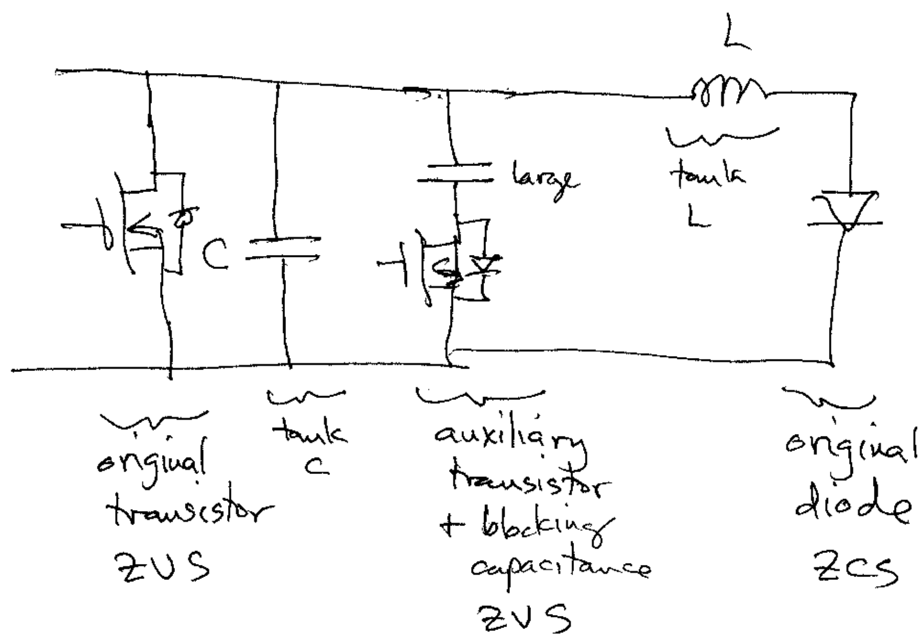
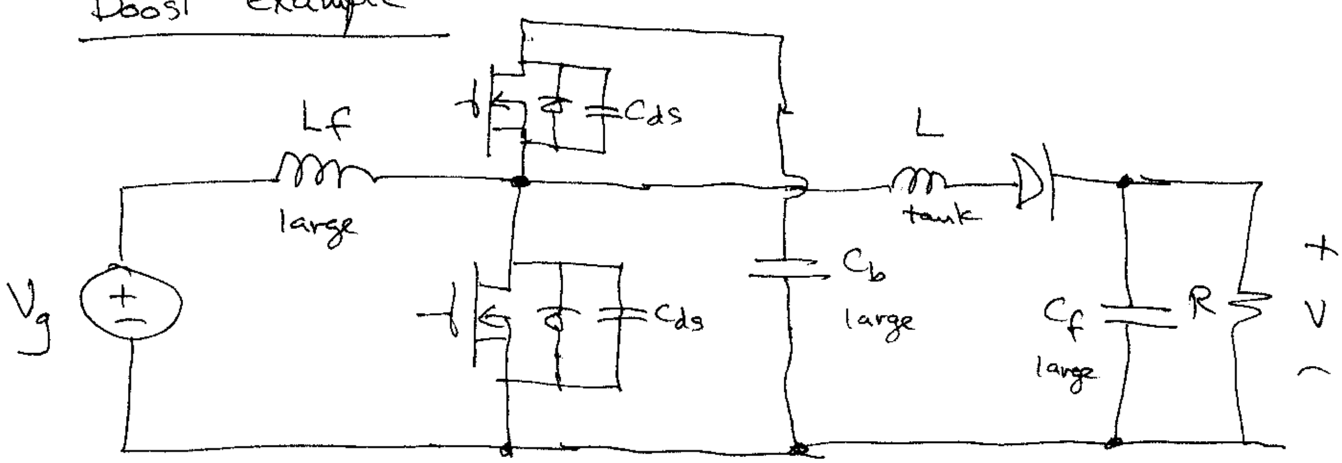
Active clamp snubber circuits

