1. An engineer measures the (step response) rise time of an amplifier as \( t_r = 0.7 \, \mu s \). Estimate the 3 dB bandwidth of the amplifier.

   \[
   BW \approx \frac{0.35}{t_r} = \frac{0.35}{0.7 \times 10^{-6}} = 500 \, \text{kHz}
   \]

2. In the current mirrors below, neglect the base currents. What is \( I_{\text{REF}} \)?

   \[ \text{Answer: 0.25 \mu A} \]

3. An engineer designs a class-AB amplifier to deliver 2 W (sinusoidal) signal power to an 8 \( \Omega \) resistive load. Ignoring saturation in the output BJTs, what is the required peak-to-peak voltage swing across the load? (2 points)

   \[ P = \frac{V_{\text{rms}}^2}{R}, \text{ so that } V_{\text{rms}} = 4 \, \text{V}, \text{ so that } V_{\text{pp}} = 11.32 \, \text{V} \]
4. Many BJT datasheets do not list $\beta$ explicitly, but list an equivalent $h$-parameter instead. What is this parameter?

**Answer:** $h_{fe}$

5. A MOSFET is biased such that $g_m = 1.78 \, \text{mA/V}$ and $I_D = 1 \, \text{mA}$. If $V_{GS}$ changes with 1 mV, by how much does the drain current change?

**Answer**

\[ \delta I_D = g_m \delta V_{GS} = (1.78 \times 10^{-3})(1 \times 10^{-3}) = 1.78 \, \mu A \]

6. Estimate the voltage gain of the following amplifier.

![Amplifier Circuit](image)

**Answer:** $A_V \approx -1K/(100) = -10$

7. For the following circuit, what is the numerical value for the two-port $y$-parameter $y_{12}$? (3 points)

\[ y_{12} = \frac{i_1}{v_2} \bigg|_{v_1=0} \]

![Port Y-Parameter Circuit](image)

**Answer:**

Short port 1, then apply a voltage $v_2$ and determine the current that flows into port 1, and apply the definition above. Then $y_{12} = -1/300K$
8. What type of negative feedback (series-shunt, series-series,…) is used in the following amplifier?

![Amplifier Diagram]

**Answer:** Shunt-shunt

9. The output voltage of a three-terminal voltage regulator is 5 V @ 5 mA load, and 4.96 V @ 1.5 A load. What is the regulator’s output resistance?

**Answer:**

\[
R = \frac{\Delta V}{\Delta I} = \frac{0.04}{1.495} = 27 \text{ m\Omega}
\]

10. The output voltage of a three-terminal voltage regulator is 5 V @ 5 mA load, and 4.96 V @ 1.5 A load. What is the regulator’s load regulation?

**Answer**

\[
\text{Load Regulation} = \frac{V_{o(NL)} - V_{o(FL)}}{V_{o(NL)}} \times 100 = \frac{5 - 4.96}{5} \times 100 = 0.8\%
\]

11. Classify the following filter as active/passive and lowpass/high-pass, etc.

![Filter Diagram]

**Answer:** Active high-pass
12. Classify the following filter as active/passive and lowpass/high-pass, etc.

**Answer:** Active low-pass

13. Classify the following filter as active/passive and lowpass/high-pass, etc.

**Answer:** Active high-pass

14. Classify the following filter as active/passive and lowpass/high-pass, etc.

**Answer:** Active low-pass

15. Classify the following filter as active/passive and lowpass/high-pass, etc. (2 points)

**Answer:** Active bandpass
16. An amplifier with gain of 200 has a 10% variation in gain over a certain frequency range. Using negative feedback, what value of β should one use to reduce the gain variation to 1%? (3 points)

**Answer.** The improvement factor we want from the negative feedback is \( \Delta A_{OL} / \Delta A_f = 10\% / 1\% = 10 \). Therefore, \( (1 + \beta A_{OL}) = 10 \Rightarrow (1 + 200\beta) = 10 \Rightarrow \beta = 0.045 \)

17. An amplifier has gain of 100,000, and a 20% variation in gain over a certain temperature range. Negative feedback is used to reduce the gain to 10. What is the variation in gain with temperature of the feedback amplifier? (3 points)

**Answer.** The gain is reduced by \( 1 + \beta A_{OL} = 100,000 / 10 = 10,000 \). The temperature variations are reduced by the same factor, so the feedback amplifier’s gain varies by \( 20\% / 10^4 = 0.002\% \)

18. An op-amp has an open-loop gain of 120 dB and an input resistance of 50 MΩ. An engineer wants to use negative feedback to obtain an amplifier with input resistance of 5 GΩ. What is the gain (in dB) of the feedback amplifier? (2 points)

**Answer.** Negative feedback increases the resistance by \( (5 \times 10^9) / (50 \times 10^6) = 100 \) (or 40 dB) and reduces the gain by the same factor, so the feedback amplifier’s gain is 80 dB.

