

1 Two-switch Forward Converter

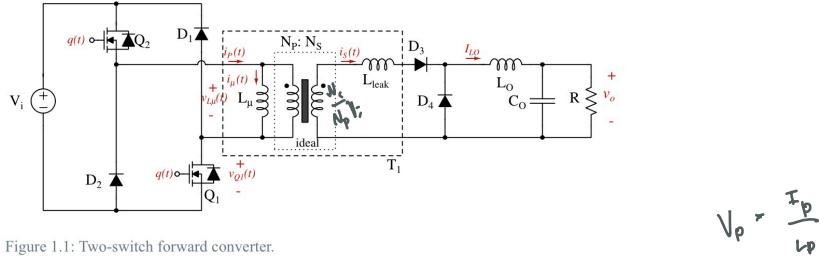
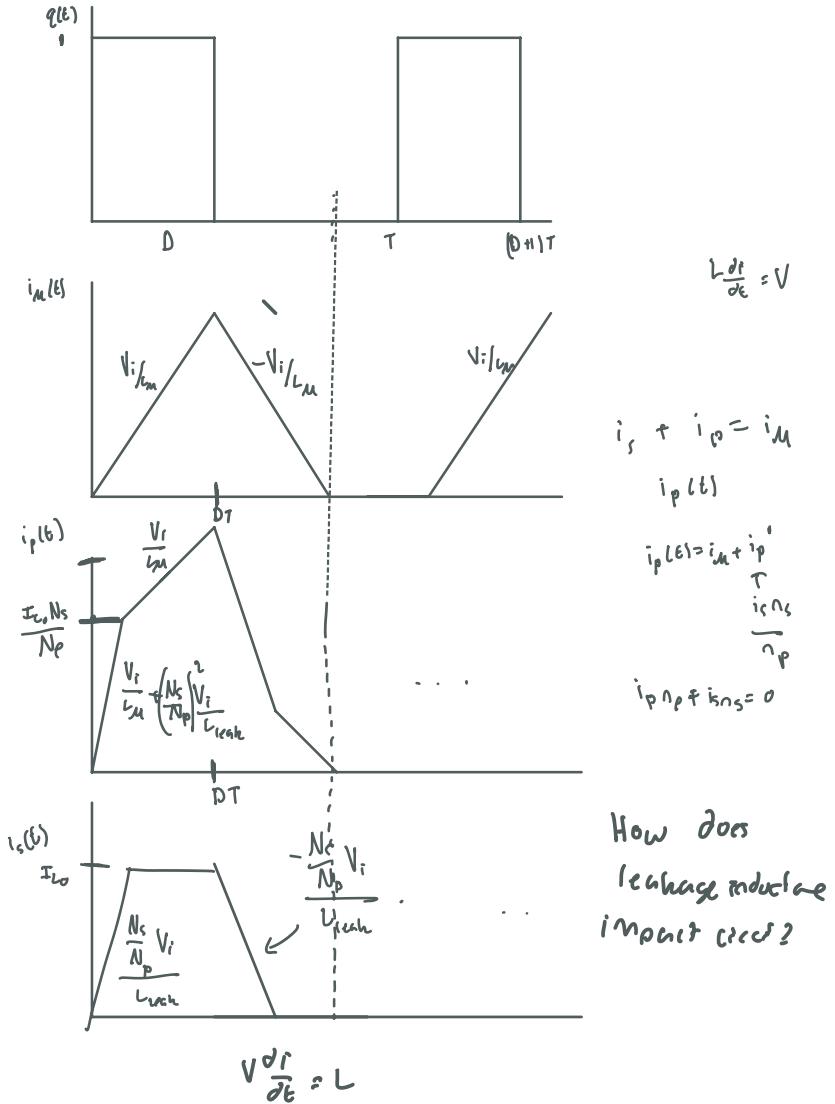


Figure 1.1: Two-switch forward converter.

Consider the two-switch forward converter in Figure 1.1. The two switches Q_1 and Q_2 are turned on-off at the same time. You may assume the converter operates in CCM and that L_O is large enough to make the current I_{LO} constant.

- Sketch the waveforms of $q(t)$, $i_p(t)$, and $i_s(t)$ of the figure. L_{leak} models the leakage inductance in the transformer. Mark and label key features of the waveforms.



- Simulate the circuit of [Figure 1.1](#) in LTspice assuming $V_i = 50$ V, $f_s = 100$ kHz, $D = 0.25$, $N_P = 14$, $N_S = 7$, $L_\mu = 125 \mu\text{H}$, and $I_{LO} = 10$ A.
 - You can consider all the devices (except the transformer) as ideal.

$$NV_i(0^+) \\ (NV_i - V_o)D + V_o(0')T = 0 \\ 1 - D - D$$

$$NV_i D = V_o \\ ND = \frac{V_o}{V_i}$$

$$N = \frac{N_S}{N_P} = \frac{1}{2} \\ \frac{1}{2} \left(\frac{1}{4} \right) = \frac{V_o}{V_i}$$

$$\frac{1}{8} = \frac{V_o}{V_i} \\ \frac{1}{8} = \frac{V_o}{50}$$

$$6.25 = V_o$$

$$\angle I_{lo} + \angle f_c = \angle I_o$$

$$\angle I_{lo} = \angle I_o$$

$$\frac{V_o}{I_o} = R_o = \frac{6.25}{10} = 0.625 \Omega$$

No voltage ripple specs, so just use large C_o

No current ripple specs " " " " large b_o

$$\frac{V_p}{14} = \frac{V_S}{7}$$

$$V_p = 2V_S$$

- In one page, plot 4 cycles of $i_\mu(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and V_{D4} when $L_{leak} = 0$.

See bottom

- What is the maximum voltage across $v_{Q1}(t)$?

50V (see bottom)

- What is the maximum and minimum of the magnetizing current $i_\mu(t)$? (only one trace per plot please).

