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

Numerical 1:

For the circuit shown in figure 1, the parameters for each transistor are $\beta = 100$, $V_A = \infty$

a) Determine Q-point value for Q1 and Q2

b) Determine overall small-signal voltage-gain $A_V = \dfrac{V_{out}}{V_S}$

c) Determine input and output resistances R_{iS} & R_o

Given:- $V_S = 20mV$

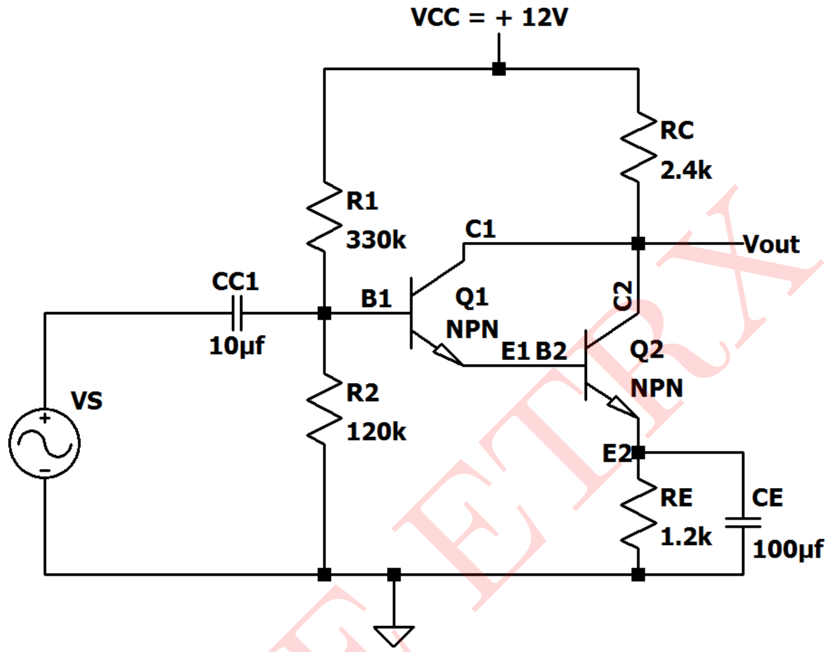

Figure 1: Circuit 1

Solution:

Above circuit 1 is a CE Darlington pair

DC Analysis:-

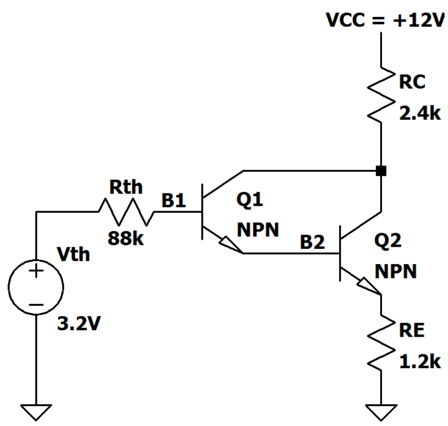

Figure 2: DC Equivalent circuit

$R_{th} = R_1 \mid\mid R_2 = 330k \mid\mid 120k = 88k\Omega$

$V_{th} = \dfrac{R_2}{R_1 + R_2} \times V_{CC} = \dfrac{120k}{450k} \times 12 = 3.2V$

$V_{BE} = 2 \times V_{BE} = 1.4V$ [Since, $V_{BE_1} = V_{BE_2}$]

Applying KVL to the base emitter loop:-

$V_{th} - I_{B_1}R_{th} - V_{BE_1} - V_{BE_2} - I_{E_2}R_E = 0$

$I_{E_1} = I_{B_2} = (1 + \beta_1)I_{B_1}$

$I_{E_2} = (1 + \beta_2)I_{B_2} = (1 + \beta_2)(1 + \beta_1)I_{B_1} \approx \beta_1\beta_2 I_{B_1}$

$I_{E_2} = \beta_D I_{B_1}$ [$\beta_D = \beta_1 \times \beta_2$]

$\beta_D = 100 \times 100 = 10^4$

$V_{th} - V_{BE} = I_B(R_{th} + \beta_D R_E)$

$I_{B_1} = \dfrac{V_{th} - V_{BE}}{R_{th} + \beta_D R_E} = \dfrac{3.2 - 1.4}{88k + 10^4 \times 1.2k} = 0.148\mu A$

