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Department	**: Electronics & Communication**
Subject	**: Analog Circuits (EC-405)**
Unit	**: II**
Topic	**: Differential Amplifier, Introduction of Operation Amplifier**

UNIT – II

Operation Amplifier

2.1 Differential Amplifier

Differential amplifier is a basic building block of an op-amp. The function of a differential amplifier is to amplify the difference between two input signals. Let us consider two emitter-biased circuits as shown in figure 2.1.

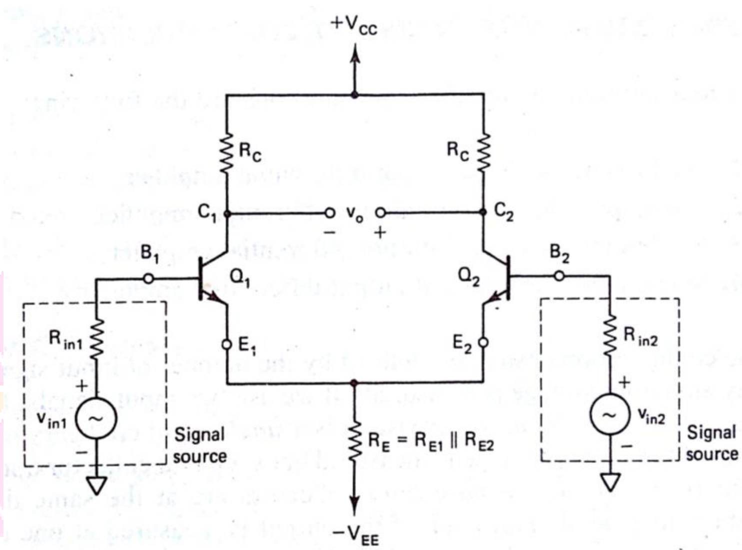


Figure 2.1 Differential Amplifier

The two transistors Q_1 and Q_2 have identical characteristics. The resistances of the circuits are equal, i.e. $R_{E1} = R_{E2}$, $R_{C1} = R_{C2}$ and the magnitude of $+V_{CC}$ is equal to the magnitude of $-V_{EE}$. These voltages are measured with respect to ground.

To make a differential amplifier, the two circuits are connected as shown in fig. The two $+V_{CC}$ and $-V_{EE}$ supply terminals are made common because they are same. The two emitters are also connected and the parallel combination of R_{E1} and R_{E2} is replaced by a resistance R_E. The two input signals V_{in1} & V_{in2} are applied at the base of Q_1 and at the base of Q_2. The output voltage is taken between two collectors. The collector resistances are equal and therefore denoted by $R_C = R_{C1} = R_{C2}$.

Ideally, the output voltage is zero when the two inputs are equal. When V_{in1} is greater than V_{in2} the output voltage with the polarity shown appears. When V_{in1} is less than V_{in2}, the output voltage has the opposite polarity.

2.1.1 Differential Amplifier Configuration

The differential amplifiers are classified as:-

(i) Dual input, balanced output differential amplifier.

(ii) Dual input, unbalanced output differential amplifier.

(iii) Single input balanced output differential amplifier.

(iv) Single input unbalanced output differential amplifier.

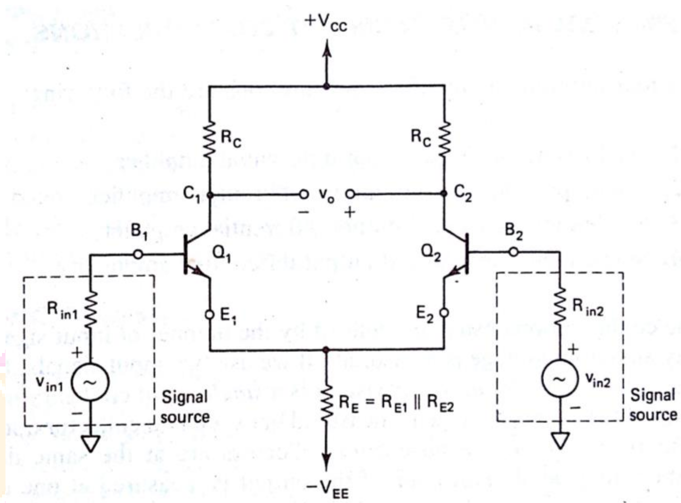


Figure 2.2 Dual inputs, balanced output differential amplifier.