Min: 0A (theoretical) Actual min: -0.1mA
 Max: $\frac{V_i}{L_\mu} DT = 1$ A (theoretical) Actual max: 998.5 mA

See bottom

- In one page, plot 4 cycles of $i_\mu(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and V_{D4} when $L_{leak} = 500$ nH.

see bottom

2 Push-pull converter

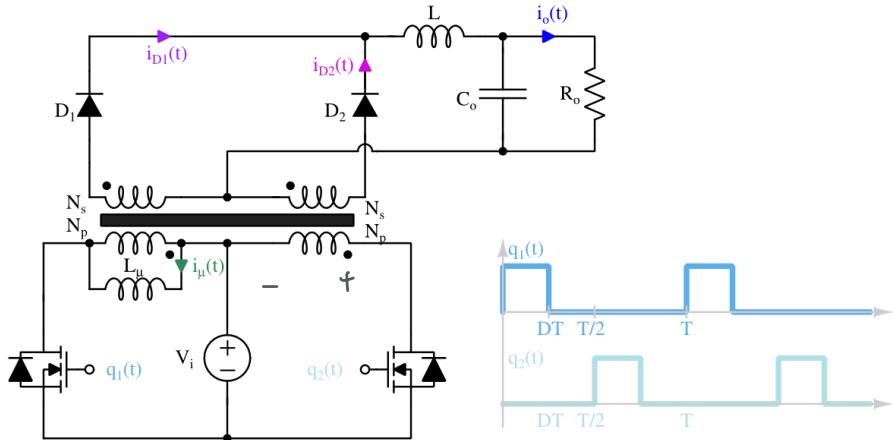
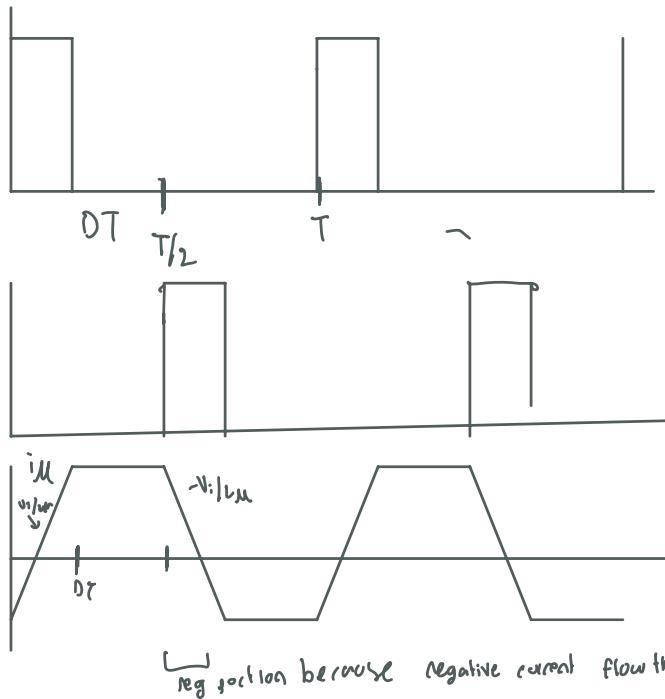


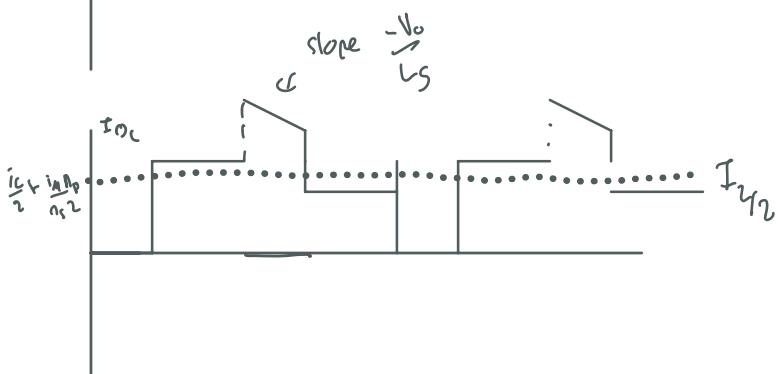
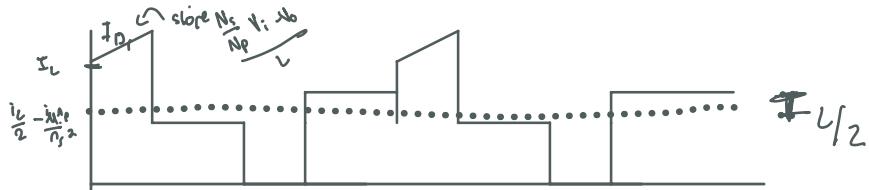
Figure 2.1: Push-pull converter.

Consider the push-pull converter of [Figure 2.1](#). Assume loss-less components and an duty ration of $D = 0.25$. The transformer has a finite magnetizing inductance L_μ .

- Draw the waveforms of $i_\mu(t)$, $i_{D1}(t)$ and $i_{D2}(t)$ for the large load case where $\frac{N_s}{N_p} i_o \gg i_\mu$.



Why start at neg? Need current flow when all switches are off. First cycle positive, then becomes negative. Symmetrical or



When q_1 & q_2 are diff

$$\begin{aligned} i_p &= i_M + i_p' = 0 \\ n_p i_p' - n_s i_{D1} + n_s i_{D2} &= 0 \\ 0 &= -i_M n_p - n_s i_{D1} + n_s i_{D2} \end{aligned}$$

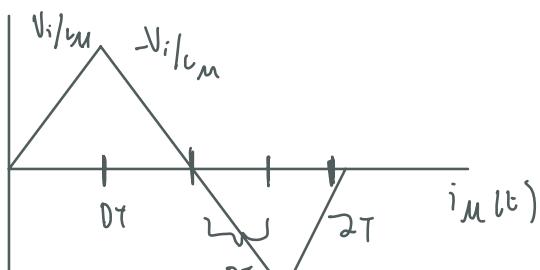
$$i_L = i_{D1} + i_{D2} \text{ to split equally}$$

$$i_L = \frac{i_M n_p + n_s i_{D1}}{n_s} + i_{D2}$$

$$\left\{ \begin{array}{l} \frac{i_L}{2} = \frac{i_M n_p}{n_s 2} = i_{D1} \\ \frac{i_L}{2} + \frac{i_M n_p}{n_s 2} = i_{D2} \end{array} \right.$$

$$\frac{N_s}{n_p} i_0 \gg i_M$$

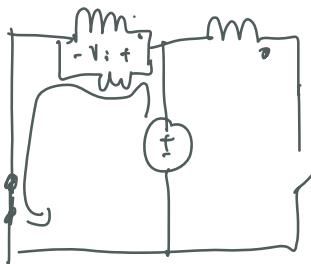
- At light load as $i_o \Rightarrow 0$ draw the magnetizing current $i_\mu(t)$. How does $i_\mu(t)$ at light load compares to the magnetizing current at heavy load?, which one is larger? Explain.



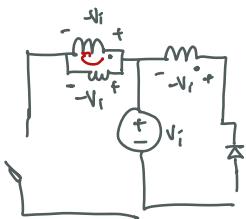
left w/ bottom of circuit
because top basically doesn't turn

$i_\mu(t)$ at light loads is 2x as large

because it starts at 0 & goes up $\frac{V_o/2M}{L}$
 $i_\mu(t)$ at full loads starts at $\sim \frac{V_o/2M}{L}$

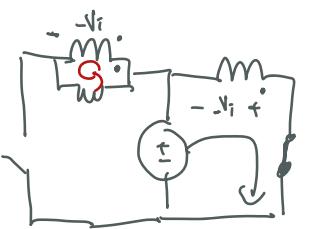


The current goes through L_m , is not reflected to the transformer bc the MOSFET does not allow current to flow initially.

