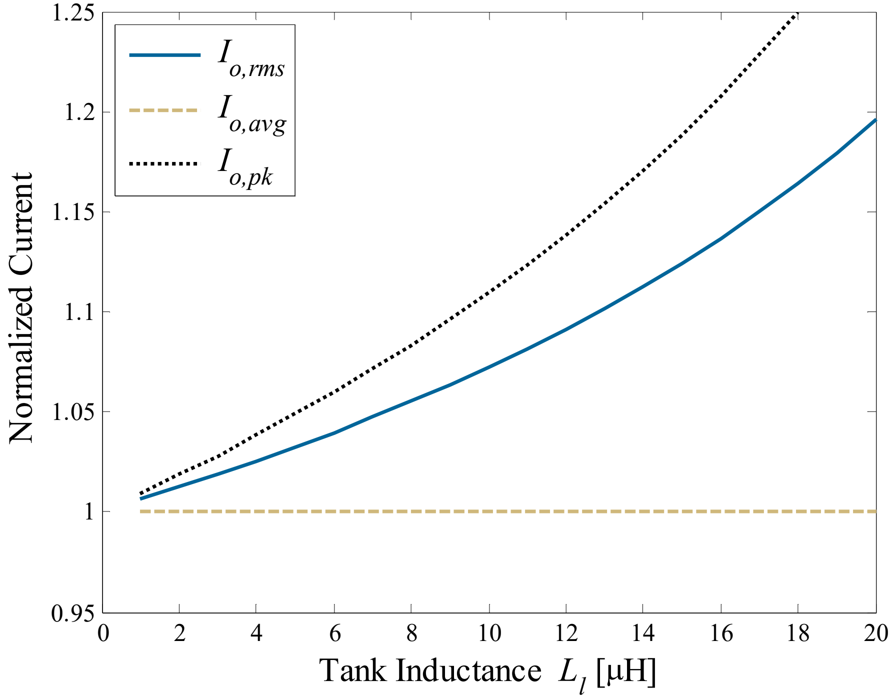


$\frac{V_g + \frac{V_o}{n}}{L_l}$

For conduction loss, want minimum L_l

Output Current Vs. Inductance





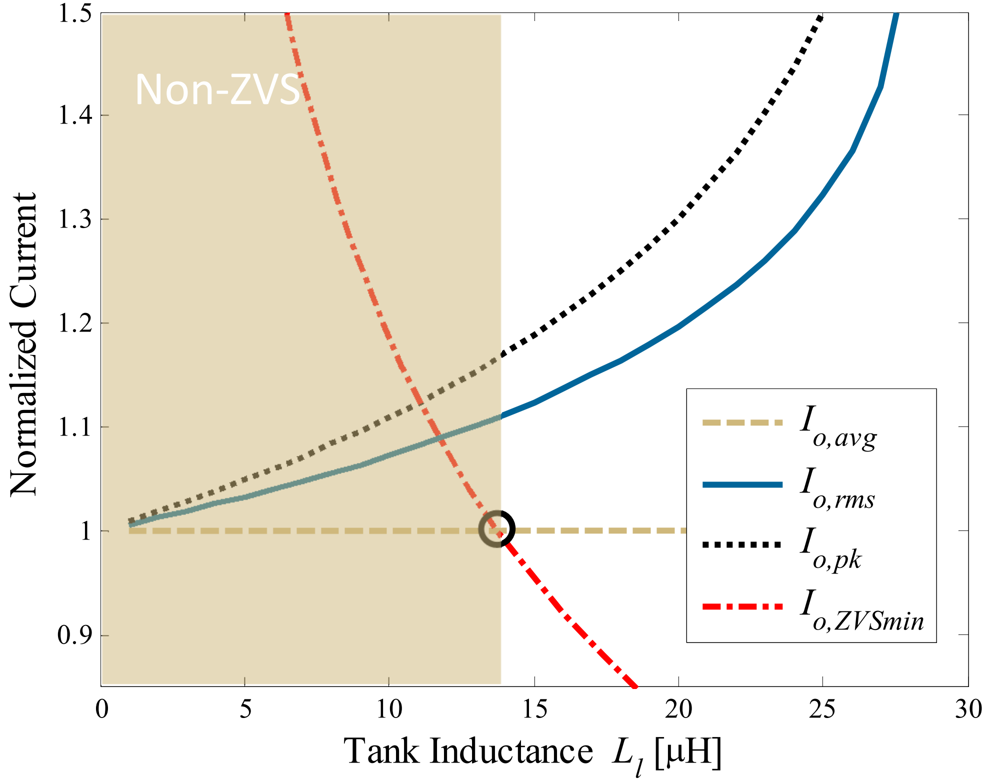
L_l → small for conduction loss
→ small for max peak power