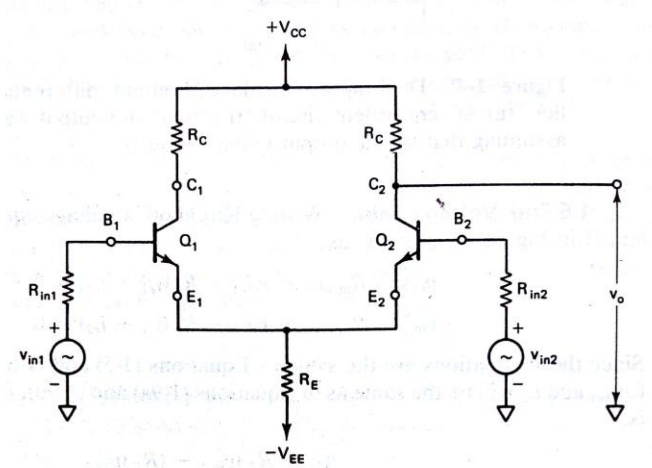


Figure 2.3 Dual input, unbalanced output differential amplifier

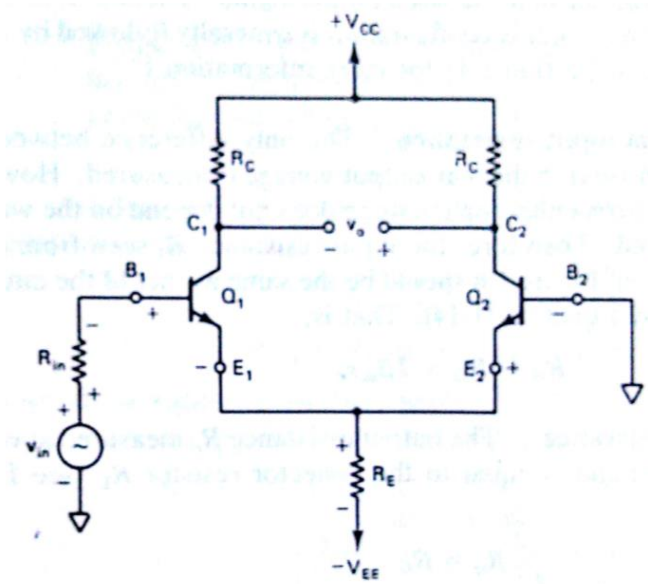


Figure 2.4 Single input balanced output differential amplifier

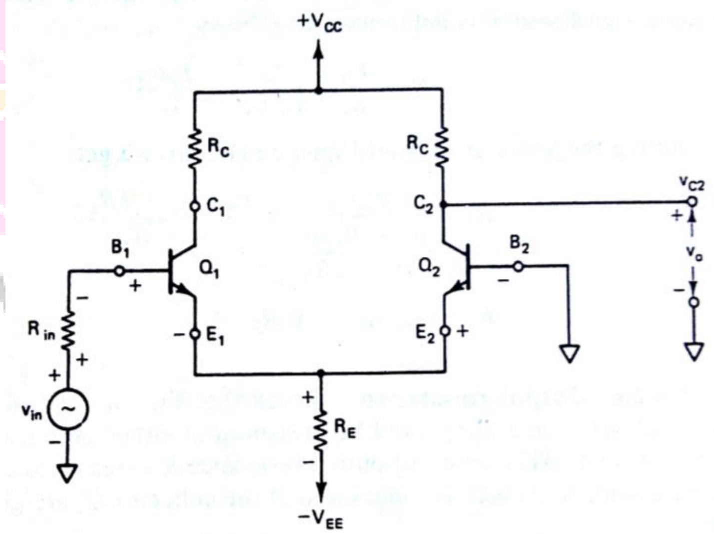


Figure 2.5 Single input unbalanced output differential amplifier

These configurations are shown in figure 2.2 to 2.5. and are defined by number of input signals used and the way an output voltage is measured. If input signals are two, the configuration is said to be dual input, otherwise it is a single input configuration. On the other hand, if the output voltage is measured between two collectors, it is referred to as a balanced output because both the collectors are at the same dc potential w.r.t. ground. If the output is measured at one of the collectors w.r.t. ground, the configuration is called an unbalanced output.

2.2 Dual Input Balanced Output Differential Amplifier (DIBO) (RGPV May-19)

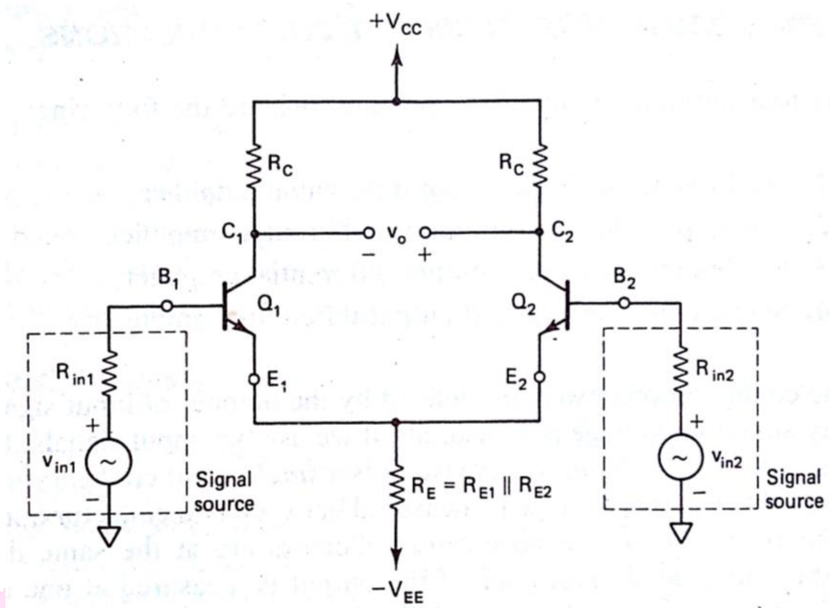


Figure 2.6 Dual Input Balanced Output Differential Amplifier

As shown in figure 2.6 V_{in1} and V_{in2} are the two inputs, applied to the bases of Q_1 and Q_2 transistors. The output voltage is measured between the two collectors C_1 and C_2 , which are at same dc potentials.

