DCM/CCM Modes of Operation

CCM → Continous conduction Mode

- every example so far
- which switches conduct is controlled entirely by PWM signals

DCM → Discontinuous Conduction Mode

- At least one uncontrolled switching action
- some element's ripple is large enough to invert a polarity of a switching device's V_{off} or I_{on}, $ switch is unidirectional
- and some diode shuts off as a result
- Most common → $\Delta i_L > I_L$ $ some diode shuts off as a result

CRM/BCM/TCM → "Critical", "Boundary", "Triangular" conduction mode

CCM/DCM boundary

e.g. $\Delta i_L = I_L$

K_{crit} and R_{crit}

For Buck Converter

DCM will occur if $\Delta i_L > I_L$

CCM when $\Delta i_L < I_L$

$$\frac{V_g - V}{2L} D T_s < \frac{V}{R}$$

$$\cancel{D} T_s \frac{\cancel{V_g}(1-D)}{2L} < \frac{\cancel{D V_g}}{R}$$

CCM when $\boxed{D' < \frac{2L}{RT_s}} \longrightarrow \boxed{R < \frac{2L}{D'T_s}}$

$K_{crit}(D) < K = \frac{2L}{RT_s}$

$= D'$ for Buck converter

$R_{crit}(D)$

Small-Ripple Modifications in DCM

In DCM, by definition, some element has large ripple but can still be used elsewhere

- SRA must be dropped on that element, but $v(t) \approx V$

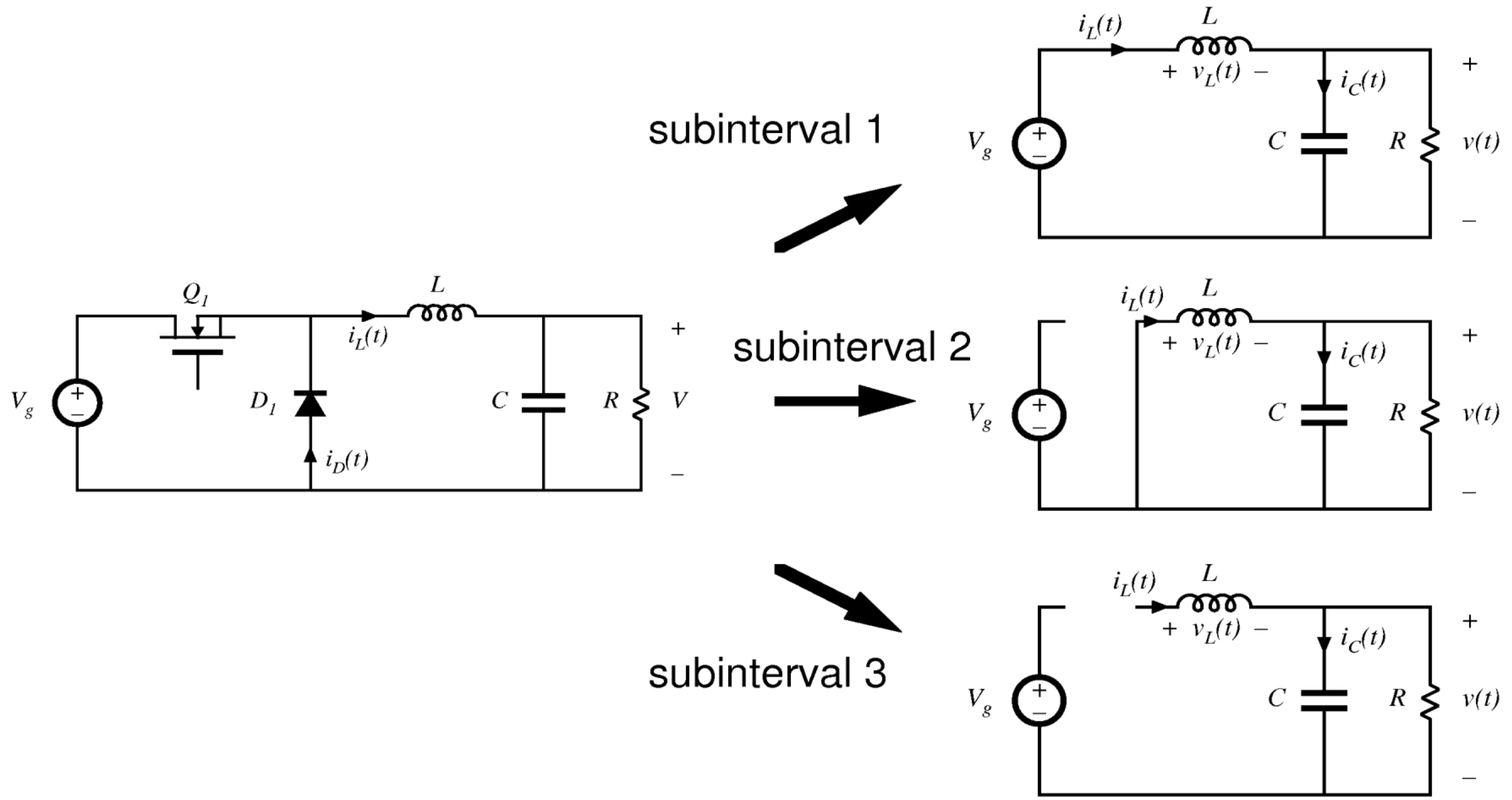
  e.g. in our DCM Buck $i_L(t) \neq I_L$

