ZVS-QR State Plane

$V_{max} = V_g$ $R_0 = \sqrt{L_r/C_r}$

Ⅰ: $\frac{I_L}{C_r} t_1 = V_g \rightarrow \theta_1 = \frac{1}{J_L}$

Ⅱ: $r_2^2 = J_L^2 = J_2^2 + 1$

$J_2 = \sqrt{J_L^2 - 1}$

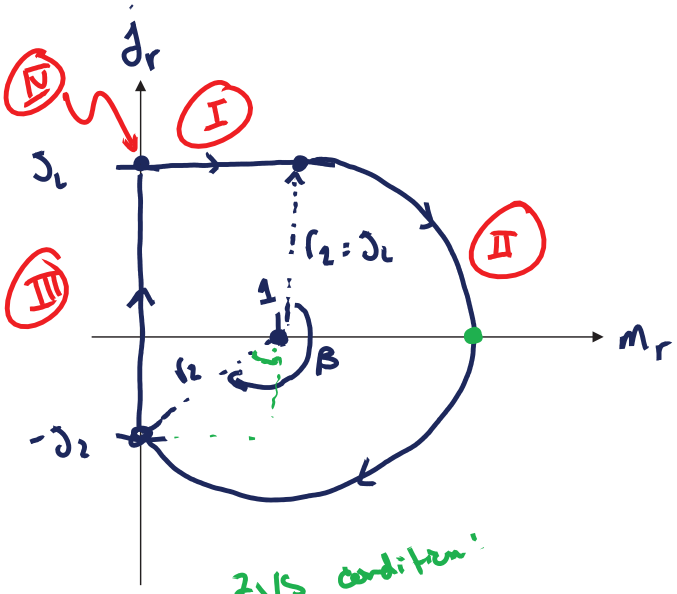
$\beta = \pi + \sin^{-1}\left(\frac{1}{J_L}\right)$

Ⅲ $\frac{V_g}{L_r} t_3 = I_2 + I_L$

$\theta_3 = J_2 + J_L$

Ⅳ : X

$\theta_1 + \beta + \theta_3 + \theta_4 = \frac{2\pi}{F}$



ZVS condition:

$r_2 \geq 1$

↓

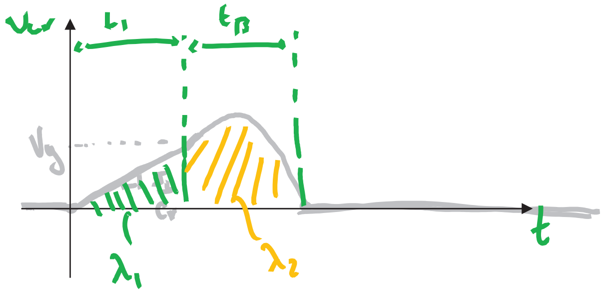
$J_L \geq 1$

Averaging

Apply volt-second balance on Lf

$\langle v_{Lf} \rangle = \phi = \langle v_{sw} \rangle - V$

$\phi = V_g - \langle v_{cr} \rangle - \underset{\phi}{\cancel{\langle v_{Lr} \rangle}} - V$



$V = V_g - \langle v_{cr} \rangle$

$V = V_g - \frac{1}{T_s}\int_0^{T_s} v_{cr}\,dt = V_g - \frac{1}{T_s}\left[\lambda_1 + \lambda_2\right]$

$V = V_g - \frac{1}{T_s}\left[\frac{1}{2}V_g t_1 + V_g t_\beta + L_r(I_2 + I_L)\right]$

$M = 1 - \frac{1}{T_s}\left[\frac{t_1}{2} + t_\beta + \frac{L_r}{V_g}(I_2 + I_L)\right]$

$\underline{M = 1 - \frac{F}{2\pi}\left[\frac{\theta_1}{2} + \beta + J_2 + J_L\right]}$

