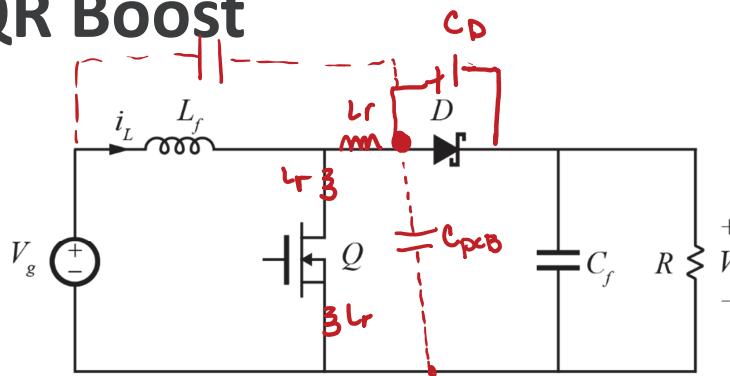


ZCS-QR Boost

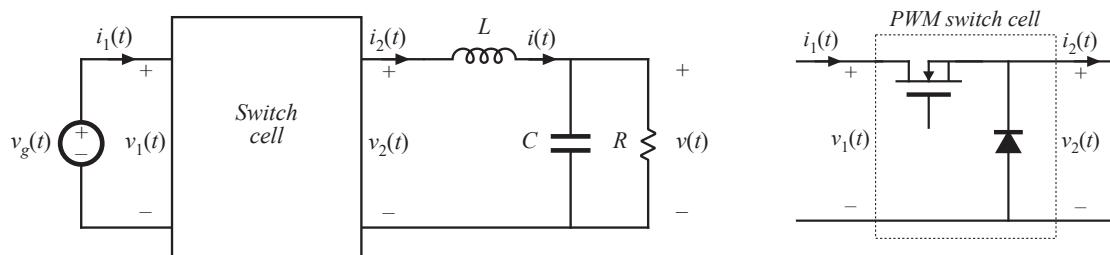


PWM Boost $M = \frac{1}{1-d(t)}$ $\frac{1}{D}$ in steady-state

ZCS-QR Boost $M = \frac{1}{1-\mu(t)}$ $\frac{1}{1-\mu}$ in steady state

$\mu = FP_{V_L}(S)$ (for half-wave)

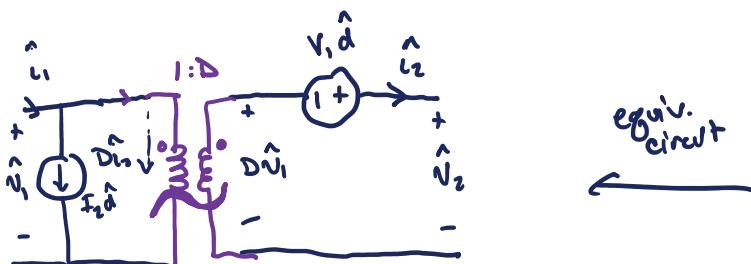
SSM - PWM Parent



DWIM:
 $\langle v_2 \rangle = \frac{d(t)}{1-d(t)} \langle v_1 \rangle$
 $\langle i_2 \rangle = \frac{d(t)}{1-d(t)} \langle i_1 \rangle$

↓
 Linearize to get SSM

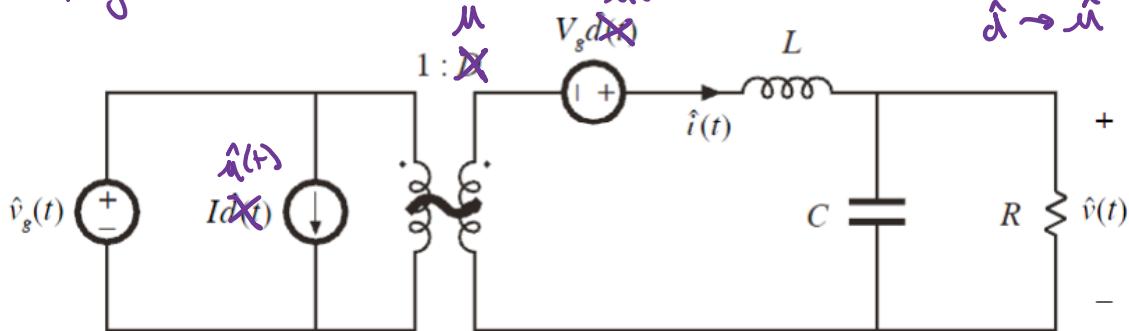
equiv. circuit
 $\hat{v}_2 = \hat{v}_1 + D\hat{i}_1$
 $\hat{i}_1 = D\hat{i}_2 + I_2 \hat{d}$