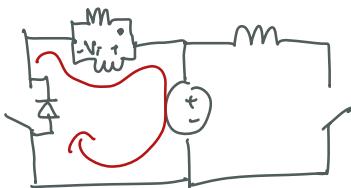


The mag current reflects to the other primary winding. The current flows across the winding. There is $-V_i$ reflected to second primary and the second loop is reverse $-V_i + V_i$ allowing current to flow in the diode

$$\begin{aligned} -V_i - V_p &= 0 \\ -V_i &= V_p \end{aligned}$$



The current goes through the secondary winding. It induces a voltage $-V_i$ on the inductor. The inductor catches the current



Current in L_m can't change immediately. Therefore, it continues to flow. V_i in L_m and $V_{Lm} - V_i = 0$

3 Forward Converter with Active Clamp

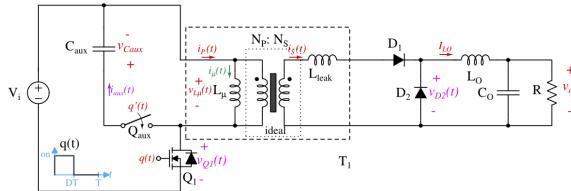


Figure 3.1: Forward converter with active clamp.

[Figure 3.1](#) shows a forward converter with active clamp. The main switch Q is modulated ON/OFF with a duty cycle D . The auxiliary switch Q_{aux} is turned ON/OFF oppositely to the main switch (while avoiding shoot-through of course). The function of the clamp circuit (comprising Q_{aux} and C_{aux}) is to reset the transformer core.

- Assuming operation in PSS and CCM, what is the voltage C_{aux} as function of V_i and D ?

When $q(t)=1$

$$V_{L\mu} = V_i \quad \frac{V_i}{V_{L\mu}} = \frac{d_i}{d_b}$$

When $q(t)=0$

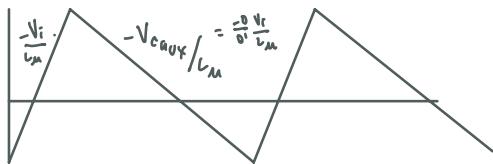
$$V_{L\mu} = -V_{aux} \quad \frac{-V_{aux}}{V_{L\mu}} = \frac{d_b}{d_i}$$

$$V_i D + -V_{aux}(1-D) = 0$$

$$\frac{V_i D}{1-D} = V_{aux}$$

- Sketch the magnetizing inductance current $i_{L\mu}$ when $V_i = 50$ V, $D = 0.25$,

- $f_s = 100$ kHz, $N_p = 14$, $N_s = 7$, $L_\mu = 125 \mu\text{H}$, $I_{LO} = 10$ A.
For this part, you can ignore L_{leak} , and assume C_{aux} is large.



goes to neg so
cap can fully discharge (PSS)
 $C_{ic} > 0$

- Simulate the converter in [Figure 3.1](#) in LTspice and plot assuming $V_i = 50$ V, $f_s = 100$ kHz, $D = 0.25$, $N_P = 14$, $N_S = 7$, $L_\mu = 125 \mu\text{H}$, and $I_{LO} = 10$ A. Make $C_{aux} = 10 \mu\text{F}$ and assume it has an $ESR = 100 \text{ m}\Omega$. - You can consider all the devices (except the transformer and C_{aux}) as ideal.

Look at bottom

same calcs for R as top

- In one page, plot 4 cycles of $i_{aux}(t)$, $i_\mu(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and $v_{D2}(t)$ when $L_{leak} = 0$. What is the maximum voltage across $v_{Q1}(t)$? What is the maximum and minimum magnetizing current $i_\mu(t)$? (only one trace per plot please)

Look at word doc

[sim]

Max voltage across $v_{Q1}(t) = 66.85$

Maximum $i_M = 500.58 \text{ mA}$

Minimum $i_M = -500.05 \text{ mA}$

calcs

$$V_i + V_{C_{aux}} = \frac{V_i}{D} = 66.667 \text{ V}$$

$$\text{Max } i_M = \frac{\Delta i_M}{2} = 500 \text{ mA}$$

$$\text{Min } i_M = -\frac{\Delta i_M}{2} = -500 \text{ mA}$$

Also on bottom

$$\Delta i_M = \frac{V_i}{L_M} \cdot DT = 1 \text{ A}$$

- In one page, plot 4 cycles of $i_\mu(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and $v_{D2}(t)$ when $L_{leak} = 500 \text{ nH}$. What is the maximum voltage across $v_{Q1}(t)$? What is the maximum and minimum of the magnetizing current $i_\mu(t)$? (only one trace per plot please)

Max voltage across $v_{Q1}(t) = 66.48 \text{ V}$

Max $i_M = 330.67 \text{ mA}$

Min $i_M = -669.67 \text{ mA}$

Also on bottom

Please,

- Compare your plots with the plots you got for the two-switch forward converter of [Figure 1.1](#). Comment on the differences and how each circuit

- handles the leakage inductance of the transformer.

On the bottom

4 Multi-output Flyback converter (E&M 6.10)

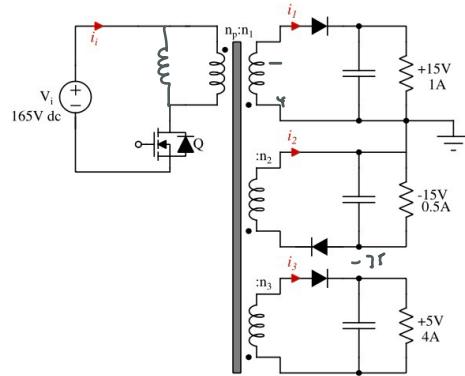


Figure 4.1: Three-output flyback converter design.

Design of a multiple-output dc-dc flyback converter. For this problem, you may neglect all losses and transformer leakage inductances. It is desired that the three-output flyback converter shown in [Figure 4.1](#) operates in the discontinuous conduction mode, switch a switching frequency of $f_s = 100$ kHz. The nominal operating conditions re given in the diagram, and you may assume that there are no variations in the input voltage or the load currents. Select $D_3 = 0.1$ (the duty cycle of sub-interval 3, in which all semiconductors are off). The objective of this problem is to find a good steady-state design, in which the semiconductor peak blocking voltages and peak currents are reasonably low.

- It is possible to find a design in which the transistor peak blocking voltage is less than 300 V and the peak diode blocking voltages are all less than 35 V, under steady-state conditions.
- Design the converter such that this is true.
- Specify: (i) the transistor duty cycle D, (ii) the magnetizing inductance L_M , referred to the primary, (iii) the turns ratios $\frac{n_1}{n_p}$ and $\frac{n_3}{n_p}$.
- For your design of the previous part, determine the rms currents of the four windings.
 - Note that they don't simply scale by the turns ratios.