Basic version reduces to

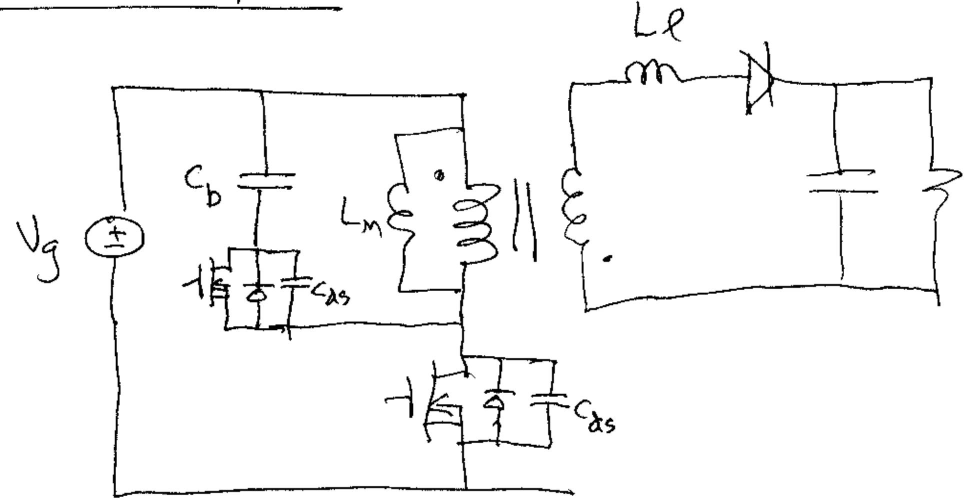


Boost example

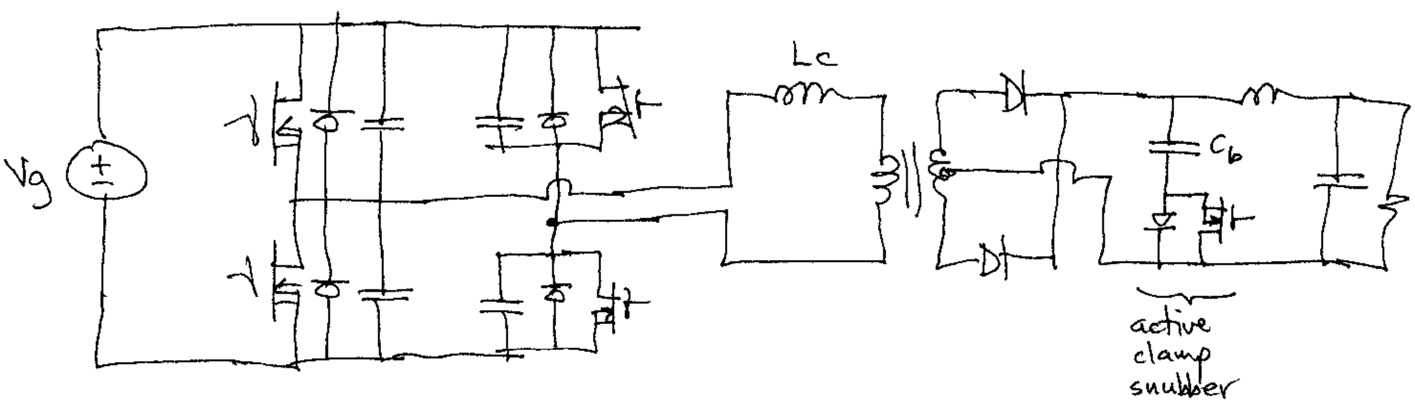


This can be viewed as a resonant switch network that employs an auxiliary switch. The two MOSFETs form a half bridge circuit

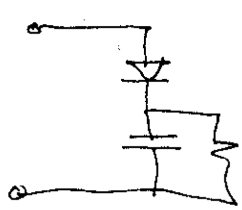
Flyback example



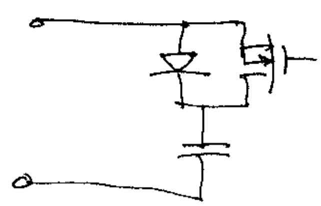
ZVT bridge example - snubbing the output diodes



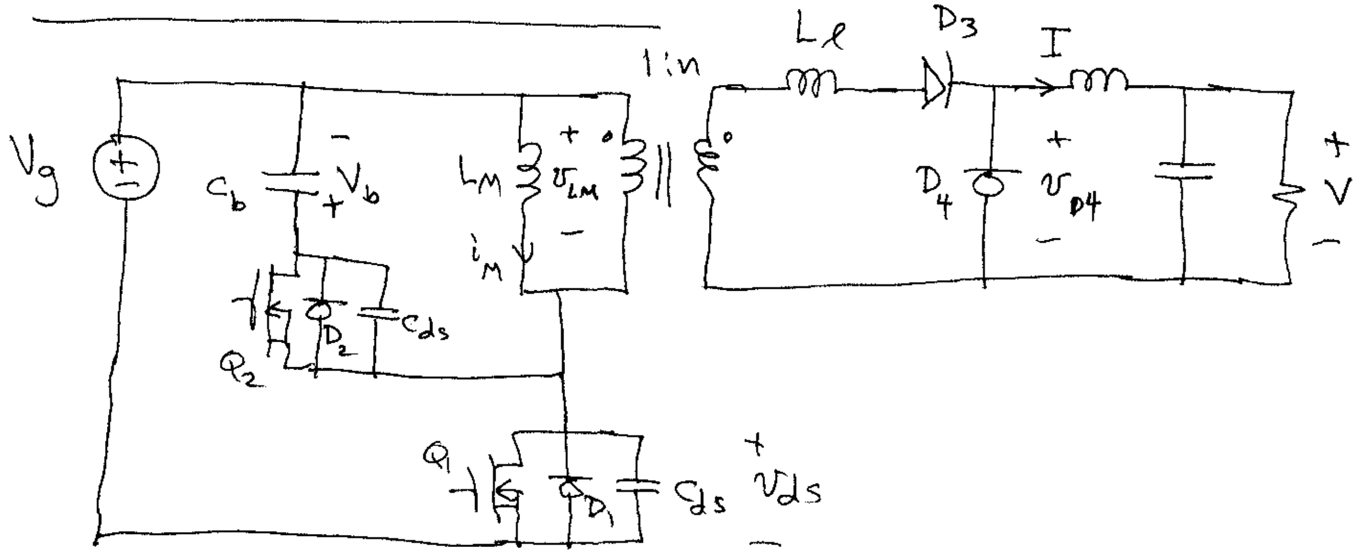
The above two applications can be viewed as improvements to the conventional dissipative voltage-clamp snubber



