COLLEGE OF ENGINEERING
PUTRAJAYA CAMPUS
FINAL EXAMINATION

SEMESTER 1   2015 / 2016

PROGRAMME	: **Bachelor of Electrical & Electronics Engineering (Honours)** **Bachelor of Electrical Power Engineering (Honours)**
SUBJECT CODE	: **EEEB273**
SUBJECT	: **ELECTRONIC ANALYSIS AND DESIGN II**
DATE	: **September 2015**
TIME	: **3 hours**

INSTRUCTIONS TO CANDIDATES:

1. This paper contains **FIVE** (5) questions in **NINE** (9) pages.
2. Answer **ALL** questions.
3. Write **all** answers in the answer booklet provided. **Use pen** to write your answer.
4. Write answer to different question on **a new page**.

THIS QUESTION PAPER CONSISTS OF NINE* (9) *PRINTED PAGES INCLUDING THIS COVER PAGE.

Question 1 [20 marks]

Figure 1 has the transistor parameters of $\boldsymbol{\beta}$ **= 180**, $\boldsymbol{V_{BE}}$**(on) = 0.7 V** (for all transistors **EXCLUDING** $\boldsymbol{Q_4}$), $V_A = \infty$ for $\boldsymbol{Q_1}$ and $\boldsymbol{Q_2}$, and V_A **= 100 V** for $\boldsymbol{Q_3}$ and $\boldsymbol{Q_4}$.

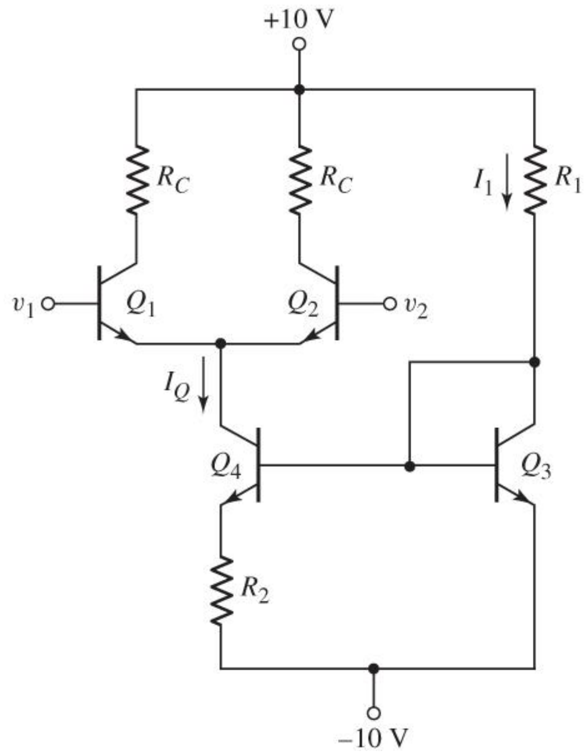


Figure 1

(a) **Calculate** $\boldsymbol{R_1}$ and $\boldsymbol{R_2}$ as such $\boldsymbol{I_1}$ **= 0.5 mA** and $\boldsymbol{I_Q}$ **= 140** $\boldsymbol{\mu}$**A.** [5 marks]

(b) **Determine** the common-mode input resistance, $\boldsymbol{R_{icm}}$, of the differential amplifier. [10 marks]

(c) **Find** the common-mode voltage gain, $\boldsymbol{A_{cm}}$, of the differential amplifier for $\boldsymbol{R_C}$ **= 50 kΩ**. The equation is given as [5 marks]

$$A_{cm} = \frac{-g_m R_C}{1 + \dfrac{2(1+\beta)R_o}{r_\pi}}$$

Q1 Answer

(a) Calculate R_1 and R_2 as such I_1 = 0.5 mA and I_Q = 140 μA. [5 marks]

Using the KVL rule,

$I_1 = \frac{10-0.7-(-10)}{R_1} = 0.5m$ **[1.5]**

R_1 = 38.60 kq **[1]**

For the Widlarôs current source,

$I_O R_E = V_T \ln\left(\frac{I_{REF}}{I_O}\right)$ **[1.5]**

Substituting for R_2,

$$I_O R_E = V_T \ln\left(\frac{I_{REF}}{I_O}\right)$$

$$R_E = \frac{V_T}{I_O}\ln\left(\frac{I_{REF}}{I_O}\right)$$

$R_2 = \frac{V_T}{I_O}\ln\left(\frac{I_{REF}}{I_O}\right) = \frac{0.026}{0.14} ln\left(\frac{0.5m}{0.14m}\right) = \mathbf{236\ \Omega}$ **[1]**

(b) Determine the common-mode input resistance, $\boldsymbol{R_{icm}}$. [10 marks]