2.2.1 D.C. Analysis:

To obtain the operating point (I_{CQ} and V_{CEQ}) for differential amplifier dc equivalent circuit is drawn by reducing the input voltages V_{in1} and V_{in2} to zero as shown in figure 2.7.

Applying KVL to the base emitter loop of the transistor Q_1

$$R_{in}I_B + V_{BE} + 2I_ER_E = V_{EE}$$

But $$I_B = \frac{I_C}{\beta_{dc}}, and\ I_E = I_C$$

$$\therefore I_E = I_C = \frac{V_{EE} - V_{BE}}{2R_E + \frac{R_{in}}{\beta_{dc}}}$$

Since V_{BE} = 0.7 V for Si and 0.3 V for Ge

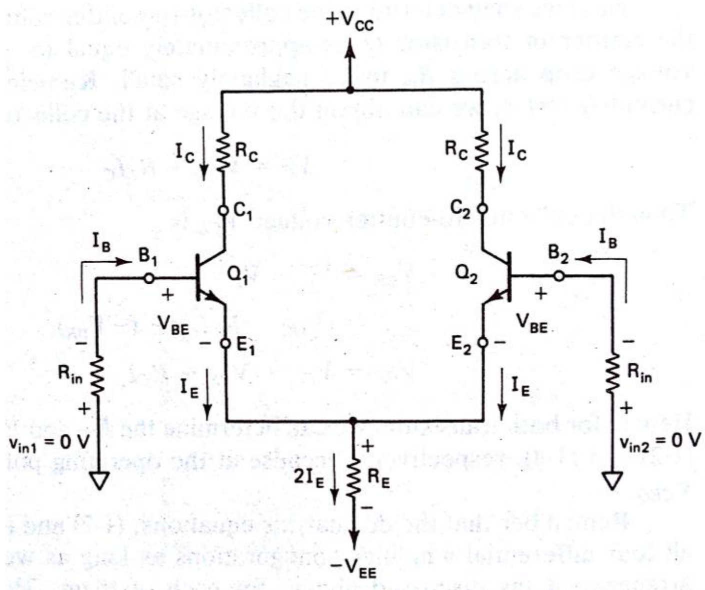


Figure 2.7 DC Equivalent Circuit of Differential Amplifier

Generally $\frac{R_{in}}{\beta_{dc}} \ll 2R_E$ because $\boldsymbol{\beta_{dc}}$ is very high

$$\boxed{\therefore \boldsymbol{I_E = I_C = \frac{V_{EE} - V_{BE}}{2R_E}}}$$

We can see that emitter current of transistors Q_1 and Q_2 are independent of collector resistance R_C.

The emitter voltage of Q_1 is approximately equal to $-V_{BE}$ if the voltage drop across R_{in} is negligible. The voltage at the collector terminal (V_C) is given by:-

$$V_C = V_{CC} - I_C R_C$$

Thus the collector to emitter voltage V_{CE} is

$$V_{CE} = V_C - V_E \qquad (V_E = -V_{BE})$$

$$V_{CE} = (V_{CC} - I_C R_C) - (-V_{BE})$$

$$V_{CE} = V_{CC} - I_C R_C + V_{BE}$$

$$\boxed{\boldsymbol{V_{CE} = V_{CC} + V_{BE} - I_C R_C}}$$

From the two equations V_{CEQ} and I_{CQ} can be determined. This dc analysis is applicable for all types of differential amplifier.

2.2.2 AC Analysis

To perform ac analysis to derive the expression for the voltage gain A_d, input resistance R_i and output resistance R_o of the differential amplifier the circuit is modified as :-

Set the dc voltage $+V_{CC}$ and $-V_{EE}$ at zero. Substitute the small signal T-equivalent model for transistors. The circuit shows the resulting ac equivalent circuit of dual input balanced output differential amplifier.

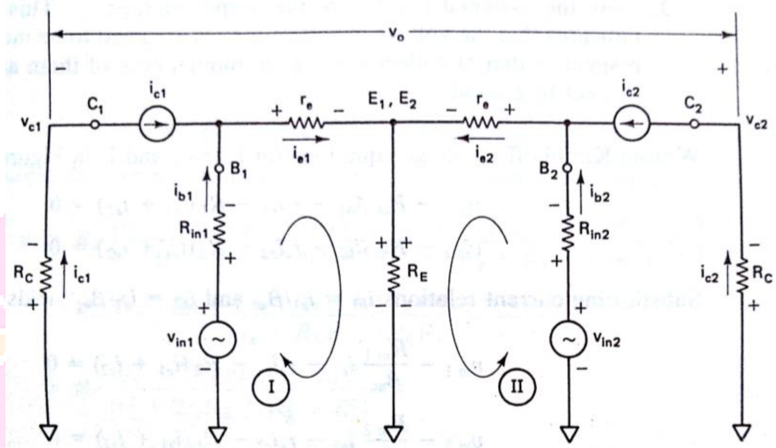


Figure 2.8 Small Signal T-Equivalent Model

Since $I_{E1} = I_{E2}$; Therefore $r_{e1} = r_{e2}$. for this reason, the ac emitter resistance of transistors are simply denoted by r_e . The voltage across each collector resistance is shown 180° out of phase with respect to the input voltages v_{in1} and v_{in2}. This is same as in CE configuration. The polarity of the output voltage is shown in figure. The collector C_2 is assumed to be more positive with respect to collector C_1 even though both are negative with respect to ground.