$\Rightarrow$

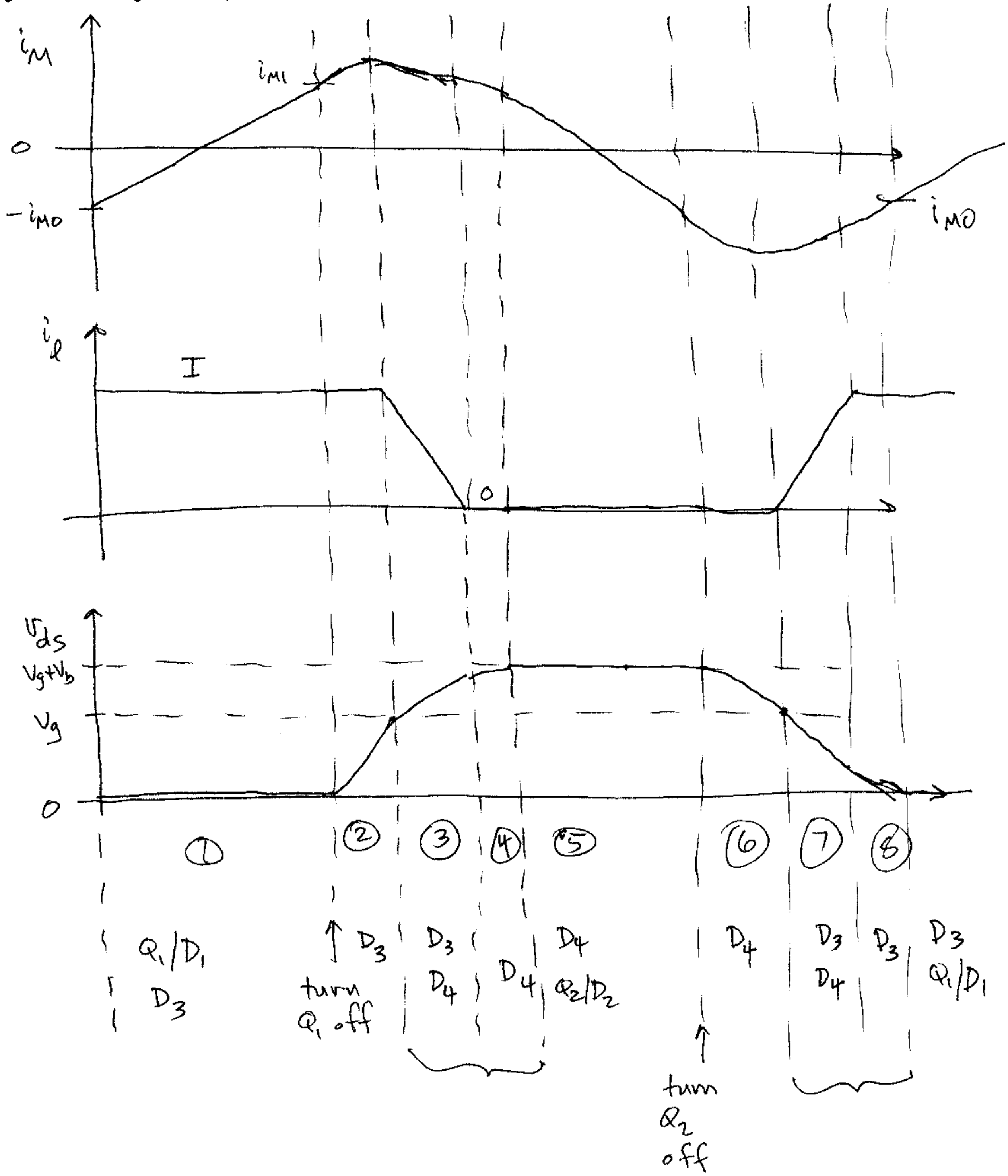


Forward converter version



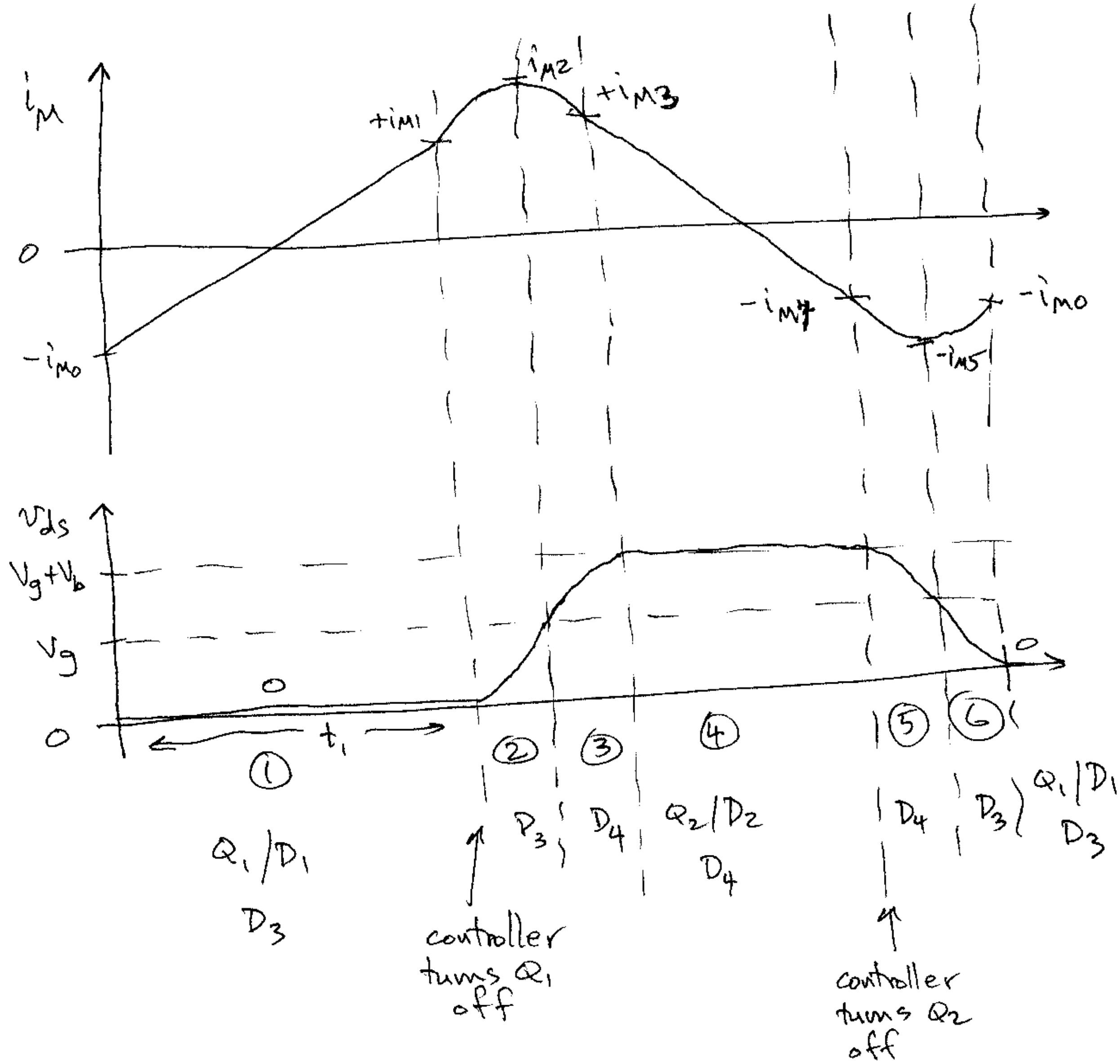
The auxiliary switch/active clamp circuit is used here to reset the transformer, as well as to provide ZVS. The transformer is modeled with L_M, L_ℓ, and ideal 1:n transformer. MOSFET output capacitances C_{ds} participate in ZVS. For the analysis below, we will lump both C_{ds} into a single effective capacitance in parallel with Q_1. Both L_M and L_ℓ participate in operation of the tank.

Including L_l



Several details can be changed, which technically lead to different modes of operation. Interval ③ can end either when D_3 becomes reverse-biased by i_l reaching zero, or by D_2 becoming forward-biased when v_{ds} reaches V_g+V_b. In either event both happen by end of interval ④. Similar discussion (in reverse) applies to intervals ⑦ & ⑧.

Simplified waveforms — neglect L_e