$\lambda_1 = \frac{1}{2} V_g t_1$

$\lambda_2 = \int_{t_3} v_{cr}\,dt = \int_{t_3} V_g - v_{Lr}\,dt$

$= \int_{t_3} V_g - L_r \frac{di_{Lr}}{dt}\,dt$

$\lambda_2 = V_g t_\beta - L_r\left[-I_2 - I_L\right]$

Complete Solution

$$\theta_1 = \frac{1}{J_L}$$

$$J_2 = \sqrt{{J_L}^2 - 1}$$

$$\beta = \pi + \sin^{-1}\left(\frac{1}{J_L}\right)$$

$$\theta_3 = J_2 + J_L$$

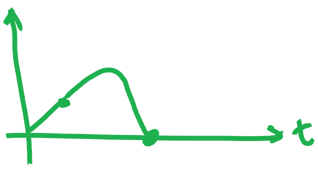
$$\frac{2\pi}{F} = \theta_1 + \beta + \theta_3 + \theta_4$$

$$M = 1 - \frac{F}{2\pi}\left[\frac{\theta_1}{2} + \beta + J_2 + J_L\right]$$

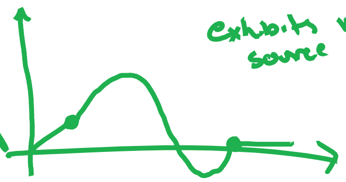
$$M = 1 - \frac{F}{2\pi}\underbrace{\left[\frac{1}{2J_L} + \pi + \sin^{-1}\left(\frac{1}{J_L}\right) + \sqrt{J_L^2 - 1} + J_L\right]}$$

$F \cdot P_{1/2}\left(\frac{1}{J_L}\right)$ in the textbook (20.61 & 20.46)

Half-wave:

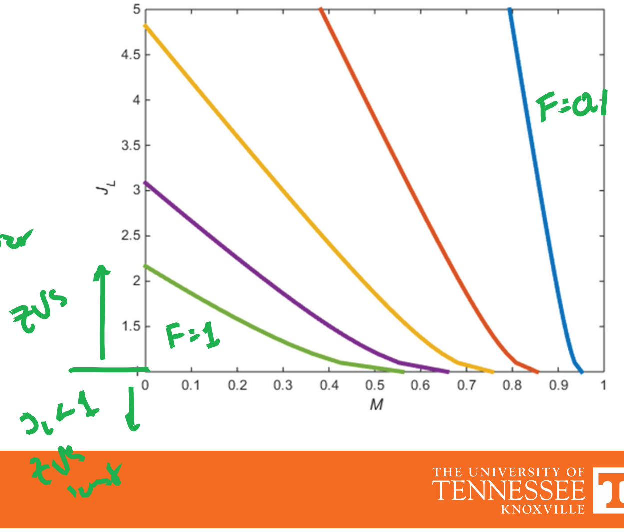


Full-wave:
- need bidirection voltage blocking



exhibits voltage source behavior

or



MOSFET Voltage Stresses

for ZVS $J_L \geq 1$

$M_{cr,pk} = 1 + J_L$

At minimum, when achieving ZVS, $J_L = 1$

$M_{cr,pk} = 2 \rightarrow V_{cr,pk} = 2V_g$

$V_{cr,pk} = V_{ds,pk}$

For example if I want ZVS down to 20% Pout

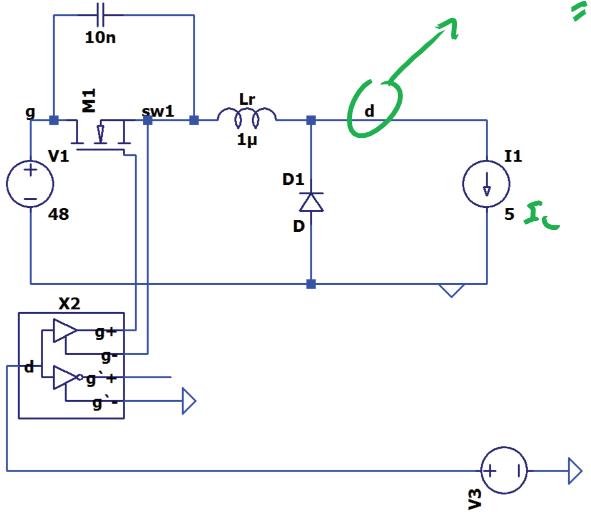
At full load $J_L = 5$

$M_{cr,pk} = 6 \rightarrow V_{cr,pk} = 6V_g$

Test Circuit

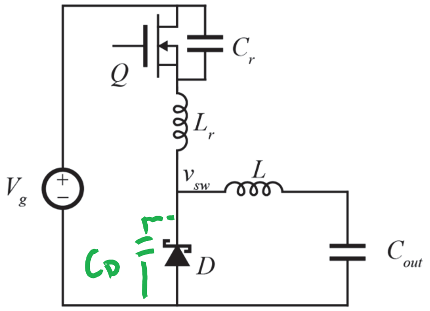
$f_s = 1MHz$

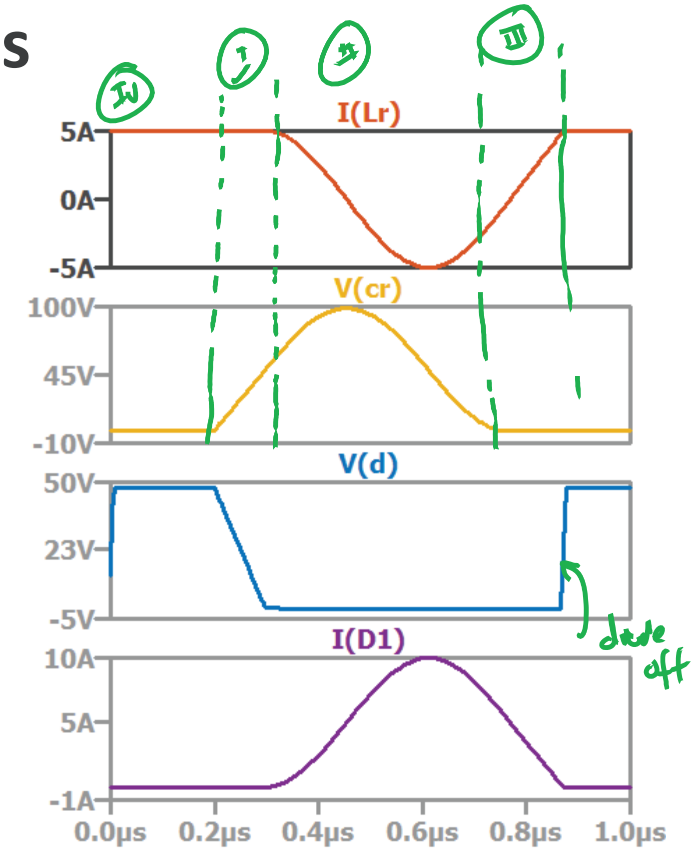
$\langle v(d) \rangle = V$
$= 16V$



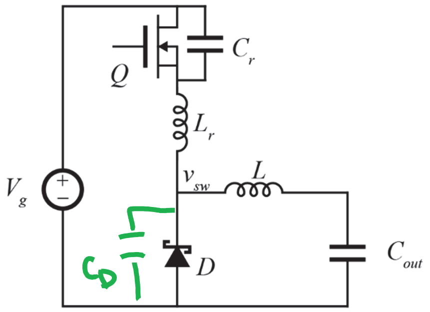
$$J_L = \frac{5A}{48V}\sqrt{\frac{1\mu H}{10nF}} \simeq 1 \rightarrow \text{operating close to ZVS boundary}$$