MOSFET Peak Voltage

$$V_{in} + V_{L_{max}} < 300$$

$$V_{L_{max}} < 135$$

MOSFET Peak Voltage

$$V_{in} + V_o \left(\frac{n_1}{n_p} \right) < 300$$

Circuit 1 & circuit 2

$$15 \left(\frac{n_1}{n_p} \right) < 135$$

35 V peak diode block

Circuit one & two

$15 - 35 = 20$

biggest voltage

35 V peak diode block ✓

Circuit one & two

$$\left| \frac{n_s V_{in}}{n_p} \right| < 20$$

$$\frac{n_s}{n_p} < \frac{4}{33}$$

$$15 - 35 = -20$$

$$V_{in\max} = 135$$

Circuit 3

$$5 \left(\frac{n_s}{n_p} \right) < 135$$

$$\frac{n_s}{n_p} < 27$$

$$\frac{1}{27} < \frac{n_s}{n_p}$$

$$\boxed{\frac{1}{9} \leq \frac{n_s}{n_p} \leq \frac{4}{33} \quad \frac{1}{27} \leq \frac{n_s}{n_p} \leq \frac{6}{33}}$$

$$\frac{n_p}{n_s} < 9$$

$$\frac{1}{9} < \frac{n_p}{n_s}$$

$$\left| \frac{V_{in\max}}{n_p} \right| < 20$$

$$\frac{n_s}{n_p} < \frac{4}{33}$$

~~Circuit 3~~

$$\frac{V_{in}}{n_p} < 30$$

$$\frac{n_s}{n_p} < \frac{6}{33}$$

$$5 - 35 = -30$$

Not implied

Circuit 3

$$\frac{n_s V_{in}}{n_p} < 30$$

$$\frac{n_s}{n_p} < \frac{6}{33}$$

$$\text{For same } D, \quad \frac{n_2}{n_p} = \frac{n_1}{n_p} \cdot 3 \quad \text{because} \quad \frac{n_3}{n_1} = 1 \quad \&$$

Voltage balance Inductorm

$$V_{in} D + (1 - D) \left(\frac{-V_o}{n} \right) = 0$$

$$\frac{V_{in} D}{(1 - D)} \left(\frac{n_1}{n_p} \right) = V_o = 15$$

$$\frac{V_{in} D}{(1 - D)} \left(\frac{n_1}{n_p} \right) = V_o = 5$$

$$\text{if } \frac{n_1}{n_{10}} = \frac{3}{25}, \text{ then } \frac{n_3}{n_p} = \frac{1}{25}$$

$$\frac{165 [D]}{0.9 - D} \left(\frac{3}{25} \right) = 15$$

$$\frac{D}{0.9 - D} = 0.7575$$

$$D = 0.681 - 0.7575 D$$

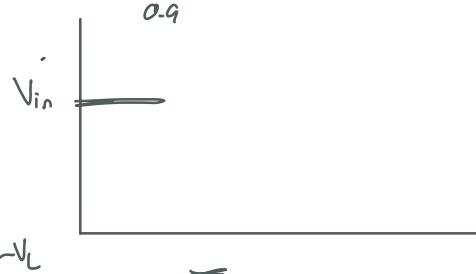
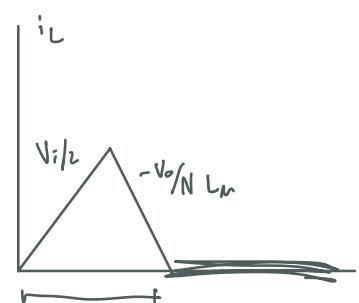
$$1.75 D = 0.681$$

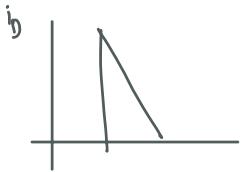
$$\boxed{D = 0.388}$$

$$i_{ph} = \frac{V_i}{L_M} D T$$

$$0 = n_p i_M + n_1 i_{b1ph} + n_2 i_{b2ph} + n_3 i_{b3ph}$$

can choose values by calculating blcak wave
or above first.





$$\frac{1}{2} D_2 i_{D, \text{peak}} = \angle \theta_0$$

$$i_{D, \text{peak}} = \frac{C \theta_0^2}{\cdot 4 \cdot 0} = \frac{2}{0.9 \cdot 0} = 3.90625$$

$$i_{D_2, \text{peak}} = \frac{\angle \theta_0^2}{\cdot 0.9 \cdot 0} = \frac{1}{0.9 \cdot 0} = 1.0631$$

$$i_{D_3, \text{peak}} = \frac{(4 \cdot 2)}{\cdot 0.9 \cdot 0} = 15.625$$

$$0 = i_M + \frac{3}{25}(3.906) + \frac{3}{25}(1.063) + \frac{1}{25}(15.625) = 0$$

$$i_M = 1.328$$

$$-\frac{DV_i}{L_{MfS}} = i_M \Rightarrow i_M = 482 \mu A$$

- For your design of the previous part, determine the rms currents of the four windings.

- Note that they don't simply scale by the turns ratios.

$$I_{\text{rms}} = \sqrt{\sum_x x^2 / N}$$

] Full Δ

$$\sqrt{\int_0^{x_0} (\alpha x)^2 dx}$$

] partial Δ

$$\frac{\alpha_0 \sqrt{\frac{x_0^3}{3x_0}}}{D_2} = \frac{\alpha_0 x_0}{D_2} \sqrt{\frac{D_2^3}{3}} = I_{\text{peak}} \sqrt{\frac{D_2}{3}}$$

$$\alpha_0 x_0 = \text{peak value so } I_{\text{peak}}$$

From above

$$I_{D_1, \text{peak}} = 3.90625$$

$$I_{D_2, \text{peak}} = 1.0631$$

$$I_{D_3, \text{peak}} = 15.625$$

$$I_M, \text{peak} = 1.328$$

$$I_{\text{rms}} = 3.90625 \sqrt{\frac{0.9 - 3.88}{3}} = 1.614 A$$

$$I_{M, \text{rms}} = 0.8068 A$$

$$I_{3, \text{rms}} = 6.455 A$$

$$I_{M, \text{peak}} = 0.3446 A$$

5 Average circuit modeling of an indirect boost-buck converter

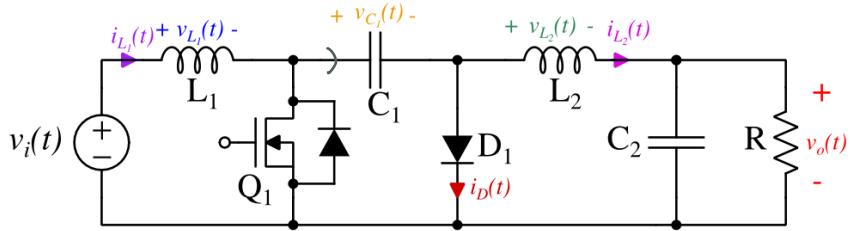
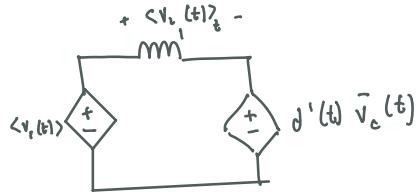


Figure 5.1: Indirect boost-buck dc-dc converter.

