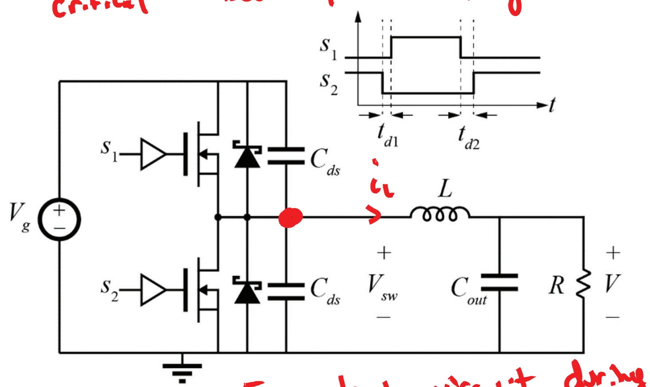
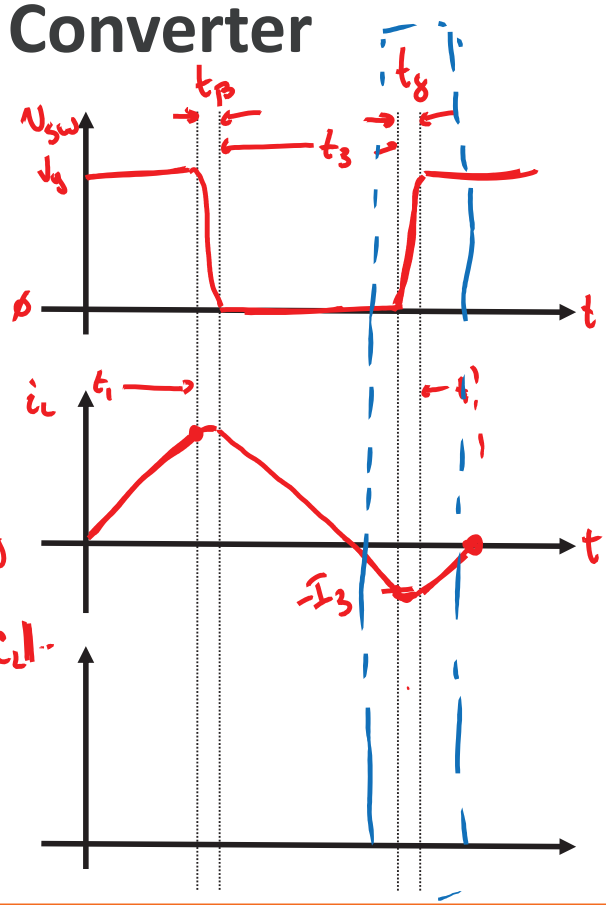
Synchronous Buck Converter

