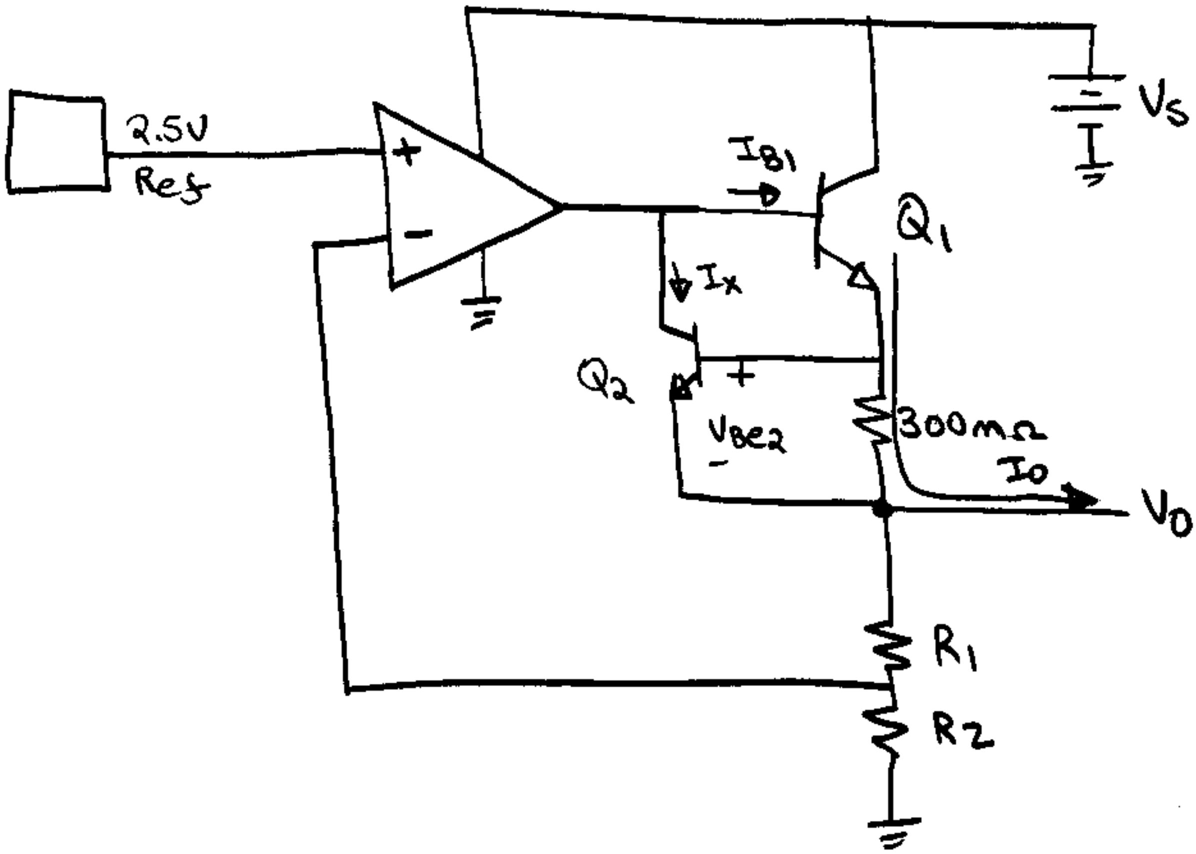
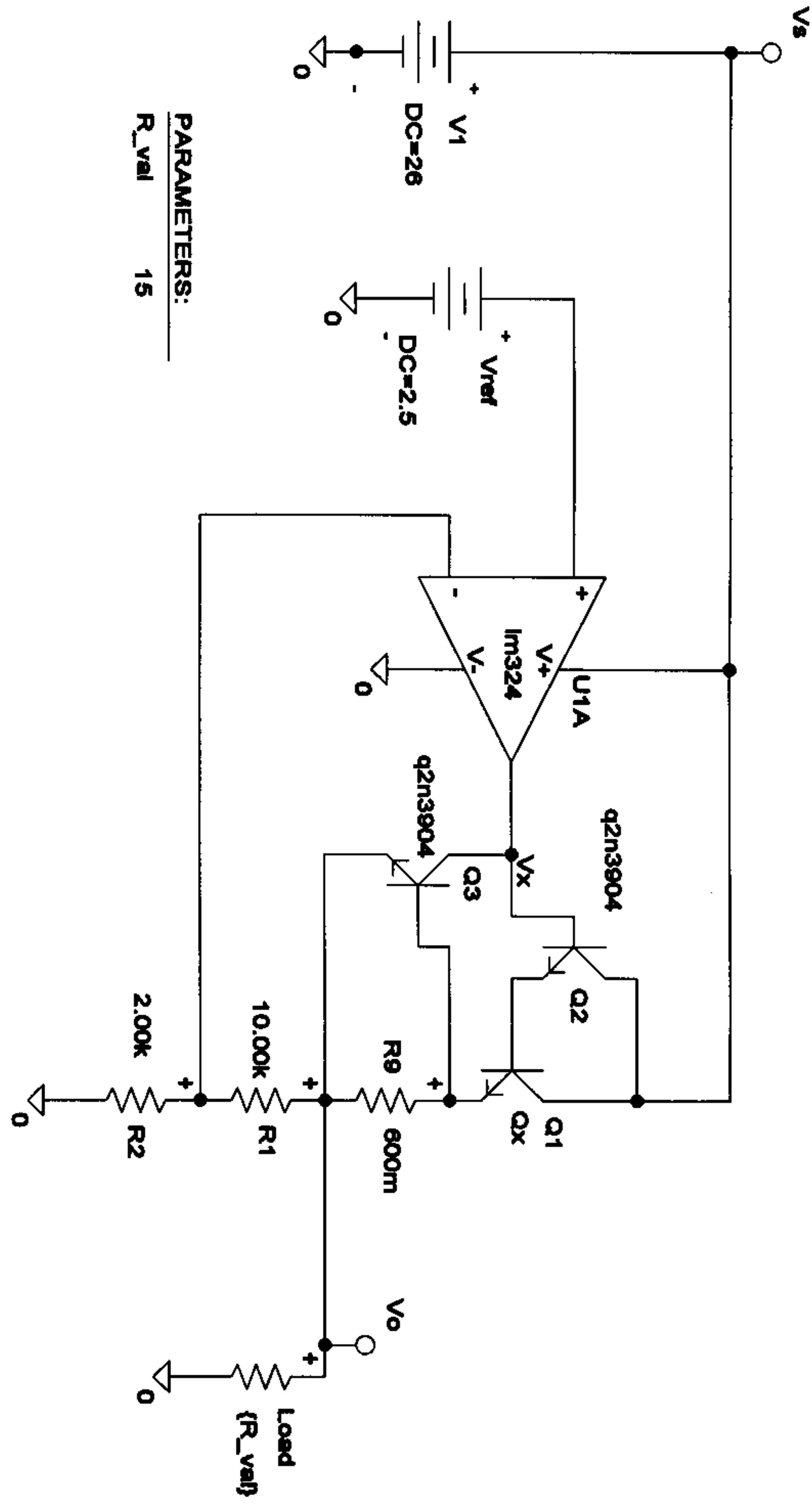
Short circuit Protection :



