Homework 5:

11.97, 11.99, 12.1 (Note: doubling the Q3 junction area $V_D$ is reduced, so that current $I$ flowing through Q2 is reduced to half), and 12.7.

Plus this one:

3. Consider the class-A output stage shown below, the input signal is a square wave. Assume $V_{CE, sat} \approx 0$, and $V_{cc}>>0.7V$, and $T_2 = 2T_1$.

(A) Find the average power efficiency (express as functions of $R_L$, $V_{cc}$ and $I$)
(B) If $R_L = 8\, \Omega$, and $V_{cc} = 12V$, find the best $I$ value to maximize power efficiency while not to cut the signal.
Solution: 11.97,

\[ A(f) = \frac{A_0}{\left(1 + j\frac{f}{f_1}\right) \left(1 + j\frac{f}{f_2}\right) \left(1 + j\frac{f}{f_3}\right)} = \frac{10^4}{\left(1 + j\frac{f}{10^3}\right) \left(1 + j\frac{f}{3.16 \times 10^5}\right) \left(1 + j\frac{f}{10^6}\right)} \]

For the phase margin of 45°, at the frequency \( f_{PM} \), the phase shift of \( A(f_{PM}) \) has to be \( \theta = -(180 - 45) = -135° \).

The phase shift of \( A(f) \) is, \( \theta = -\theta_1 - \theta_2 - \theta_3 \)

where \( \theta_1 = \tan^{-1}\left(\frac{f}{10^5}\right), \theta_2 = \tan^{-1}\left(\frac{f}{3.16 \times 10^5}\right), \) and \( \theta_3 = \tan^{-1}\left(\frac{f}{10^6}\right) \) so that

\[ \tan^{-1}\left(\frac{f}{10^5}\right) + \tan^{-1}\left(\frac{f}{3.16 \times 10^5}\right) + \tan^{-1}\left(\frac{f}{10^6}\right) = 135° \]

Numerically solve to obtain \( f = f_{PM} = 3.16 \times 10^5 \text{ Hz} \)

Then, at \( f = f_{PM} = 3.16 \times 10^5 \text{ Hz} \), we must have \( |A(f_{PM})\beta| = 1 \),

that is

\[ \beta = \frac{1}{|A(f_{PM})|} = 10^{-4} \left|\left(1 + j\frac{3.16 \times 10^5}{10^5}\right) \left(1 + j\frac{3.16 \times 10^5}{3.16 \times 10^5}\right) \left(1 + j\frac{3.16 \times 10^5}{10^6}\right)\right| \]

\[ = 4.91 \times 10^{-4} = -66.18 \text{ dB} \]

The closed loop gain at DC is,

\[ A_f(0) = \frac{A(0)}{1 + \beta A(0)} = \frac{10^4}{1 + 4.91 \times 10^{-4} \times 10^4} = \frac{10^4}{5.91} = 1.69 \times 10^3 = 64.6 \text{ dB} \]
11.99 Figure 1 is a replica of Fig. 11.37 except here we locate on the phase plot the points at which the phase margin is 90° and 135°, respectively. Drawing a vertical line from each of those points and locating the intersection with the |A| line enables us to determine the maximum β that can be used in each case. Thus, for PM = 90°, we have

\[
20 \log \frac{1}{\beta} = 90 \text{ dB}
\]

\[\Rightarrow \beta = 3.16 \times 10^{-5}\]

and the corresponding closed-loop gain is

\[A_f = \frac{A_0}{1 + A_0\beta} = \frac{10^5}{1 + 10^5 \times 3.16 \times 10^{-5}} = 2.4 \times 10^4 \text{ V/V or 87.6 dB}\]

and for PM = 45°, we have

\[20 \log \frac{1}{\beta} = 80 \text{ dB}\]

\[\Rightarrow \beta = 10^{-4} \text{ V/V}\]

and the corresponding closed-loop gain is

\[A_f = \frac{A_0}{1 + A_0\beta} = \frac{10^5}{1 + 10^5 \times 10^{-4}} = 9.09 \times 10^3 \text{ V/V}\]

or 79.2 dB
\[ l = \frac{0 - (V_{CC} - V_D)}{R} \]
\[ = \frac{10 - 0.7}{1} = 9.3 \text{ mA} \]

