K. J. SOMAIYA COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
Differential Amplifier Circuits

Numerical 1

Determine the following for the circuit given in figure 1. Assume $\beta_1 = \beta_2 = 100$

a) Name the circuit

b) I_C, I_B

c) V_{CE}

d) Differential voltage gain

e) Common mode gain

f) CMRR in dB

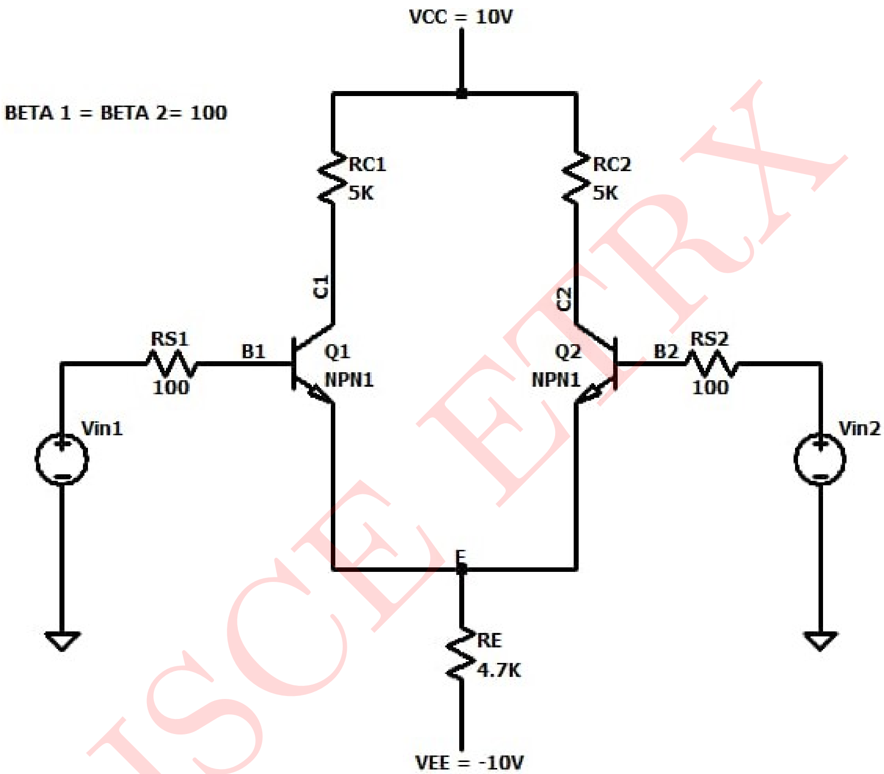

Figure 1: Circuit for Design 1

Solution:

a) Name the circuit:

The given above is dual input balanced output (DIBO)

DC Analysis:

b) Applying KVL to the first part we get,

$V_{EE} - V_{BE} - (1+\beta)I_B R_E = 0$

$I_B = \dfrac{V_{EE} - V_{BE}}{(1+\beta)R_E}$

$$I_B = \frac{10 - 0.7}{100 + (101)4.7k}$$

$$I_B = \frac{9.3}{100 + 101 \times 9.4k}$$

$\mathbf{I_B} = 9.79\mu A$

$I_{CQ} = \beta I_{BQ}$

$I_{CQ} = 100 \times 9.79\mu A$

$\mathbf{I_{CQ} = 0.979mA}$

$I_{CQ_1} = I_{CQ_2} = 0.979mA$

c) Calculation of $\mathbf{V_{CEQ}}$:

$V_{CEQ} = V_{CC} + V_{EE} - I_C(R_C + 2R_E)$

$V_{CEQ} = 10 + 10 - 0.97mA(5k + 9.4k)$

$V_{CEQ_1} = V_{CEQ_2} = 5.91V$

Q-Point=$(V_{CEQ_1}, I_{CQ_1}) = (V_{CEQ_2}, I_{CQ_2}) = (5.91V, 0.979mA)$

Find $\mathbf{A_d}$, $\mathbf{A_{cm}}$ and CMRR:

d) Calculation of differential voltage gain A_d

$$r_\pi = \frac{\beta \times V_T}{I_C} = \frac{100 \times 26mV}{0.979mA}$$

$\mathbf{r_\pi = 2.655k\Omega}$

$$|A_d| = \frac{\beta R_C}{R_S + r_\pi} = \frac{100 \times 5}{0 + 2.655k} \qquad \text{(Since } R_S = 0\text{)}$$

$$|A_d| = \frac{500}{2.655k\Omega}$$

$\mathbf{|A_d| = 188.31}$

e) Calculation of common mode gain A_{cm}:

$$A_{cm} = \left| \frac{R_c}{2R_E} \right|$$

$$A_{cm} = \left| \frac{5k}{9.4k} \right|$$

$\mathbf{A_{cm} = 0.532}$

$$\text{CMRR}=\left|\frac{A_d}{A_{cm}}\right| = \left|\frac{188.32}{0.532}\right|$$

$$\textbf{CMRR} = \textbf{353.984}$$

$$\text{CMRR(dB)}=20log_{10}\left(\frac{A_d}{A_{cm}}\right) = 20log_{10}(353.984)$$

$$\textbf{CMRR(dB)} = \textbf{50.97dB}$$

SIMULATED RESULTS:

Above circuit is simulated in LTspice and results are as follows:

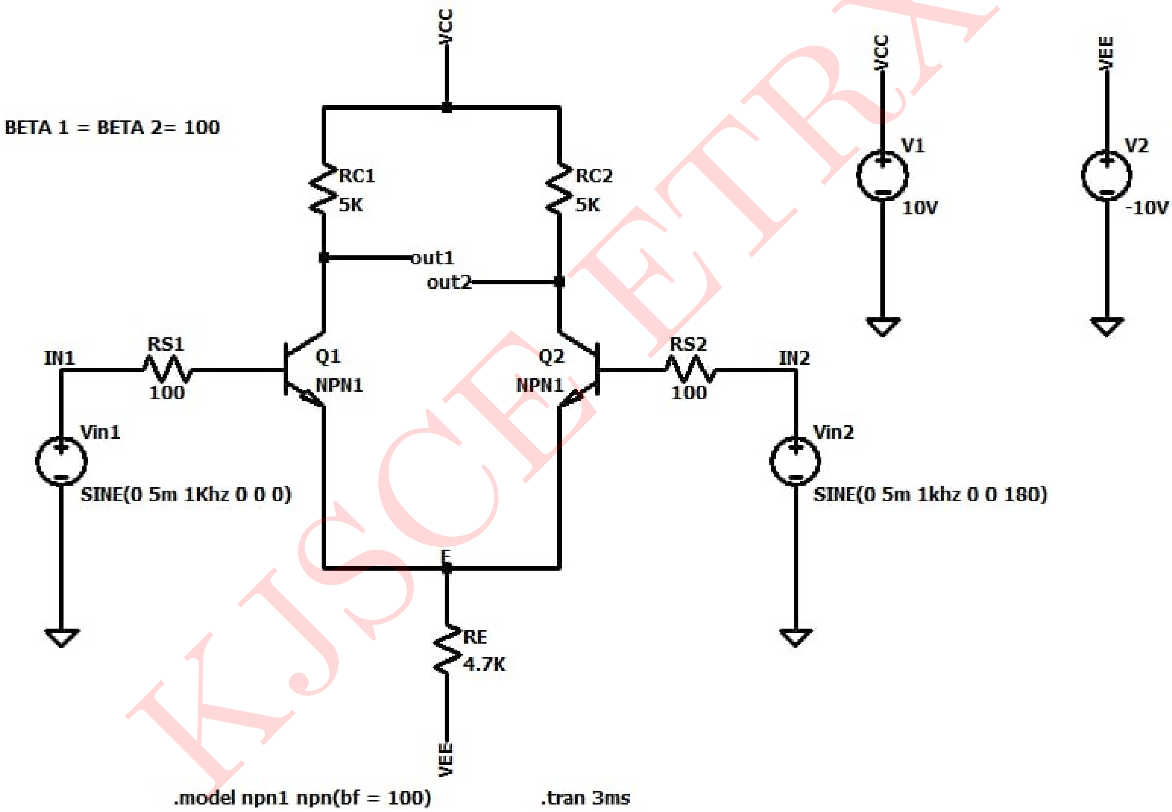

Figure 2: Circuit Schematic: Results

Output Waveforms:

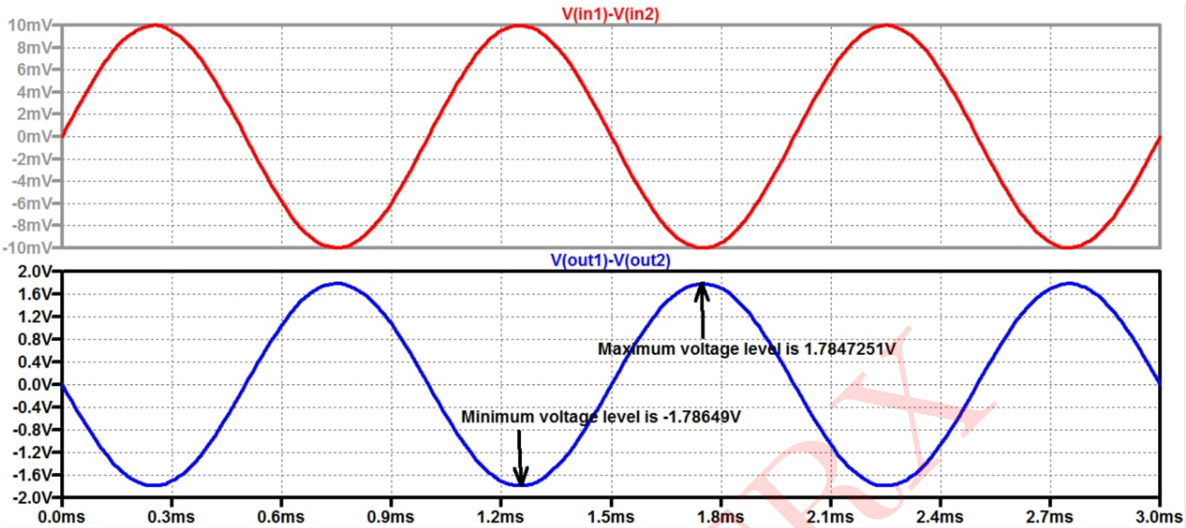

Figure 3: Input and Output waveforms

Comparison between theoretical and simulated values is given below:

Parameters	Theoretical Values	Simulated Values
I_{C_1}	$0.979mA$	$0.971mA$
I_{C_2}	$0.979mA$	$0.971mA$
V_{CE_1}	$5.91V$	$5.93V$
V_{CE_2}	$5.91V$	$5.93V$
$\|A_d\|$	188.32	178.5
A_{cm}	0.532	–
CMRR(dB)	50.97	–

Table 1: Numerical 1

Numerical 2

Determine the following for the circuit given in figure 4. The transistor parameters are $k_{n_1} = k_{n_2} = 50\mu A/V^2$, $\lambda_1 = \lambda_2 = 0.02V^{-1}$ and $V_{TN_1} = V_{TN_2} = 1V$

a) I_{D_1}, I_{D_2}

b) V_{GS_1}, V_{GS_2}

c) Differential voltage gain

d) Common mode voltage gain

e) CMRR in dB

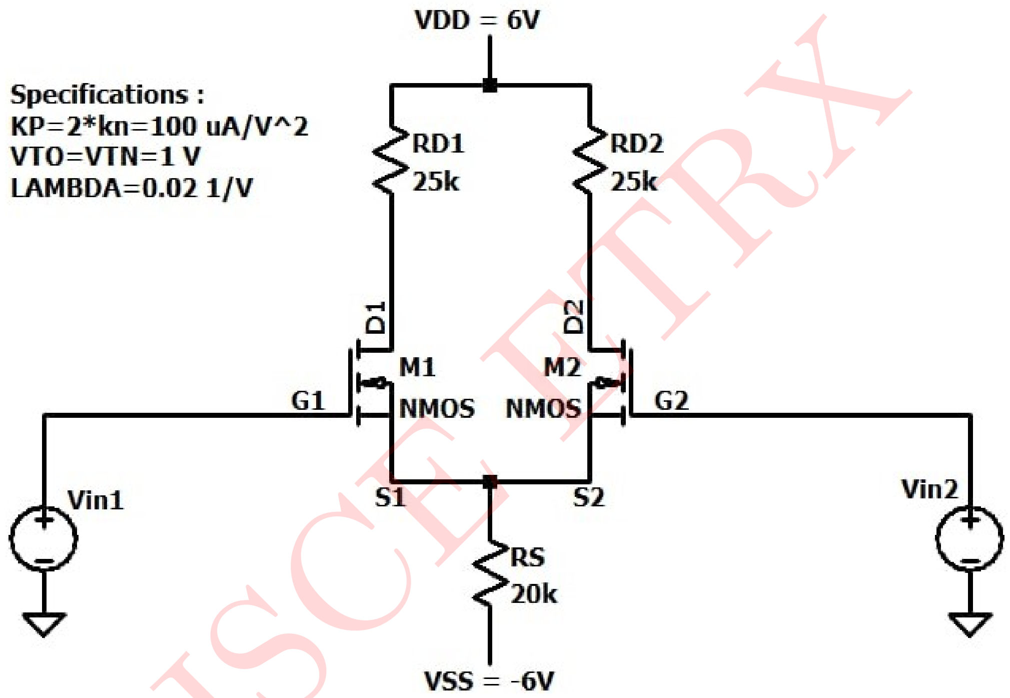

Figure 4: Circuit for Numerical 2

Solution:

DC Analysis:

$V_{GS} = V_{SS} - 2I_D R_S$

$V_{GS} = 6 - 2I_D R_S$ .....(1)

Given, $k_{n_1} = k_{n_2} = 50\mu A/V^2$

The given circuit is a dual input unbalanced output (DIUO) differential amplifier. For DC analysis, consider only one transistor as both transistors are identical.