- when $I_o = 1A$, $V_{BE2} \cong 0.3V \Rightarrow I_x = 0$
- when $I_o > 1A$, $V_{BE2} > 0.3V$, I_x increases
- as $I_o\uparrow$, $I_x\uparrow$, $I_{B1}\downarrow \Rightarrow I_o\downarrow$

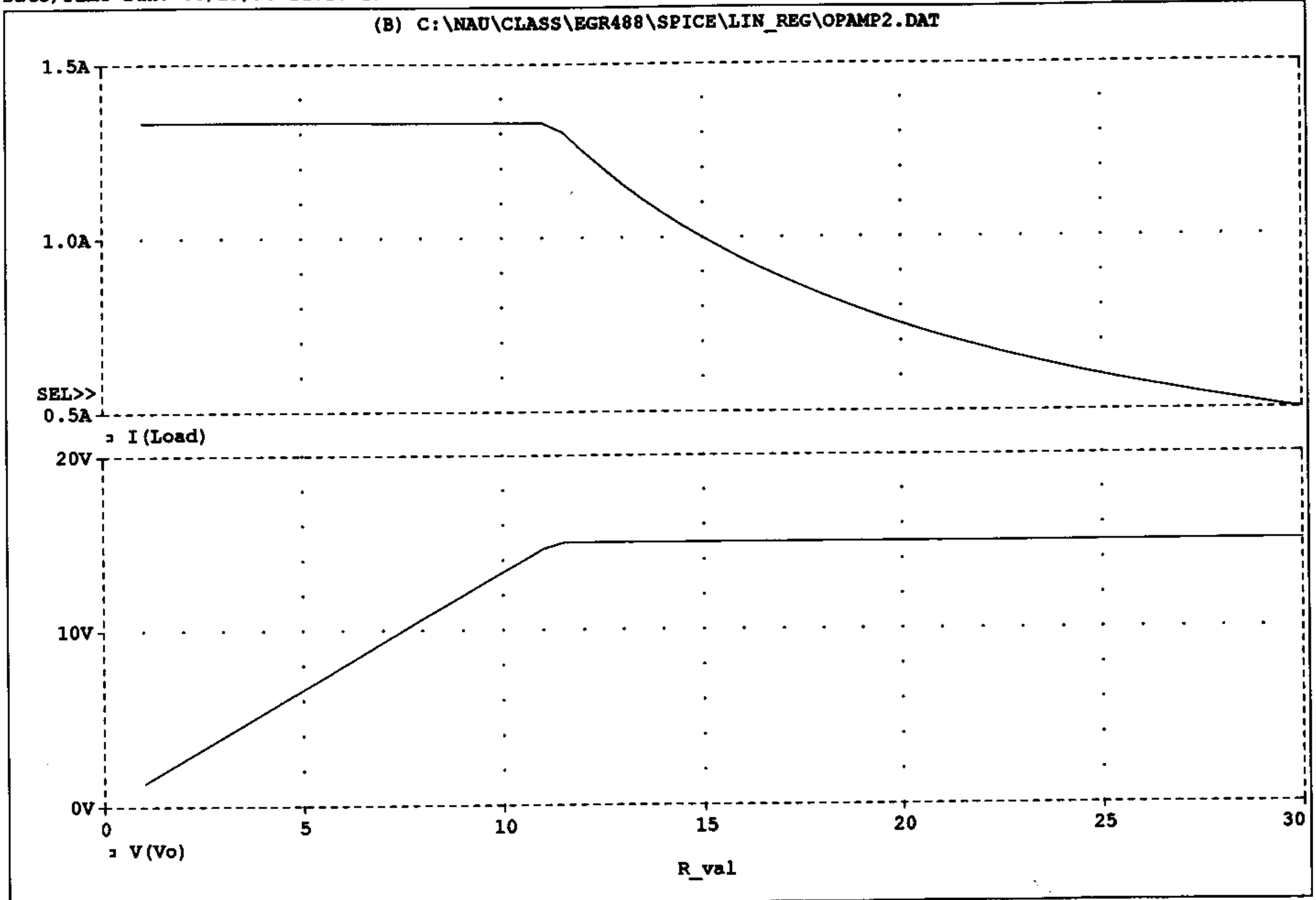
$\Rightarrow$ at some safe value of I_o The CKT stabilizes + I_o = const > 1A

57A


Vs
V1
DC=26
Vref
DC=2.5
PARAMETERS:
R_val 15
U1A
lm324
V+
V-
q2n3904
Q3
Vx
q2n3904
Q2
Q1
Qx
R9
600m
10.00k
R1
2.00k
R2
Vo
Load
{R_val}