- Volt-second balance & cap charge balance still apply

$$\langle v_L \rangle = \frac{1}{T_s}\int_0^{T_s} v_L(t)\,dt = 0$$

$$\langle i_c \rangle = \frac{1}{T_s}\int_0^{T_s} i_c(t)\,dt = 0$$

Buck Converter in DCM



FET ON

$D_1T_s \rightarrow$ old DT_s

controlled by PWM signal

Diode ON

D_2T_s

time for $i_L(t) \rightarrow \emptyset$

Nothing ON

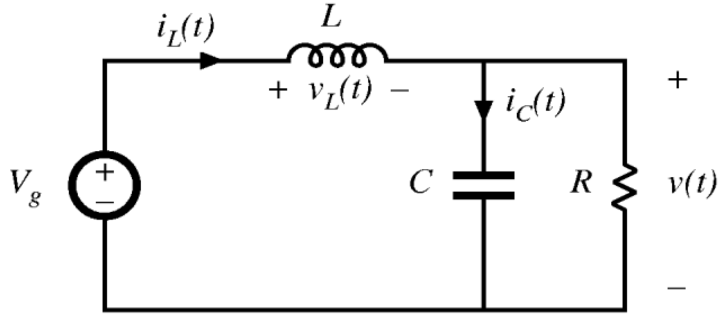
$D_3T_s = T_s - D_1T_s - D_2T_s$

Subinterval Analysis

$$v_L(t) = V_g - v(t) \xrightarrow[\text{SRA}]{} V_g - V$$

1

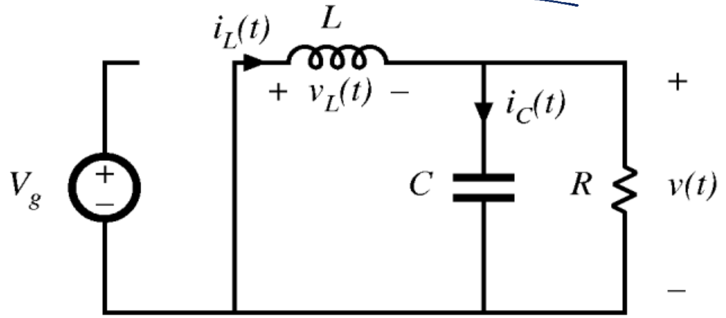
$$i_C(t) = i_L(t) - \frac{v(t)}{R} \xrightarrow[\text{SRA on } v(t) \text{ only}]{} i_L(t) - \frac{V}{R}$$



$$v_L(t) = 0 - v(t) \xrightarrow{\text{SRA}} -V$$

2

$$i_C(t) = i_L(t) - \frac{v(t)}{R} \xrightarrow{\text{SRA}^*} i_L(t) - \frac{V}{R}$$