If we ignore L_e, then the model predicts that the load current I commutes instantly from D_2 to D_3 and vice-versa — secondary-side switching waveforms are idealized. But the primary-side switching behavior is modeled well. The predicted ZVS boundary is pessimistic.

Analysis

With L_e neglected, there is no multiresonant behavior. We can use the following base normalizing quantities for every subinterval:

$$V_{base} = V_g \qquad I_{base} = \frac{V_g}{R_o} \qquad R_o = \sqrt{\frac{L_M}{C_{ds}}}$$

$$\omega_o = \frac{1}{\sqrt{L_M C_{ds}}}$$

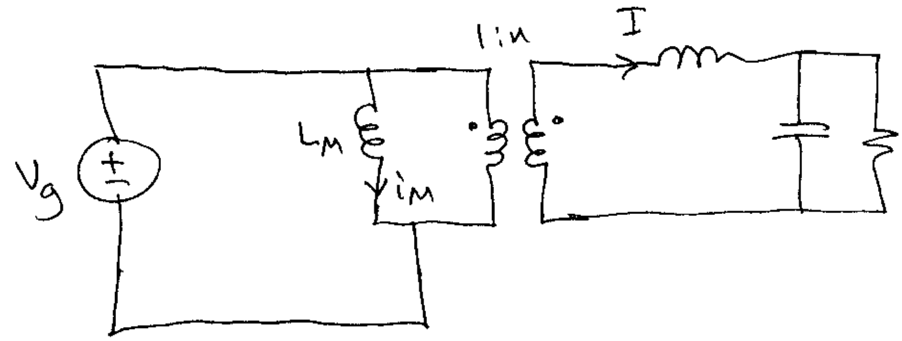
where C_{ds} is the total capacitance seen at the drain of Q_1 (including the output capacitances of both Q_1 and Q_2)

Define $J = \frac{nIR_o}{V_g}$, $m_{ds} = v_{ds}/V_g$, $j_m = i_M R_o/V_g$

Subinterval 1 — Q_1/D_1, D_3 conduct

interval ends when controller turns off Q_1

initial $j_m = -j_{M0}$, final $j_m = +j_{M1}$



$$\frac{di_M}{dt} = \frac{V_g}{L_M}, \qquad i_{M1} = -i_{M0} + \frac{V_g t_1}{L_M} \Rightarrow t_1 = (i_{M1} + i_{M0})\frac{L_M}{V_g}$$