* C:\NAU\CLASS\EGR488\SPICE\LIN_REG\OPAMP2.SCH

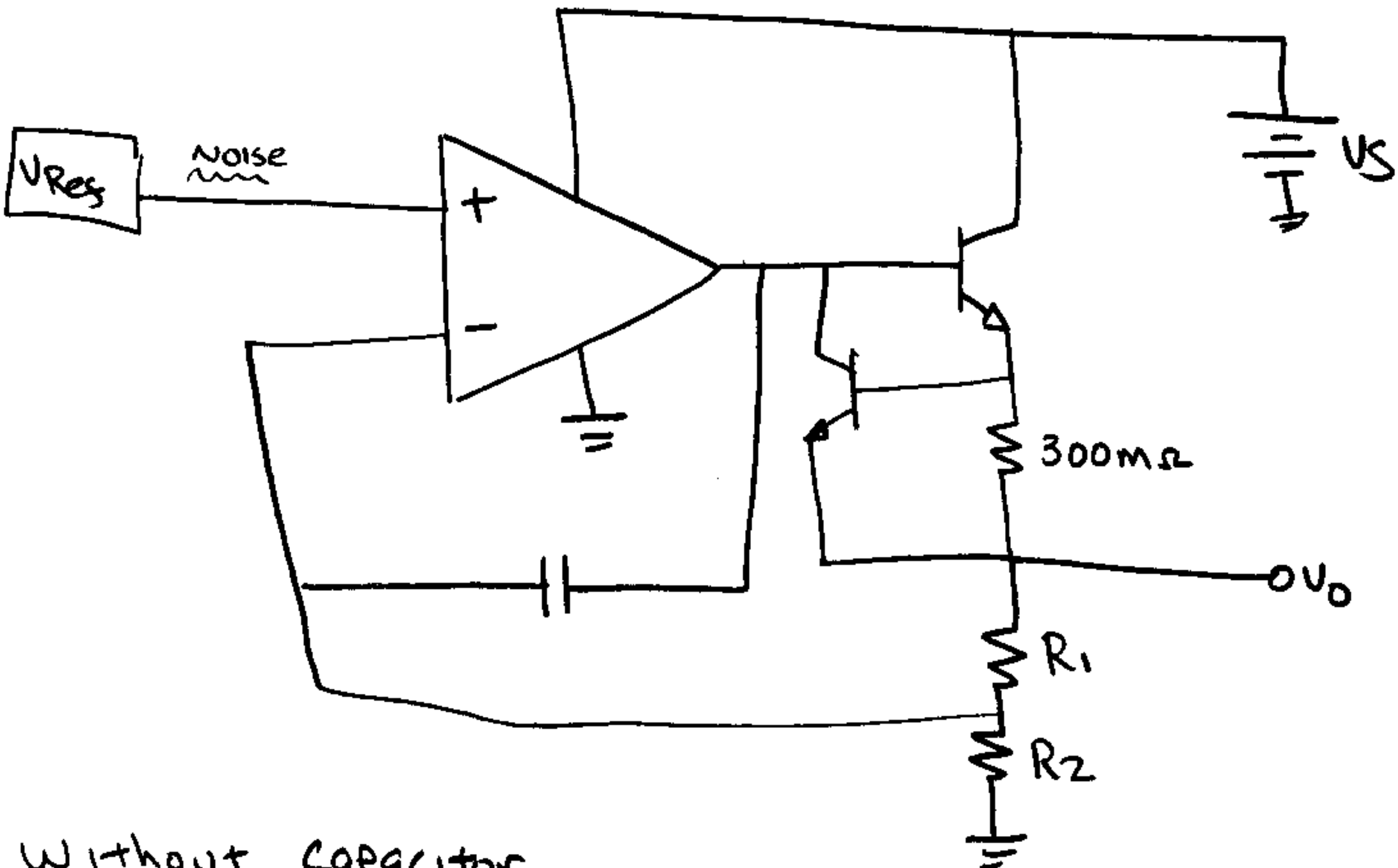
Date/Time run: 08/29/95 21:20:19 Temperature: 27.0



Date: August 29, 1995 Page 1 Time: 21:20:50

57B 56I

Frequency compensation



Without capacitor

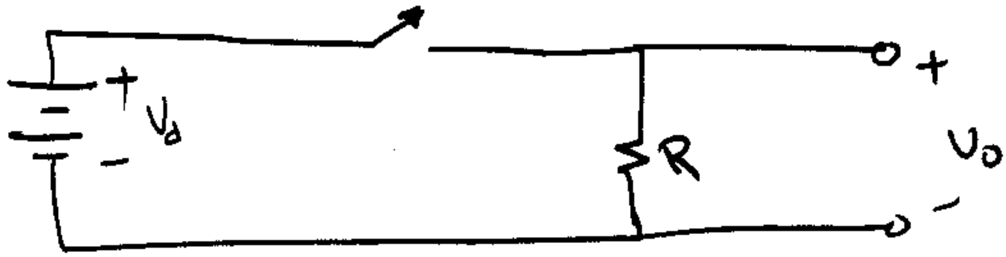
$$V_o = \left(1 + \frac{R_1}{R_2}\right)\left(V_{Ref} + \text{noise}\right) \quad ; \text{ without capacitor}$$

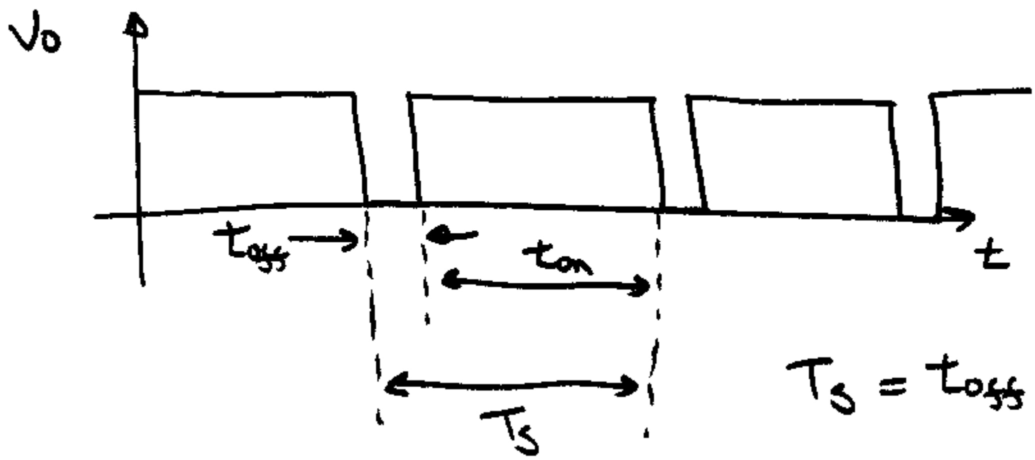
With capacitor

- Assume cap is short to noise
- Unity gain connection
- noise is not amplified by $1 + \frac{R_1}{R_2}$