SSM, PWM Case

Textbook, Fig.7.17(a)

To get ZVS-QR Buck small signal model, replace $d(t)$ w/ $M(t)$
 $D \rightarrow M$
 $\hat{d} \rightarrow \hat{M}$



Complete Solution (L28)

$$M = 1 - \frac{E}{2\pi} \left[\frac{\alpha}{2} + \beta + \beta_L + \beta_L \right]$$

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

→ same as 20.46 in Fundamentals of Power Electronics 2nd edition
 23.46 in 3rd edition

$$\text{M} = 1 - \text{FP}_{Y_L}\left(\frac{1}{\beta_L}\right)$$

e.g. $\beta_L \rightarrow \frac{1}{x}$

ZCS-QR

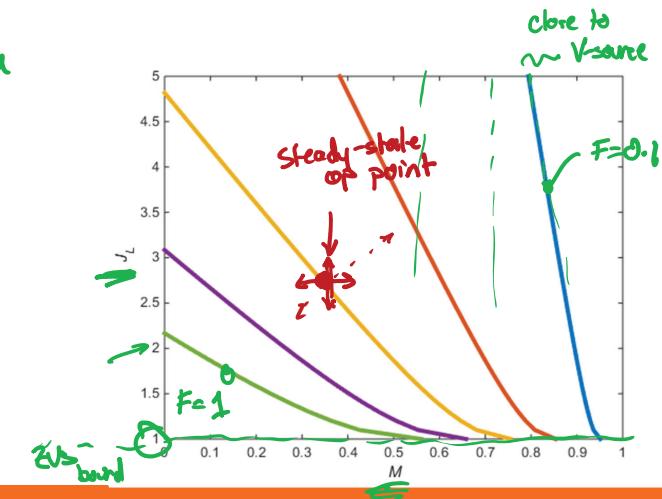
This is the half-wave implementation of a ZVS-QR Buck



A full-wave implementation



Requires a bidirectional-blocking switch Q



ZVS-QR Switch Cell SSM

$$M = 1 - \left(\frac{E}{2\pi} \left[\frac{1}{2\beta_L} + \pi + \sin^{-1}\left(\frac{1}{\beta_L}\right) + \sqrt{\beta_L^2 - 1} + \beta_L \right] \right) = 1 - F P_{Y_L} \left(\frac{1}{\beta_L} \right)$$

$$F = \frac{f_s}{f_0} \quad \beta_L = \frac{I_L}{V_g} R_o$$

$$M = f(f_s, I_L, V_g)$$

R_o & f_0 are constant

$$\hat{\mu} = K_i \hat{i}_L + K_v \hat{v}_g + K_c \hat{f}_s \rightarrow \text{small-signal linearization}$$

$$\left\{ \begin{array}{l} K_i = \frac{\partial M}{\partial i_L} \Big|_{DC} = -F \frac{\partial P_{Y_L}}{\partial \beta_L} \cdot \frac{R_o}{V_g} \\ K_v = \frac{\partial M}{\partial v_g} \Big|_{DC} = -F \frac{\partial P_{Y_L}}{\partial \beta_L} \cdot \left(-\frac{I_L R_o}{V_g^2} \right) \\ K_c = \frac{\partial M}{\partial f_s} \Big|_{DC} = -\frac{1}{f_0} P_{Y_L} \left(\frac{1}{\beta_L} \right) \end{array} \right.$$



$$\frac{\partial P_{Y_L}}{\partial \beta_L} = \frac{1}{2\pi} \left[\frac{-1}{2\beta_L^2} + \left(\frac{1}{\beta_L^2} \right) \frac{1}{\sqrt{1 - (\frac{1}{\beta_L})^2}} + \frac{1/2}{\sqrt{\beta_L^2 - 1}} (2\beta_L) + 1 \right]$$

$$= \frac{1}{2\pi} \left[1 - \frac{1}{2\beta_L^2} + \frac{-1/\beta_L}{\sqrt{\beta_L^2 - 1}} + \frac{\beta_L}{\sqrt{\beta_L^2 - 1}} \right]$$

