The Art of Electronics, 3rd Edition - Solutions

This is an ongoing project with solutions to problems in "The Art of Electronics, 3rd edition" by Paul Horowitz and Winfield Hill. There is no guarantee for the correctness of the solutions and any suggestions for improvement are more that welcome.

Contents

1 Foundations

Exercise 1.30

V_{out} is the voltage at the output of the impedance voltage divider. We know that $Z_R = R$ and $Z_C = \frac{1}{j\omega C}$. So we have

$$V_{\text{out}} = \frac{Z_C}{Z_R + Z_C} V_{\text{in}} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} V_{\text{in}} = \frac{1}{1 + j\omega RC} V_{\text{in}}$$

The magnitude of this expression follows:

$$|V_{\text{out}}| = \sqrt{V_{\text{out}} V_{\text{out}}^*} = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} V_{\text{in}}$$

where V_{out}^* is the complex conjugate of V_{out}.

Exercise 1.37

The Norton equivalent circuit can be found by measuring I_{short} and V_{open}:

$$I_{\text{Norton}} = I_{\text{short}} = \frac{10\text{V}}{10\text{k}\Omega} = \boxed{\mathbf{1}\text{mA}}$$

and since $V_{\text{open}} = 5\text{V}$, we have

$$R_{\text{Norton}} = \frac{5\text{V}}{1\text{mA}} = \boxed{\mathbf{5k\Omega}}$$

2 Bipolar Transistors

Exercise 2.1

We assume a forward voltage for the LED of 1.5V. Then for I_{LED} we have

$$I_{LED} = \frac{V_R}{R} = \frac{3.3\text{V} - 1.5\text{V}}{330\Omega} \approx \boxed{\mathbf{5.5}\text{mA}}$$

To estimate the β_{min} we need the current entering the base

$$I_B = \frac{3.3\text{V} - 0.6\text{V}}{10\text{k}\Omega} = 0.27\text{mA}$$

Thus

$$\beta_{min} \geq \frac{I_{LED}}{I_B} = \boxed{\mathbf{20}}$$

Exercise 2.2

NOTE: According to the errata 0.63 should be replaced by 0.76 and 63μsec by 76μsec.

Starting from the hint that the capacitor charges from -4.4V towards $+5$V, we would result to a total 9.4V for a full charge. However, the V_{BE} of Q_2 is clipping the charging process at only 5V of the total (from

-4.4V to 0.6V). Thus, the capacitor will be 53% charged at the end.
Solving the voltage equation for a charging capacitor gives us

$$V_C(t) = V_f * (1 - e^{-\frac{t}{RC}})$$

set $V_C(t_1) = 0.53 * V_f$

$$0.53 = 1 - e^{-\frac{t_1}{R_3 C_1}}$$

$$\Rightarrow$$

$$t_1 = -R_3 C_1 * ln(0.47) \approx \boxed{\mathbf{0.76 * R_3 C_1}}$$

Exercise 2.3

The output voltage is reduced due to the $R_4 - R_5$ voltage divider

$$V_{\text{out}} = \frac{R_5}{R_4 + R_5} * (V_{CC} - 0.6\text{V}) \approx \boxed{\mathbf{4.18}\text{V}}$$

To estimate the minimum β_3, we need first to find the maximum (worst-case) collector current for which Q_3 should still be in saturation. For this we can assume a 0V drop across C and Q_3 while the current travels through the parallel connected resistors $R_2||R_3$.

$$I_{C_3,max} = \frac{V_{CC}}{R_2||R_3} = 5.5\text{mA}$$

$$\Rightarrow \beta_{3,min} = \frac{I_{C_3,max}}{I_{B_3}} = \frac{5.5\text{mA}}{\frac{(4.18\text{V}-0.6\text{V})}{20\text{k}\Omega}} \approx \boxed{\mathbf{31}}$$

Exercise 2.4

By using KCL and the fact that the transistor is in the active region we get

$$i_E = i_C + i_B = (\beta + 1) * i_B = (\beta + 1)\frac{v_B}{Z_{source}}$$

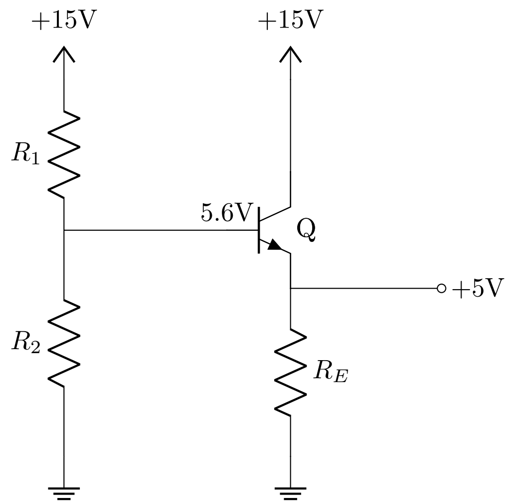
For small signals $Z_{\text{out}} = \frac{v_E}{i_E} = \frac{v_B}{i_E}$. Thus:

$$\boxed{\mathbf{Z}_{\text{out}} = \frac{\mathbf{v_B}}{(\beta + \mathbf{1})\frac{\mathbf{v_B}}{\mathbf{Z_{source}}}} = \frac{\mathbf{Z_{source}}}{\beta + \mathbf{1}}} \qquad q.e.d.$$

Note: In practice one will often see $Z_{\text{out}} \approx \frac{Z_{source}}{\beta}$. When $\beta \approx 100$ the "+1" part is often being ignored to simplify calculations.

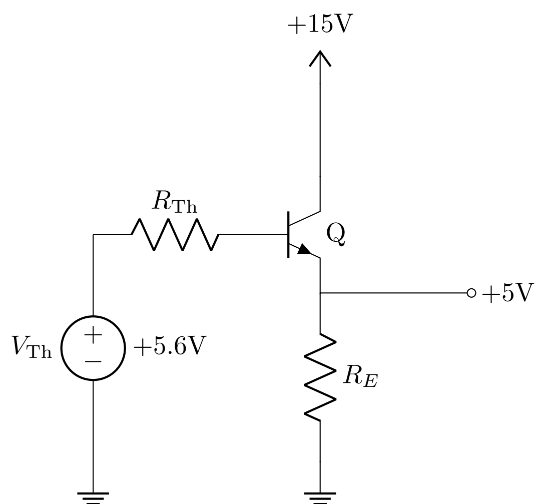
Exercise 2.5

Figure 1: Follower driven by voltage divider



We can simplify the voltage divider with it equivalent Thévenin voltage source depicted in Figure 2 below.

Figure 2: Follower driven by equivalent Thévenin source



With $R_{\text{Th}} = R_1 || R_2$ which is also our R_{source}. The output impedance of our circuit then is

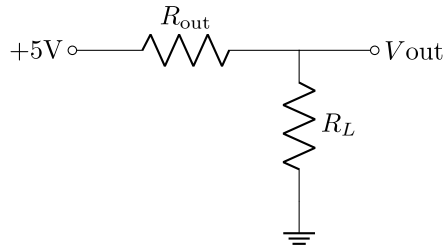
$$R_{\text{out}} = \frac{R_{\text{Th}}}{\beta + 1} \approx \frac{R_{\text{Th}}}{100} = \frac{R_1 || R_2}{100} \qquad \text{(assuming } \beta \approx 100\text{)}$$

We also know that the following condition needs to be true in order to achieve the wished 5.6V at the base:

$$\frac{R_2}{R_1 + R_2} = \frac{5.6\text{V}}{15\text{V}} \Rightarrow R_2 \approx 0.6 * R_1$$

Now let's observe the equivalent circuit *with* load.

Figure 3: Equivalent voltage source of emitter follower with load



Our goal is to have a maximum voltage drop of 5% with maximum load:

$$V_{\text{out}} = \frac{R_L}{R_{\text{out}} + R_L} * 5\text{V} \geq 0.95 * 5\text{V}$$

$\Rightarrow$

$$R_{\text{out}} \leq \frac{R_L}{19} \leq \frac{\frac{4.75\text{V}}{25\text{mA}}}{19} = 10\Omega$$

$\Rightarrow$

$$\frac{R_{\text{Th}}}{100} \leq 10\Omega$$

$\Rightarrow$

$$\frac{R_1||R_2}{100} \leq 10\Omega$$

$\Rightarrow$

$$R_1 \leq 2.7\text{k}\Omega \text{ and } R_2 \leq 1.62\text{k}\Omega$$

We choose the following values for R_1 and R_2:

$$\boxed{\mathbf{R_1 = 2.7\text{k}\Omega}} \text{ and } \boxed{\mathbf{R_2 = 1.6\text{k}\Omega}}$$

NOTE 1: We could have picked more conservative (smaller) values for the resistors. However, this would increase the idle power consumption.

NOTE 2: We could also define a value for R_E i.e. to limit the quiescent current, but this is out of the scope of this exercise. Basically we see now R_E as our load or put differently, our total load is $R_E||Z_{whatever-the-user-wants}$.