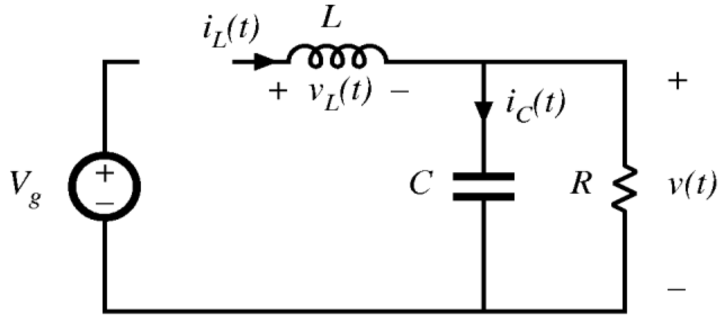


$i_L(t) = \phi$ in 3

$$v_L(t) = \phi$$

3

$$i_C(t) = i_L(t) - \frac{v(t)}{R} \xrightarrow{\text{SRA}^*} i_L(t) - \frac{V}{R} \longrightarrow -\frac{V}{R}$$



Waveforms in DCM

<u>Volt-sec Balance</u>

$$\langle v_L \rangle = 0 = D_1(V_g - V) + D_2(-V) + D_3(0)$$

$$0 = D_1 V_g - V(D_1 + D_2)$$

$$\boxed{V = V_g \frac{D_1}{D_1 + D_2}}$$

<u>Cap-Charge Balance</u>

$$\langle i_c \rangle = 0 = \frac{1}{T_s}\int_0^{T_s} i_c(t)\,dt = \frac{1}{T_s}\int_0^{T_s}\left(i_L(t) - \frac{V}{R}\right)dt$$