19. An single-pole op-amp has an open-loop low-frequency gain of \( A = 10^5 \) and an open loop, 3-dB frequency of 4 Hz. If an inverting amplifier with closed-loop low-frequency gain of \( \left| A_f \right| = 50 \) uses this op-amp, determine the closed-loop bandwidth. (2 points)

**Answer.** The gain-bandwidth product is \( 4 \times 10^5 \) Hz. The bandwidth of the closed-loop amplifier is then \( 4 \times 10^5 / 50 = 8 \) kHz.
20. An engineer wants to reduce the output amplitude of the Wien bridge oscillator below by adjusting $R_5$. Should she increase or decrease the resistor’s value? Briefly explain you answer. (3 points)

Answer:

She should decrease $R_5$’s value, as this will cause the diodes to “turn on” at a lower output voltage. With the diodes turned on, the negative feedback resistance consisting of $R_5$, $R_5$, and the diodes are reduced, which reduces the overall gain.

21. Briefly explain the purpose of the “.IC (VA) = 0.01V” in the SPICE schematic. (2 points)

Answer:

This sets the initial condition (i.e., at startup) for the voltage at node A to 0.001 V. This is required, since there is no other signal source in the circuit.
**Question 2** The open-loop low-frequency gain of an op-amp is 100 dB. At a frequency of $f = 10^4$ Hz, the magnitude of the open-loop gain is 38 dB. The op-amp has a dominant-pole open-loop response. Determine the frequency of the dominant pole and the unity-gain bandwidth. (5 points)

**Solution**

Open-loop dominant pole response implies constant GBP, which is

$$GBP = 10^{38/20} \times 10^4 = 794.4 \times 10^3$$

The dominant-pole frequency is

$$f = \frac{GBP}{10^{100/20}} = 7.94 \text{ Hz}$$

The unity-gain bandwidth is the same as GBP.

---

**Question 3** With inputs $v_{i1} = -50 \text{ mV}$, and $v_{i2} = +50 \text{ mV}$, a difference amplifier has output $v_O = 1.0043 \text{ V}$. With inputs $v_{i1} = v_{i2} = 5 \text{ V}$, the output is $v_O = 0.4153 \text{ V}$. Determine the CMRR, expressed in dB. (5 points)

**Solution**

The differential input voltage is $v_{i2} - v_{i1} = 100 \text{ mV}$, and the differential-mode gain is $1.0043/0.1 = 10.043$

With $v_{i1} = v_{i2} = 5 \text{ V}$ the common-mode voltage gain is $A_{cm} = 0.4152/5 = 0.083$

The common-mode rejection ratio is

$$\text{CMRR} = \left| \frac{A_d}{A_{cm}} \right| = \left| \frac{10.043}{0.083} \right| = 120.85$$

Expressed in dB

$$\text{CMRR}_{dB} = 20 \log_{10} 120.85 = 41.65 \text{ dB}$$
Question 4  For the circuit below $\beta = 120, V_{BE(ON)} = 0.7 \text{ V}$, and $V_A = \infty$ Further, $R_1 = 110 \text{ k}\Omega$ and $R_2 = 82 \text{ k}\Omega$ and a dc analysis show that $I_{CQ} = 1 \text{ mA}$. (10 points)

What is the lower 3 dB corner frequency? **Hint: use BJT scaling and determine $R_o$. Then use the time-constant technique.**

**Solution**

Using BJT impedance scaling

$$R_o = R_E \left( \frac{r_n}{1 + \beta} \right)$$

$$r_n = \frac{\beta}{g_m} = \frac{120}{40 \times 1 = 3 \text{ k}\Omega}$$

$$\Rightarrow R_o \approx 25 \text{ } \Omega$$

The time constant associated with the coupling capacitor is

$$\tau = C_{c2}(R_o + R_L) = 2 \times 10^{-6}(25 + 4 \times 10^3)$$

$$= 8.1 \text{ ms}$$

The lower corner frequency is then

$$f_L = \frac{1}{2\pi\tau} = 19.8 \text{ Hz}$$
Question 5  A power MOSFET has thermal characteristics given below. The device operates without a heat sink and dissipates 0.2 W. What is the junction temperature if the ambient temperature is 25 °C? Start by drawing and labeling a thermal model. (8 points)

\[
\begin{align*}
\theta_{\text{dev-case}} &= 1.75 \degree \text{C/W}, \\
\theta_{\text{case-amb}} &= 50 \degree \text{C/W}, \\
T_{J,\text{max}} &= 150 \degree \text{C}
\end{align*}
\]