Writing KVL for loop-I and loop-II gives

$$v_{in1} - R_{in1} i_{b1} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0 \qquad \text{------(1)}$$

$$v_{in2} - R_{in2} i_{b2} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0 \qquad \text{------(2)}$$

Substituting current relation $i_{b1} = i_{e1}/\beta_{ac}$ and $i_{b2} = i_{e2}/\beta_{ac}$

$$v_{in1} - \frac{R_{in1}}{\beta_{ac}} i_{e1} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0$$

$$v_{in2} - \frac{R_{in2}}{\beta_{ac}} i_{e2} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0$$

generally, R_{in1}/β_{ac} and R_{in2}/β_{ac} values are very small, therefore we can neglect them for simplicity and rearranging these equation as:-

$$(r_e + R_E)i_{e1} + (R_E)i_{e2} = v_{in1} \quad \text{------ (3)}$$

$$(R_E)i_{e1} + (r_e + R_E)i_{e2} = v_{in2} \quad \text{------ (4)}$$

equation (3) and (4) can be solved simultaneously for i_{e1} and i_{e2} by using Cramer's rule**:**

$$i_{e1} = \frac{\begin{vmatrix} v_{in1} & R_E \\ v_{in2} & r_e + R_E \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}}$$

$$i_{e1} = \frac{(r_e + R_E)v_{in1} - (R_E)v_{in2}}{(r_e + R_E)^2 - (R_E)^2} \quad \text{------ (5)}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & v_{in1} \\ R_E & v_{in2} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}}$$

$$i_{e2} = \frac{(r_e + R_E)v_{in2} - (R_E)v_{in1}}{(r_e + R_E)^2 - (R_E)^2} \quad \text{------ (6)}$$

The output voltage is

$$v_o = v_{c2} - v_{c1}$$

$$= -R_c i_{c2} - (-R_c i_{c1})$$

$$= R_c i_{c1} - R_c i_{c2} \qquad (i_c \approx i_e)$$

$$= R_c(i_{e1} - i_{e2}) \quad \text{------ (7)}$$

substituting the current relations i_{e1} and i_{e2} in equation (7) we get

$$v_o = R_c\left[\frac{(r_e + R_E)v_{in1} - (R_E)v_{in2}}{(r_e + R_E)^2 - (R_E)^2} - \frac{(r_e + R_E)v_{in2} - (R_E)v_{in1}}{(r_e + R_E)^2 - (R_E)^2}\right]$$

$$= R_c\frac{(r_e + R_E)(v_{in1} - v_{in2}) + (R_E)(v_{in1} - v_{in2})}{(r_e + R_E)^2 - (R_E)^2}$$

$$= R_c\frac{(r_e + 2R_E)(v_{in1} - v_{in2})}{r_e^2 + 2R_E r_e + {R_E}^2 - {R_E}^2}$$

$$= R_c\frac{(r_e + 2R_E)(v_{in1} - v_{in2})}{r_e(r_e + 2R_E)}$$

$$v_o = \frac{R_c}{r_e}(v_{in1} - v_{in2})$$

Thus the differential amplifier amplifies the difference between two input signals. If $v_{id} = v_{in1} - v_{in2}$ (differential input) The voltage gain of dual input balanced output differential amplifier is given by

$$\boxed{A_d = \frac{v_o}{v_{id}} = \frac{R_c}{r_e}}$$

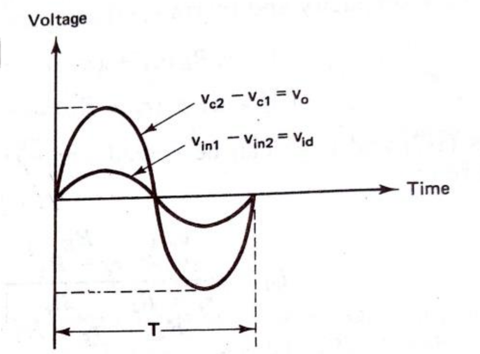


Figure 2.9 Input and Output Waveform

2.2.3 Differential Input Resistance (R_i)

Differential input resistance is defined as the equivalent resistance that would be measured at either input terminal with the other terminal grounded.