$R_{icm} \approx (1+\beta)R_O$ **[2]**

For Widlarôs current source, $R_O - r_{O4}(1 + g_{m4}R_E')$ **[2]**

$g_{m4} = \frac{I_Q}{V_T} = \frac{0.14m}{0.026} = 5.385\ mA/V$ **[1]**

$r_{\pi4} = \frac{\beta V_T}{I_Q} = \frac{(180)(0.026)}{0.14m} = 33.40\ k\Omega$ **[1]**

$R_E' = r_{\pi4}||R_2 = 0.234\ k\Omega$ **[1]**

$r_{O4} = \frac{V_A}{I_Q} = \frac{100}{0.14m} = 714\ k\Omega$ **[1]**

Substituting into the main equation,

$R_o = 714k(1 + (5.385)(0.234k)) = 1614\ k\Omega$ **[1]**

$\therefore R_{icm} = (180+1)1614k \approx 292M\Omega$ **[1]**

(c) Find the common-mode voltage gain, $\boldsymbol{A_{cm}}$, for $\boldsymbol{R_C}$ **= 50 kΩ**. [5 marks]

$$Given\ A_{cm} = \frac{-g_m R_C}{1 + \frac{2(1+\beta)R_O}{r_\pi}}$$

$g_{m1} = \frac{I_Q}{V_T} = \frac{0.14m/2}{0.026} = \frac{0.07m}{0.026} = 2.692\ mA/V$ **[2]**

$r_{\pi1} = \frac{\beta V_T}{I_Q} = \frac{(180)(0.026)}{0.14m/2} = 66.86\ k\Omega$ **[2]**

Substituting these into the equation,

$A_{cm} = \frac{-(2.692m)(50k)}{1+\frac{2(1+180)(1614k)}{66.86k}} = -0.0154$ **[1]**

Question 2 [20 marks]

For the differential amplifier **with 2-transistor active load** circuits in **Figure 2** it is given that the circuit parameters are: V^{+} **= 10 V,** V^{-} **= –10 V,** and I_Q **= 0.1 mA**.

NMOS transistor parameters are: V_{TN} **= 1 V**, k'_n **= 80** μ**A/V**^{2}, and λ_n **= 0.01 V**$^{-1}$; and the **PMOS** transistor parameters are: V_{TP} **= -1 V**, k'_p **= 40** μ**A/V**^{2}, and λ_p **= 0.015 V**$^{-1}$.

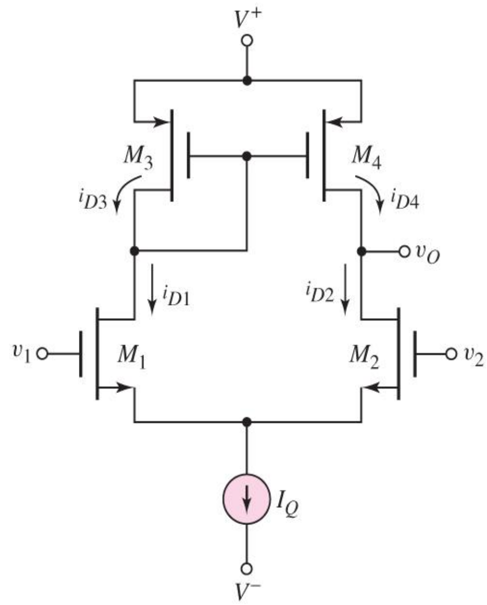


Figure 2

(a) **Find** the differential gain A_d, given $(W/L)_1 = (W/L)_2 = 2$ and $(W/L)_3 = (W/L)_4 = 4$. [5 marks]

(b) **Redesign** the differential pair M_1 and M_2 if the value of the gain is **to be increased 5 times** than that calculated in **part (a)**. [6 marks]

(c) It is given that the **constant current source** I_Q is implemented with a two-transistor current source with $(W/L) = 5$ for the transistors. **Sketch** the differential amplifier circuit **together** with the two-transistor current source. Then, **calculate** the value of the minimum common-mode input voltage, V_{cm}**(min)** of the differential pair. [9 marks]

Q2 Answer

Question 2(a) [5 marks]

$$A_d = g_{m1}\left(r_{o2} \| r_{o4}\right) \text{ [2]}$$

$$I_{D1} = I_Q / 2 = I_{D2} = I_{D3} = I_{D4} = 0.1mA/2 = 0.05mA$$

$$g_{m1} = 2\sqrt{K_n I_{D1}} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_1 I_{D1}} = 2\sqrt{\left(\frac{80\varepsilon}{2}\right)(2)(0.05m)} = 0.1265mA/V \quad [1]$$

$$r_{o2} = \frac{1}{\lambda_n I_{D2}} = \frac{1}{(0.01)(0.05m)} = 2M\Omega \quad [0.5]$$

$$r_{o4} = \frac{1}{\lambda_p I_{D4}} = \frac{1}{(0.015)(0.05m)} = 1.33M\Omega \quad [0.5]$$

$$A_d = (0.1265m)(2M \| 1.33M) = 101V/V \quad [1]$$

Question 2(b) [6 marks]

