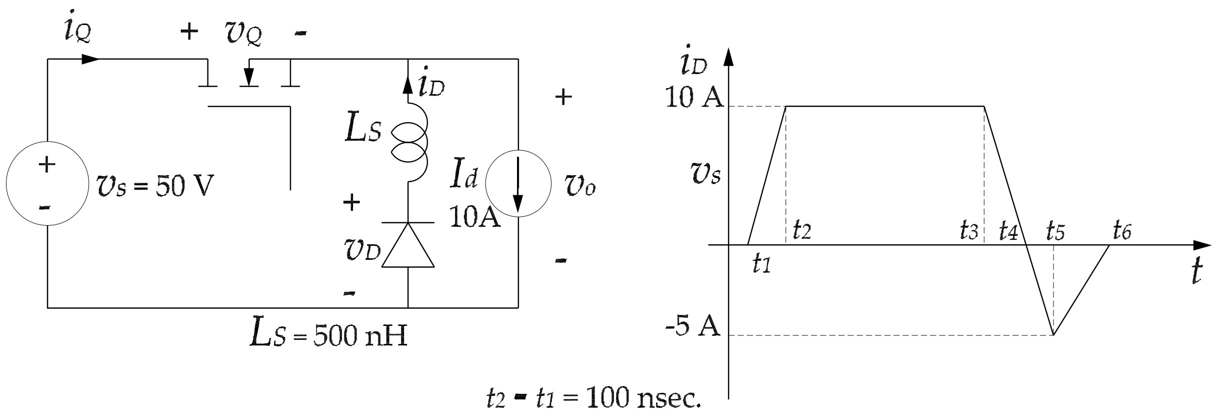
EE4643: Power Electronics

Assignment 1: Solutions

Q1:

Q2 Consider the converter shown in Figure 1. Assume that the MOSFET Q and diode D are ideal in that their ON-state voltages are zero, and they can turn turn-ON and turn-OFF instantly. The waveform of the diode switching is also included in Figure 1.



$t_2 - t_1 = 100$ nsec.

$t_5 - t_3 = 150$ nsec.

$t_6 - t_5 = 20$ nsec.

Figure 1: The converter for Q2.

1. Calculate and sketch to scale the diode and MOSFET voltages v_D and v_Q, and i_Q;

   The waveforms of $i_D,\ v_D,\ v_Q$, and i_Q are shown in Figure 2.

2. Estimate the switching losses in the diode and the MOSFET if the converter is operated at a switching frequency of $f_s = 200\,\text{kHz}$.

   The switching losses will be determined for ON and OFF switching for both D and Q.

   (a) **D**: The instantaneous ON switching losses $(P_{ON1})_D$ are determined as:

$$(P_{ON1})_D = v_D(t)i_D(t);\ v_D(t) = v_s\left(1 - \frac{t}{t_2}\right);\ \ i_D(t) = \frac{I_d}{t_2}t$$

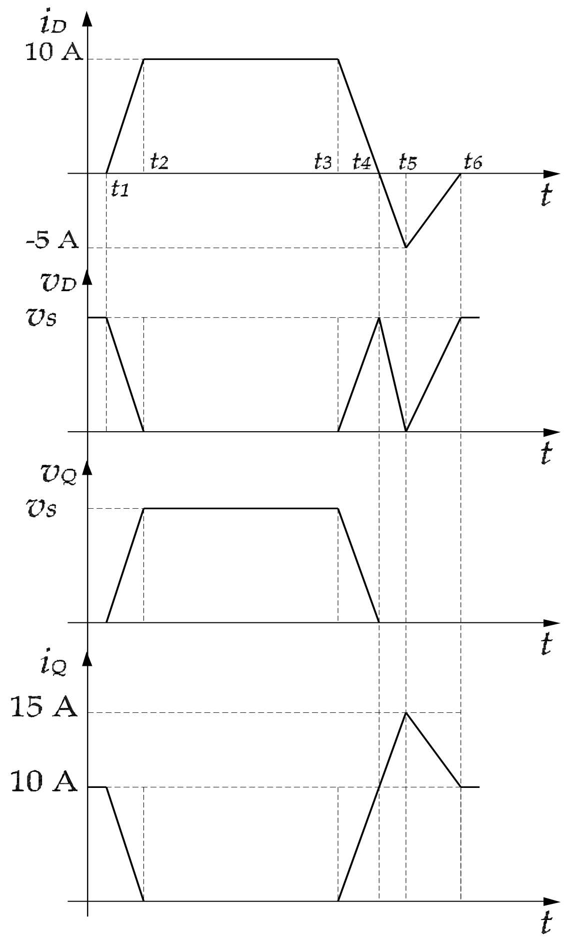


Figure 2: The waveforms of $i_D,\ v_D,\ v_Q$, and i_Q.