$$R_{i1} = \left|\frac{v_{in1}}{i_{b1}}\right| v_{in2=0}$$

$$= \left|\frac{v_{in1}}{i_{e1}/\beta_{ac}}\right| v_{in2=0}$$

Substituting the value of i_{e1} from equation (5)

$$R_{i1} = \frac{\beta_{ac} v_{in1}}{\frac{(r_e + R_E) v_{in1} - (R_E)(0)}{(r_e + R_E)^2 - (R_E)^2}}$$

$$= \frac{\beta_{ac}(r_e^2 + 2r_e R_E)}{(r_e + R_E)}$$

$$= \frac{\beta_{ac} r_e (r_e + 2R_E)}{(r_e + R_E)}$$

Generally $R_E >> r_e$

$$R_{i1} = \frac{\beta_{ac} r_e (2R_E)}{(R_E)}$$

Hence $\boxed{R_{i1} = 2\beta_{ac} r_e}$

Similarly $\boxed{R_{i2} = 2\beta_{ac} r_e}$

2.2.4 Output Resistance (R_o)

Output resistance is defined as the equivalent resistance that would be measured at either output terminal with respect to ground. Therefore, the output resistance R_{o1} measured between collector C_1 and ground is equal to that of collector resistor R_C. Similarly the output resistance R_{o2} measured between collector C_2 and ground is equal to that of collector resistor R_C. Thus

$$\boxed{R_{o1} = R_{o2} = R_C}$$

2.3 Dual Input Unbalanced Output Differential Amplifier (DIUBO)

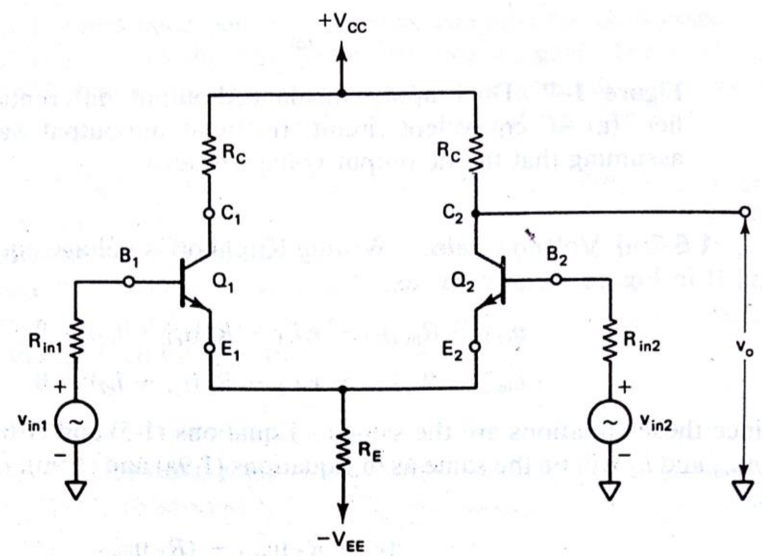


Figure 2.10 Dual Input unbalanced output Differential Amplifier

In this configuration as shown in figure 2.10 two input signals are used, however the output is measured at only one of the two collectors with respect to ground. The output is referred as an ***unbalanced*** output, because the collector at which the output voltage is measured is at some finite dc potential with respect to ground.

2.3.1 DC Analysis

The DC analysis is same as given for dual input balanced output differential amplifier.

$$\therefore I_E = I_C = \frac{V_{EE} - V_{BE}}{2R_E + \frac{R_{in}}{\beta_{dc}}}$$

$$\boldsymbol{V_{CE} = V_{CC} + V_{BE} - I_C R_C}$$

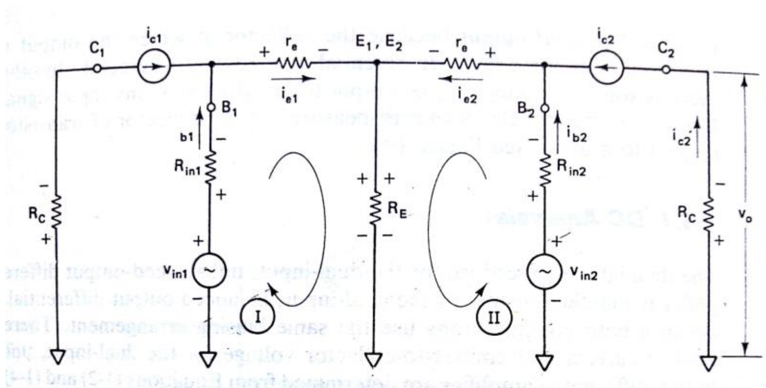
2.3.2 AC Analysis

Writing KVL for loop-I and loop-II in T equivalent model gives

$$v_{in1} - R_{in1} i_{b1} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0 \qquad \text{------(1)}$$

$$v_{in2} - R_{in2} i_{b2} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0 \qquad \text{------(2)}$$

substituting current relation $i_{b1} = i_{e1}/\beta_{ac}$ and $i_{b2} = i_{e2}/\beta_{ac}$



(a)