$$A_{dNew} = 5 \times A_d = 5 \times 101 = 505V/V \quad [1]$$

$$A_{dNew} = g_{m1New}\left(r_{o2} \| r_{o4}\right)$$

$$505 = g_{m1New}\left(0.79M\right) \quad [2]$$

$$g_{m1New} = 0.6395mA/V \quad [1]$$

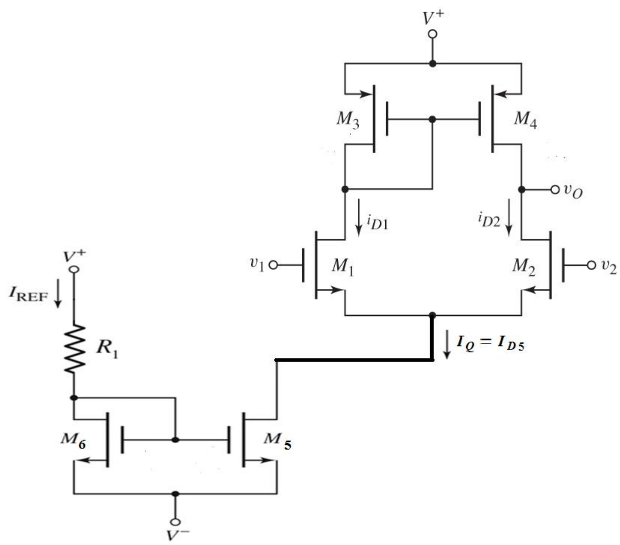
$$g_{m1New} = 2\sqrt{\left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_{1New} I_{D1}} = 2\sqrt{\left(\frac{80\varepsilon}{2}\right)\left(\frac{W}{L}\right)_{1New}(0.05m)}$$

$$0.6395m = \sqrt{\left(\frac{W}{L}\right)_{1New}}(8.94 \times 10^{-5}) \quad [1]$$

$$\left(\frac{W}{L}\right)_{1New} = 51.1 \quad [1]$$

Question 2(c) [9 marks]

Diagram [1]



Q2(c)

$V_{cm}(\min) = V_{GS1} + V_{D5}(sat) + V^-$ [2]

$;V_{GS1}$

$$I_{D1} = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{TN})^2$$

$$0.05m = \left(\frac{80\varepsilon}{2}\right)(2)(V_{GS1} - 1)^2$$

$\rightarrow V_{GS1} = 1.791V$ [2]

$;V_{D5}(sat)$

$$I_{D5} = I_Q = \left(\frac{k_n'}{2}\right)\left(\frac{W}{L}\right)_5 (V_{GS5} - V_{TN})^2$$

$$0.1m = \left(\frac{80\varepsilon}{2}\right)(5)(V_{GS5} - 1)^2$$

$\rightarrow V_{GS5} = 1.707V$ [2]

$V_{D5}(sat) = V_{GS5} - V_{TN} = 1.707 - 1 = 0.707V$ [1]

$V_{cm}(\min) = 1.791 + 0.707 + (-10) = -7.5V$ [1]

Question 3 [20 marks]

(a) Please **refer** to the multistage amplifier circuit shown in **Figure 3**. **Calculate** the small-signal input impedance of the gain stage indicated by $\boldsymbol{R_{i2}}$. It is given that current $\boldsymbol{I_{R4}}$ **= 0.4 mA**, and for the transistors β **= 200** and V_A **= 100 V**. [4 marks]

(b) Refer to **Figure 3** also. If the gain of the differential amplifier: $\boldsymbol{A_{d1} = v_{o2}/v_d}$, the gain of the gain stage: $\boldsymbol{A_{v2} = v_{o3}/v_{o2}}$, and the gain of the output stage: $\boldsymbol{A_{v2} = v_o/v_{o3}}$,

(i) Express $\boldsymbol{A_{vtotal}}$, i.e. the overall gain of the op-amp circuit in terms of $\boldsymbol{A_{d1}}$, $\boldsymbol{A_{v2}}$ and $\boldsymbol{A_{v3}}$. [2 marks]

(ii) How does value of $\boldsymbol{R_{i2}}$ calculated in **part (a)** affects the gain $\boldsymbol{A_{d1}}$. [2 marks]