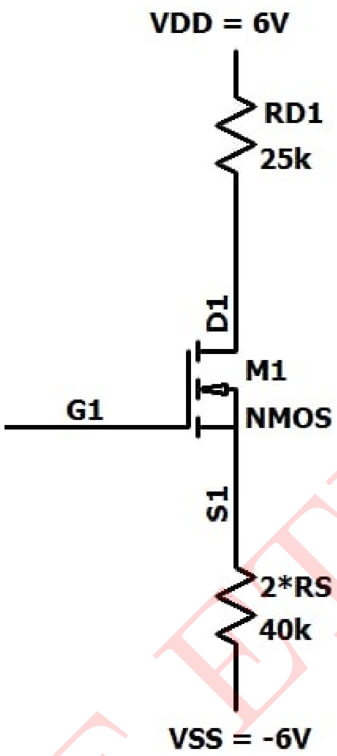

Figure 5: GS loop of MOSFET

Applying KVL to G-S loop we get,

$-V_{GS_1} - 2I_{D_1}R_S - V_{SS} = 0$

$V_{GS_1} = -V_{SS} - 2I_{D_1}R_S$

$V_{GS_1} = 6 - 2I_{D_1}20k$

$V_{GS_1} = 6 - I_{D_1}40k$

Applying KVL to D-S loop we get,

$V_{DD} - I_{D_1}R_{D_1} - V_{DS_1} - I_{D_1}2R_S - V_{SS} = 0$

$V_{DS_1} = V_{DD} - I_{D_1}R_{D_1} - I_{D_1}2R_S - V_{SS} = 0$

$V_{DS_1} = 6 - I_{D_1}25k - I_{D_1}40k + 6$

$V_{DS_1} = 12 - I_{D_1}65k$ .....(2)

From current equation we get,

$I_{D_1} = k_n(V_{GS_1} - V_{TN_1})^2(1 + \lambda V_{DS_1})$

$I_{D_1} = 50 \times 10^{-6}(6 - I_{D_1}40k - 1)^2(1 + 0.02(12 - I_{D_1}65k))$

$I_{D_1} = 50 \times 10^{-6}(5 - I_{D_1}40k)^2(1 + 0.24 - I_{D_1}1.3k)$

$I_{D_1} = 50 \times 10^{-6}(5 - I_{D_1}40k)^2(1.24 - I_{D_1}1.3k)$

$I_{D_1} = 50 \times 10^{-6}(36 + I_{D_1}^2 1600 \times 10^6 - I_{D_1} 400 \times 10^3)(1.24 - I_{D_1} 1.3k)$

$I_{D_1} = 50 \times 10^{-6}(31 + 19844 I_{D_1}^2 \times 10^6 - 496 I_{D_1} \times 10^3 - 32.5 I_{D_1} \times 10^3 - 2.080 I_{D_1}^3 \times 10^9 + 520 I_{D_1}^2 \times 10^6)$

$I_{D_1} = 50 \times 10^{-6}(31 - 528.5 I_{D_1} \times 10^3 + 2504 \times 10^6 I_{D_1}^2 - 2080 I_{D_1}^3 \times 10^9)$

$I_{D_1} = 1.55 \times 10^{-4} - 26.42 I_{D_1} + 125.200 I_{D_1}^2 - 104 \times 10^6 I_{D_1}^3$

$104 \times 10^6 I_{D_1}^3 - 125.200 I_{D_1}^2 + 27.42 I_{D_1} - 1.55 \times 10^{-4} = 0$

Solving the above cubic equation we get,

$I_{D_1} = 9.4 \times 10^{-4}$ or $I_{D_1} = 1.7 \times 10^{-4}$ or $I_{D_1} = 9.28 \times 10^{-5}$

Now let, $I_{D_1} = 9.28 \times 10^{-5} A$

$V_{GS} = 6 - I_D 40k$ (From (1))