DC - DC

Step Down Converter (Buck)





$T_s = t_{off} + t_{on} = \text{const}$

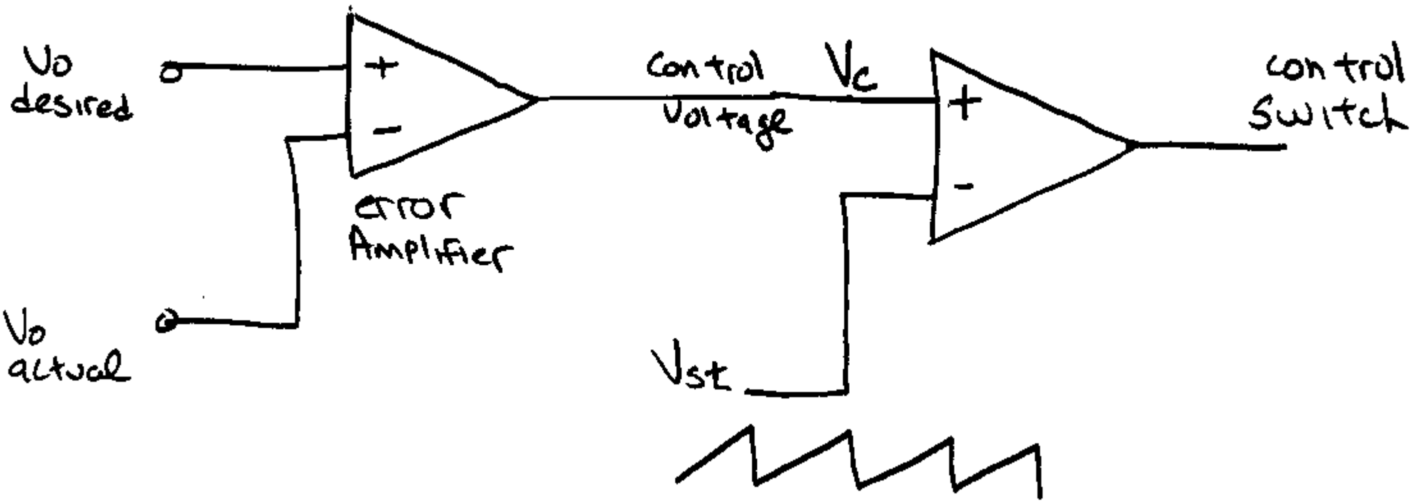
$$\langle V_o \rangle = \frac{1}{T_s}\int_{T_s} V_o(t)\,dt = \frac{1}{T_s}\int_0^{t_{off}} 0\cdot dt + \frac{1}{T_s}\int_{t_{off}}^{t_{on}+t_{off}} V_d\,dt$$

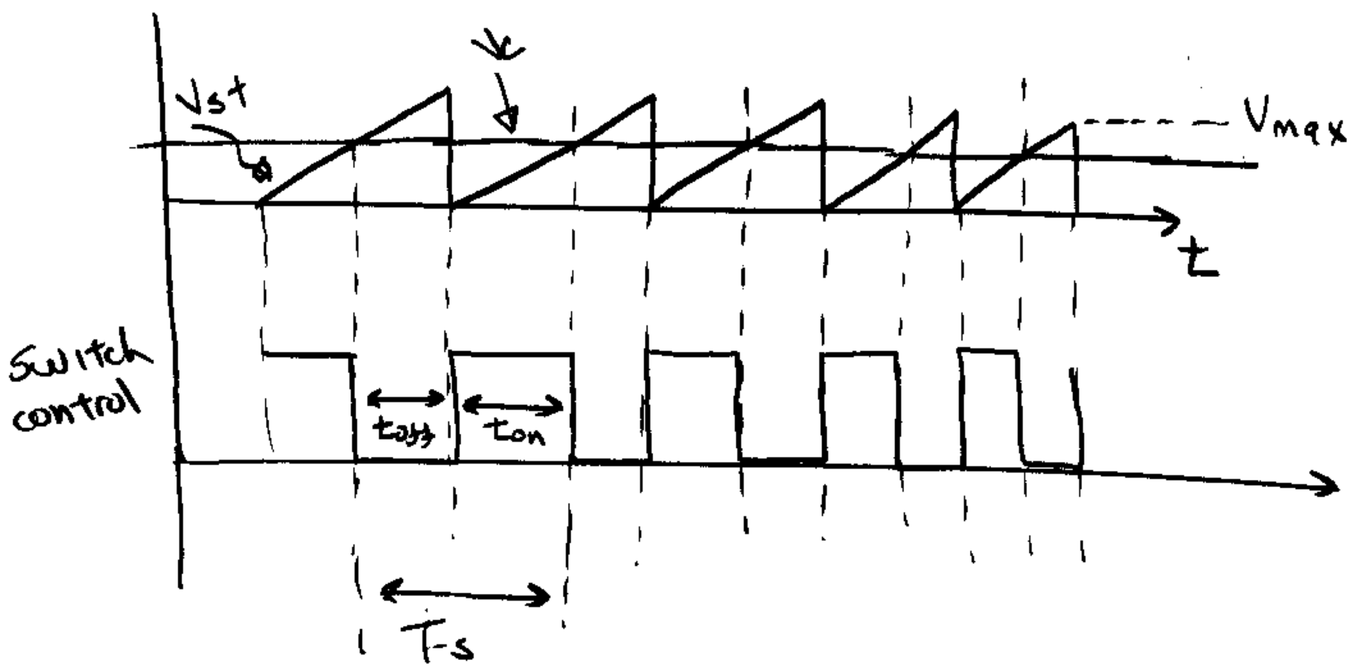
$$\boxed{\langle V_o \rangle = \frac{t_{on}}{T_s} V_d}$$