small L_l will require high resolution phase shift modulation

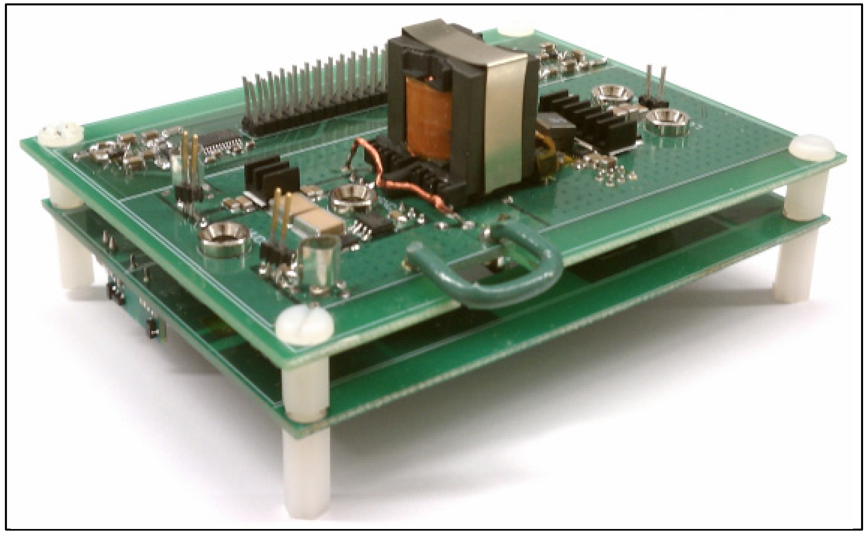
Constraints on Inductance

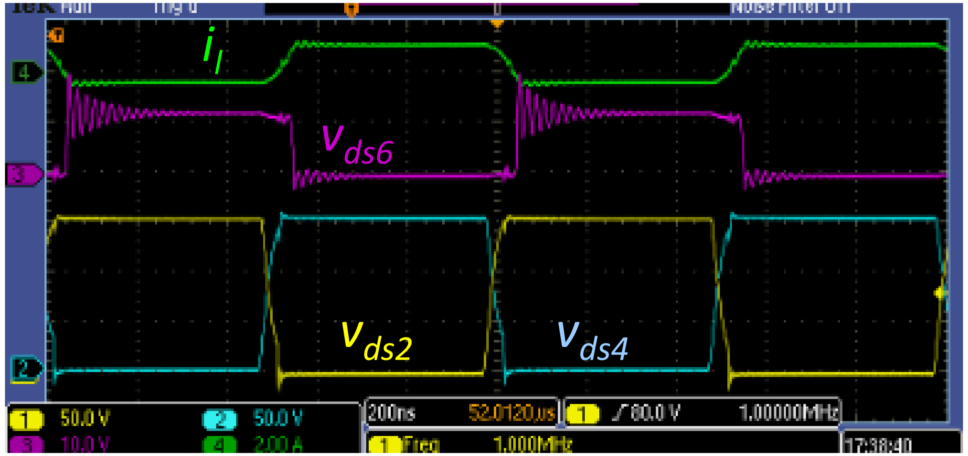
Smaller L_l means we lose ZVS
at higher powers

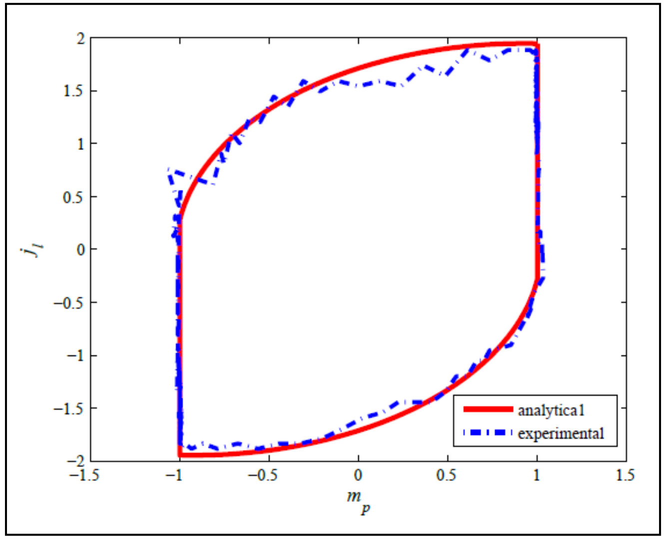
Cannot keep ZVS to zero power
in this mode of operation
(Phase shift modulation)
ϕ (M=n)