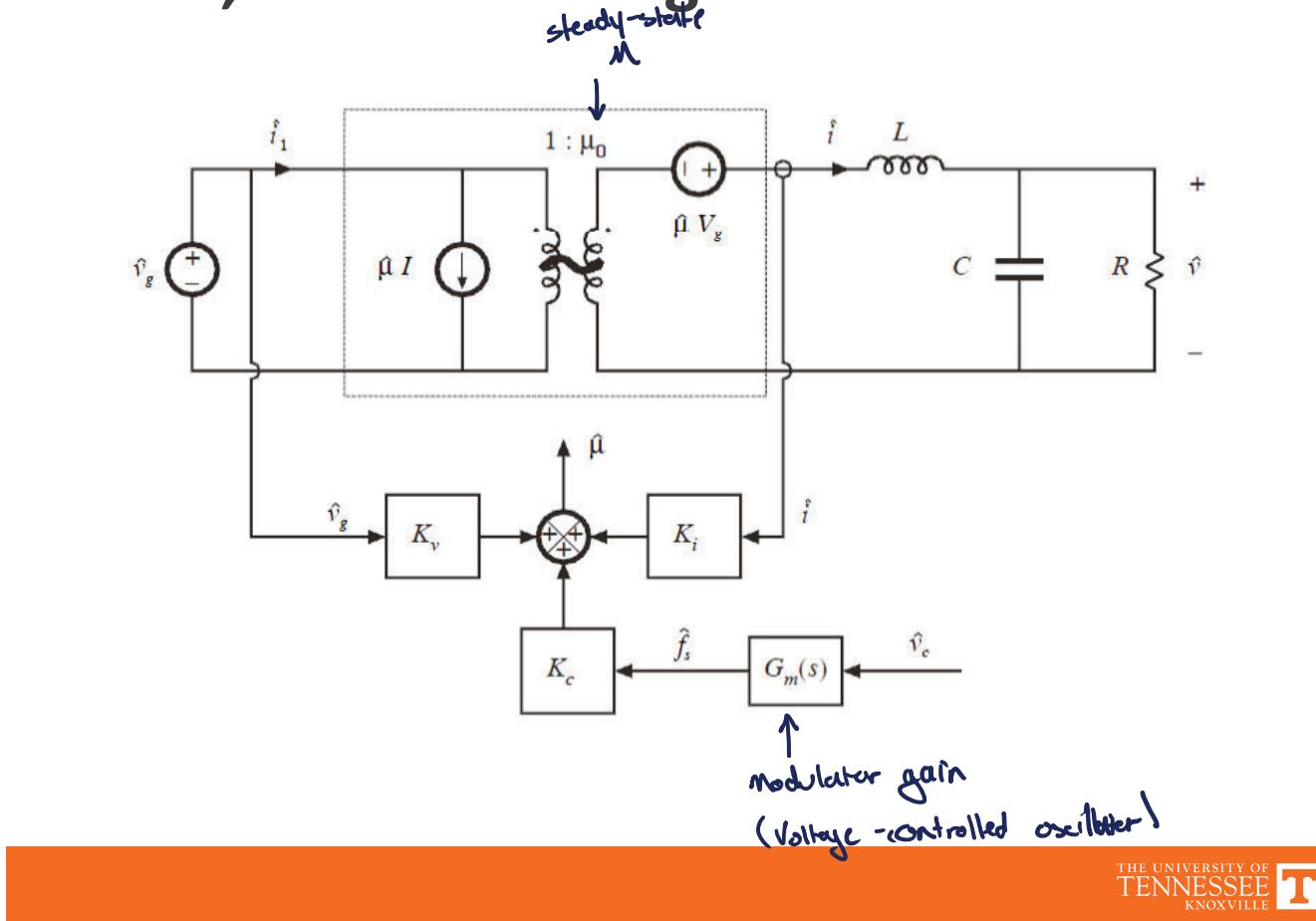
$$= \frac{1}{2\pi} \left[1 - \frac{1}{2\beta_L^2} + \frac{\beta_L - 1/\beta_L}{\sqrt{\beta_L^2 - 1}} \right]$$