Let $D = \frac{t_{on}}{T_s}$ = duty Cycle

$\Rightarrow \langle V_o \rangle = D\,V_d$ $\Rightarrow$ V_o only depends on Duty Cycle, NOT Frequency

Control of DC-DC supply

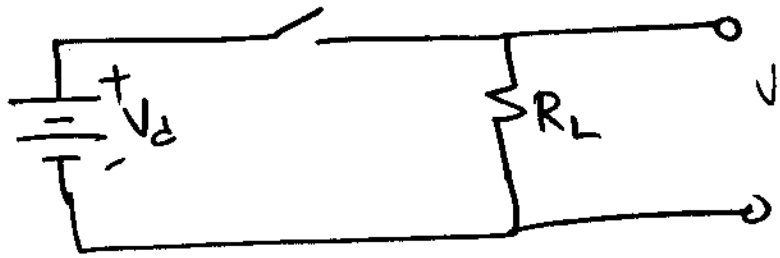




- Switching Frequency $F_s = \frac{1}{T_s}$

- as error increases, t_{on} increases

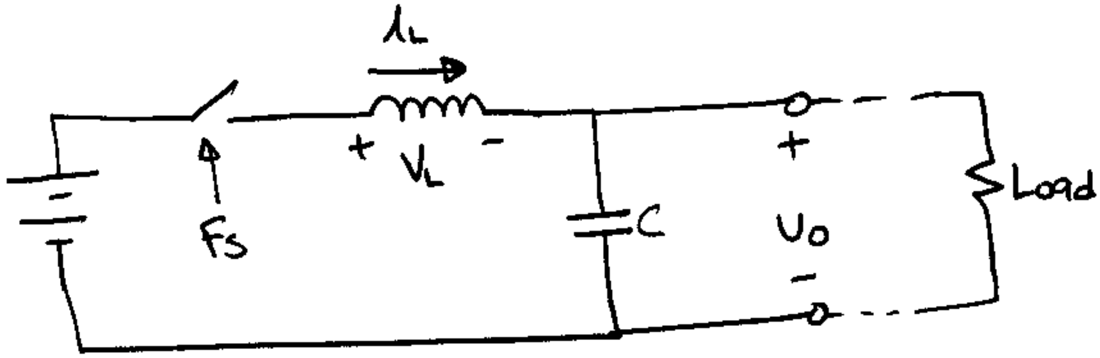
$$D = \frac{t_{on}}{T_s} = \frac{V_c}{V_{max}}$$



$V_o = \frac{t_{on}}{T_s} V_d = D V_d$

V_o has lots of ripple:

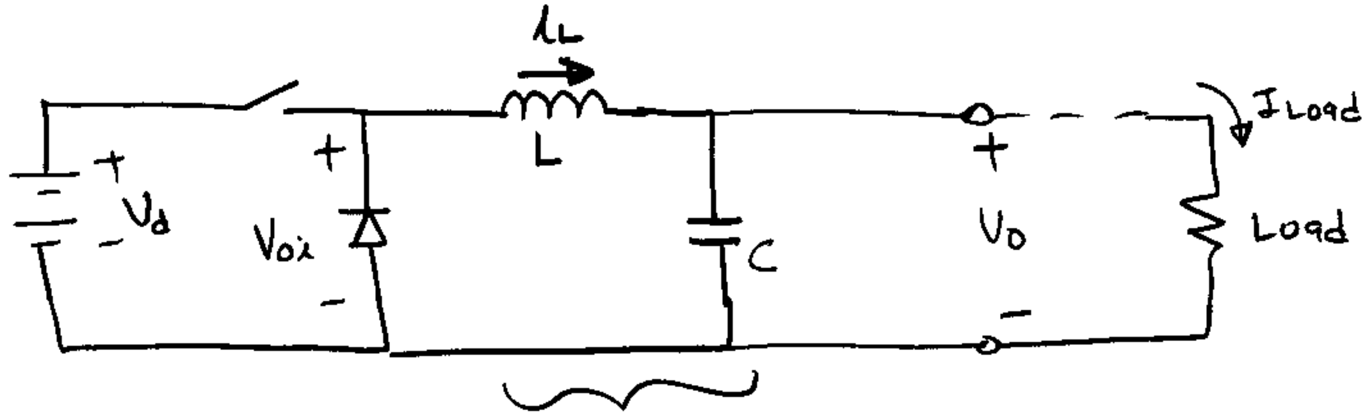
$\Rightarrow$ add a low pass filter



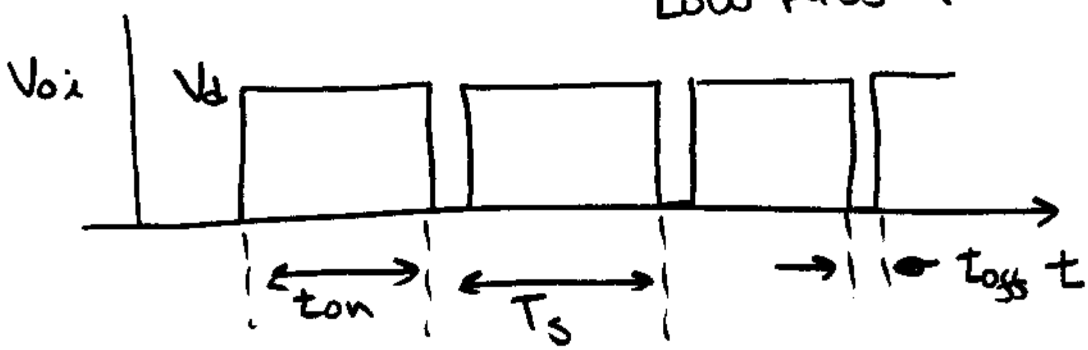
f_s = Switching frequency

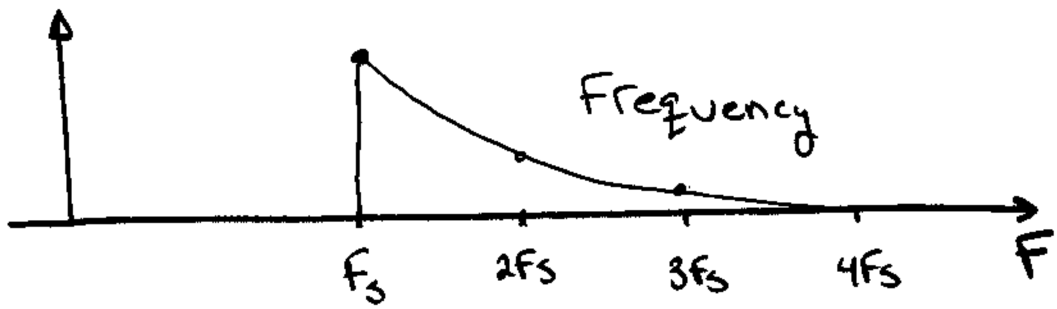
- What is the problem with this circuit?