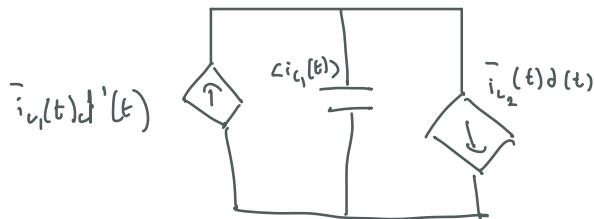
Consider the indirect boost-buck converter of [Figure 5.1](#). Assume the converter is operating in CCM and that all components are ideal.

- Obtain the non-linear averaged circuit model of the converter

$$\underline{L_1} \quad \langle v_{L_1}(t) \rangle_{r_s} = \bar{v}_i(t) + \bar{v}_o(t) + d'(t) \left(\bar{v}_i(t) - \bar{v}_{c_1}(t) \right)$$



$$\underline{C_1} \quad \bar{i}_{L_2}(t) d(t) + \bar{i}_{L_1}(t) d'(t) = \langle i_{c_1}(t) \rangle$$

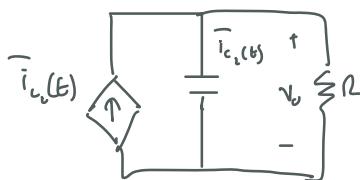


$$\underline{L_2} \quad \langle v_{L_2}(t) \rangle_{r_s} = \left(-\bar{v}_{c_1}(t) - \bar{v}_o(t) \right) d(t) + \bar{v}_o(t) d'(t)$$

$$\langle v_{L_2}(t) \rangle_{r_s} = -\bar{v}_{c_1}(t) d(t) + -\bar{v}_o(t)$$

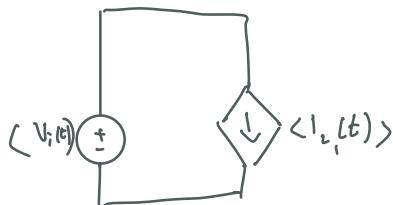


$$\underline{C_2} \quad \left(\bar{i}_{L_2}(t) - \frac{\bar{v}_o(t)}{R} \right) = \langle i_{c_2}(t) \rangle$$

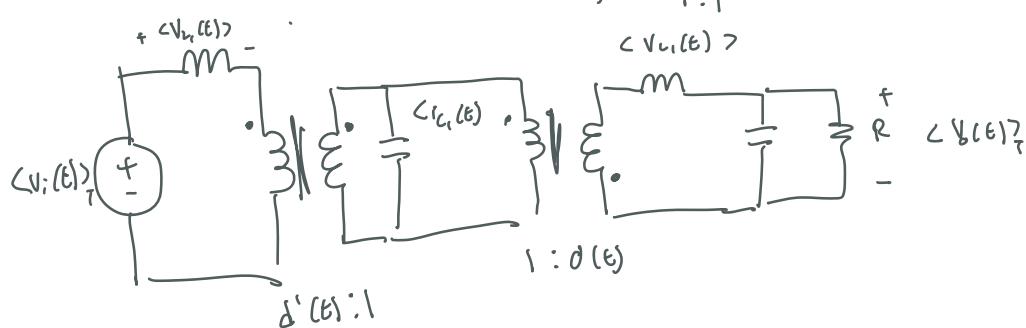
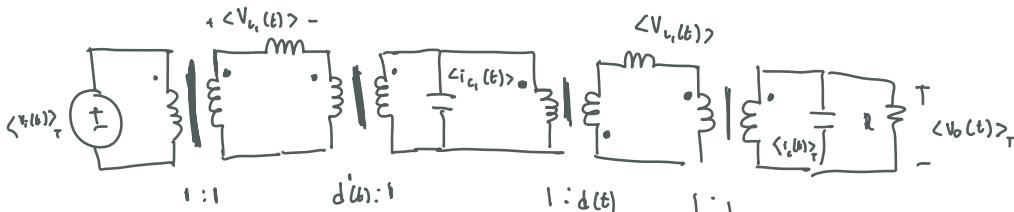
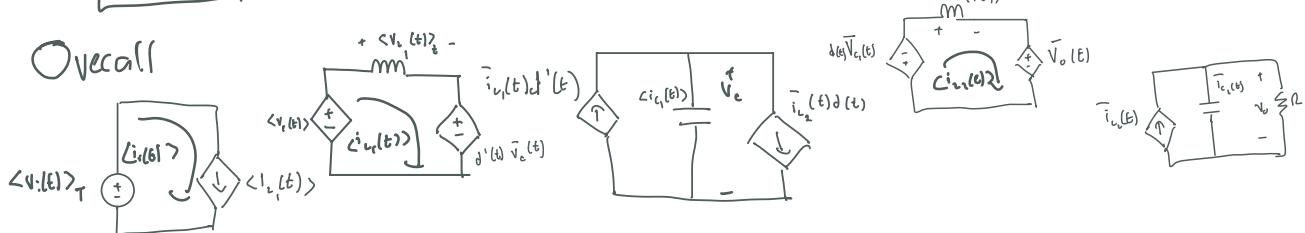


input

$$\hat{i}_L(t) = i_L(t)$$



Overall



- Perturb and linearize the non-linear averaged circuit model and obtain the ac linearized equivalent circuit model for the converter.

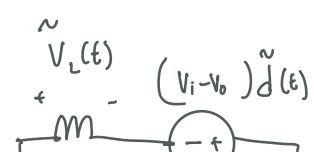
$$\langle V_L(t) \rangle_{\tau_s} = \bar{V}_i(b) + (b) + d'(t) \left(\bar{V}_i(t) - \bar{V}_o(t) \right)$$

$$\langle V_L(t) \rangle_{\tau_s} = V_i(t) - d'(t) \tilde{V}_o(t)$$

$$d'(t) = 1 - b + d'(b)$$

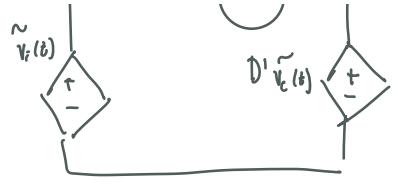
$$L \left(\frac{dI_L}{dt} + \frac{d\tilde{V}_o}{dt} \right) = \left[V_i + \tilde{V}_o(b) - (D' - d(b)) (V_c + \tilde{V}_o(t)) \right]$$

$$= V_i - D' V_c \quad \text{constants cancel derivative = 0}$$



$$+ \tilde{V}_i(t) + \tilde{d}(t)V_c - D\tilde{V}_c(t)$$

$$+ \tilde{d}(t)\tilde{V}_c(t) \quad \text{and order (Very small)}$$



$$\tilde{V}_c(t) = L \frac{d\tilde{I}_c(t)}{dt} = \tilde{V}_i(t) + \underbrace{\tilde{d}(t)V_c}_{= V_i - V_o} - D\tilde{V}_c(t)$$