Figure 2.11 T equivalent model of DIUBO differential amplifier

$$v_{in1} - \frac{R_{in1}}{\beta_{ac}} i_{e1} - r_e i_{e1} - R_E(i_{e1} + i_{e2}) = 0$$

$$v_{in2} - \frac{R_{in2}}{\beta_{ac}} i_{e2} - r_e i_{e2} - R_E(i_{e1} + i_{e2}) = 0$$

generally, $\boldsymbol{R_{in1}/\beta_{ac}}$ and $\boldsymbol{R_{in2}/\beta_{ac}}$ values are very small, therefore we can neglect them for simplicity and rearranging these equation as:-

$$(r_e + R_E)i_{e1} + (R_E)i_{e2} = v_{in1} \qquad \text{------ (3)}$$

$$(R_E)i_{e1} + (r_e + R_E)i_{e2} = v_{in2} \qquad \text{------ (4)}$$

equation (3) and (4) can be solved simultaneously for $\boldsymbol{i_{e1}}$ and $\boldsymbol{i_{e2}}$ by using Cramer's rule:

$$i_{e1} = \frac{\begin{vmatrix} v_{in1} & R_E \\ v_{in2} & r_e + R_E \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}}$$

$$i_{e1} = \frac{(r_e + R_E)v_{in1} - (R_E)v_{in2}}{(r_e + R_E)^2 - (R_E)^2} \qquad \text{------ (5)}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & v_{in1} \\ R_E & v_{in2} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}}$$

$$i_{e2} = \frac{(r_e + R_E)v_{in2} - (R_E)v_{in1}}{(r_e + R_E)^2 - (R_E)^2}$$ ------ *(6)*

The output voltage is $v_o = v_{c2} = -R_c i_{c2} = -R_c i_{e2}$ $(i_c \approx i_e)$

substituting the value of i_{e2}

$$v_o = -R_c\left[\frac{(r_e + R_E)v_{in2} - (R_E)v_{in1}}{(r_e + R_E)^2 - (R_E)^2}\right]$$

$$v_o = R_c\frac{(R_E)v_{in1} - (r_e + R_E)v_{in2}}{r_e(r_e + 2R_E)}$$

Generally $R_E >> r_e$

Hence $(r_e+R_E) \approx R_E$ *and* $(r_e+2R_E) \approx 2R_E$

Therefore

$$v_o = R_c\frac{(R_E)v_{in1} - (R_E)v_{in2}}{2r_e R_E}$$

$$= R_c\frac{R_E(v_{in1} - v_{in2})}{2r_e R_E}$$

$$= \frac{R_c}{2r_e}(v_{in1} - v_{in2})$$

Which give differential gain

$$\boxed{A_d = \frac{v_o}{v_{id}} = \frac{R_c}{2r_e}}$$

Thus the voltage gain of DIUBO differential amplifier is half the gain of DIBO differential amplifier. In DIUBO differential amplifier the dc voltage at the output terminal is the error voltage in the desired output signal. Therefore to reduce the undesired dc voltage to zero, this configuration is generally followed by ***level translator*** circuit.

Differential ***Input Resistance*** (R_i) and ***Output Resistance*** (R_o) are same as DIBO differential amplifier.

2.4 Single Input Balanced Output Differential Amplifier (SIBO)

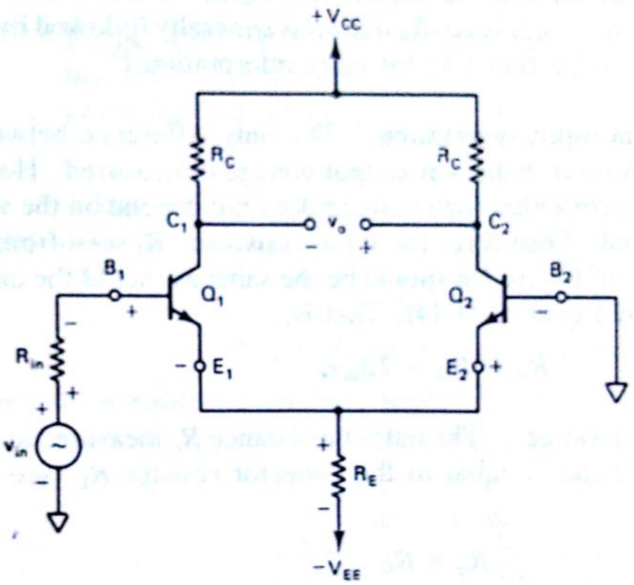


Figure 2.12 Single input balanced output differential amplifier

As shown in figure 2.12 input is applied only to the base of transistor Q_1, and the output is measured between the two collectors.

2.4.1 DC Analysis

The DC analysis is same as given for dual input balanced output differential amplifier.

$$\therefore I_E = I_C = \frac{V_{EE} - V_{BE}}{2R_E + \frac{R_{in}}{\beta_{dc}}}$$

$$V_{CE} = V_{CC} + V_{BE} - I_C R_C$$

2.4.2 AC Analysis

The ac equivalent circuit of the single input, balanced output (SIBO) differential amplifier with T-equivalent model is shown in figure 2.13.