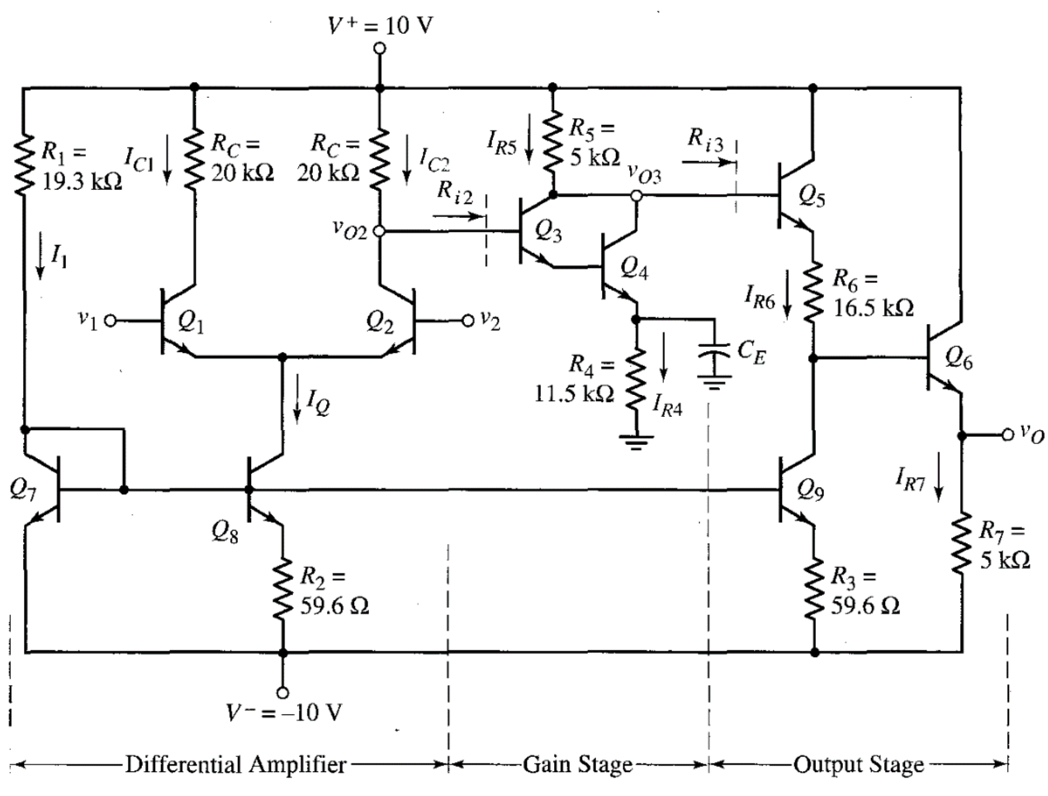


Figure 3

(c) **Figure 4** shows the **Class-AB** output stage circuit. Assume that V_{CC} **= 10 V**, V_{BB} **= 1.35 V**, and R_L **= 1 kΩ**. Transistors Q_n and Q_p are matched, with I_S **= 4×10^{-15} A**. It is given that output voltage v_O **= -8 V**. **Calculate** the voltages v_{BEN}, v_{EBP}, and input voltage v_I, as well as currents i_L, i_{Cn}, and i_{Cp}. Then **calculate** the power dissipated in the transistors P_{Qn} and P_{Qp}.

[12 marks]

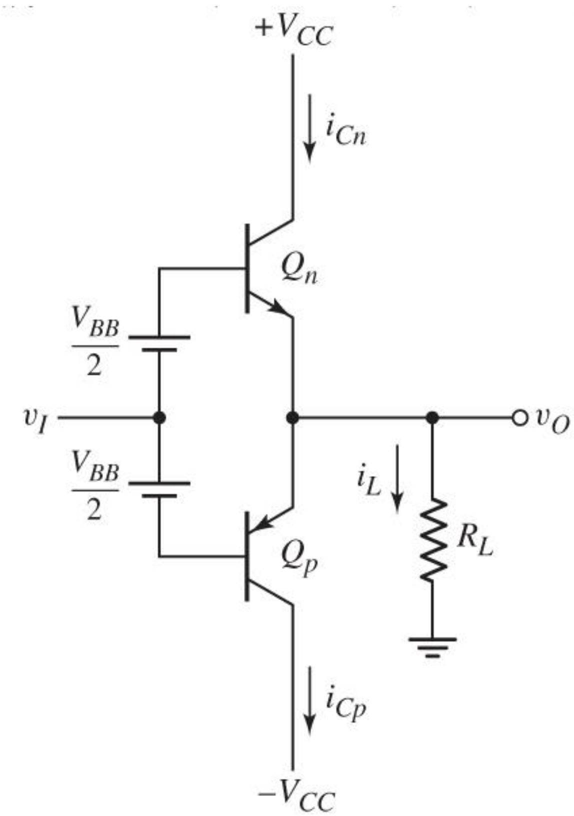


Figure 4

Q3 Answer

Question 3(a) [4 marks]

$$R_{i2} = r_{\pi 3} + (1+\beta) r_{\pi 4} \quad [1.5]$$

$$I_{E4} = I_{R4} = 0.4mA$$

$$I_{C4} = \frac{\beta}{1+\beta} I_{E4} = \frac{200}{201}(0.4m) = 0.398mA$$

$$r_{\pi 4} = \frac{\beta V_T}{I_{C4}} = \frac{(200)(26m)}{0.398m} = 13.07k\Omega \quad [0.5]$$