Upper limit on \( v_o = V_{CC} - V_{CE_{sat}} \)
\[ = 10 - 0.3 = 9.7 \text{ V} \]

Corresponding input = \( 9.7 + 0.7 = 10.4 \text{ V} \)

Lower limit on \( v_o = -IR_L = -9.3 \times 1 \)
\[ = -9.3 \text{ V} \]

Corresponding input = \( -9.3 + 0.7 = -8.6 \text{ V} \)

If the EBJ area of \( Q_3 \) is twice as large as that of \( Q_2 \), then
\[ I = \frac{1}{2} \times 9.3 = 4.65 \text{ mA} \]

There will be no change in \( v_{O_{max}} \) and in the corresponding value of \( v_I \). However, \( v_{O_{min}} \) will now become
\[ v_{O_{min}} = -IR_L \]
\[ = -4.65 \times 1 = -4.65 \text{ V} \]

and the corresponding value of \( v_I \) will be
\[ v_I = -4.65 + 0.7 = -3.95 \text{ V} \]

If the EBJ area of \( Q_3 \) is made half as big as that of \( Q_2 \), then
\[ I = 4 \times 9.3 = 18.6 \text{ mA} \]

There will be no change in \( v_{O_{max}} \) and in the corresponding value of \( v_I \). However, \( v_{O_{min}} \) will now become
\[ v_{O_{min}} = -V_{CC} + V_{CE_{sat}} \]
\[ = -10 + 0.3 = -9.7 \text{ V} \]

and the corresponding value of \( v_I \) will be
\[ v_I = -9.7 + 0.7 = -9 \text{ V} \]

\[ V_{CC} = 16, 12, 10, \text{ and } 8 \text{ V} \]
\[ I = 100 \text{ mA}, \ R_L = 100 \text{ } \Omega \]
\[ \hat{V}_o = 8 \text{ V} \]
\[ \eta = \frac{1}{4} \left( \frac{V_{\hat{o}}}{IR_L} \right) \left( \frac{V_{\hat{o}}}{V_{CC}} \right) \]
\[ = \frac{1}{4} \left( \frac{8}{10} \right) \left( \frac{8}{V_{CC}} \right) = \frac{1.6}{V_{CC}} \]

<table>
<thead>
<tr>
<th>( V_{CC} )</th>
<th>16</th>
<th>12</th>
<th>10</th>
<th>8</th>
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<td>( \eta )</td>
<td>10%</td>
<td>13.3%</td>
<td>16%</td>
<td>20%</td>
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5. (Handout problem)

(A) Power to the load during $T_1$ and $T_2$ are $P_{L,T1} = \frac{V_{cc}^2}{R_L}$ and $P_{L,T2} = \frac{V_{cc}^2}{4R_L}$

The average power to load is then,

$$P_{L,ave} = \frac{1}{3}(P_{L,T1} + 2P_{L,T2}) = \frac{1}{3}\frac{V_{cc}^2}{R_L}(1 + \frac{2}{4}) = \frac{V_{cc}^2}{2R_L}$$

(2) Power from positive power supply during $T_1$ and $T_2$ are,

$$P_{S+,T1} = V_{cc}\left(I + \frac{V_{cc}}{R_L}\right) \quad \text{and} \quad P_{S+,T2} = V_{cc}\left(I - \frac{V_{cc}}{2R_L}\right)$$

Average power from positive power supply is,

$$P_{S+,ave} = \frac{1}{3}(P_{S+,T1} + 2P_{S+,T2}) = \frac{V_{cc}}{3}\left[I + \frac{V_{cc}}{R_L}\right] + 2\left[I - \frac{V_{cc}}{2R_L}\right] = V_{cc}I$$

Average power from negative power supply is, $P_{S-,} = V_{cc}I$

Average power from all power supplies is: $P_{S,ave} = 2V_{cc}I$

Power efficiency is, $\eta = \frac{P_{L,ave}}{P_{S,ave}} = \frac{V_{cc}^2 / 2R_L}{2V_{cc}I} = \frac{V_{cc}}{4R_L I}$

(B) Since the minimum level of the signal is $-V_{cc}/2$, $R_L I = V_{cc} / 2$ has to be satisfied, so that $I = \frac{V_{cc}}{2R_L} = \frac{12}{2 \times 8} = 0.75A$, and the total power efficiency is $\eta = \frac{12}{4 \times 8 \times 0.75} = 0.5$