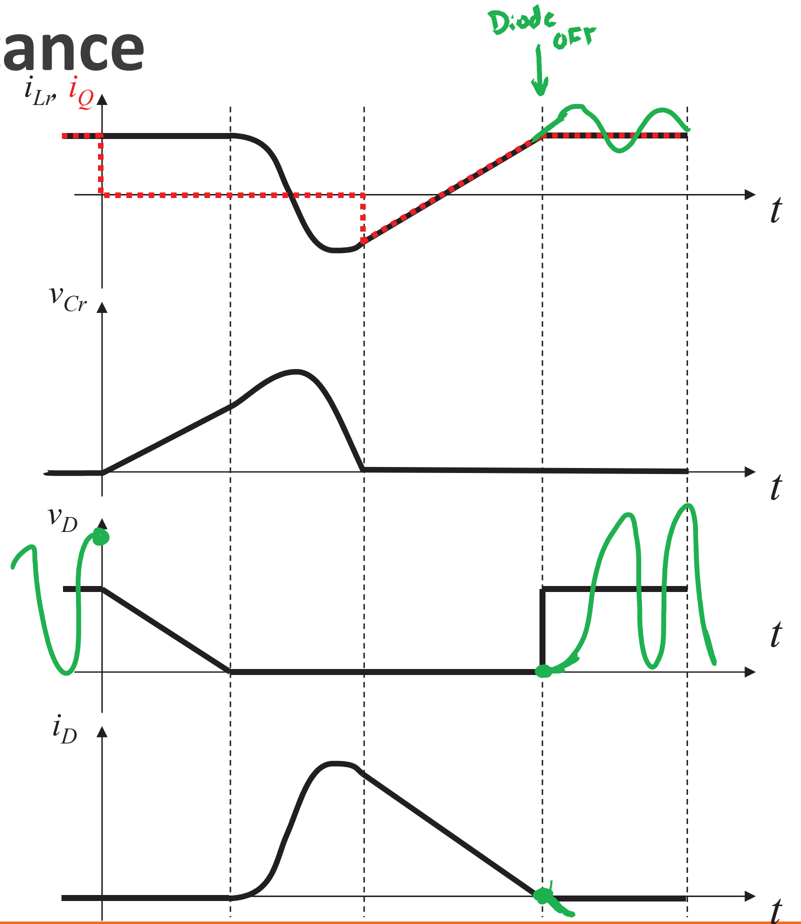
Simulation Results



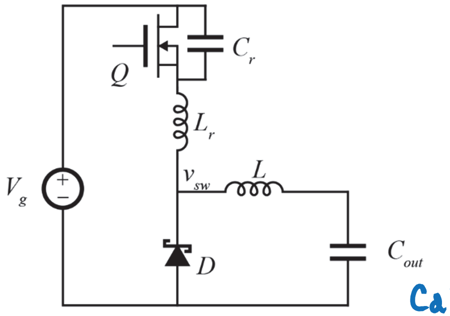


Diode Capacitance

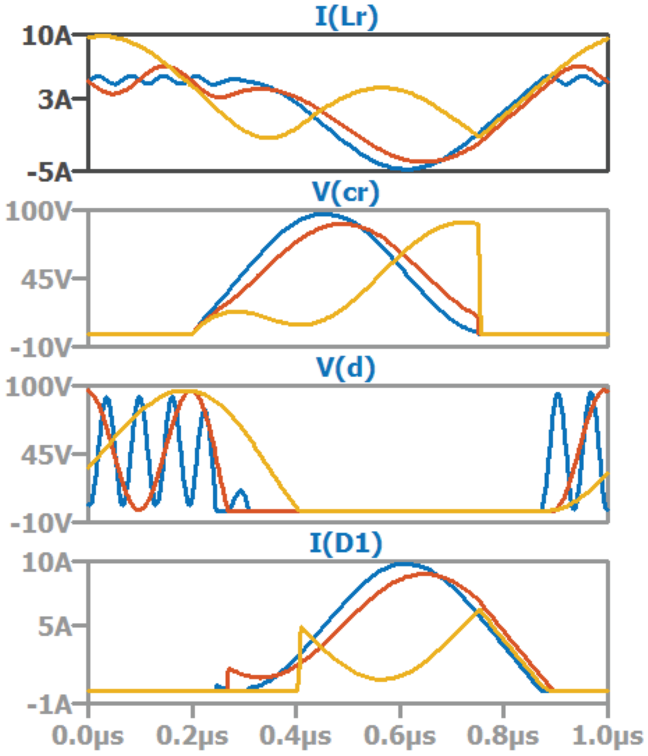




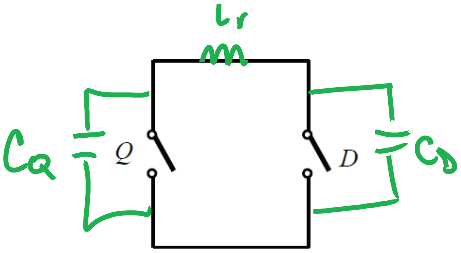
Simulation Results: Diode Capacitance



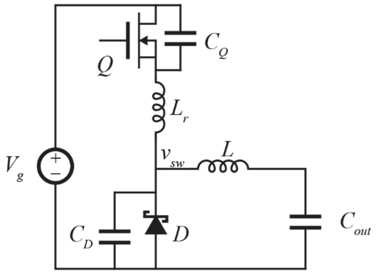
Cd = 100pF
Cd = 1nF
Cd = 10nF



Wishlist: Multi-Resonant



ZVS-MR Buck



W. A. Tabisz and F. C. Lee, "Zero-voltage-switching multi-resonant technique-a novel approach to improve performance of high frequency quasi-resonant converters," *Power Electronics Specialists Conference, 1988.*