- when switch opens, inductor current can not go to zero instantaneously.



Low pass Filter

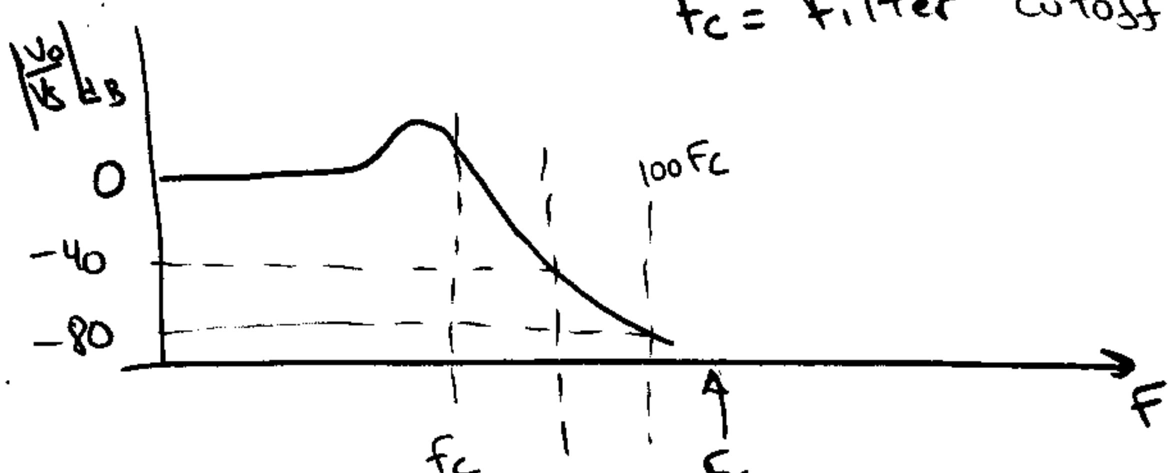




$F_s = \frac{1}{T_s}$

Low Pass Filter

F_c = Filter Cutoff Frequency



NOTE: $\langle I_L \rangle = \langle I_{Load} \rangle$

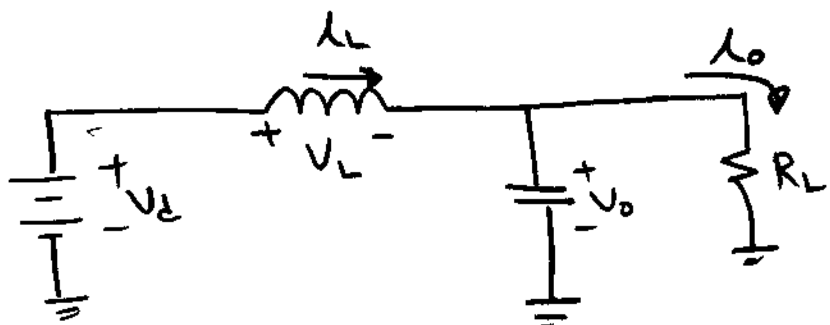
⇒ average inductor current = average output I

Continuous - Conduction mode

⇒ definition: inductor current never goes to ϕ.

⇒ $i_L(t) > 0$

When the switch is closed: t_{on}

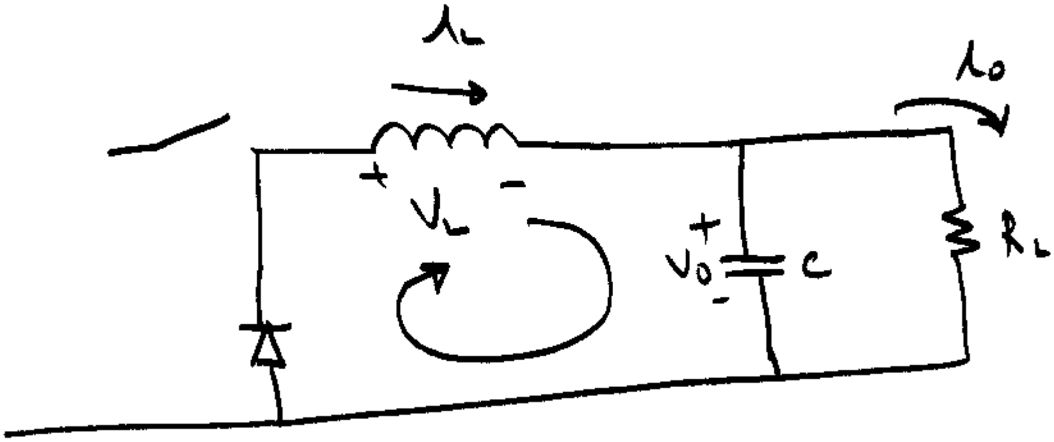


$V_L = V_d - V_o$

$$V_L = L\frac{di_L}{dt} \Rightarrow i(t) = \frac{1}{L}\int (V_d - V_o)\,dt$$

since $V_d - V_o > 0$, $i(t)$ increases with slope $\frac{V_d - V_o}{L}$

- During t_{off}, the switch is off current must continue to flow:



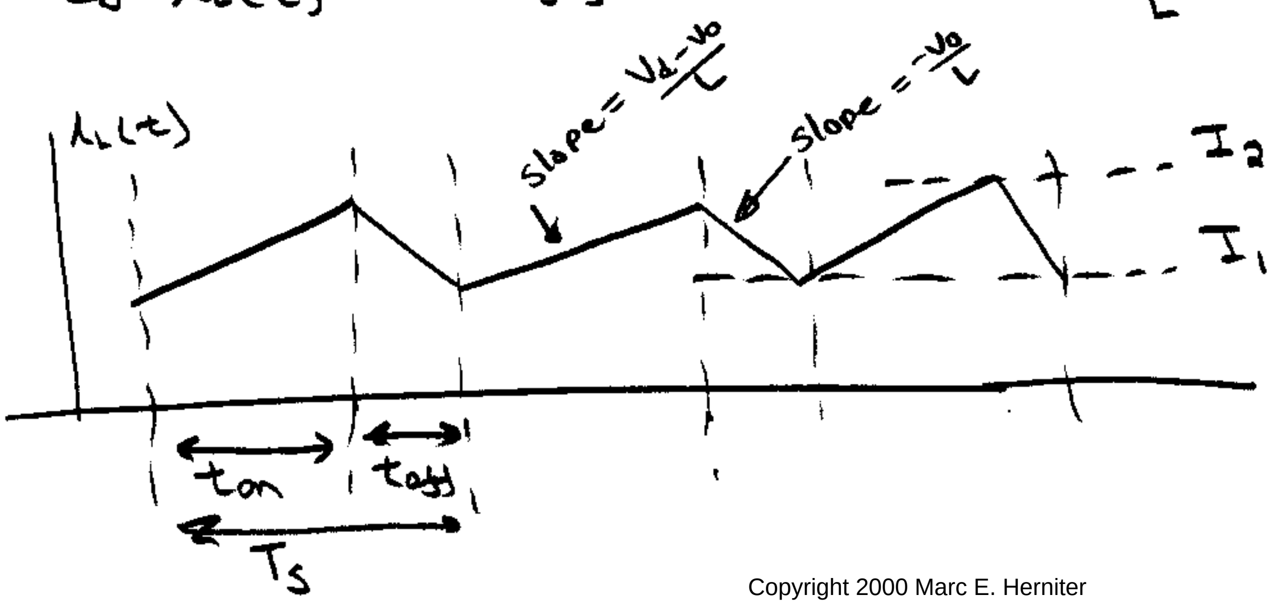
Assume the diode is ideal

$\Rightarrow V_L = -V_o$

$\Rightarrow V_L = L\frac{di_L}{dt} \Rightarrow i_L(t) = \frac{1}{L}\int V_L\,dt$

OR $i_L(t) = \frac{1}{L}\int -V_o\,dt$

$\Rightarrow i_L(t)$ decreases with slope $-\frac{V_o}{L}$



average output current = average $i_L(t)$

$$\langle i_o \rangle = \langle i_L(t) \rangle = \frac{I_2 + I_1}{2} = I_{Load}$$

In steady state, the average voltage $= 0$

why?

$$\int_0^T v_L \, dt = \int_0^{t_{on}} v_L \, dt + \int_{t_{on}}^T v_L \, dt = 0$$

$$= \int_0^{t_o} (V_d - V_o) \, dt + \int_{t_{on}}^T -V_o \, dt = 0$$

$$= (V_d - V_o) t_{on} + (-V_o)(T - t_{on}) = 0$$

$$\Rightarrow V_d t_{on} - V_o T = 0$$

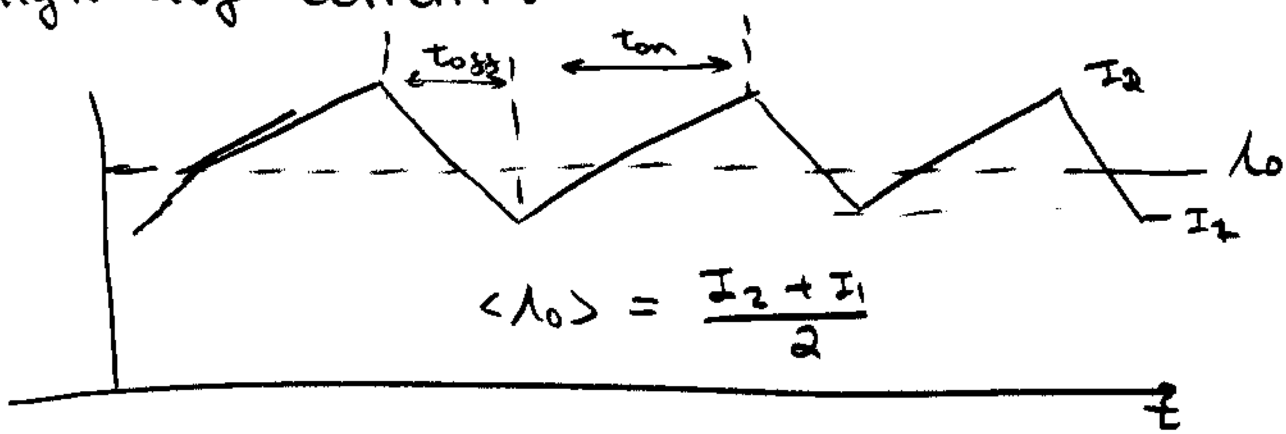
$$\Rightarrow \boxed{V_o = V_d \frac{t_{on}}{T}}$$

V_o is directly controlled by the Duty Cycle.