Writing KVL for loop I and II gives

$$v_{in} - R_{in} i_{b1} - r_e i_{e1} - R_E i_E = 0$$

$$v_{in} - R_{in} i_{b1} - r_e i_{e1} - r_e i_{e2} = 0$$

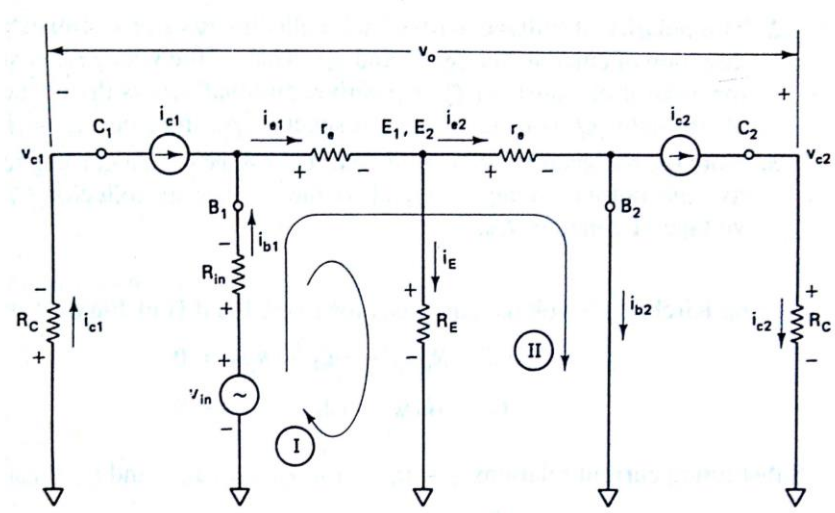


Figure 2.13 T equivalent model of SIBO differential amplifier

substituting current equation $i_E = (i_{e1} - i_{e2})$, $i_b \approx i_e/\beta_{ac}$

$$v_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - R_E(i_{e1} - i_{e2}) = 0$$

$$v_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - r_e i_{e2} = 0$$

Generally, the ***$R_{in}/\beta ac$*** value is very small; therefore for simplicity we shall neglect it and rearrange the equation as follows

$$(r_e + R_E)i_{e1} - R_E i_{e2} = v_{in}$$

$$r_e i_{e1} + r_e i_{e2} = v_{in}$$

solving the above equation foe ***i_{e1}*** and ***i_{e2}*** using Cramer's rule:

$$i_{e1} = \frac{\begin{vmatrix} v_{in} & -R_E \\ v_{in} & r_e \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{r_e v_{in} + R_E v_{in}}{r_e(r_e + R_E) + r_e R_E}$$

$$= \frac{(r_e + R_E)v_{in}}{r_e(r_e + 2R_E)}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & v_{in} \\ r_e & v_{in} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{(r_e + R_E)v_{in} - r_e v_{in}}{r_e(r_e + R_E) + r_e R_E}$$

$$= \frac{R_E v_{in}}{r_e(r_e + 2R_E)}$$

The output voltage is given by

$$v_o = v_{c2} - v_{c1}$$

$$= R_C i_{c2} - (-R_C i_{c1})$$

$$= R_C(i_{c1} + i_{c2})$$

$$= R_C(i_{e1} + i_{e2}) \quad since\ i_e \approx i_c$$

substituting the value of $\boldsymbol{i_{e1}}$ and $\boldsymbol{i_{e2}}$

$$v_o = R_C\left[\frac{R_E v_{in}}{r_e(r_e + 2R_E)} + \frac{(r_e + R_E)v_{in}}{r_e(r_e + 2R_E)}\right]$$

$$= R_C \frac{(r_e + 2R_E)v_{in}}{r_e(r_e + 2R_E)}$$

$$= \frac{R_C}{r_e} v_{in}$$

Therefore $$\boxed{\boldsymbol{A_d = \frac{v_o}{v_{in}} = \frac{R_C}{r_e}}}$$

2.4.3 Differential input Resistance (R_i)

The input resistance $\boldsymbol{R_i}$ seen from the input signal source is determine as follows:

$$R_i = \frac{v_{in}}{i_{b1}} = \frac{v_{in}}{i_{e1}/\beta_{ac}} = \frac{\beta_{ac} v_{in}}{i_{e1}}$$

substituting the value of $\boldsymbol{i_{e1}}$ we get

$$R_i = \frac{\beta_{ac} v_{in}}{\frac{(r_e + R_E) v_{in}}{r_e (r_e + 2R_E)}} = \frac{\beta_{ac} r_e (r_e + 2R_E)}{r_e + R_E}$$

since $R_E >> r_e$ $\quad \boxed{R_i = 2\beta_{ac} r_e}$

2.4.4 Output Resistance (R_o):

The output resistance R_o measured at collector C_2 with respect to ground is equal to the collector resistance R_C.