L2

$$\langle V_{L_2}(t) \rangle_T = -\tilde{V}_{L_1}(t)d(t) + -\tilde{V}_o(t)$$

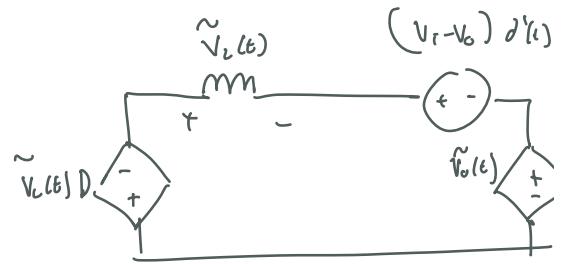
$$L \left(\frac{d\tilde{I}_{L_2}}{dt} + \frac{d\tilde{I}_{L_1}}{dt} \right) = -(V_c + \tilde{V}_c(t)) (D + \tilde{d}(t)) - (V_o + \tilde{V}_o(t))$$

$$= -DV_c - V_o \quad \times$$

$$\in -\tilde{V}_c(t)D - \tilde{d}(t)V_c - \tilde{V}_o(t)$$

$$+ \tilde{V}_c(t)d'(t) \quad \times$$

$$\tilde{V}_c(t) = -\tilde{V}_c(t)D - \tilde{d}'(t)V_c - \tilde{V}_o(t)$$



C1

$$-i_{L_2}(t)d(t) + \bar{i}_{L_1}(t)d'(t) : \langle i_{C_1}(t) \rangle$$

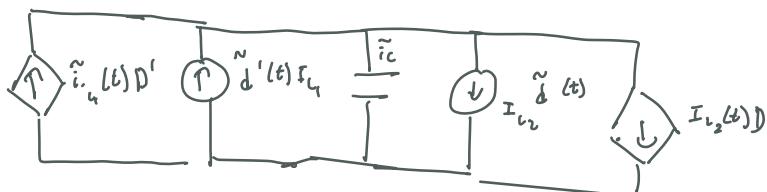
$$- (I_{L_2} + \tilde{i}_{L_2}(t))(D + \tilde{d}(t)) + (I_{L_1} + \tilde{i}_{L_1}(t))(D' - \tilde{d}'(t)) = \langle i_{C_1}(t) \rangle$$

$$= -I_{L_2}D + I_{L_1}D' \quad \times$$

$$+ -I_{L_2}\tilde{d}(t) - \tilde{i}_{L_2}(t)D + \tilde{i}_{L_1}(t)D' - \tilde{d}'(t)I_{L_1}$$

$$+ \tilde{i}_{L_2}(t)\tilde{d}(t) - \tilde{i}_{L_1}(t)\tilde{d}'(t) \quad \times$$

$$\tilde{i}_c = -I_{L_2}\tilde{d}(t) - \tilde{i}_{L_2}(t)D + \tilde{i}_{L_1}(t)D' - \tilde{d}'(t)I_{L_1}$$



C₂

$$\left(\tilde{i}_{c_2}(t) - \frac{\tilde{v}_o(t)}{R} \right) = \tilde{i}_{c_2}(t)$$

$$\tilde{i}_{c_2} + \tilde{i}_{c_1}(t) - \frac{\tilde{v}_o + \tilde{v}_i(t)}{R} = \tilde{i}_{c_2}(t)$$

$$= \tilde{I}_{c_2} - \frac{\tilde{v}_o}{R}$$

$$+ \tilde{i}_{c_2} - \frac{\tilde{v}_o(t)}{R}$$

$$\tilde{i}_{c_2}(t) - \frac{\tilde{v}_o(t)}{R} = i_c$$

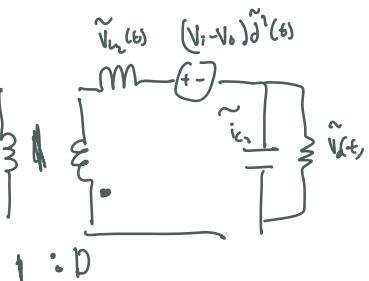
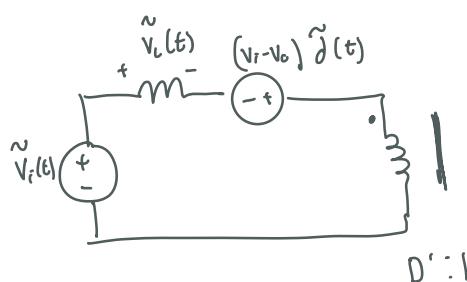
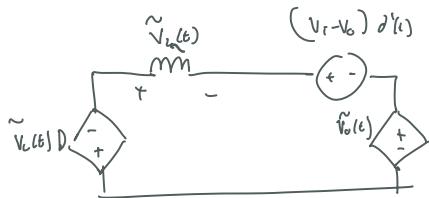
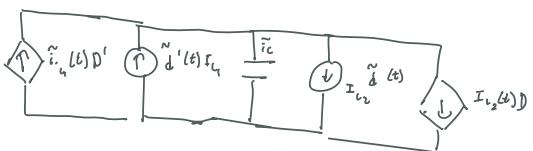
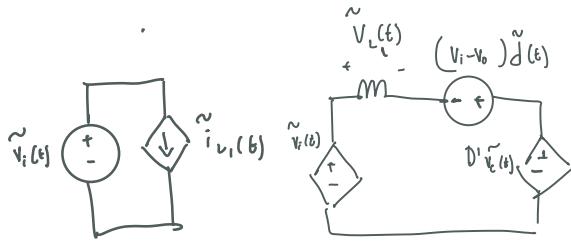
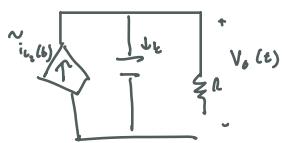
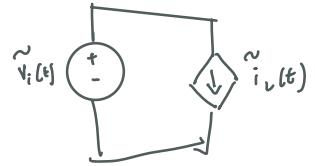
input current