$\boldsymbol{I_{B_1} = 0.148\mu A}$

$I_{B_2} = (1 + \beta_1)I_{B_1} = I_{E_1}$

$I_{B_2} = 101 \times 0.148\mu A = 14.95\mu A$

$\boldsymbol{I_{B_2} = 14.95\mu A}$

$\boldsymbol{I_{E_1} = 14.95\mu A}$

$I_{C_1} = \beta_1 I_{B_1} = 14.8\mu A$

$\boldsymbol{I_{C_1} = 14.8\mu A}$

$I_{C_2} = \beta_1 I_{B_2} = 1.49mA$

$\boldsymbol{I_{C_2} = 1.49mA}$

$I_{E_2} = \beta_D I_{B_1} = 10^4 \times 0.148\mu A = 1.51mA$

$\boldsymbol{I_{E_2} = 1.51mA}$

$V_{E_2} = I_{E_2}R_E = 1.51mA \times 1.2k = 1.812V$

$\boldsymbol{V_{E_2} = 1.812V}$

$V_{C_2} = V_{CC} - I_{C_2}R_C = 12 - (1.49 \times 2.4) = 8.24V$

$\boldsymbol{V_{C_2} = 8.24V}$

Small-Signal parameters:-

$$g_{m_1} = \frac{I_{C_1}}{V_T} = \frac{14.9\mu A}{26mV} = 0.569\ mA/V$$

$$\boldsymbol{g_{m_1} = 0.569\ mA/V}$$

$$g_{m_2} = \frac{I_{C_2}}{V_T} = \frac{1.49mA}{26mV} = 57.3\ mA/V$$

$$\boldsymbol{g_{m_2} = 57.3\ mA/V}$$

$$r_{\pi_1} = \frac{V_T}{I_{B_1}} = \frac{26mV}{0.148\mu A} = 175.67k\Omega$$

$$\boldsymbol{r_{\pi_1} = 175.67k\Omega}$$

$$r_{\pi_2} = \frac{V_T}{I_{B_2}} = \frac{26mV}{14.95\mu A} = 1.74k\Omega$$

$$\boldsymbol{r_{\pi_2} = 1.74k\Omega}$$

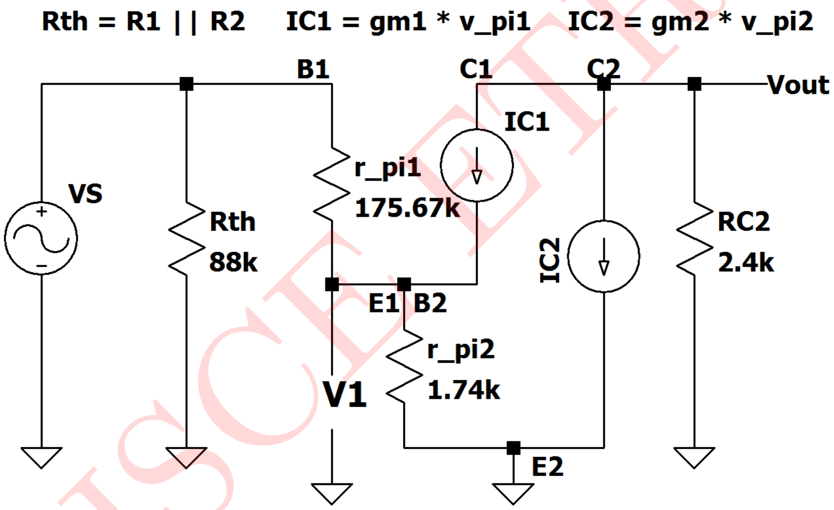

Figure 3: Mid-frequency AC Equivalent Circuit

Input Impedance

$$Z_{i_1} = r_{\pi_1} + (1+\beta_1)r_{\pi_2} = 175.67k\Omega + (101 \times 1.74k) = 351.41k\Omega$$

$$Z_i = R_{th} \mid\mid Z_{i_1} = 88k \mid\mid 351.41k = 70.376k\Omega$$

$$\boldsymbol{Z_i = 70.376k\Omega}$$

Output Impedance:-

$$Z_{o_1} = \frac{R_{th} + r_{\pi_1}}{1+\beta_1} = \frac{88k + 175.67k}{101} = 2.91k\Omega$$

$$Z_{o_2} = \frac{Z_{o_1} + r_{\pi_2}}{1+\beta_2} = \frac{2.61k + 1.74k}{101} = 43.07\Omega$$

$$Z_o = Z_{o_2} \mid\mid R_C = 43.07 \mid\mid 2400 = 42.31\Omega$$

$$\boldsymbol{Z_o = 42.31\Omega}$$

Current gain:-

Stage 1:-

$A_{i_1} = \dfrac{I_{C_1}}{I_{B_1}} = \dfrac{\beta_1 I_{B_1}}{I_{B_1}} = \beta_1 = 100$