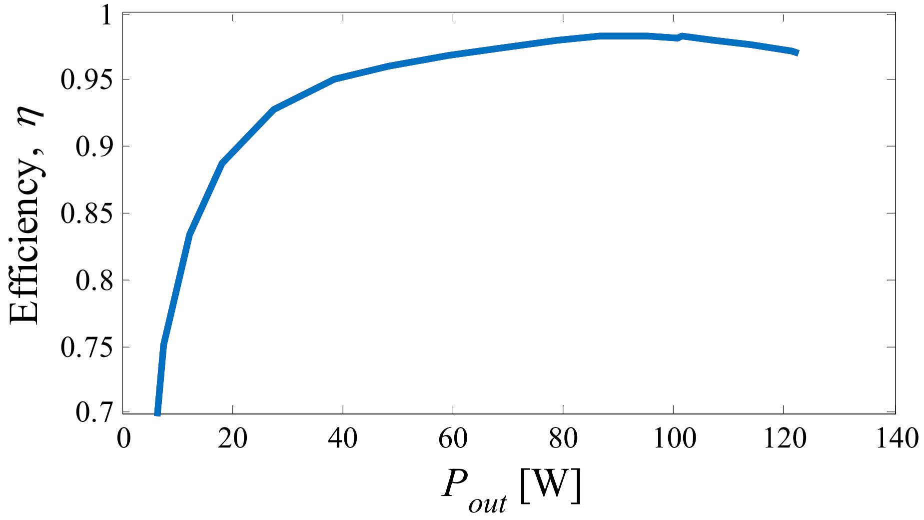


DAB: Experimental Results



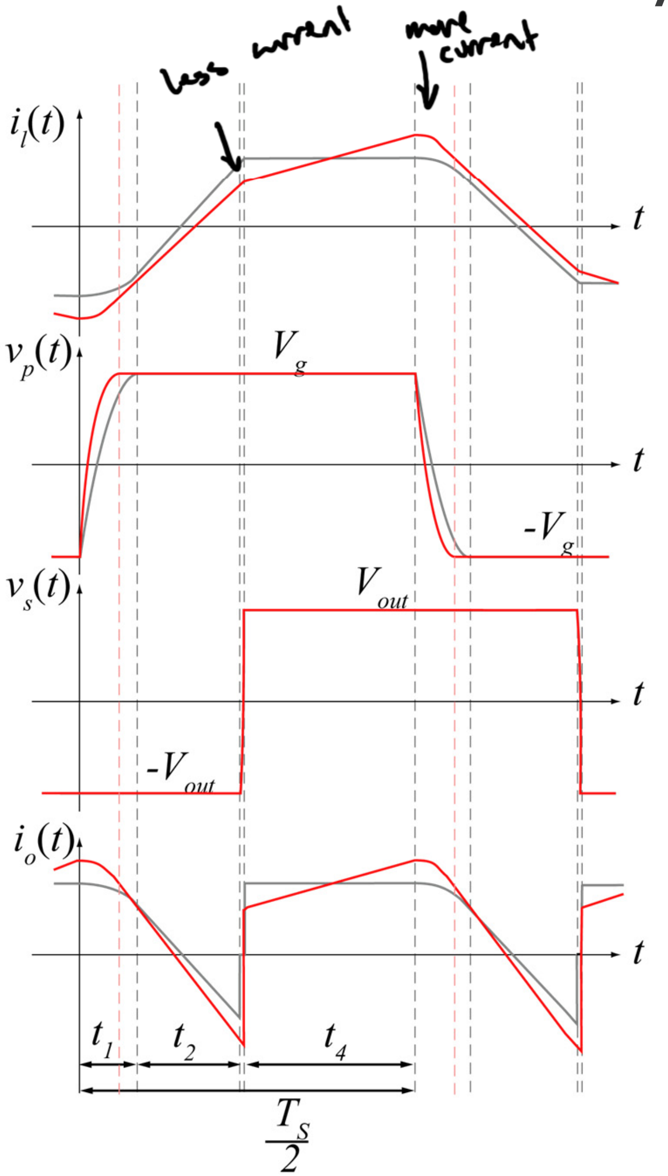


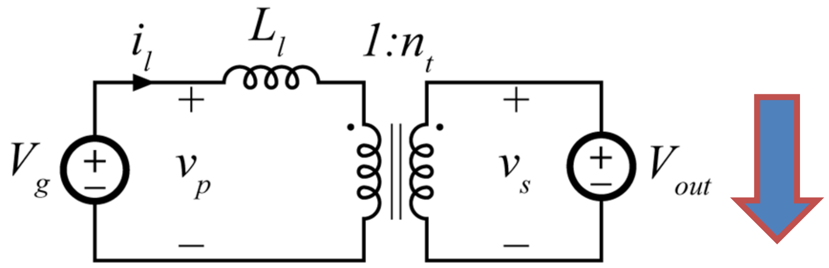




D. Costinett, D. Maksimovic, and R. Zane, “Design and control for high efficiency in high step-down dual active bridge converters operating at high switching frequency,” IEEE Trans. Power Electron., vol. PP, no. 99, p. 1, 2012.

Operation with $V \neq nV_g$





M < n