- For fixed V_o, V_D, $\frac{t_{on}}{T} = const$

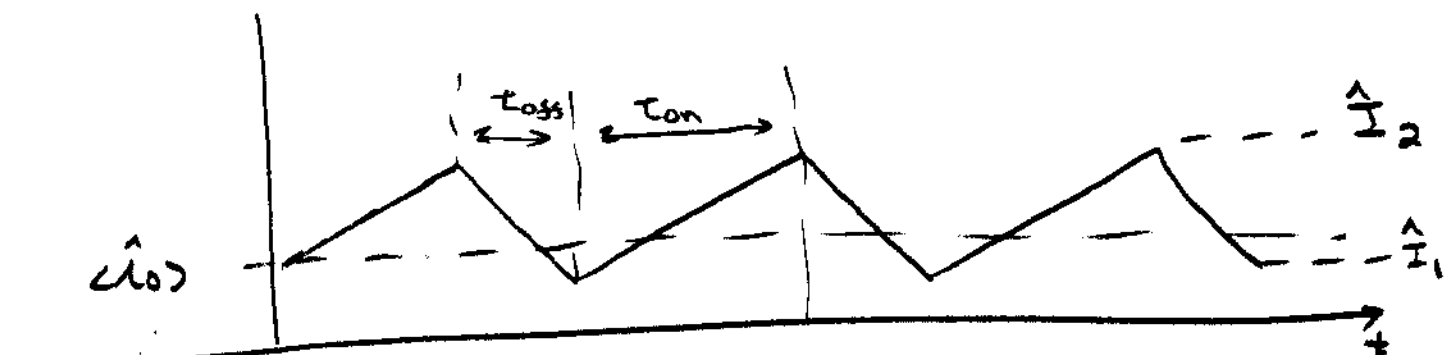
- as the current varries the ~~period~~ $D = const$, $V_o = Const$, $V_D = const$, independent of L

high avg current:



$$\langle i_o \rangle = \frac{I_2 + I_1}{2}$$

Low Avg current



$$\langle \hat{i}_o \rangle = \frac{\hat{I}_2 + \hat{I}_1}{2}$$

For high or low current $\hat{D} = D$

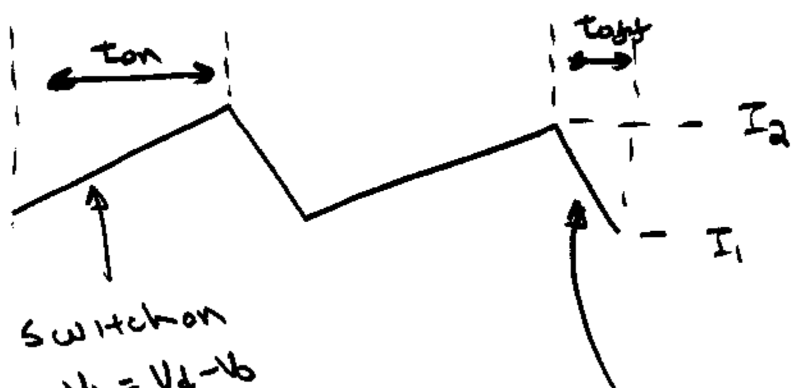
$\Rightarrow$ Same Duty Cycle

– Since the Duty cycles are the same and Voltages are the same

$$\hat{I}_2 - \hat{I}_1 = I_2 - I_1$$

⇒ For different average I_o, ΔI_L is the same.

– How do we find I_1 & I_2



$$i_L(t) = \underbrace{\frac{1}{L}\int_0^{t_{on}} (V_d - V_o)\,dt}_{\Delta i_L} + I_1$$

1

$$i_L(t) = \underbrace{\frac{1}{L}\int_{t_{on}}^{T} (-V_o)\,dt}_{\Delta i_L} + I_2$$

Use equation 1

$$i_L(t) = \frac{1}{L}\int_0^t (V_d - V_o)\,dt + I_1$$

@ $t = t_{on}$, $i_L(t_{on}) = I_2$

$$I_2 = \frac{1}{L}\int_0^{t_{on}} (V_d - V_o)\,dt + I_1$$

$$\Rightarrow \boxed{(I_2 - I_1) = \left(\frac{V_d - V_o}{L}\right) t_{on}} \quad \text{1A}$$

Use equation 2

$$i_L(t) = \frac{1}{L}\int_{t_{on}}^{T} -V_o\,dt + I_2$$

@ $t = T$, $i_L(t) = I_1$

$$I_1 = \frac{1}{L}\int_{t_{on}}^{T} -V_o\,dt + I_2$$

$$I_1 - I_2 = \frac{-V_o}{L}(T - t_{on})$$

in continuous mode $V_o = \frac{t_{on}}{T} V_d$

$$\Rightarrow \quad T = t_{on} \frac{V_d}{V_o}$$

$$I_1 - I_2 = \frac{-V_o}{L}\left(\frac{t_{on} V_d}{V_o} - t_{on}\right)$$

$$I_1 - I_2 = \frac{1}{L}\left(-t_{on} V_d + t_{on} V_o\right)$$

$$\Rightarrow \quad I_2 - I_1 = \frac{1}{L}(V_o - V_d)\, t_{on}$$

— Same as eq 1A on previous page

ALSO

$$\boxed{\frac{I_2 + I_1}{2} = I_o}$$

Avg output current = Avg inductor current

In continuous mode

① $V_o = \frac{t_{on}}{T} V_d = D V_D$

② $I_2 - I_1 = \frac{V_d - V_o}{L} t_{on}$

③ $\frac{I_1 + I_2}{2} = I_o$ – Avg output current

The current is continuous if $I_1 > 0$
– find condition when circuit operates in the continuous mode

Find I_1:

$$I_1 - I_2 = \frac{V_o - V_d}{L} t_{on} \quad ②$$

$$I_1 + I_2 = 2 I_o \quad ③$$

Add

$$2 I_1 = \left(\frac{V_o - V_d}{L}\right) t_{on} + 2 I_o$$

Solve for $I_1 = 0$

$$2I_1 = \left(\frac{V_o - V_D}{L}\right)T_{on} + 2I_o = 0$$

$$t_{on}\left(\frac{V_o - V_D}{L}\right) + 2I_o = 0 \quad \Rightarrow \quad \boxed{I_o = \left(\frac{V_D - V_o}{2L}\right)t_{on}}$$

So $I_1 > 0$ if $I_o > \left(\frac{V_D - V_o}{2L}\right) t_{on}$

so for continus mode

$$\boxed{\begin{aligned} V_o &= \frac{t_{on}}{T} V_D = D\,V_D \\ I_2 - I_1 &= \frac{V_d - V_o}{L} t_{on} \\ \frac{I_1 + I_2}{2} &= I_o \\ I_o &> \left(\frac{V_D - V_o}{2L}\right) t_{on} \end{aligned}}$$

as I_o changes, $D = \text{const}$