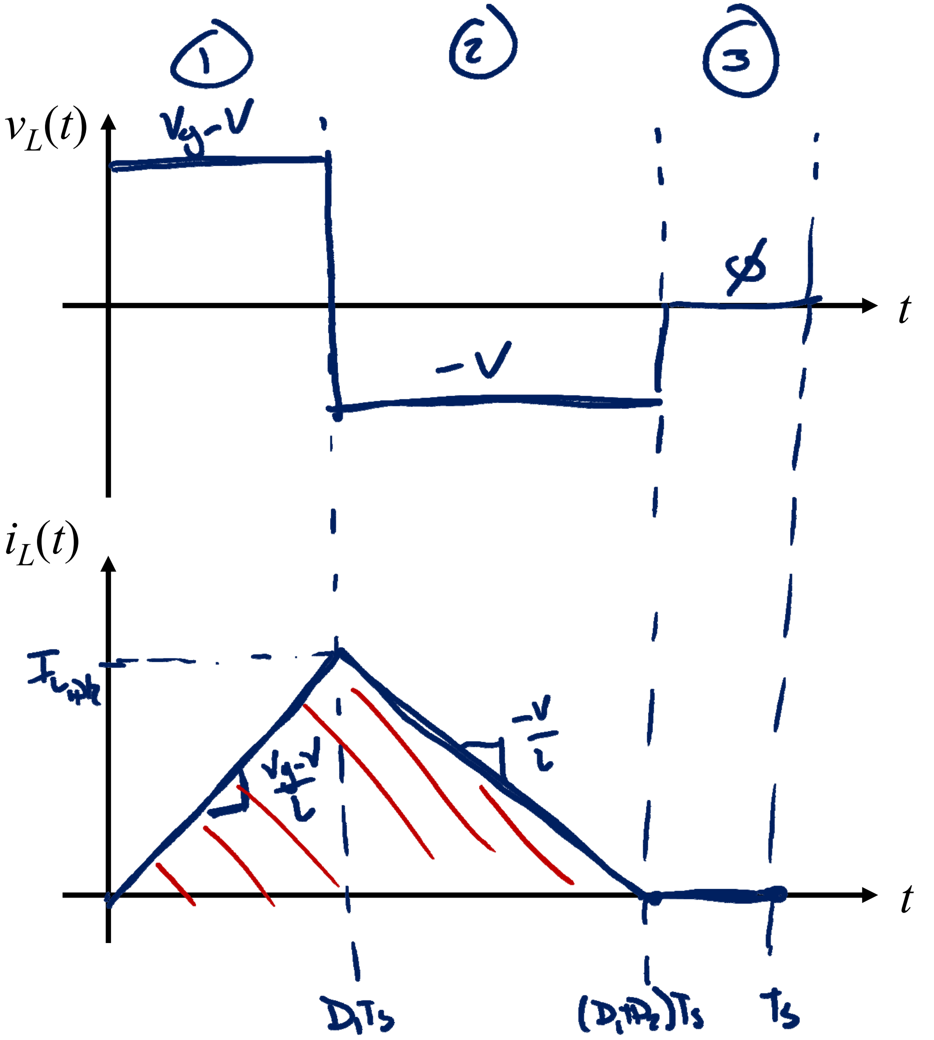
$$0 = \frac{1}{T_s}\int_0^{T_s} i_L(t)\,dt - \frac{V}{R}$$

$$0 = \frac{1}{T_s}\left[\frac{1}{2}(D_1 + D_2)T_s I_{L,pk}\right] - \frac{V}{R}$$

$$I_{pk} = \frac{V_g - V}{L} D_1 T_s$$

$$0 = \frac{1}{\cancel{T_s}}\left[\frac{1}{2}(D_1 + D_2)\cancel{T_s}\,\frac{V_g - V}{L} D_1 T_s\right] - \frac{V}{R}$$

$$\boxed{\frac{V}{R} = D_1 \frac{T_s}{2L}(D_1 + D_2)(V_g - V)}$$



$$V = V_g \frac{D_1}{D_1 + D_2}$$

$$V(D_1 + D_2) = V_g D_1$$

$$\boxed{D_2 = \frac{V_g}{V} D_1 - D_1}$$

$$V = D_1 \frac{RT_S}{2L} (D_1 + D_2)(V_g - V)$$

$$V = \frac{D_1}{k}\left(\cancel{D_1} + \frac{V_g}{V} D_1 - \cancel{D_1}\right)(V_g - V)$$

$$V = \frac{D_1^2}{k}\left(\frac{V_g^2}{V} - V_g\right)$$

$$\frac{k}{D_1^2} = V_g^2 \frac{1}{V^2} - V_g \frac{1}{V}$$

$$\emptyset = V_g^2 \left(\frac{1}{V}\right)^2 - V_g\left(\frac{1}{V}\right) - \frac{k}{D_1^2} \rightarrow \frac{1}{V} = \frac{V_g \pm \sqrt{V_g^2 - 4V_g^2\left(-\frac{k}{D_1^2}\right)}}{2V_g^2}$$

Recall: $k = \frac{2L}{RT_S}$

Solving $M(D,K)$

$$\frac{1}{V} = \frac{\cancel{V_g}}{V_g^{\cancel{2}}} \frac{1 \pm \sqrt{1 + 4\frac{K}{D^2}}}{2}$$

$$M(D,K) = \frac{V}{V_g} = \frac{2}{1 \pm \sqrt{1 + 4\frac{K}{D^2}}} \quad , \quad K = \frac{2L}{RT_s}$$