Solution

\[
T_J = \frac{T_A + P_D (\theta_{\text{dev-case}} + \theta_{\text{case-amb}})}{1 + \left(\theta_{\text{dev-case}} + \theta_{\text{case-amb}}\right)}
\]

\[
= 25 + 0.2(50 + 1.7)
\]

\[
= 35.34 \degree \text{C}
\]
**Question 6** In the circuit below, the FETs have $g_m = 900 \times 10^{-6}$ A/V, $C_{gd} = 6$ pF and $C_{gs} = 4$ pF. The signal source has $R_s = 100$ kΩ. Determine the low frequency differential gain, namely $A_d = (v_x - v_y)/v_i$. Then draw and fully label (i.e., slopes, intercepts, etc.) the Bode plot of the gain $A_d(\omega)$. *Hint: you can simply your work by using the concept of a “half-amplifier”.* (15 points)

![Circuit Diagram](image)

**Solution** Below is a small-signal equivalent for the amplifier that includes $C_{gd}$ and $C_{gs}$ for the FETs. Half-amplifier analysis will simplify our work, but note that the load $R_L$ is not connected to ground, and the signal source is unbalanced.

![Small-Signal Equivalent](image)

Split the load and signal source in two, and redraw the circuit as follows. If we have $v_{lx} = 0.5v_{lx} = -0.5v_{ly} = 0.5v_i$, then we will have the same differential gain $A_d = (v_x - v_y)/v_i$. Note, however, that the voltages at nodes $K$ and $Z$ do not change, and we can treat them as virtual grounds.
The resulting half amplifier circuit is then

\[ v_x = -\frac{1M}{1M + 50K} g_m(50K\|50K) v_{lx} = -21.43 \frac{v_l}{2} = -10.71 v_l \]

Similarly, \( v_y = 10.71 v_l \), so that \( A_d = (v_x - v_y)/v_l = -21.42 = -26.62 \) dB. This is an inverting amplifier and the 6 pF capacitor between the drain and gate will experience the Miller multiplication. The Miller gain is the gain from node \( a \) to \( x \), or \( A_M = g_m(R_x\|50K) = -22.5 \). Now

\[ C_M = (1 + |A_M|)(6 \text{ pF}) = 141 \text{ pF} \]
\[ C_{EQ} = 141 \text{ pF} + 4 \text{ pF} = 145 \text{ pF} \]
\[ 1/\omega_{EQ} = (145 \text{ pF})(50K\|1M) \Rightarrow \omega_{EQ} = 144.8 \times 10^3 \text{ rad/s} = 23 \text{ kHz} \]

The calculated values match those obtained via SPICE.
In the circuit above, the maximum power the transistor may dissipate is $P_{Q,max} = 25 \text{ W}$.

(a) Determine $R_L$ such that maximum power is delivered to the load. (4 points)

(b) For $V_p = 12 \text{ mV}$, determine average power dissipated in the transistor. (6 points)

Do not calculate $R_B$, and neglect the base current when calculating power.

Solution

Part (a) The transistor will dissipate the maximum power (25 W) when $V_C = V_{CC}/2 = 12 \text{ V}$. From this follows that $I_C = 25/12 = 2.0843 \text{ A}$, and $R_L = 12/2.083 = 5.76 \Omega$.

Part (b) The gain of the amplifier is $A_V = -g_m R_L = -(40 I_C) R_L = -(40)(2.083)(5.76) = -480$, so that the amplitude of the signal output voltage is $0.012 \times 480 = 5.76 \text{ V}$.

The signal power dissipated in the resistor is

$$V_{rms}^2/R_L = V_p^2/(2 R_L) = (5.76^2)/(2 \times 5.76) = 2.88 \text{ W}$$

The average power dissipated in the transistor is $25 - 2.88 = 22.1 \text{ W}$
Question 8 Consider a four-pole feedback system with a loop gain given by

\[ T(f) = \frac{\beta(10^3)}{(1 + j \frac{f}{10^3})(1 + j \frac{f}{10^4})(1 + j \frac{f}{10^5})(1 + j \frac{f}{10^6})} \]

Determine the value of \( \beta \) that produces a phase margin of \( 45^\circ \) \( (12 \text{ points}) \)

**Solution**

A phase margin of \( 45^\circ \) implies \( \phi = -135^\circ \). Thus

\[ \phi = -\tan^{-1} \frac{f}{10^3} - \tan^{-1} \frac{f}{10^4} - \tan^{-1} \frac{f}{10^5} - \tan^{-1} \frac{f}{10^6} \]