$$\tilde{i}_{i_2}(t) = i_i(t)$$

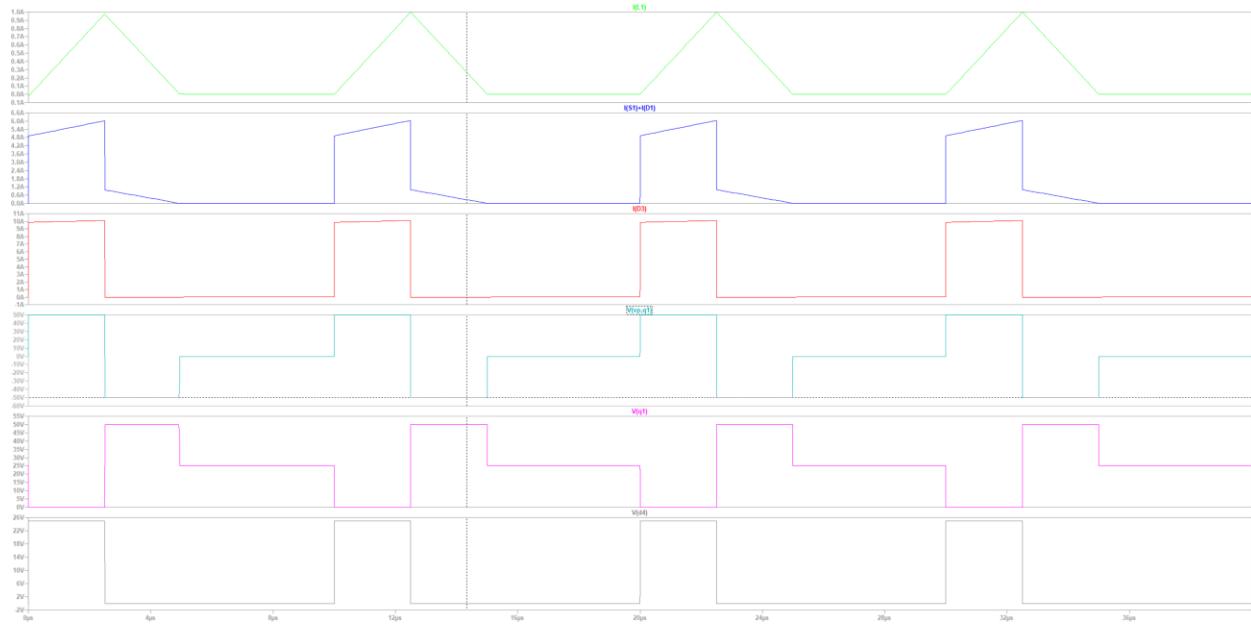
$$\tilde{I}_c + \tilde{i}_i(t) = I_c + \tilde{i}_i(t)$$

I_c ignore

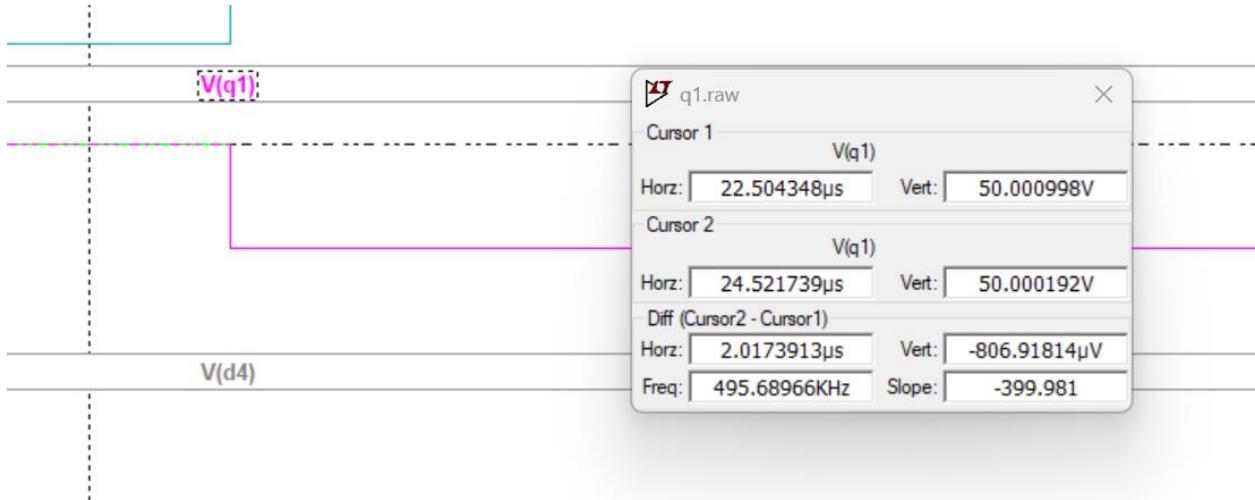
$$\tilde{i}_i(t) = i_i(t)$$



In one page, plot 4 cycles of $i_{\mu}(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and v_{D4} when $L_{leak}=0$.



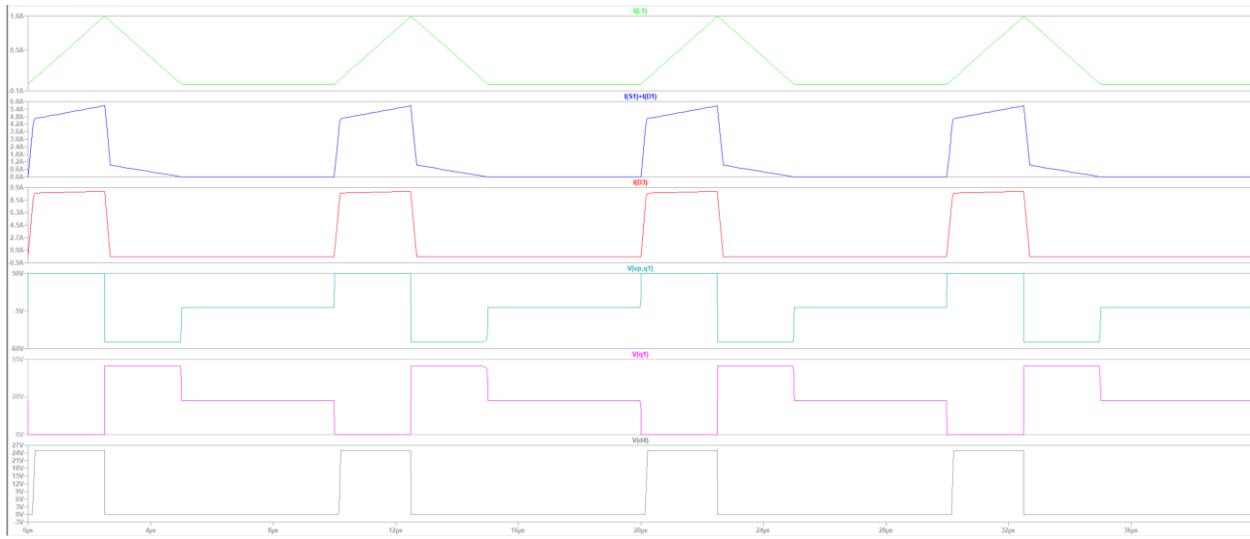
- What is the maximum voltage across $v_{Q1}(t)$?