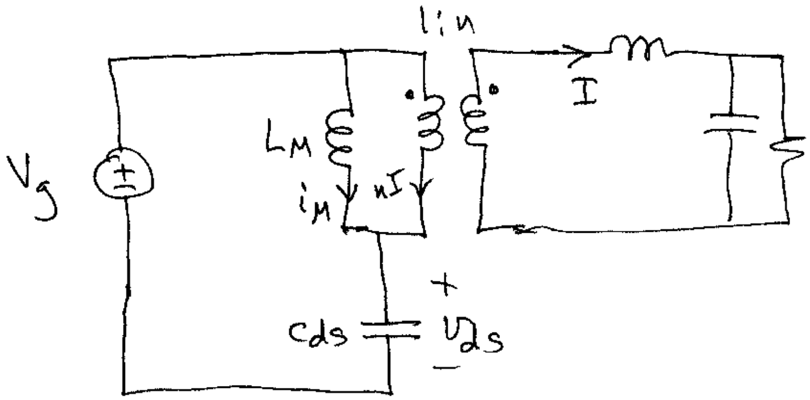
$$\alpha = \omega_o t_1 = j_{M1} + j_{M0}$$

Subinterval 2

D_3 conducts

C_{ds} is charged by $i_M + nI$

interval ends when v_{ds} reaches V_g, causing the output diodes to switch

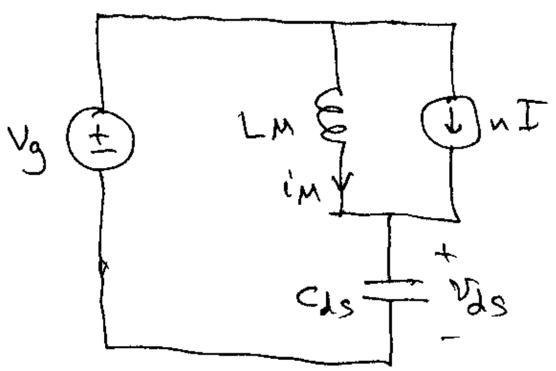


initial values:

$v_{ds} = 0$

$i_M = i_{M1}$

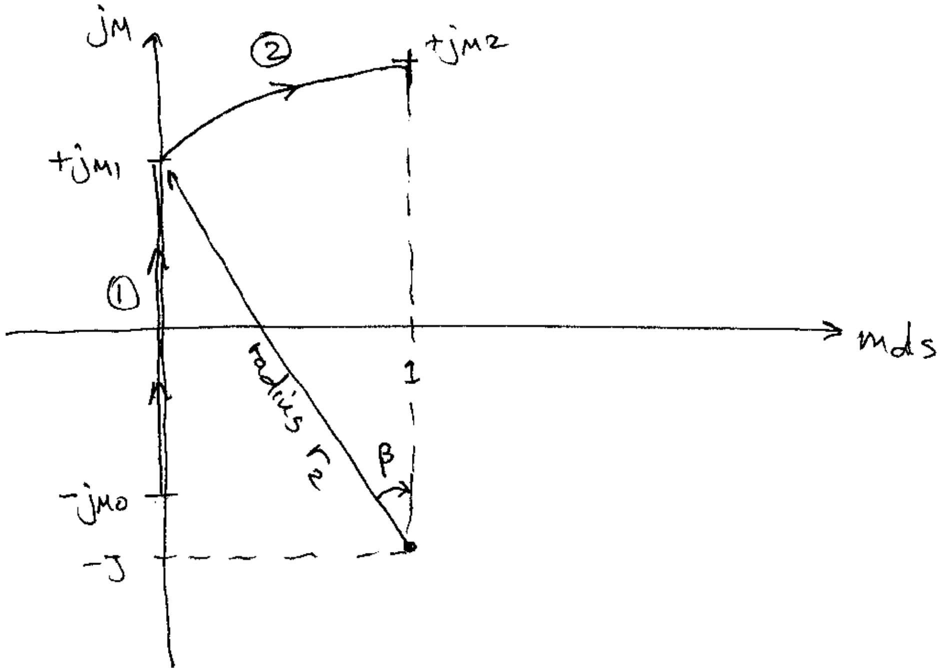
Assume output filter inductor is very large. Circuit reduces to:



State plane trajectory is circular, and is centered at the dc solution

$v_{ds} = V_g, \quad i_M = -nI$

$\Rightarrow m_{ds} = 1, \quad j_M = -J$



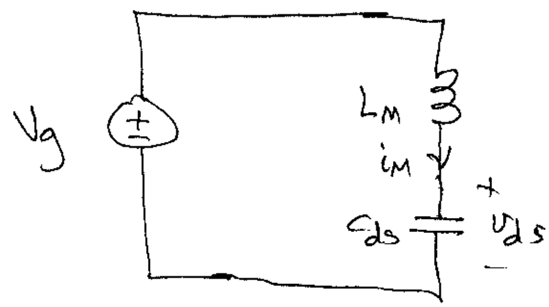
circle radius $r_2 = \sqrt{1 + (jM_1 + J)^2}$