Operating Modes

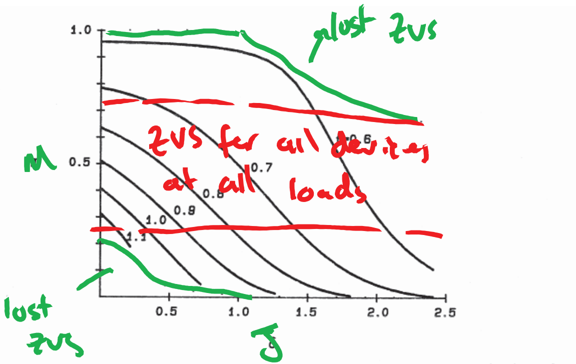
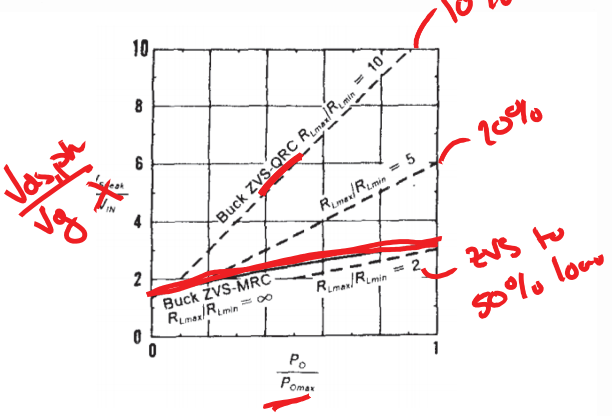


Figure 10.7: Load-to-output DC characteristics of a ZV-MR converter operating in modes $(I, II)_1$.



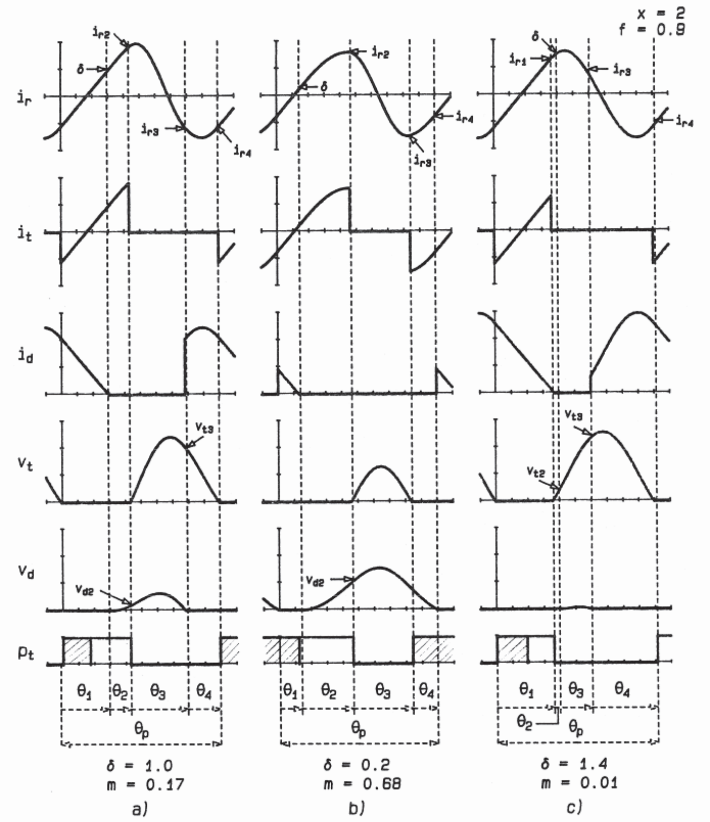


Figure 10.2: Typical waveforms for a ZV-MR converter operating in modes I_1 (a), II_1 (b) or III_1 (c).

D Maksimovic, “Synthesis of PWM and Quasi-Resonant DC-to-DC Power Converters,” Ph.D. Thesis, CalTech 1989