$$(P_{ON1})_D = \frac{v_s I_d}{t_2} t - \frac{v_s I_d}{t_2^2} t^2$$

The energy losses during ON switching $(W_{ON})_D$ is determined as:

$$(W_{ON})_D = \int_0^{t_2} (P_{ON1})_D \, dt = \int_0^{t_2} \frac{v_s I_d}{t_2} t dt - \int_0^{t_2} \frac{v_s I_d}{t_2^2} t^2 dt = \frac{v_s I_d}{2} t_2 - \frac{v_s I_d}{3} t_2$$

The average power losses during ON switching $(P_{ON})_D$ is determined as:

$$(P_{ON})_D = (W_{ON})_D \times f_s = 1.6667 \quad W$$

The instantaneous OFF switching power losses $(P_{OFF1})_D$ are determined as:

$$(P_{OFF1})_D = v_D(t) i_D(t);$$

During the OFF switching $i_D(t)$ has 2 portions, which can be expressed as:

$$(i_D(t))_1 = I_d - \frac{I_d + 5}{t_5} t, \;\; (i_D(t))_2 = \frac{5}{t_6} t - 5$$

$v_D(t)$ has 3 portions that can be expressed as:

$$(v_D(t))_1 = \frac{v_s}{t_4} t, \;\; (v_D(t))_2 = v_s \left(1 - \frac{1}{t_5} t\right), \;\; (v_D(t))_3 = \frac{v_s}{t_6} t$$

The energy losses during OFF switching $(W_{OFF})_D$ is determined as:

$$(W_{OFF})_D = \int_{t_3}^{t_4} (v_D(t))_1 (i_D(t))_1 \, dt + \int_{t_4}^{t_5} (v_D(t))_2 (i_D(t))_1 \, dt + \int_{t_5}^{t_6} (v_D(t))_3 (i_D(t))_2 \, dt$$

$$(W_{OFF})_D = \int_{0}^{t_4 - t_3} (v_D(t))_1 (i_D(t))_1 \, dt + \int_{0}^{t_5 - t_4} (v_D(t))_2 (i_D(t))_1 \, dt + \int_{0}^{t_6 - t_5} (v_D(t))_3 (i_D(t))_2 \, dt$$

$$(W_{OFF})_D = \frac{I_d v_s}{2t_4} (t_4 - t_3) - \left(\frac{I_d v_s + 5v_s}{3t_4 t_5}\right) (t_4 - t_3)^3 + v_s I_d (t_5 - t_4) - \left(\frac{I_d v_s + 5v_s}{2t_5}\right) (t_5 - t_4)^2$$
$$- \frac{I_d v_s}{2t_5} (t_5 - t_4)^2 + \left(\frac{I_d v_s + 5v_s}{3t_5^2}\right) (t_5 - t_4)^3 + \frac{5v_s}{3t_6^2} (t_6 - t_5)^3 - \frac{5v_s}{2t_6} (t_6 - t_5)^2$$
$$(W_{OFF})_D = 2.1307 \times 10^{-5} \quad J$$

Assuming that t_4 is the mid point between t_3 and t_5, the average power losses during OFF switching $(P_{OFF})_D$ is determined as:

$$(P_{OFF})_D = (W_{OFF})_D \times f_s = 4.2614 \quad W$$

The switching power losses for D are $(P_{SW})_D$ is determined as:

$$(P_{SW})_D = (P_{ON})_D + (P_{OFF})_D = 5.9281 \quad W$$

(b) **Q**:

The instantaneous OFF switching losses $(P_{OFF1})_Q$ are determined as:

$$(P_{OFF1})_Q = v_Q(t) i_Q(t);\ v_Q(t) = \frac{v_s}{t_2}t;\ \ i_Q(t) = I_d\left(1 - \frac{t}{t_2}\right)$$

$$(P_{OFF1})_Q = \frac{v_s I_d}{t_2}t - \frac{v_s I_d}{t_2^2}t^2$$

The energy losses during OFF switching $(W_{OFF})_Q$ is determined as:

$$(W_{OFF})_Q = \int_0^{t_2} (P_{ON1})_Q \, dt = \int_0^{t_2} \frac{v_s I_d}{t_2} t dt - \int_0^{t_2} \frac{v_s I_d}{t_2^2} t^2 dt = \frac{v_s I_d}{2} t_2 - \frac{v_s I_d}{3} t_2$$

The average power losses during OFF switching $(P_{OFF})_Q$ is determined as:

$$(P_{OFF})_Q = (W_{OFF})_Q \times f_s = 1.6667 \quad W$$

The instantaneous ON switching power losses $(P_{ON1})_Q$ are determined as:

$$(P_{ON1})_Q = v_Q(t) i_Q(t);$$

$$i_Q(t) = \frac{I_d + 5}{t_5}t, \quad v_Q(t) = v_s\left(1 - \frac{t}{t_4}\right)$$

The value of $(P_{ON1})_Q$ is determined as:

$$(P_{ON1})_Q = \frac{15 v_s}{t_5}t - \frac{15 v_s}{t_4 t_5}t^2$$

The energy losses during ON switching $(W_{ON})_Q$ is determined as:

$$(W_{ON})_Q = \int_0^{t_4} (P_{ON1})_Q \, dt = \int_0^{t_4} \frac{15v_s}{t_5} t dt - \int_0^{t_4} \frac{15v_s}{t_4 t_5} t^2 dt = \frac{15v_s}{2t_5} t_4^2 - \frac{15v_s}{3t_5} t_4^2$$

Assuming that t_4 is the mid point between t_3 and t_5, the average power losses during ON switching $(P_{ON})_Q$ is determined as:

$$(P_{ON})_Q = (W_{ON})_Q \times f_s = 0.9375 \quad W$$

The switching power losses for Q are $(P_{SW})_Q$ are determined as:

$$(P_{SW})_Q = (P_{ON})_Q + (P_{OFF})_Q = 2.61 \quad W$$

3. If the total losses for the MOSFET and diode are modeled as:

$$P_{LQ} = 20 + 50 \times 10^{-6} f_s \quad and \quad P_{LD} = 10 + 0.44 \times 10^{-6} f_s$$

where f_s is the switching frequency. Determine the maximum switching frequency so that the junction temperature of both Q and D does not exceed 120 C°. Assume that both D and Q are mounted on the same heat sink, and the ambient temperature is 40 C°. The thermal resistances are in C°/W as:

$$(R_{\theta JC})_Q = 0.8, \; (R_{\theta CS})_Q = 1.2,$$

$$(R_{\theta JC})_D = 0.6, \; (R_{\theta CS})_D = 1.4,$$

$$R_{\theta SA} = 0.4$$

The equivalent thermal circuit for $D, \; Q$, cases, and the heat sinks are shown in Figure 3.

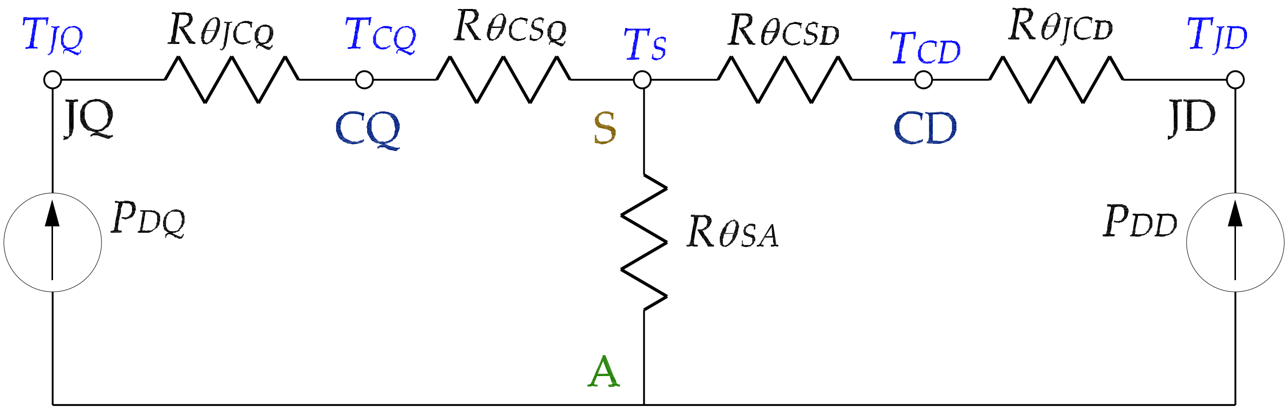


Figure 3: The thermal circuit for the Q2-3.

