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}:

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

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

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

2 Bipolar Transistors

Exercise 2.1

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

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

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

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

Exercise 2.2

> **NOTE: According to the errata** 0.63 **should be replaced by** 0.76 **and** $63\mu\sec$ **by** $76\mu\sec.$

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 $V_C(t_1) = 0.53 * V_f$

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

$$\Rightarrow$$

$$t_1 = -R_3 C_1 * ln(0.47) \approx \boxed{\textbf{0.76} * \textbf{R}_3 \textbf{C}_1}$$

Exercise 2.3

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

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

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 $R_2 || R_3$.

$$I_{C3,max} = \frac{V_{CC}}{R_2 || R_3} = 5.5\text{mA}$$

$$\Rightarrow \beta_{3,min} = \frac{I_{C3,max}}{I_{B_3}} = \frac{5.5\text{mA}}{\frac{(4.18\text{V} - 0.6\text{V})}{20\text{k}\Omega}} \approx \boxed{\textbf{31}}$$

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:

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

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.