$[r_{\pi 4} = 13k\Omega$ with $I_{C4} \cong I_{E4}$ is also okay]

$$I_{E3} = I_{B4} = \frac{I_{E4}}{1+\beta}$$

$$I_{C3} = \frac{\beta}{1+\beta} I_{E3} = \frac{\beta}{(1+\beta)} \frac{I_{E4}}{(1+\beta)} = \frac{200}{(201)^2}(0.4m) = 1.98 \times 10^{-6} A \quad [0.5]$$

$$r_{\pi 3} = \frac{\beta V_T}{I_{C3}} = \frac{(200)(26m)}{1.98 \times 10^{-6}} = 2.63M\Omega \quad [0.5]$$

$$\therefore R_{i2} = (2.63M) + (201)(13.07k) = 5.26M\Omega \quad [1]$$

Question 3(b) [4 marks]

(i) $A_{vTOTAL} = V_o/V_d = A_{d1} \times A_{v2} \times A_{v3}$ [2]

(ii) The value of Ri2 is very large, hence the input impedance of the 2nd gain stage will not load down or decrease the gain of the 1st stage, Ad1. I.e. the loading effect of the 2nd stage onto the 1st stage can be neglected. [2]

Question 3(c) [12 marks]

For v_O **= -8 V,**

$i_L = V_O / R_L = (-8V)/(1\ k\Omega) = -8\ mA$ **[1]**

Therefore, Q_p **is conducting** and Q_n is OFF.

Approximation:

$i_{Cp} \approx | i_L | = 8\ mA$ **[1]**

$v_{EBp} = V_T \ln(i_{Cp} / I_S)$

$= (0.026) \ln(8m / 4x10^{-15}) = 0.7364\ V$ **[1]**

$v_{BEn} = V_{BB} - v_{EBp} = 1.35 – 0.7364 = 0.6136\ V$ **[1]**

$V_{In} = V_O + V_{BB}/2 - v_{EBp} = -8 + 1.35/2 - 0.7364 = -8.06\ V$ **[1]**

$i_{Cn} = I_S \exp(V_{BEn} / V_T)$

$= (4x10^{-15}) \exp(0.6136 / 0.026) = 7.102x10^{-5}\ A$ **[1]**

$i_{Cn} = i_{Cp} + i_L$ **[1]**

$i_{Cp} = i_{Cn} - i_L$ **Recalculate** i_{Cp}

$= 7.102x10^{-5} - (-8m) = 8.071\ mA$ **[1]**

For Q_n**:**

$V_{CEn} = V_{CC} - V_O = 10 – (-8) = 18\ V$ **[0.5]**

$P_{Qn} = i_{Cn} V_{CEn} = (7.102x10^{-5})(18) = 1.278\ mW$ **[0.5]**

[1]

For Q_p**:**

$V_{ECp} = V_O – (-V_{CC}) = (-8) – (-10) = 2\ V$ **[0.5]**

$P_{Qp} = i_{Cp} v_{ECp} = (8.071m)(2) = 16.14\ mW$ **[0.5]**

[1]

Question 4 [20 marks]

Consider a **standard 741 operational amplifier** (op-amp) circuit as shown in **Figure 5**. Study **Figure 5** carefully and observe the output stage of the operational amplifier. Assume load resistance connected to the Output of the 741 op-amp is $R_L = 2\ \text{k}\Omega$.

The op-amp is supplied by **±5 V DC** voltages. The transistors have $\beta_n = 200$, $\beta_p = 50$, $V_{AN} = V_{AP} = 50$ V, $V_{BE}(\text{on}) = V_{EB}(\text{on}) = 0.6$ V, and the reverse saturation currents $I_{S18} = I_{S19} = 2\text{x}10^{-14}$ A, and $I_{S14} = I_{S20} = 5\text{x}10^{-14}$ A.

From **DC analysis**, bias currents for selected transistors are $I_{C13A} = 0.125$ mA, $I_{C13B} = 0.375$ mA, $I_{C19} = 0.113$ mA. **Determine** the output stage quiescent currents I_{C14} and I_{C20}. **Analyse the changes** in output current i_{C20} if $i_{C14} = 1$ mA. Please **state the class** of this output stage.