$V_{GS} = 6 - 9.28 \times 10^{-5} \times 40 \times 10^3$

$V_{GS} = 2.288V$

V_{GS} must be greater than V_{TN_1}

$\mathbf{V_{GS} = 2.288V}$

$I_{D_1} = 9.28 \times 10^{-5} A$

$\mathbf{I_{D_1} = 0.0928mA}$

From eq(2) we get,

$V_{DS_1} = 12 - I_{D_1} 65k$

$V_{DS_1} = 12 - 0.0928 \times 10^{-3} 65 \times 10^3$

$\mathbf{V_{DS_1} = 5.968V}$

Now, $V_{D_1} = V_{DD} - I_{D_1} R_{D_1}$

$V_{D_1} = 6 - 0.0928 \times 10^{-3} \times 25 \times 10^3$

$\mathbf{V_{D_1} = 3.68V}$

As both the transistors are equal,

$I_{D_1} = I_{D_2} = 0.0928mA$

$V_{DS_1} = V_{DS_2} = 5.968V$

$V_{D_1} = V_{D_2} = 3.68V$

And $I_S = 2 I_{D_1}$

$I_S = 2 \times 0.0928 \times 10^{-3}$

$\mathbf{I_S = 0.1964mA}$

AC Analysis:

$g_{m_1} = 2k_n(V_{GS_1} - V_{TN_1})(1 + \lambda V_{DS_1})$

$g_{m_1} = 2 \times 0 \times^{-6} (2.288 - 1)(1 + 0.02 \times 5.968)$

$g_{m_1} = (100 \times 1.288)(1.119)$

$\mathbf{g_{m_1} = 0.144mA/V}$

$r_{d_1} = \dfrac{1}{\lambda I_{D_1}} = \dfrac{1}{0.02 \times 0.0928 \times 10^{-3}}$

$\mathbf{r_{d_1} = 538.79k\Omega}$

As both transistors are identical,

$g_{m_1} = g_{m_2} = 0.144$

$r_{d_1} = r_{d_2} = 538.79k\Omega$

Calculation of differential voltage gain $\mathbf{A_d}$:

$|A_d| = \dfrac{g_m(r_d \parallel R_D)}{2}$

$|A_d| = \dfrac{0.144(538.79k \parallel 25k)}{2}$

$|\mathbf{A_d}| = \mathbf{1.72}$

Calculation of common mode gain $\mathbf{A_{cm}}$:

$|A_{cm}| = \dfrac{g_m(r_d \parallel R_D)}{1 + 2g_m R_S}$

$|A_{cm}| = \dfrac{0.144(538.79k \parallel 25k)}{1 + 2 \times 0.144 \times 20k}$

$|\mathbf{A_{cm}}| = \mathbf{0.597}$

CMRR=$\left|\dfrac{A_d}{A_{cm}}\right| = \left|\dfrac{1.72}{0.597}\right|$

$\mathbf{CMRR = 2.88}$

CMRR(dB)=$20log_{10}\left(\dfrac{A_d}{A_{cm}}\right) = 20log_{10}(2.88)$

$\mathbf{CMRR(dB) = 9.18dB}$

SIMULATED RESULTS:

Above circuit is simulated in LTspice and results are as follows:

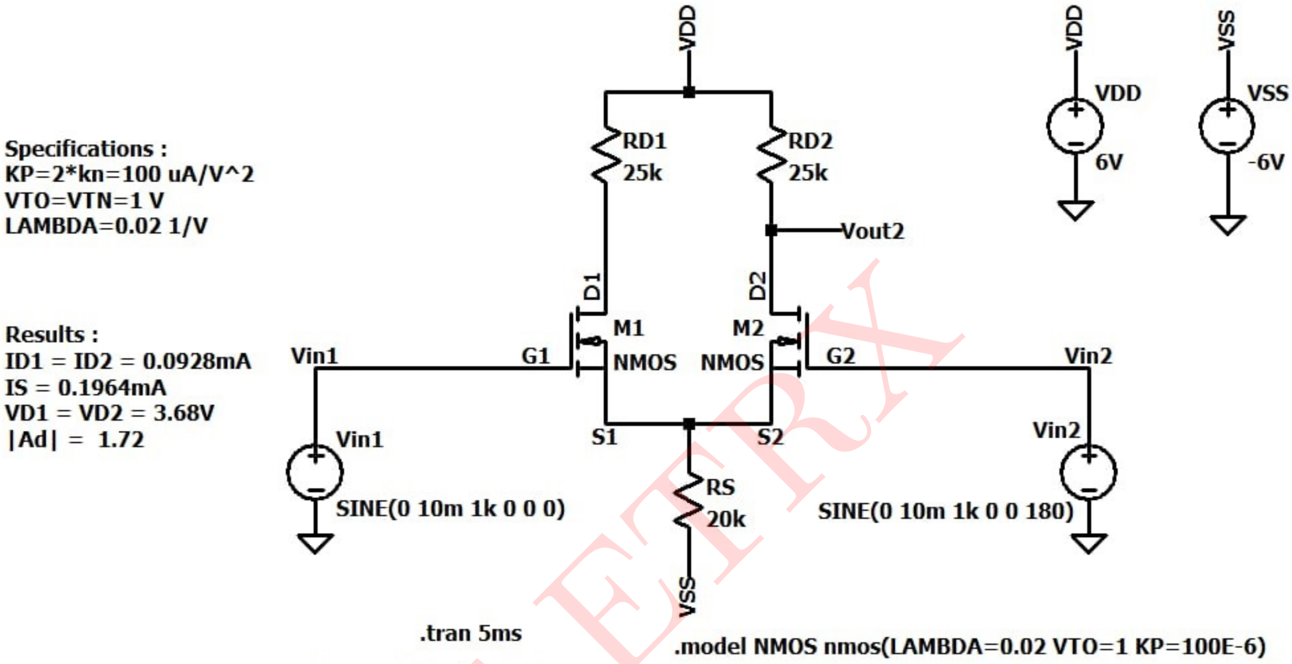

Figure 6: Circuit Schematic: Results

Output Waveforms:

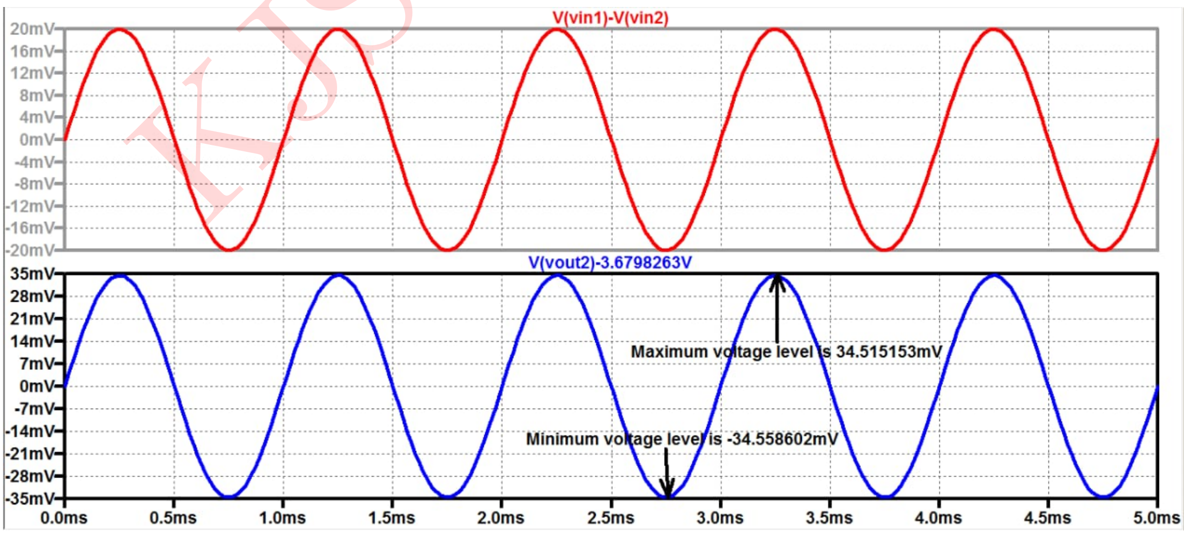

Figure 7: Input and Output waveforms

Comparison between theoretical and simulated values is given below:

Parameters	Theoretical Values	Simulated Values
I_S	$0.1964mA$	$0.092mA$
$I_{D_1} = I_{D_2}$	$0.0928mA$	$0.0928mA$
$V_{DS_1} = V_{DS_2}$	$5.968V$	$5.95V$
$V_{D_1} = V_{D_2}$	$3.68V$	$3.67V$
Differential voltage gain(A_d)	1.72	1.72
Common mode voltage gain(A_{cm})	0.597	–
CMRR(dB)	$9.18dB$	–

Table 2: Numerical 2

Numerical 3

Determine the following for the circuit given in figure 8. The transistor parameters are $I_{DSS} = 12mA$, $V_P = -2.5V$