final value $jM_2 = r_2 - J$

angle $\beta = \omega_0 t_2 = \tan^{-1}\left(\frac{1}{jM_1 + J}\right)$

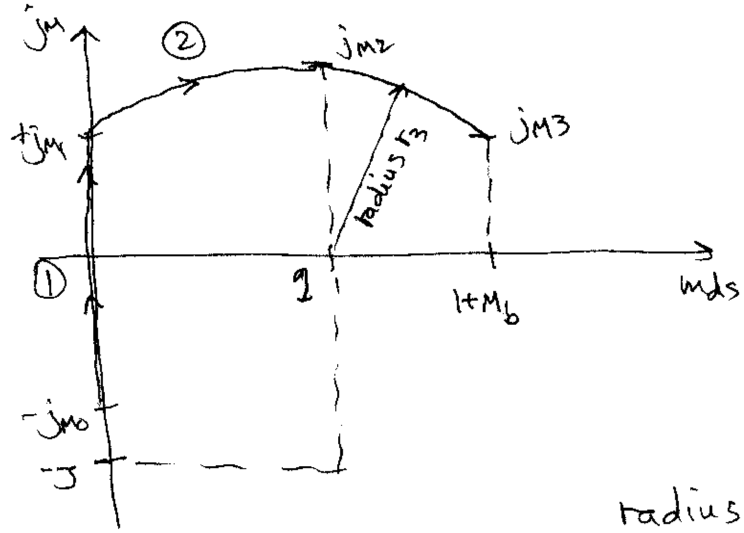
Subinterval 3

D_4 conducts. We are ignoring the process by which the load current shifts from D_3 to D_4 — this commutation takes place during this subinterval.



initial $v_{ds} = V_g$, $i_M = i_{M2}$

interval ends when v_{ds} reaches $V_g + V_b$, forward-biasing D_2



state plane trajectory is circle centered at $j_M = 0$, $m_{ds} = 1$

radius $r_3 = j_{M2}$

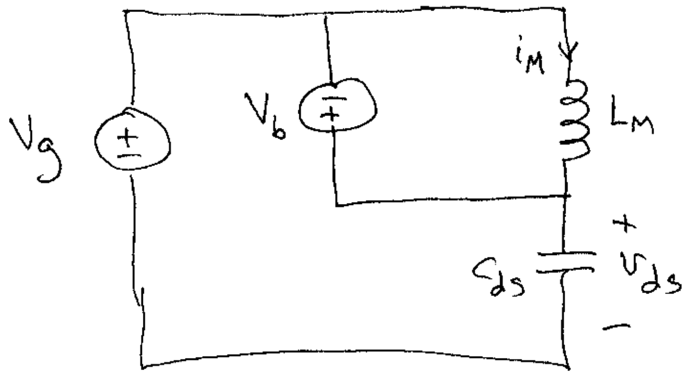
At end of interval: $m_{ds} = 1 + M_b$ with $M_b = \dfrac{V_b}{V_g}$

final current: $j_{M3} = \sqrt{r_3^2 - M_b^2}$

For ZVS, require $r_3 > M_b$

interval length $\delta = \tan^{-1}\left(\dfrac{j_{M3}}{M_b}\right)$

Subinterval 4 Q_2/D_2, D_4 conduct



initial $i_M = i_{M3}$

$$\frac{di_M}{dt} = -\frac{V_b}{L_M}$$

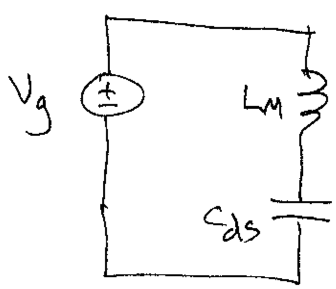
interval ends when controller turns off Q_2

final current is $i_M = -i_{M4}$

$$-i_{M4} = i_{M3} - \frac{V_b}{L_M} t_4$$

$$-j_{M4} = j_{M3} - M_b \xi \qquad \text{with } \xi = \omega_0 t_4$$

Subinterval 5 D_4 conducts. interval ends when $v_{ds} = V_g$



initial $i_M = -i_{M4}$

$v_{ds} = V_g + V_b$

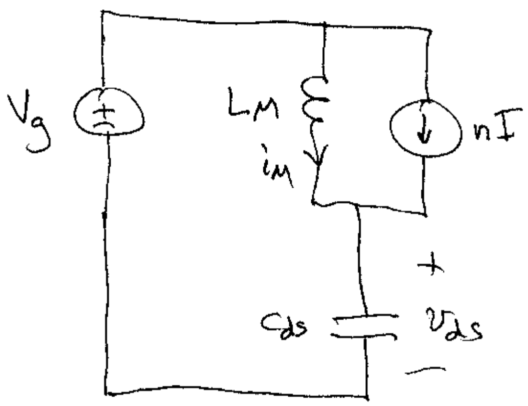
(see next page)

circle radius $r_4 = \sqrt{M_b^2 + j_{M4}^2}$

final value $-j_{M5} = -r_4$

angle $\zeta = \omega_0 t_5 = \tan^{-1}\left(\frac{M_b}{j_{M4}}\right)$

subinterval 6 D_3 conducts. interval ends when $v_{ds} = 0$



Note magnetizing current i_M must oppose reflected load current nI to discharge C_{ds}.