- What is the maximum and minimum of the magnetizing current $i_{\mu}(t)$? (only one trace per plot please).



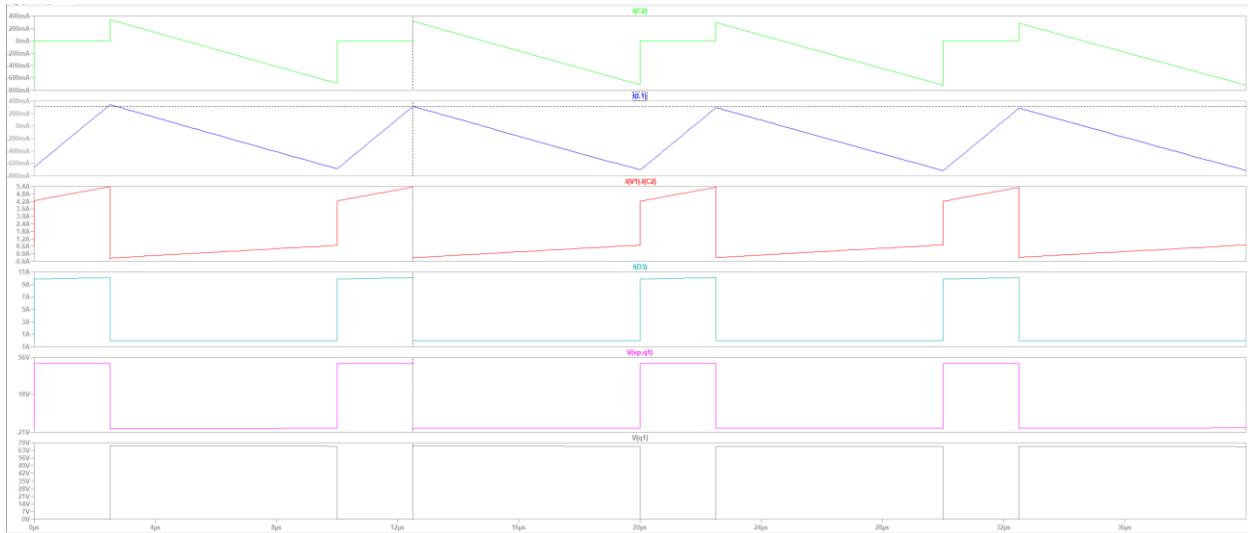
In one page, plot 4 cycles of $i_{\mu}(t)$, $i_p(t)$, $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and v_{D4} when $L_{leak}=500$ nH.



Very similar to without leakage current but the transition between different periods in $I(p)$ and $I(d)$ are more smooth (less steep and sudden) because the inductor is trying to maintain current. This is only a small change because the leakage inductance is quite small so the inductance can only store so much energy and therefore only can ramp up and down a certain amount. The slope is high because the inductance is low.

Question 3

In one page, plot 4 cycles of $i_{aux}(t)$, $i_\mu(t)$, $i_p(t)$, $i_s(t)$, $v_{L\mu}(t)$, $v_{Q1}(t)$ and $v_{D2}(t)$ when $L_{leak}=0$. What is the maximum voltage across $v_{Q1}(t)$? What is the maximum and minimum magnetizing current $i_\mu(t)$? (only one trace per plot please)

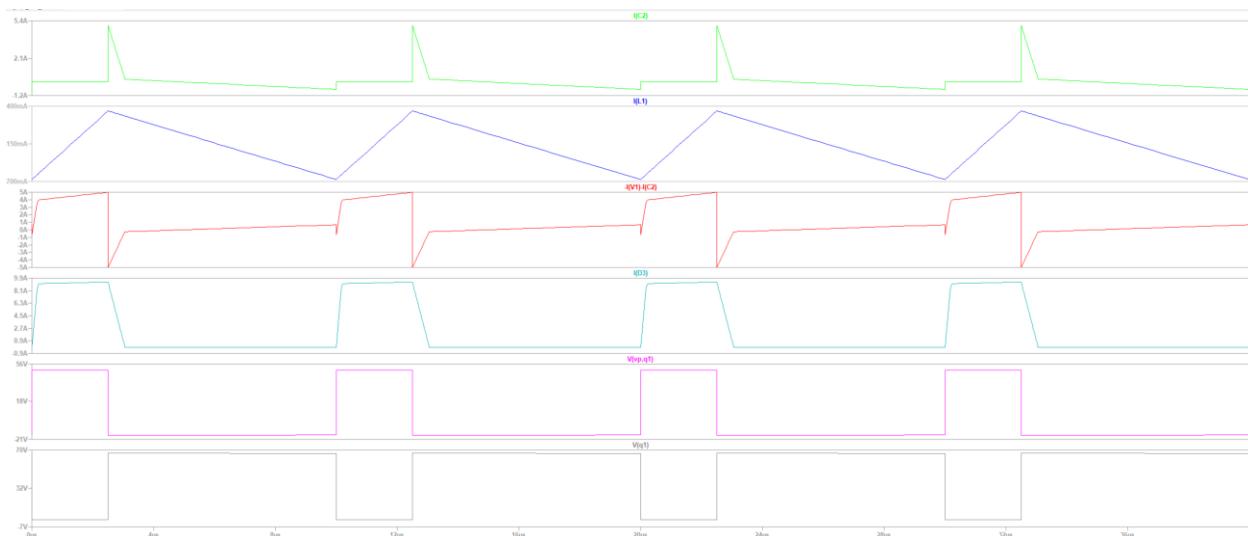


Max voltage across = 66.85 V

Min magnetizing current = 500.58mA

Minimum magnetizing current = -500.05 mA

- In one page, plot 4 cycles of $i_\mu(t)$, $i_p(t)$, and $i_s(t)$ and $v_{L\mu}(t)$, $v_{Q1}(t)$ and $v_{D2}(t)$ when $L_{leak}=500 \text{ nH}$. What is the maximum voltage across $v_{Q1}(t)$? What is the maximum and minimum of the magnetizing current $i_\mu(t)$? (only one trace per plot please)



Max voltage across =66.48 V

Min magnetizing current = 330.67 mA

Minimum magnetizing current = -669.17 mA

Compare your plots with the plots you got for the two-switch forward converter of [Figure 1.1](#). Comment on the differences and how each circuit handles the leakage inductance of the transformer.

The two switch forward converter handles the leakage inductance with little impact to the peak values of the waveforms. The biggest difference is that current ramps up with a steep slope rather than immediately turning from one value to the next. However, leakage current in the active clamps causes the current in the capacitor to spike, which also causes the I_p to spike. Overall, the switch still handles the same amount of maximum voltage. However, the capacitor would have to be specified to handle higher currents. In addition, the average value of the magnetic current is no longer centered around 0 because when the capacitor current spikes, the inductor current can no longer be as large. Therefore, the peak to peak graph is shifted down.