$$T_{JQ} - T_S = P_{LQ}\left((R_{\theta JC})_Q + (R_{\theta CS})_Q\right) \Longrightarrow T_S = 120 - 2P_{LQ}$$

$$T_S - T_A = (P_{LQ} + P_{LD})\, R_{\theta SA} \Longrightarrow 120 - 2P_{LQ} - 40 = (30 + 50.44 \times 10^{-6} f_s)0.4$$

$$80 - 40 - 100 \times 10^{-6} f_s = 12 + 20.176 \times 10^{-6} f_s \Longrightarrow f_s = 232.997 \;\; kHz$$

Q3: Design a BJT drive circuit with an initial base current of 5 A, for this BJT having $I_C = 25$ A. This BJT is to be switched at a switching frequency $f_s = 8$ kHz with a duty cycle of 75%. This BJT has $h_{fe} = 30$, a drive signal is 10 V (ON), and $V_{BE}(sat) = 1$ V.

The schematics of the driver is shown in Figure 4.

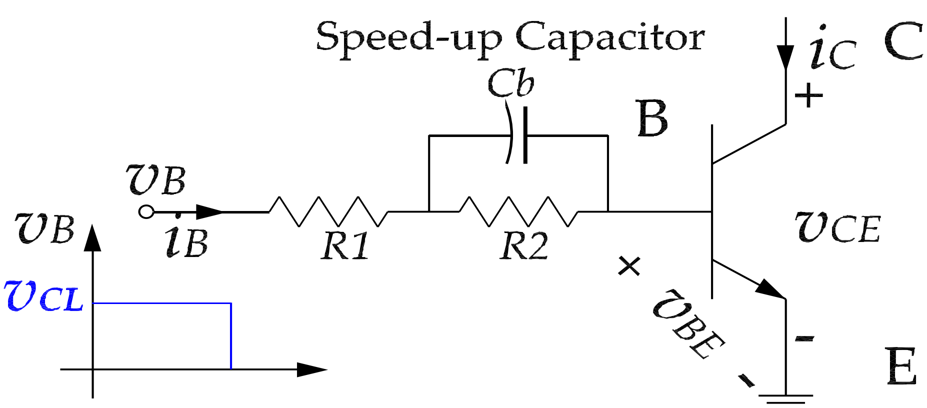


Figure 4: The desired drive circuit for the BJT

The initial base activation current $I_{B1} = 5$. The minimum current to ensure an ON state is I_{B2} that can be determined as:

$$I_{B2} = \frac{I_C}{h_{fe}} = \frac{25}{30} = 0.8333 \quad A$$

Assume overdrive required current I_{B2} as:

$$I_{B2} = 3 \times I_{B2} = 2.5 \quad A$$

$$I_{B1} = \frac{V_B - V_{BE}(sat)}{R_1} = \frac{10-1}{R_1} \Longrightarrow R_1 = \frac{9}{5} = 1.8 \ \Omega$$

$$I_{B2} = \frac{V_B - V_{BE}(sat)}{R_1 + R_2} \Longrightarrow R_2 = \frac{9}{2.5} - 1.8 = 1.8 \ \Omega$$

Assume charging time (5τ) to be $0.2T_{ON}$, the value of T_{ON} can be determined as:

$$D = \frac{T_{ON}}{T_s} = T_{ON} \times f_s \Longrightarrow T_{ON} = \frac{0.75}{8000} = 93.75 \ \mu sec.$$

$$5\tau = 0.2 \times 93.75 \times 10^{-6} = 18.75 \times 10^{-6} \Longrightarrow \tau = 3.75 \times 10^{-6} \quad sec$$

The value of C is determined as:

$$\tau = R_{eq}C; \ R_{eq} = R_1 // R_2 = 0.9 \ \Omega$$

get the value of $C = 4.2\mu$F.