Trajectory is circle centered at $j_M = -J$, $m_{ds} = 1$

radius $r_5 = j_{M5} - J$

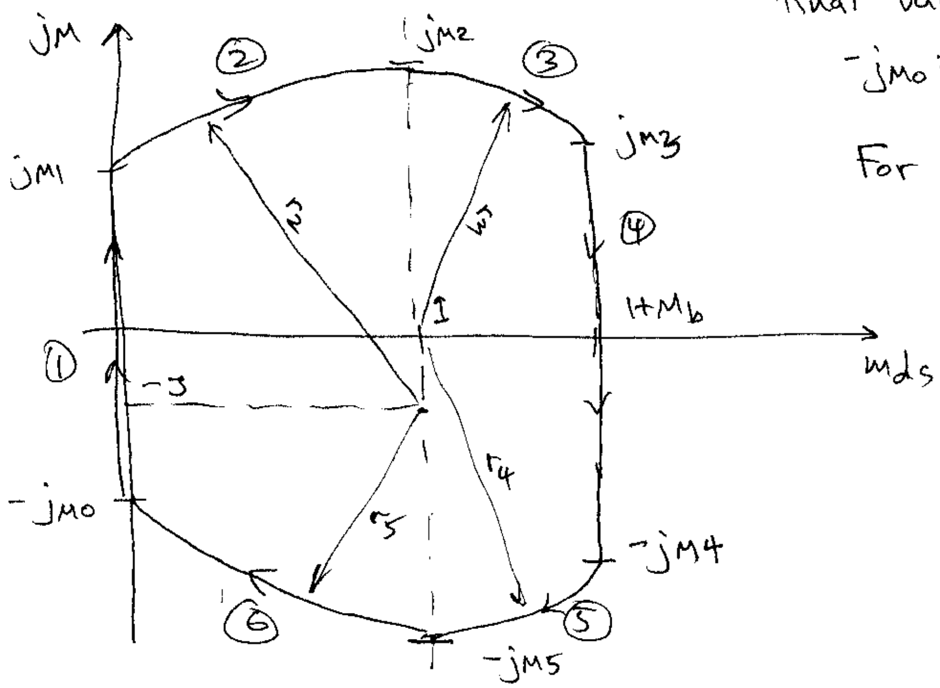
final value:

$$-j_{M0} = -J - \sqrt{r_5^2 - 1}$$

For ZVS, require

$$r_5 \geq 1$$

$$\Rightarrow j_{M5} \geq 1 + J$$

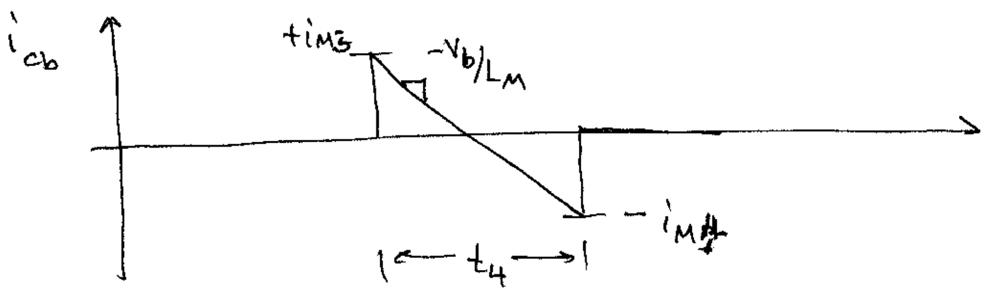


subinterval 6 length: $\psi = \omega_0 t_6 = \tan^{-1}\left(\dfrac{1}{j_{M0} - J}\right)$

Averaging

A. Charge balance on C_b

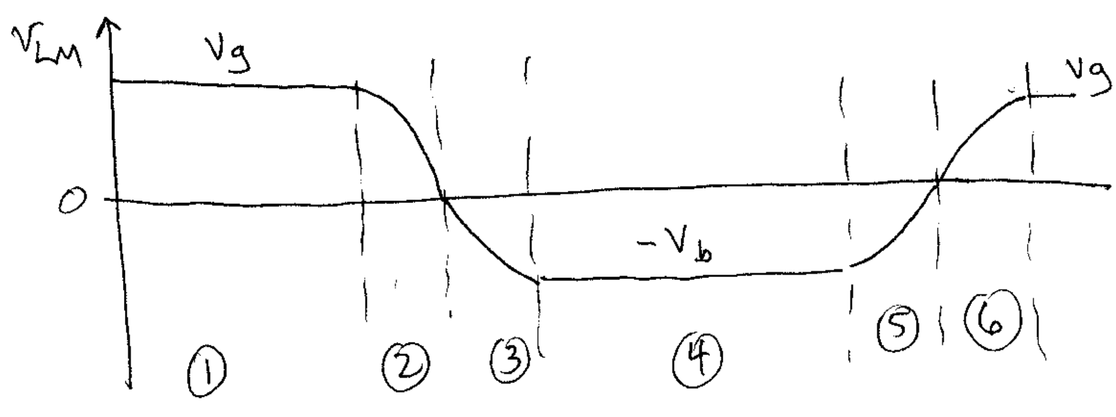
current flows through C_b only during subinterval 4, when Q_2/D_2 conduct:



For the net charge to be zero, we must have $i_{M3} = i_{M4}$. By symmetry of the state plane trajectory, this also implies that $i_{M2} = i_{M5}$