This output stage includes a number of transistors that are ñ**off**ò during the normal operation. By providing example, **identify and discuss** the functional operation of these transistors when they are ñ**on**ò. [20 marks]

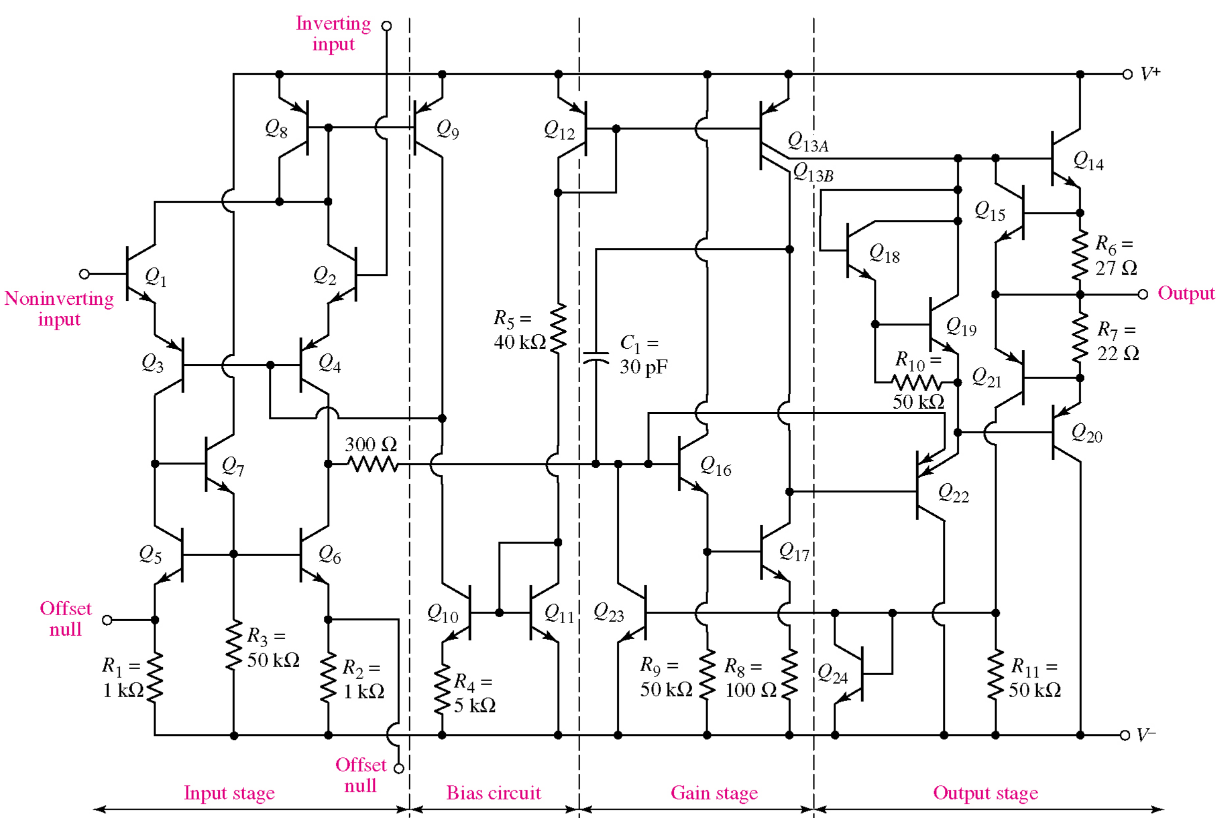


Figure 5

<u>Q4 Answer</u> [20 marks]

$V_{BE19} = V_T \ln (I_{C19}/I_{S19}) = 0.026 \ln (0.113m/2E\text{-}14) = 0.58383$ V [1.5]

$I_{C18} = I_{B19} + (I_{R10}) = (I_{C19}/\beta) + (V_{BE19}/R_{10})$

$= (0.113m/200) + (0.58383/50k) = 12.242\mu A$ [3]

$V_{BE18} = V_T \ln (I_{C18}/I_{S18}) = 0.026 \ln (12.242\mu/2E\text{-}14) = 0.52604$ V [1.5]

$V_{BB} = V_{BE18} + V_{BE19} = 0.52604 + 0.58383 = 1.1099$ V [1.5]

$V_{BE14} = V_{BE20} = V_{BB}/2 = 1.1099/2 = 0.5549$ V [1]

$I_{C14} = I_{C20} = I_S \exp [V_{BE}/V_T] = (5E\text{-}14)\exp[0.5549/0.026] = 92.99\ \mu A$ [2.5]

Class A-B Output Stage [1]

At $i_{C14} = 1mA$; $v_{BE14} = V_T \ln (i_{C14}/I_{S14}) = 0.026 \ln (1m/5E\text{-}14) = 0.6167$ V [1]

$v_{BE20} = V_{BB} - v_{BE14} = 1.1099$ ï $0.6167 = 0.4932$ [1]

$i_{C20} = I_S \exp [v_{BE20}/V_T] = (5E\text{-}14)\exp[0.4932/0.026] = 8.654\ \mu A$ [1]

Keywords:

short circuit protection circuitry; when R_L is shorted ï large current in Q_{14} during positive input cycle; R_6 and Q_{15} limits short circuit current in Q_{14} [5]

OR

short circuit protection circuitry; when R_L is shorted ï large current in Q_{20} during negative input cycle; $R_{7,}$ Q_{21} and Q_{24} limits short circuit current in Q_{20}.