$$= \frac{1}{2\pi} \left[1 - \frac{1}{2\beta_L^2} + \left(\frac{1}{\beta_L} \right) \frac{\beta_L^2 - 1}{(\beta_L^2 - 1)^{1/2}} \right]$$

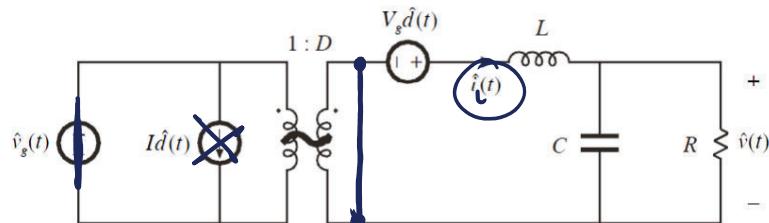
$$\boxed{\frac{\partial P_{Y_L}}{\partial \beta_L} = \frac{1}{2\pi} \left[1 - \frac{1}{2\beta_L^2} + \frac{\sqrt{\beta_L^2 - 1}}{\beta_L} \right]}$$



SSM, Soft-Switching Buck

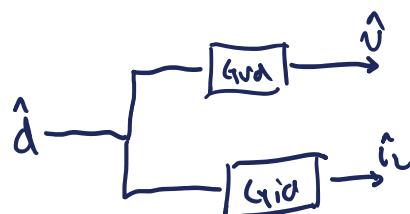


PWM Transfer Functions

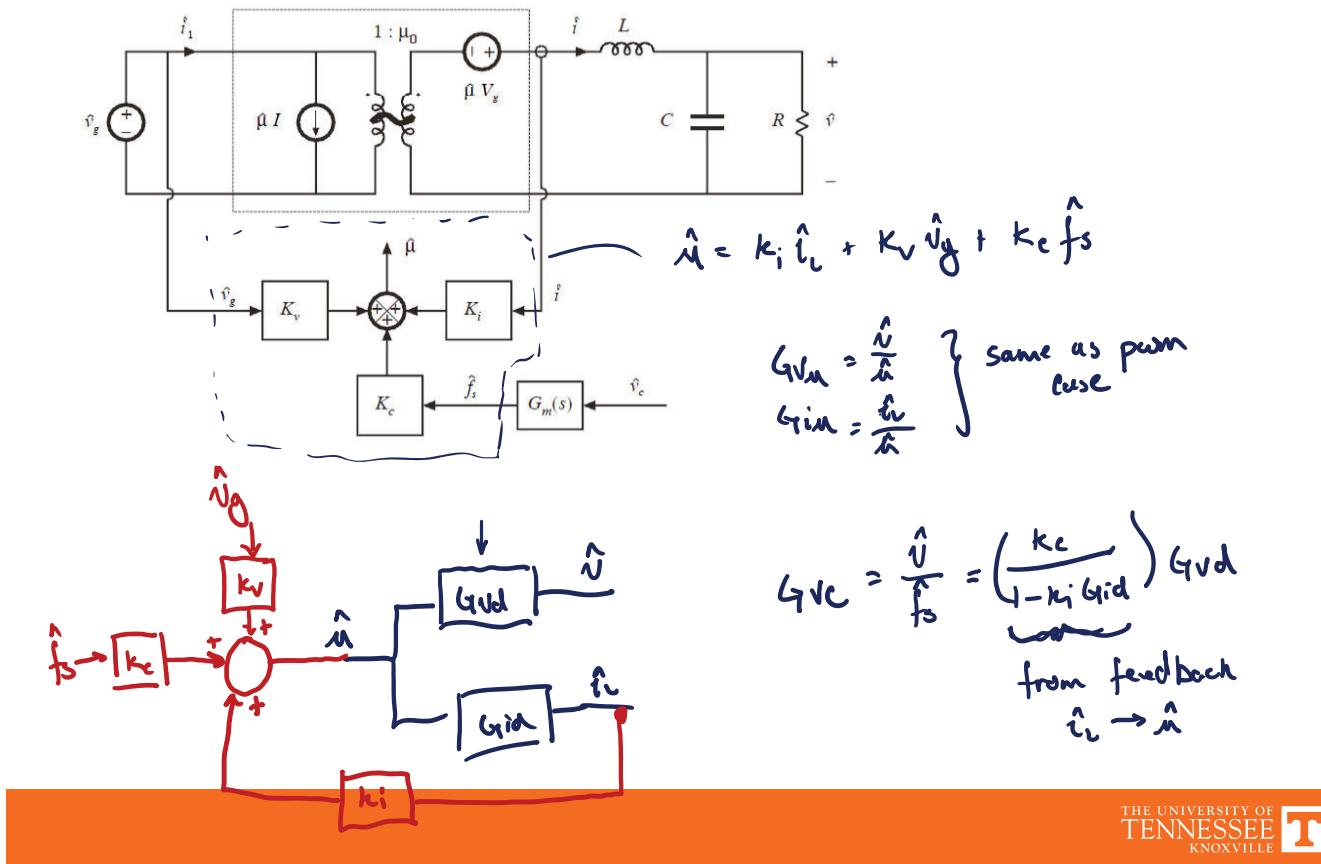