B. Volt-second balance on LM

$$v_{LM} = v_{ds} - V_g$$



$$\langle v_{LM} \rangle = 0 \Rightarrow \langle v_{ds} \rangle = V_g$$

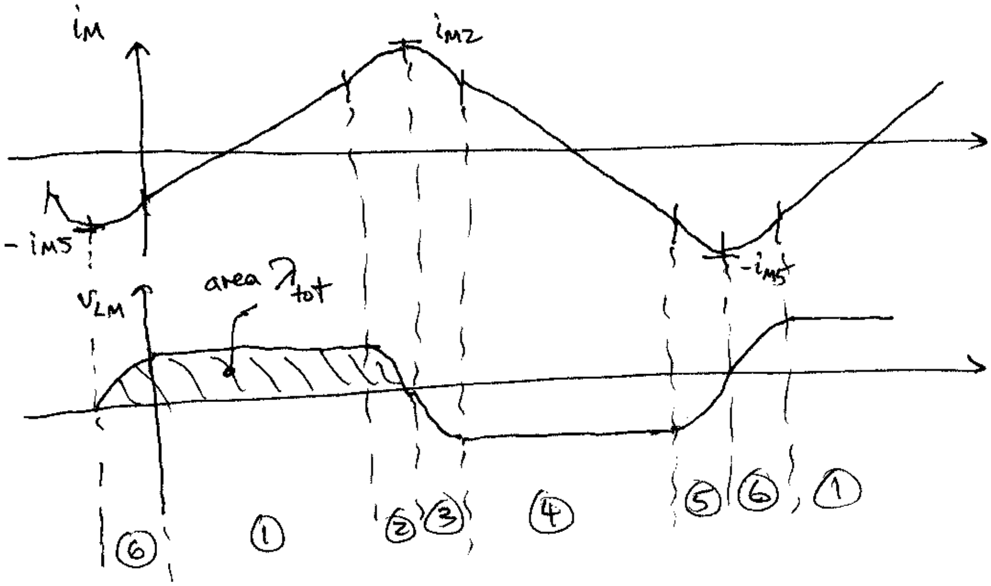
Note that volt-second balance is inherent in the state plane equations — if the state plane trajectory is closed, then the volt-seconds must balance.

C. Average output voltage

$$V = \langle v_{D4} \rangle$$

Note that $v_{D4} = 0$ while D_4 conducts — subintervals ③, ④, and ⑤. While D_3 conducts (subintervals ①, ②, and ⑥), $v_{D4}(t) = n\, v_{LM}(t)$. So

$$V = \frac{1}{T_s} \int_{①,②,⑥} n\, v_{LM}(t)\, dt \;=\; \frac{n}{T_s} \lambda_{tot} \quad \text{with } \lambda_{tot} = \int_{①,②,⑥} v_{LM}(t)\, dt$$



Note $\lambda_{tot} = L_M \left(i_{M2} + i_{M5} \right) = 2 L_M\, i_{M2}$

So $$V = \frac{2 n L_M\, i_{M2}}{T_s}$$

and $$M = \frac{V}{n V_g} = \frac{2 L_M\, i_{M2}}{V_g T_s} = \frac{2 \overbrace{\omega_0 L_M}^{=R_0}\, i_{M2}}{V_g \underbrace{\omega_0 T_s}_{=2\pi/F}} = \frac{j_{M2} F}{\pi}$$

$$\Rightarrow j_{M2} = \frac{M\pi}{F}$$

Summary of equations

$$\alpha = \omega_0 t_1 = j_{M1} + j_{M0}$$ subinterval 1

$$j_{M2} = \sqrt{1 + (j_{M1} + J)^2} - J$$ subinterval 2

$$\beta = \omega_0 t_2 = \tan^{-1}\left(\frac{1}{j_{M1} + J}\right)$$

$$j_{M3} = \sqrt{j_{M2}^2 - M_b^2} \quad , \quad j_{M2} > M_b$$ subinterval 3

$$\delta = \omega_0 t_3 = \tan^{-1}\left(\frac{M_b}{j_{M3}}\right)$$

$$\xi = \omega_0 t_4 = \frac{j_{M3} + j_{M4}}{M_b}$$ subinterval 4

$$j_{M5} = \sqrt{M_b^2 + j_{M4}^2}$$ subinterval 5

$$\zeta = \omega_0 t_5 = \tan^{-1}\left(\frac{M_b}{j_{M4}}\right)$$

$$j_{M0} = J + \sqrt{(j_{M5} - J)^2 - 1} \quad , \quad j_{M5} \geq 1 + J$$ subinterval 6

$$\psi = \omega_0 t_6 = \tan^{-1}\left(\frac{1}{j_{M0} - J}\right)$$

$$j_{M3} = j_{M4} \quad ; \quad j_{M2} = j_{M5} = M\pi/F$$ results of averaging

$$\omega_0 T_s = \frac{2\pi}{F} = \alpha + \beta + \delta + \xi + \zeta + \psi$$ switching period

$$\omega_0 D T_s = \zeta + \psi + \alpha = \omega_0 (t_5 + t_6 + t_1)$$ duty cycle definition

Solution requires computer iteration

Approximate results: $M \approx D$ output voltage

$$M_b \approx \frac{D}{1-D}$$ clamp capacitor voltage

$$\frac{M\pi}{F} \geq 1 + J$$ ZVS boundary

"Exact" solution for M_b:

$$M_b = \frac{M\pi}{F} \cdot \sin\left[\omega_0 D T_s - \sqrt{\left(\frac{M\pi}{F} + J\right)^2 - 1} + \sqrt{\left(\frac{M\pi}{F} - J\right)^2 - 1} + \sin^{-1}\left(\frac{1}{\left(\frac{M\pi}{F} - J\right)^2} \right) \right]$$

Peak magnetizing current is $j_{M2} = \frac{M\pi}{F}$