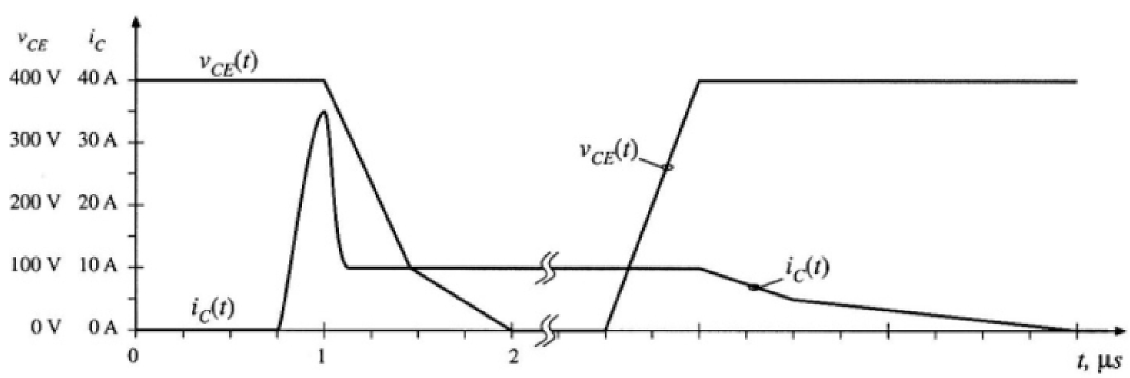
EE 452 – Power Electronics Design, Fall 2021

Homework 4

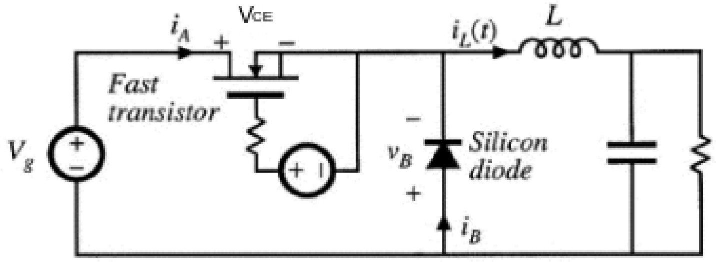
Due Date: Wednesday November 3rd 2021 at 11:59 pm Pacific Time

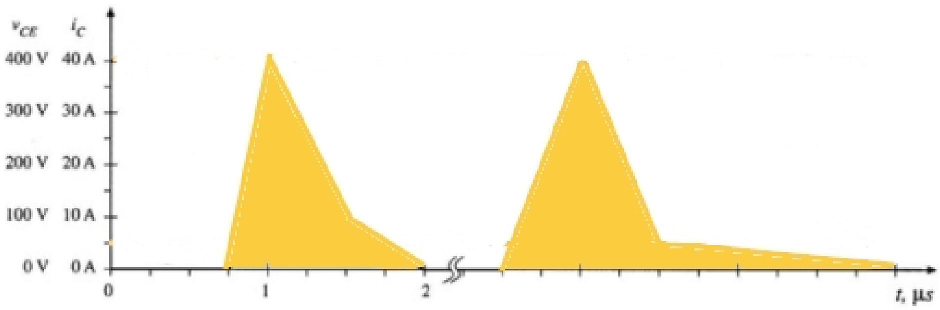
Instructions. You must scan your completed homework assignment into a pdf file, and upload your file to the Canvas Assignment page by the due date/time above. All pages must be gathered into a single file of moderate size, with the pages in the correct order. Set your phone or scanner for basic black and white scanning. You should obtain a file size of hundreds of kB, rather than tens of MB. I recommend using the "Tiny Scanner" app. Please note that the grader will not be obligated to grade your assignment if the file is unreadable or very large.

Problem 1: An IGBT and a silicon diode operate in a buck converter, with the IGBT waveforms illustrated in Fig. 1. The converter operates with input voltage $V_g = 400\,\mathrm{V}$ output voltage $V = 200\,\mathrm{V}$, and load current $I = 10\,\mathrm{A}$.



(a) Estimate the total energy lost during the switching transitions.





*Current from [0.75,1] seconds reaches 35A

$$P_{sw} = \frac{1}{T_s}\int p_a(t)\,dt = (W_{on} + W_{off})\,f_s$$

$$W_{on} = \left[\frac{1}{2}\cdot 400\cdot 35\cdot(1-0.75)\cdot 10^{-6}\right] + \left[100\cdot 10\cdot(1.5-1)\cdot 10^{-6}\right] + \left[\frac{1}{2}\cdot 300\cdot 10\cdot(1.5-1)\cdot 10^{-6}\right] + \left[\frac{1}{2}\cdot 100\cdot 10\cdot(2-1.5)\cdot 10^{-6}\right]$$

$$W_{on} == 3.25mJ$$

$$W_{off} = \left[\frac{1}{2}\cdot 400\cdot 10\cdot(3-2.5)\cdot 10^{-6}\right] + \left[400\cdot 5\cdot(3.5-3)\cdot 10^{-6}\right] + \left[\frac{1}{2}\cdot 400\cdot 5\cdot(3.5-3)\cdot 10^{-6}\right] + \left[\frac{1}{2}\cdot 400\cdot 5\cdot(5-3.5)\cdot 10^{-6}\right]$$

$$W_{off} = 4mJ$$

$$W_{\text{total}} = W_{on} + W_{off}$$

$$W_{\text{total}} = 3.25mJ + 4mJ = 7.25mJ$$

(b) The forward voltage drop of the IGBT is 2.5 V, and the diode has forward voltage drop 1.5 V. All other sources of conduction loss and fixed loss can be neglected. Estimate the semiconductor conduction loss.