CRM BCM TCM

critical boundary Triangular



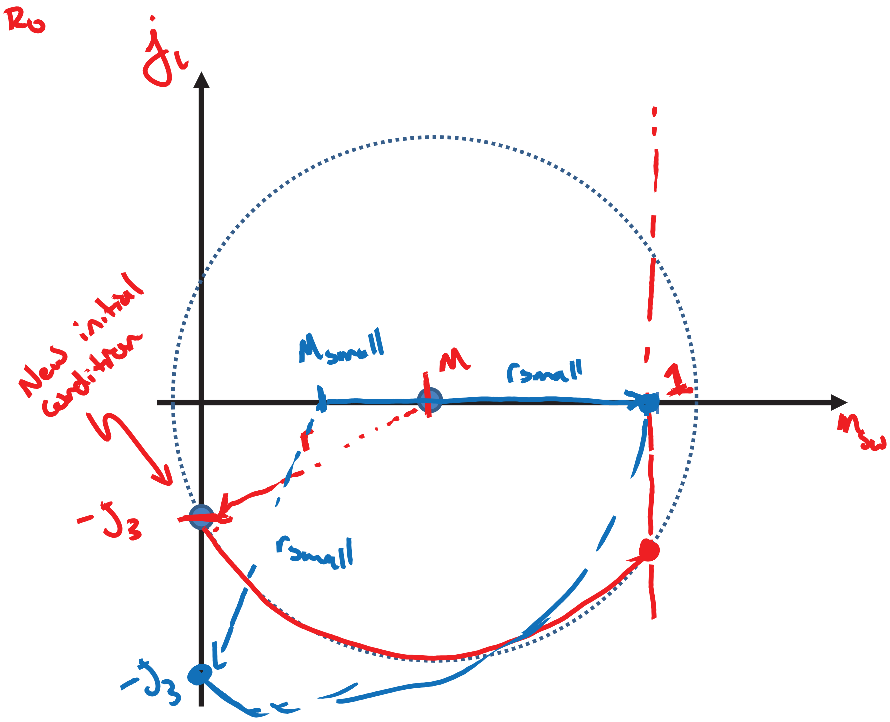


Equivalent circuit during dead times

$C_{sw} = C_{ds_1} \| C_{ds_2} \| C_L \| \ldots$

Sync-Buck State Plane (t_g interval)

$V_{base} = V_g \quad I_{base} = \frac{V_{base}}{R_0}$



Sync-Buck ZVS Condition (t_g interval)

To get ZVS, need

$$M + r \geq 1$$

$$\boxed{M + \sqrt{J_3^2 + M^2} \geq 1}$$

$$R_0 = \sqrt{\frac{L}{C_{sw}}}$$

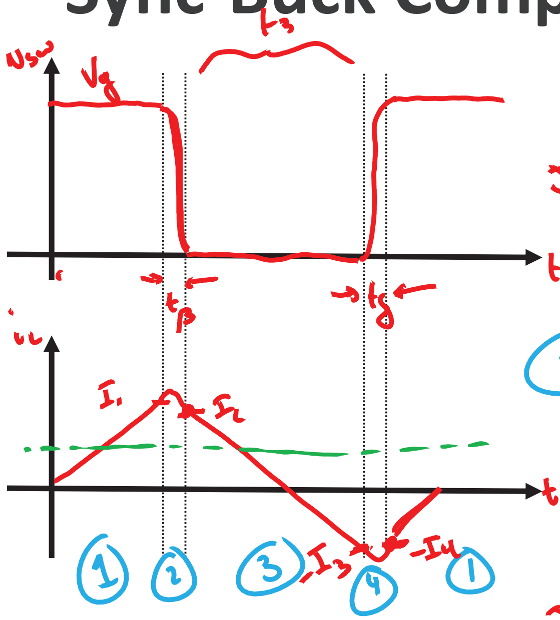
$$\frac{V}{V_g} + \sqrt{\left(\frac{I_3 R_0}{V_g}\right)^2 + \left(\frac{V}{V_g}\right)^2} \geq 1$$