Question 5 [20 marks]

(a) With an **input resistor (R_1) of 50 kΩ**, **design** an amplifier using **op-amp** with a **closed-loop gain** of **25 V/V. Draw and label clearly** your circuit design. [4 marks]

(b) Consider the two inverting op-amp circuit connected in cascade as shown in **Figure 6**. Let $R_1 = 25$ kΩ, $R_2 = 100$ kΩ, $R_3 = 80$ kΩ, and $R_4 = 50$ kΩ. **Calculate** v_O/v_I for the circuit. [4 marks]

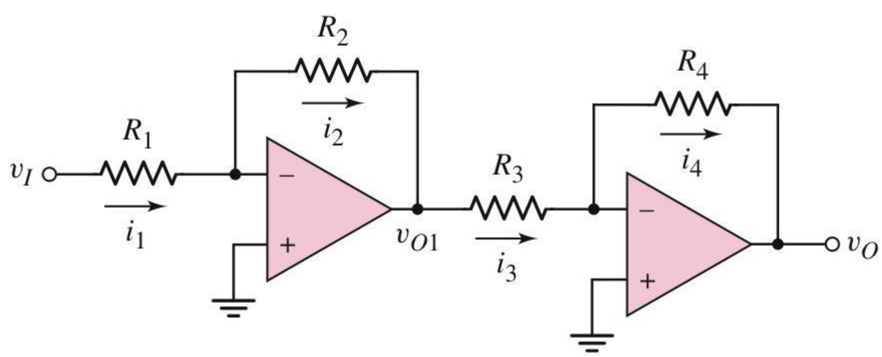


Figure 6

(c) **Figure 7** in the following page shows a design for an **instrumentation amplifier with variable differential voltage gain** using op-amps. In the design, R_{1POT} is a **potentiometer** (or a variable resistor) used **to provide variable resistance** so that differential voltage gain (A_v) of the instrumentation amplifier can be adjustable. With analysis, it can be shown that output voltage (v_O) for the **difference amplifier** constructed using op-amp A_3, resistors R_3, and resistors R_4 is

$$v_O = \frac{R_4}{R_3}\left(v_{O2} - v_{O1}\right)$$

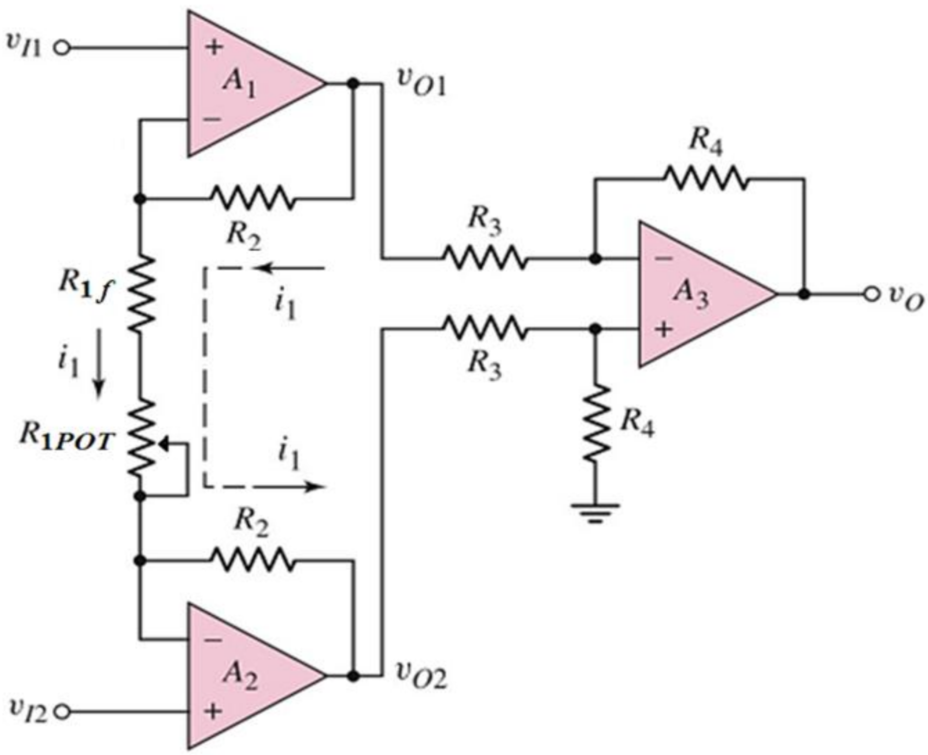


Figure 7

(i) **Study Figure 7 carefully**. Using same labels for all resistors, voltages and currents given in the **Figure 7**, **show** that the output voltage (v_O) of the **instrumentation amplifier with variable differential voltage gain** is [8 marks]

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_{1f} + R_{1POT}}\right)\left(v_{I2} - v_{I1}\right)$$

(ii) For the circuit in **Figure 7,** given that $\boldsymbol{R_4 = 2\,R_3}$, $\boldsymbol{R_2 = 495\ k\Omega}$, $\boldsymbol{R_{1f} = 10\ k\Omega}$, $\boldsymbol{R_{1POT}}$ is set at **40 kÝ**, $\boldsymbol{v_{I1} = 0.90\ V}$, and $\boldsymbol{v_{I2} = 1.25\ V}$. **Calculate** A_v and v_O.