Conduction loss occurs only when the device is on.

$$P_{\text{Conduction}} = \frac{1}{T_s}\int_0^{DT_s}(I \cdot V_{\text{IGBT}})dt + \frac{1}{T_s}\int_{DT_s}^{T_s}(I \cdot V_{\text{Diode}})dt$$
$$= D(I \cdot V_{\text{IGBT}}) + (1-D)(I \cdot V_{\text{Diode}})$$

Switch $[0 < t < DT_s]$

$$0 = V_g - V_{CE} - v_L - v$$
$$v_L = V_g - V_{CE} - v$$

Switch $[DT_s < t < T_s]$

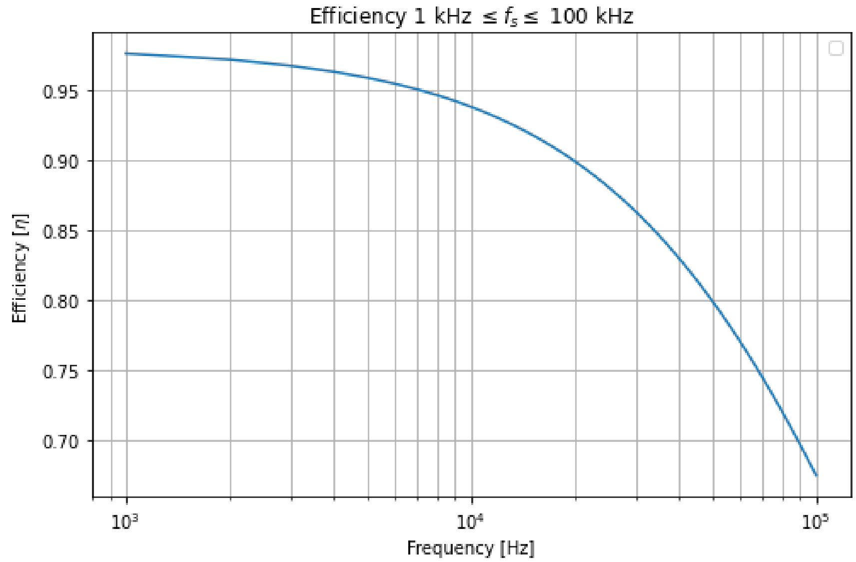
$$0 = -V_B - v_L - v$$
$$v_L = -(V_B + v)$$

Total Volt Seconds over 1 period for Inductor Voltage (small ripple approx)

$$< v_L > = \frac{1}{T_S}\int_o^{T_S} v_L(t)dt$$
$$0 = \left[D \cdot (V_g - V_{CE} - V)\right] + \left[D' \cdot (-V_B - V)\right]$$
$$0 = -(D + D')V + DV_g - DV_{CE} - D'V_B$$
$$0 = -V + DV_g - DV_{CE} - (1-D)V_B$$
$$0 = -(V + V_B) + D(V_g - V_{CE} + V_B)$$
$$D = \frac{V + V_B}{V_g - V_{CE} + V_B} = \frac{200 + 1.5}{400 - 2.5 + 1.5} = 0.505 \text{ [Duty Cycle Ratio]}$$

$$P_{\text{Conduction}} = D(I \cdot V_{\text{IGBT}}) + (1-D)(I \cdot V_{\text{Diode}})$$
$$= 0.505 \cdot (10 \cdot 2.5) + (1 - 0.505) \cdot (10 \cdot 1.5)$$
$$= 20.05 \text{ Watts}$$

(c) Sketch the converter efficiency over the range of switching frequencies $1\,\text{kHz} \le f_s \le 100\,\text{kHz}$ and label numerical values.



Switch $[0 < t < DT_s]$

$$i_C = i_L - \frac{v}{R}$$

Switch $[DT_s < t < T_s]$

$$i_C = i_L - \frac{v}{R}$$

Total Volt Seconds over 1 period for Capacitor Current (small ripple approx)

$$< i_C > = \frac{1}{T_S}\int_o^{T_S} i_C(t)dt$$

$$0 = \left[D \cdot (I - \frac{V}{R})\right] + \left[(D') \cdot (I - \frac{V}{R})\right]$$

$$0 = (D + D')I - (D + D')(\frac{V}{R})$$

$$I = \frac{V}{R} = 10A \qquad \text{[Inductor Current } I\text{]}$$

$$\eta = \frac{P_{out}}{P_{in}}$$

$$P_{out} = VI = (200)(10) = 2000W$$

$$P_{in} = V_g I_T + P_{\text{Conduction}} + P_{sw}$$

$$= V_g\left(\frac{I_L DT_S + I_L t_r + Q_R}{T_s}\right) + P_{\text{Conduction}} + P_{sw}$$

$$\approx V_g\left(\frac{I_L DT_S + I_L t_r}{T_s}\right) + P_{\text{Conduction}} + P_{sw}$$

$$\approx V_g(I_L D + I_L t_r f_s) + P_{\text{Conduction}} + P_{sw}$$

$$\approx 400[(10 \cdot 0.505) + (10 \cdot 0.5 \cdot 10^{-6})f_s] + (20.05) + (7.25 \cdot 10^{-3} f_s)$$

$$\eta \approx \frac{2000}{2040.05 + (9.25 \cdot 10^{-3})f_s}$$