a) I_{D_1}, I_{D_2}

b) DC values of V_{o_1}, V_{o_2}

c) Single ended output gain $\dfrac{V_{o_1}}{V_1 - V_2}$

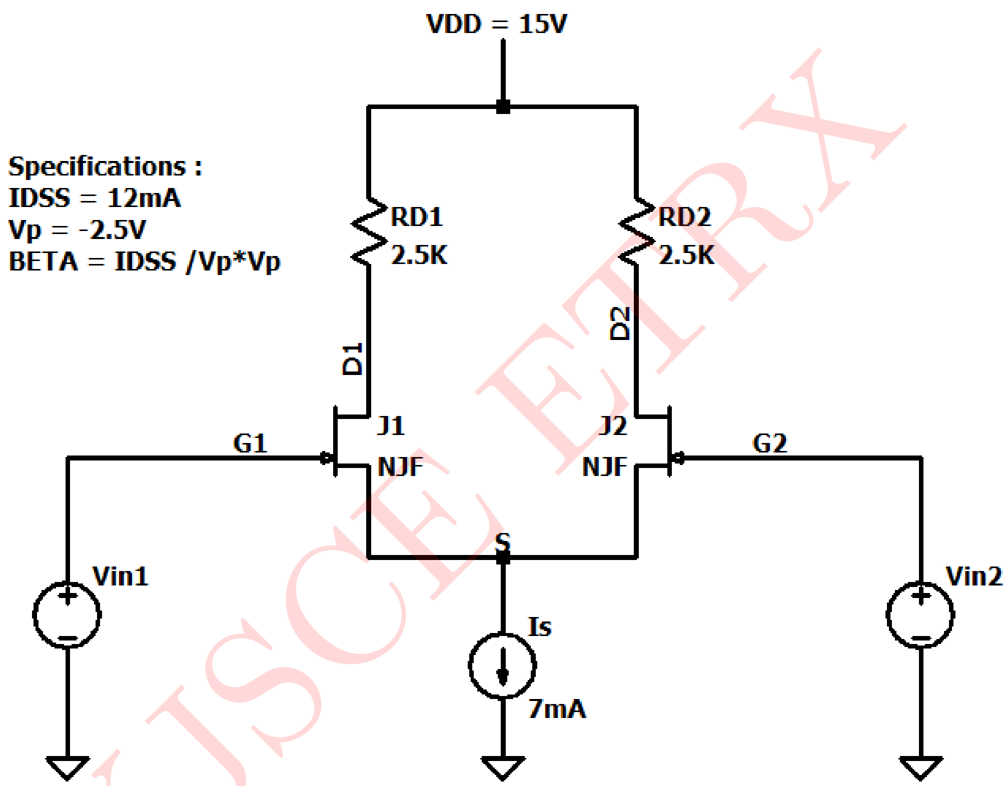

Figure 8: Circuit for Numerical 3

Solution:

DC Analysis:

Above circuit is a differential amplifier using JFET

1) $I_{D_1} = I_{D_2} = \dfrac{7mA}{2}$

$\mathbf{I_{D_1} = I_{D_2} = 3.5mA}$

2) DC value of $V_{o_1} = V_{o_2} = V_{DD} - I_D R_D$

$V_{o_1} = V_{o_2} = 15 - 3.5mA \times 2.5k$

$\mathbf{V_{o_1} = V_{o_2} = 6.25V}$

3) $\dfrac{V_{o_1}}{V_1 - V_2}$, means output is taken from drain D_1 of transistor

Assuming $V_{o_2} > V_{o_1}$; DIUO

$$A_d = \left(\frac{V_{o_1}}{V_1 - V_2}\right) = \frac{-g_m R_D}{2}$$

For JFET, $I_D = I_{DSS}\left(1 - \dfrac{V_{GS}}{V_P}\right)^2$

i.e. $\dfrac{I_D}{I_{DSS}} = \left(1 - \dfrac{V_{GS}}{V_P}\right)^2$

i.e. $\left(1 - \dfrac{V_{GS}}{V_P}\right) = \sqrt{\dfrac{I_D}{I_{DSS}}}$

$$g_m = \frac{2I_{DSS}}{|V_P|}\left(1 - \frac{V_{GS}}{V_P}\right)$$

$$g_m = \frac{2I_{DSS}}{|V_P|}\sqrt{\frac{I_D}{I_{DSS}}}$$

$$g_m = \frac{2 \times 12mA}{2.5V}\sqrt{\frac{3.5mA}{12mA}}$$

$\mathbf{g_m = 5.08mA/V}$

$$A_d = \frac{V_{o_1}}{V_1 - V_2} = -\frac{g_m R_D}{2} = \frac{-5.08 \times 10^{-3} \times 2.5k}{2}$$

$$|\mathbf{A_d}| = \frac{\mathbf{V_{o_1}}}{\mathbf{V_1 - V_2}} = \mathbf{6.35}$$

SIMULATED RESULTS:

Above circuit is simulated in LTspice and results are as follows:

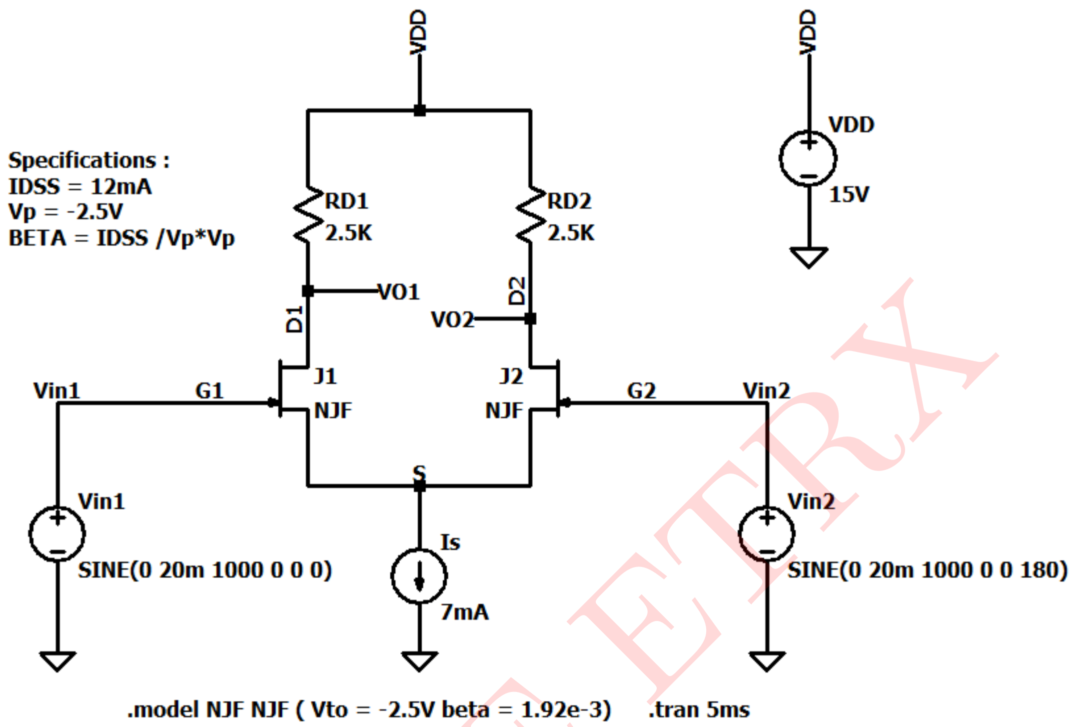

Figure 9: Circuit Schematic: Results

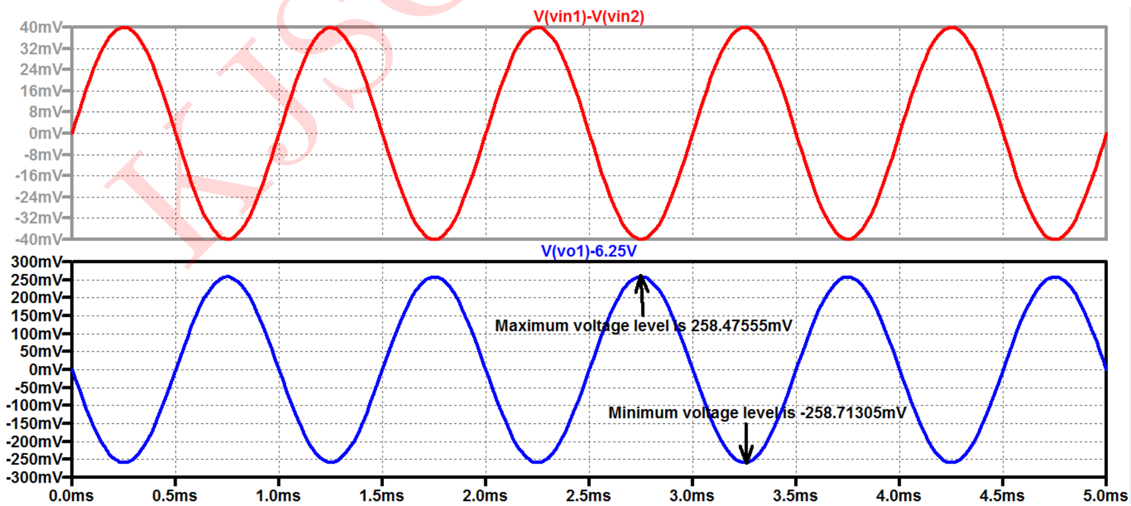

Figure 10: Input and Output waveforms

Comparison between theoretical and simulated values is given below:

Parameters	**Theoretical Values**	**Simulated Values**
$I_{D_1} = I_{D_2}$	$3.5mA$	$3.5mA$
$V_{D_1} = V_{D_2}$	$6.25V$	$6.25V$
Differential voltage gain$\lvert A_d \rvert$	6.35	6.46

Table 3: Numerical 3

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