Stage 2:-

$A_{i_2} = \dfrac{I_{C_2}}{I_{B_2}} = \dfrac{\beta_2 I_{B_2}}{I_{B_2}} = \beta_2 = 100$

$A_{i_T} = A_{i_1} \times A_{i_2} = 100 \times 100 = 10^4$

Overall Voltage gain:-

$A_{i_S} = \dfrac{I_o}{I_i} = \dfrac{I_o}{I_{B_2}} \times \dfrac{I_{B_2}}{I_{B_1}} \times \dfrac{I_{B_1}}{I_i}$

$\therefore A_{i_S} = A_{i_2} \times A_{i_1} \times \dfrac{I_B}{I_i}$ $\quad [I_{B_2} = I_{E_1}, I_{E_1} = I_{C_1}]$

$\therefore A_{i_S} = A_{i_2} \times A_{i_1} \times \dfrac{R_B}{R_B + Z_{i_1}}$ $A_{i_S} = 100 \times 100 \times \dfrac{88k}{88k + 551.41k} = 2002.685$

$\boldsymbol{A_{i_S} = 2002.685}$

$A_{V_1} = \dfrac{V_1}{V_S} = \dfrac{I_{E_1}}{I_{B_1}} \times \dfrac{r_{\pi_2}}{Z_{i_1}}$

$A_{V_1} = \dfrac{I_{C_1}}{I_{B_1}} \times \dfrac{r_{\pi_2}}{Z_{i_1}} = A_{i_1} \times \dfrac{r_{\pi_2}}{Z_{i_1}} = 100 \times \dfrac{1.74k}{351.41k} = 0.495$

$\boldsymbol{A_{V_1} = 0.495}$

$A_{V_2} = \dfrac{V_o}{V_1} = \dfrac{I_o}{I_{B_2}} \times \dfrac{R_C}{r_{\pi_2}}$

$A_{V_2} = \dfrac{I_{C_2}}{I_{B_2}} \times \dfrac{R_C}{r_{\pi_2}} = A_{i_2} \times \dfrac{R_C}{r_{\pi_2}} = 100 \times \dfrac{2.4k}{1.74k} = 137.93$

$\boldsymbol{A_{V_2} = 137.93}$

$A_{V_t} = A_{V_1} \times A_{V_2} = 0.475 \times 137.93 = 68.275$

$\boldsymbol{A_{V_t} = 68.275}$

$\boldsymbol{A_{V_t}}$ **in dB** $\boldsymbol{= 20 log_{10}(68.275) = 36.68 dB}$

Also, $A_{V_t} = \dfrac{V_{out}}{V_S}$

$V_{out} = A_{V_t} \times V_S = 68.275 \times 20mV = 2.731V$

$\boldsymbol{V_{out} = 2.731V}$

SIMULATED RESULTS:
Above circuit was simulated in LTSpice and results are presented below:

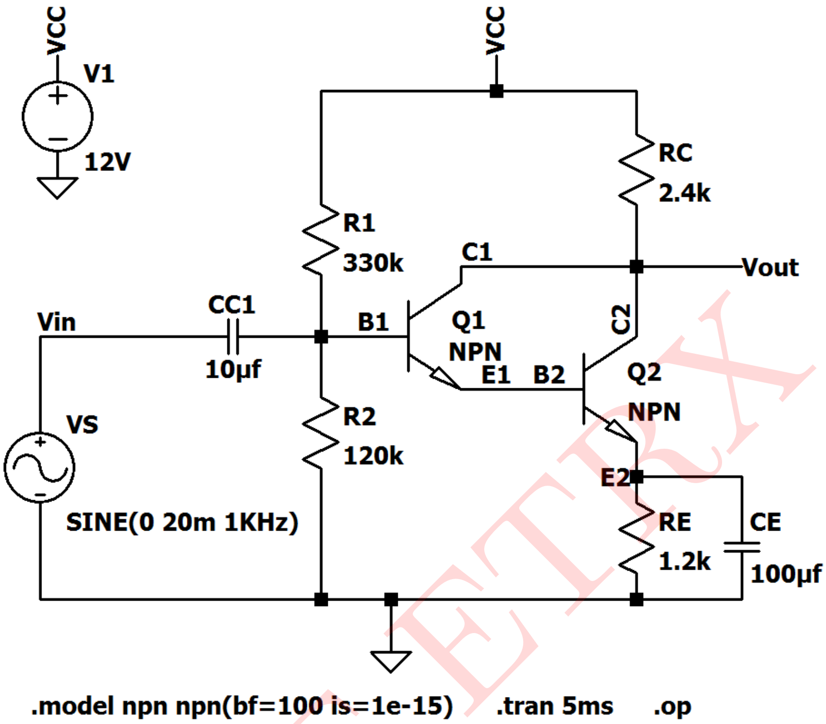

Figure 4: Circuit Schematic 1

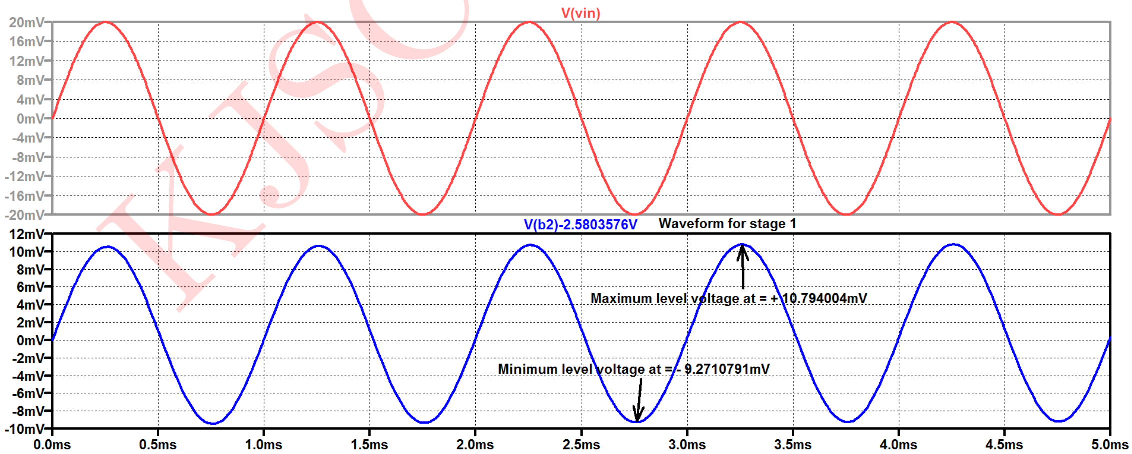

Figure 5: Input and Output waveform for stage 1

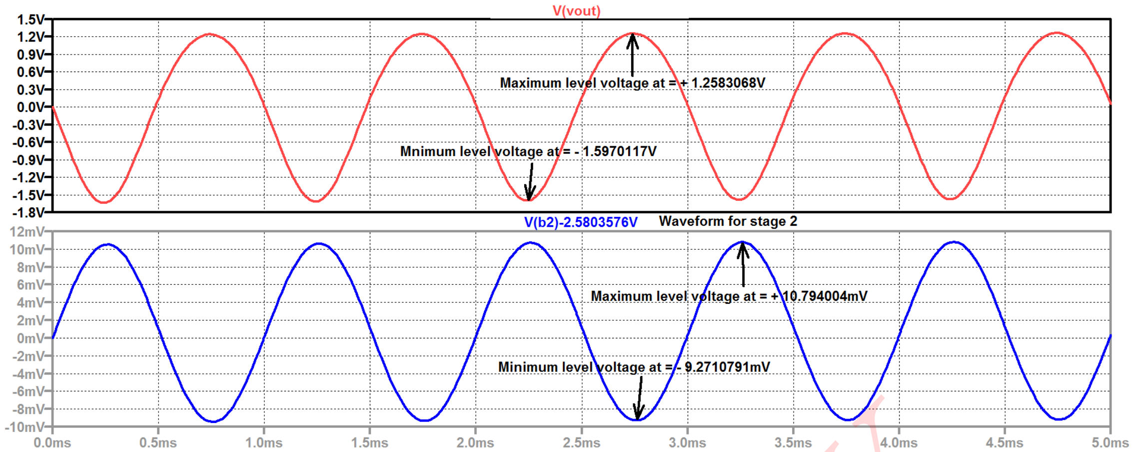

Figure 6: Input and Output waveform for stage 2

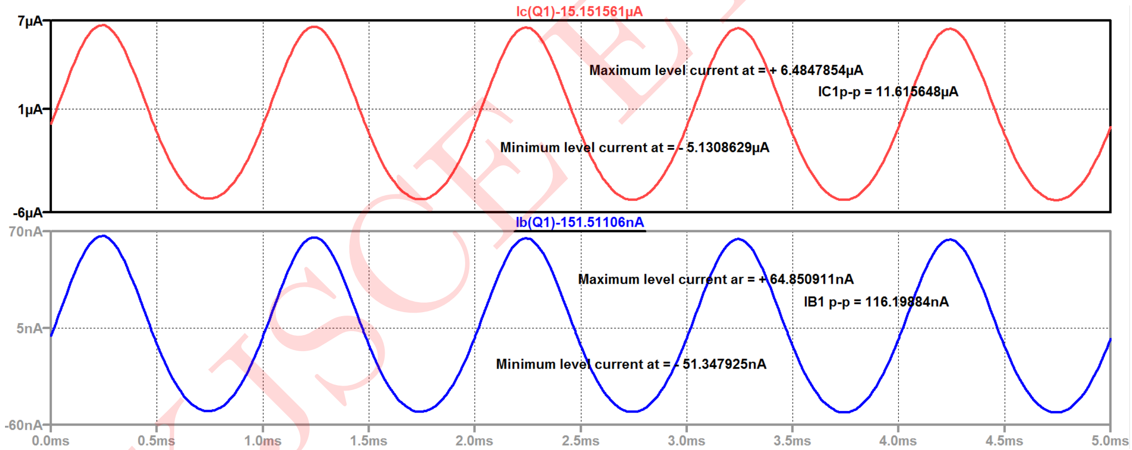

Figure 7: Input and Output Waveforms for A_{i_1}

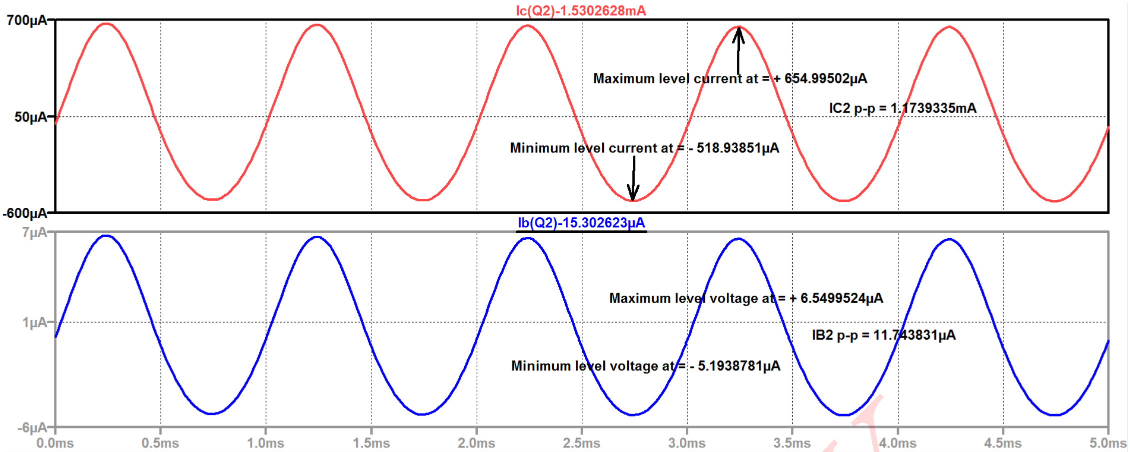

Figure 8: Input and Output Waveforms for A_{i_2}

Comparison of Theoretical and Simulated Values:

Parameters	Theoretical	Simulated
$I_{B_1}, I_{C_1}, I_{E_1}$	$0.148\mu A$, $14.8\mu A$, $14.95\mu A$	$0.151\mu A$, $15.1\mu A$, $15.3\mu A$
$I_{B_2}, I_{C_2}, I_{E_2}$	$14.95\mu A$, $1.49mA$, $1.51mA$	$15.3\mu A$, $1.53mA$, $1.54mA$
V_{E_2}, V_{C_2}	$1.812V$, $8.24V$	$1.84V$, $8.27V$
A_{V_1}, A_{V_2}	0.495, 137.83	0.501, 141.64
$A_{V_t}(dB)$	36.68	37.02
A_{i_1}, A_{i_2}	100, 100	99.96, 99.96
A_{i_T}	10000	9992.0016
V_{out}	$2.731V$	$2.855V$
Z_i, Z_o	$70.38k\Omega$, 42.31Ω	–

Table 1: Numerical 1

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