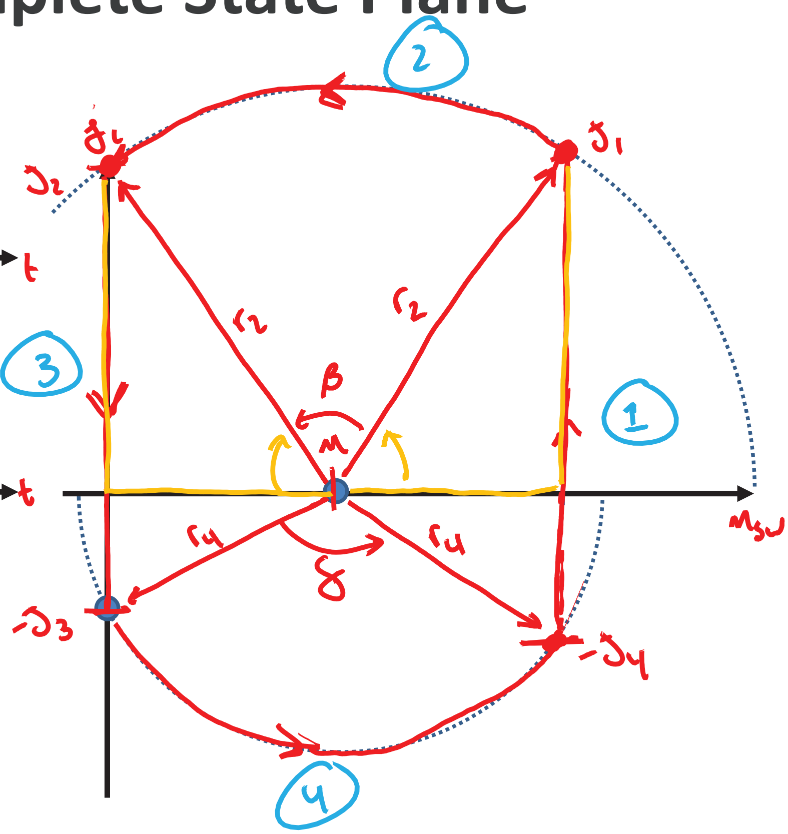
$$(I_3 R_0)^2 + V^2 \geq (V_g - V)^2$$

$$I_3^2 \frac{L}{C_{sw}} + V^2 \geq (V_g - V)^2$$

$$\frac{1}{2} L I_3^2 \geq \frac{1}{2} C_{sw} (V_g - V)^2 - \frac{1}{2} C_{sw} V^2$$

Sync-Buck Complete State Plane





(4) ZVS condition:

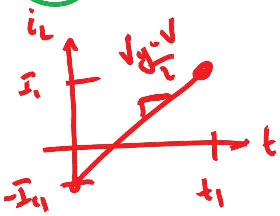
$$\sqrt{J_3^2 + m^2} + m \geq 1$$

(2) ZVS condition

$$\sqrt{J_2^2 + m^2} \geq m$$

State Plane Solution: Intervals 1 & 2

1 Non-resonant → equation comes from time-domain



$$\left(\frac{1}{I_{base}}\right)\frac{V_g - V}{L} t_1 = (I_1 + I_4)\left(\frac{1}{I_{base}}\right)$$

$$\frac{V_g - V}{V_g}\,\frac{R_0}{L}\, t_1 = J_1 + J_4$$

$$\boxed{(1-M)\,\theta_1 = J_1 + J_4}$$

$$\frac{R_0}{L} = \frac{\sqrt{L/C_{sw}}}{L} = \frac{1}{\sqrt{LC_{sw}}} = \omega_0$$

2 Resonant interval → get equations from state plane

$$\left\{\begin{array}{l} r_1^2 = J_1^2 + (1-M)^2 \\ r_2^2 = J_2^2 + M^2 \end{array}\right\}$$

$$\boxed{J_1^2 + (1-M)^2 = J_2^2 + M^2}$$

$$\boxed{\beta = \pi - \tan^{-1}\left(\frac{J_1}{1-M}\right) - \tan^{-1}\left(\frac{J_2}{M}\right)}$$

State Plane Solution: Intervals 3 & 4

3 Non-resonant

$$-\frac{V}{L} t_3 = -(I_2 + I_3)$$ normalize

$$\boxed{M\theta_3 = (J_2 + J_3)}$$

4 Resonant

$$\boxed{J_3^2 + M^2 = J_4^2 + (1-M)^2}$$

$$\boxed{\delta = \pi - \tan^{-1}\left(\frac{J_3}{M}\right) - \tan^{-1}\left(\frac{J_4}{1-M}\right)}$$

State Plane Solution: Averaging Step

$$I_{out} = \frac{1}{T_s}\int_0^{T_s} i_{out}(\tau)\,dt = \frac{1}{T_s}\int_0^{T_s} i_L\,dt$$

$$I_{out} = \frac{1}{T_s}\left[\underbrace{\int_0^{t_1} i_L(\tau)\,dt}_{1} + \underbrace{\int_{t_1}^{t_1+t_2} i_L(\tau)\,dt}_{2} + \ldots\right]$$

$$I_{out} = \frac{1}{T_s}\left[\underbrace{\frac{I_1 - I_4}{2}t_1}_{1} + \underbrace{\cancel{-q_c}}_{2} + \underbrace{\frac{I_2 - I_3}{2}t_3}_{3} + \underbrace{\cancel{q_c}}_{4}\right]$$

$$q_c = C_{sw} V_g$$