[4 marks]

-END OF QUESTION PAPER-

<u>Q5 Answer</u>

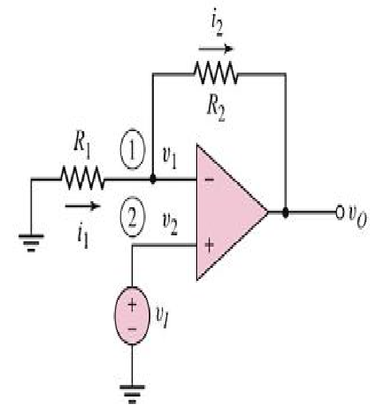
Question 5(a) [4 marks]

$A_v = v_O / v_I = 1 + (R_2/R_1)$ [1]

$25 = 1 + (R_2/50k)$ $R_2 = 1200$ kÝ [1]

Drawing: [2]

$R_1 = 50$ kÝ, $R_2 = 1200$ kÝ, correct op-amp symbol, GND, v_O, and v_I



Question 5(b) [4 marks]

$v_O = (-R_4/R_3)v_{O1}$ [1]

$v_{O1} = (-R_2/R_1)v_I$ [1]

$v_O = (-R_4/R_3)(-R_2/R_1)v_I$ [1]

$v_O / v_I = (R_4/R_3)(R_2/R_1)$

$= [(50k/80k)(100k/25k)] = 2.5$ V/V [1]

Question 5(c)(i) [8 marks]

$$i_1 = \frac{v_{I1} - v_{I2}}{R_{1f} + R_{1POT}} \quad [1]$$

$$v_{O1} = v_{I1} + i_1 R_2 = \left(1 + \frac{R_2}{R_{1f} + R_{1POT}}\right) v_{I1} - \frac{R_2}{R_{1f} + R_{1POT}} v_{I2} \quad [2]$$

$$v_{O2} = v_{I2} - i_1 R_2 = \left(1 + \frac{R_2}{R_{1f} + R_{1POT}}\right) v_{I2} - \frac{R_2}{R_{1f} + R_{1POT}} v_{I1} \quad [2]$$

$$v_O = \frac{R_4}{R_3}\left(v_{O2} - v_{O1}\right) \quad [1]$$

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_{1f} + R_{1POT}}\right)\left(v_{I2} - v_{I1}\right) \quad [2]$$

Question 5(c)(ii) [4 marks]

$$A_v = \frac{v_O}{(v_{I2} - v_{I1})} = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_{1f} + R_{1POT}}\right) \quad [1]$$

$$A_v = \frac{2R_3}{R_3}\left(1 + \frac{2(495k)}{10k + 40k}\right) = 41.6 \text{ V/V} \qquad [1]$$

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_{1f} + R_{1POT}}\right)(v_{I2} - v_{I1}) \qquad [1]$$

$$v_O = A_v(v_{I2} - v_{I1}) = (41.6)(1.25 - 0.90) = 16.224 \text{ V} \qquad [1]$$

APPENDIX:

A) BASIC FORMULA FOR TRANSISTOR

BJT

$$i_C = I_S e^{v_{BE}/V_T} \quad ;\text{NPN}$$

$$i_C = I_S e^{v_{EB}/V_T} \quad ;\text{PNP}$$

$$i_C = \beta i_B = \alpha i_E$$

$$i_E = i_B + i_C$$

$$\alpha = \frac{\beta}{\beta + 1}$$

;Small signal

$$\beta = g_m r_\pi$$

$$g_m = \frac{I_{CQ}}{V_T}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}}$$

$$r_o = \frac{V_A}{I_{CQ}}$$

$$V_T = 26\,\text{mV}$$

MOSFET

;N – MOSFET

$$v_{DS}(\text{sat}) = v_{GS} - V_{TN}$$

$$i_D = K_n[v_{GS} - V_{TN}]^2$$

$$K_n = \frac{\mu_n C_{ox} W}{2L} = \frac{k_n'}{2} \cdot \frac{W}{L}$$

;P – MOSFET

$$v_{SD}(\text{sat}) = v_{SG} + V_{TP}$$

$$i_D = K_p[v_{SG} + V_{TP}]^2$$

$$K_p = \frac{\mu_p C_{ox} W}{2L} = \frac{k_p'}{2} \cdot \frac{W}{L}$$

;Small signal

$$g_m = 2\sqrt{K_{?} I_{DQ}}$$

$$r_o \cong \frac{1}{\lambda I_{DQ}}$$

B) HYBRID-´ EQUIVALENT CIRCUITS