$$G_{vd} = \frac{\hat{v}}{\hat{d}} \Big|_{\hat{v}_g=\phi} = \sqrt{g} \frac{R \parallel \frac{1}{sC}}{sC + R \parallel \frac{1}{sC}} = \sqrt{g} \frac{1}{s^2LC + s\frac{L}{R} + 1}$$

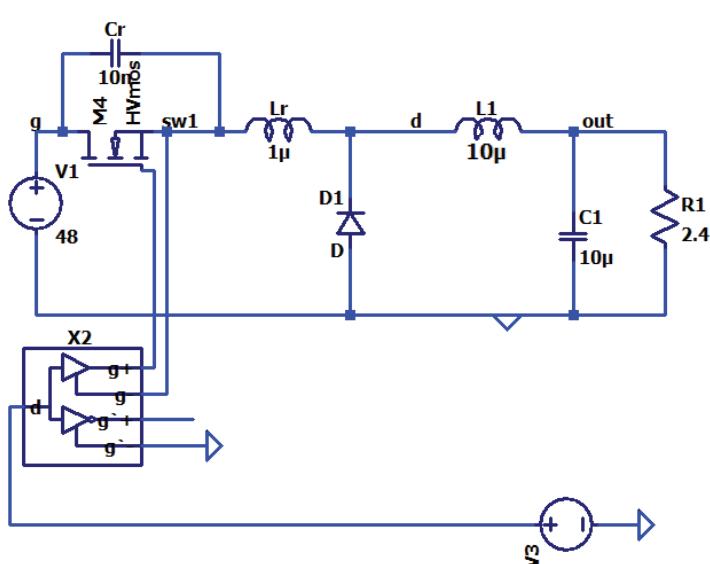
$$G_{id} = \frac{\hat{i}_s}{\hat{d}} \Big|_{\hat{v}_g=0} = \sqrt{g} \frac{1}{sC + R \parallel \frac{1}{sC}} = \frac{1 + sCR}{s^2LC + s\frac{L}{R} + 1}$$



QR Transfer Functions



Example



$$f_s = 1\text{ MHz}$$

$$\tau_L \approx 1$$

$$P_o = 60\text{W}$$

$$V = 12\text{V}$$

$$F = 0.6$$

$$k_c = 6.24 e^{-12}$$

$$k_i = -0.005$$

$$k_v = 5.6 e^{-4}$$

Control-to-Output Transfer Function