Program the equation into a programmable calculator and try different values for \( f \) to find \( f \approx 10^4 \text{ Hz} \)

Next, determine \( \beta \) from \( |T(f)| = 1 \) at this frequency

\[ T(f) = 1 = \frac{\beta(10^3)}{\sqrt{1 + (10)^2} \sqrt{1 + (1)^2} \sqrt{1 + (0.1)^2} \sqrt{1 + (0.01)^2}} \]

\[ = \frac{\beta(10^3)}{(10.05)(1.414)(1.005)(1)} \]

\[ \beta = 0.01428 \]
Problem 9. Consider the circuit below. Determine the voltage at which the output stabilizes (10 points)

Solution

Assume the diodes act as switches and close when the voltage across them exceeds $v_{D(ON)}$ V.

An equivalent circuit at the instant $v_o$ crests is adjacent. Note that $v_- = v_o/3$ for a stable Wien bridge. The current through $R_1$ is $(v_o/3)/R_1$, which is the same current that flows through $R_2$. Since $R_1 = R_2$, it follows that $v_1 = 2v_o/3$. KCL at the junction of $R_2, R_3,$ and $R_1$ gives

$$\frac{v_o/3}{R_1} + \frac{2v_o/3 - v_o}{R_3} + \frac{2v_o/3 - v_o + v_D}{R_4} = 0$$

Solving and substituting circuit values yields $v_o = 5 \ v_D$

- $v_{D(ON)} = 0.4 \ \text{V} \rightarrow v_o = 2 \ \text{V}$
- $v_{D(ON)} = 0.6 \ \text{V} \rightarrow v_o = 3 \ \text{V}$
- $v_{D(ON)} = 0.7 \ \text{V} \rightarrow v_o = 3.5 \ \text{V}$
**Question 10** For the switched-capacitor circuit below, the parameters are $C_1 = 30 \text{ pF}, C_2 = 5 \text{ pF}, C_F = 12 \text{ pF}$. The clock frequency is 100 kHz. Determine the low-frequency gain and the cutoff frequency. **(10 points)**

**Solution**

The switched capacitors $C_1$ and $C_2$ function as resistors with values $R_1 = 1/f_c C_1 = 333.3 \text{ k}\Omega$, and $R_2 = 1/f_c C_2 = 2 \text{ M}\Omega$ respectively. At low frequencies $C_F$ is an open circuit and the low-frequency gain is

$$A_V = -\frac{R_2}{R_1} = -\frac{C_1}{C_2} = -6$$

The cutoff frequency is determined by $C_F$ and the switched capacitor $R_2$

$$f_{3dB} = \frac{1}{2\pi R_2 C_F} = \frac{1}{2\pi (2 \times 10^6) 12 \times 10^{-12}} = 6.63 \text{ kHz}$$
Question 11  Consider the difference amplifier below.  A dc analysis shows that $I_1 = 1.94 \text{ mA} \approx I_{C5}$, and $I_{C3} = 1.07 \text{ mA}$. Determine the voltage gain $|A_d| = |v_o/(v_1 - v_2)|$.  

(6 points)

You may assume that the output stage ($Q_{3}, R_E, R_{C2}$) does not load the differential input stage.

Solution

Transistor $Q_{3}, R_E, R_{C2}$ form a common-emitter stage with gain $A_3 \approx R_{C2}/R_E = 1.212$.

Further,

$$g_{m2} = 40I_{C2} = 40 \left(1.94 \times 10^{-2}\right) = 38.8 \text{ mS}$$

The gain of the differential stage is

$$A_{d2} = \frac{1}{2} g_{m2} R_c = \frac{1}{2} (38.8 \times 10^{-3})(8 \times 10^3) = 155$$

The overall gain is $A_d = A_{d2}A_3 = 1.212 \times 155 = 188$
**Problem 12**  An amplifier has open-loop gain and phase shown below. An engineer uses the amplifier in a negative feedback configuration such that the closed-loop gain is 1,000.

(a) What is the feedback factor $\beta$?  
(b) What is the closed-loop bandwidth?  
(c) What are the phase- and gain margins?  \(\text{(10 points)}\)

Solution

**Part (a)**

$$\beta \approx 1/A_f = 1/1,000 = 0.001$$

**Part (b)** A gain of 1,000 is equivalent to 60 dB. Draw a horizontal line at 60 dB (red horizontal line above) The line intersects the gain plot at 70 kHz, which is the closed-loop bandwidth.

**Part (c)** The phase at 70 kHz is $-88^\circ$. Another $92^\circ$ phase shift will make the phase $-180^\circ$ so the phase margin is $92^\circ$.

**Part (c)** The gain margin is 70 dB, as indicated in with the blue arrows.