Thus $\quad \boxed{R_o = R_C}$

2.5 Single Input Unbalanced Output Differential Amplifier (SIUBO)

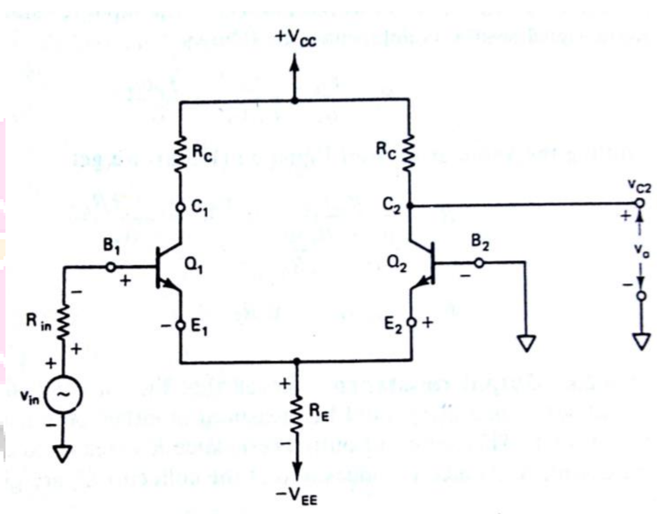


Figure 2.14 Single Input Unbalanced Output Differential Amplifier

As shown in figure 2.14, input is applied only to the base of transistor Q_1, and the output is measured from the collector of Q_2 with respect to ground.

2.5.1 DC Analysis

The DC analysis is same as given for dual input balanced output differential amplifier.

$$\therefore I_E = I_C = \frac{V_{EE} - V_{BE}}{2R_E + \frac{R_{in}}{\beta_{dc}}}$$

$$V_{CE} = V_{CC} + V_{BE} - I_C R_C$$

2.5.2 AC Analysis

The ac equivalent circuit of the single input, unbalanced output (**SIUBO**) differential amplifier with T-equivalent model is shown in figure 2.15.

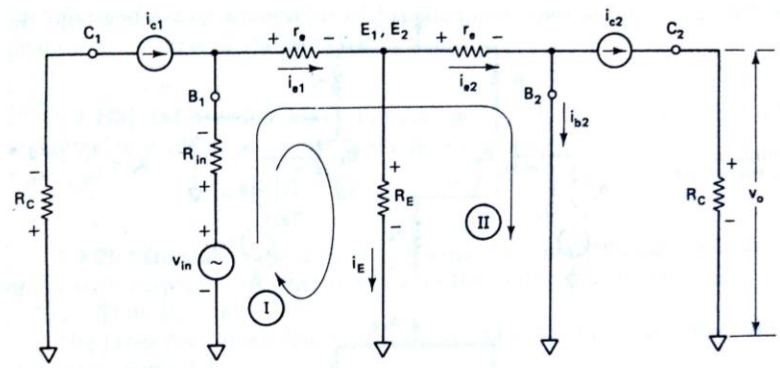


Figure 2.15 T equivalent model of SIUBO differential amplifier

Writing KVL for loop I and II gives

$$v_{in} - R_{in} i_{b1} - r_e i_{e1} - R_E i_E = 0$$

$$v_{in} - R_{in} i_{b1} - r_e i_{e1} - r_e i_{e2} = 0$$

substituting current equation $i_E = (i_{e1} - i_{e2})$, $i_b \approx i_e/\beta_{ac}$

$$v_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - R_E (i_{e1} - i_{e2}) = 0$$

$$v_{in} - \frac{R_{in}}{\beta_{ac}} i_{e1} - r_e i_{e1} - r_e i_{e2} = 0$$

Generally, the **Rin/βac** value is very small; therefore for simplicity we shall neglect it and rearrange the equation as follows

$$(r_e + R_E) i_{e1} - R_E i_{e2} = v_{in}$$

$$r_e i_{e1} + r_e i_{e2} = v_{in}$$

solving the above equation foe $\boldsymbol{i_{e1}}$ and $\boldsymbol{i_{e2}}$ using Cramer's rule:

$$i_{e1} = \frac{\begin{vmatrix} v_{in} & -R_E \\ v_{in} & r_e \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{r_e v_{in} + R_E v_{in}}{r_e(r_e + R_E) + r_e R_E}$$

$$= \frac{(r_e + R_E) v_{in}}{r_e(r_e + 2R_E)}$$

Similarly

$$i_{e2} = \frac{\begin{vmatrix} r_e + R_E & v_{in} \\ r_e & v_{in} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & -R_E \\ r_e & r_e \end{vmatrix}} = \frac{(r_e + R_E) v_{in} - r_e v_{in}}{r_e(r_e + R_E) + r_e R_E}$$

$$= \frac{R_E v_{in}}{r_e(r_e + 2R_E)}$$

The output voltage is given by

$$v_o = v_{c2}$$

$$= R_C i_{c2}$$

$$= R_C i_{e2} \qquad \text{since } i_e \approx i_c$$

$$v_o = R_C \frac{R_E v_{in}}{r_e(r_e + 2R_E)}$$

since $r_e << R_E$

$$v_o = R_C \frac{R_E v_{in}}{r_e(2R_E)}$$

$$v_o = R_C \frac{v_{in}}{2r_e}$$

The gain of DIUBO differential amplifier is given by:

$$\boxed{A_d = \frac{v_o}{v_{in}} = \frac{R_C}{2r_e}}$$

Differential Input Resistance (Ri) and ***Output Resistance (Ro)*** are same as SIBO differential amplifier.

2.6 Operational Amplifier

An operational amplifier (Op-Amp) is a direct coupled, high gain multistage differential amplifier that can perform various mathematical operations such as addition, subtraction, multiplication, differentiation, integration etc. The operation amplifier (Op-Amp) is a versatile device that can be used to amplify dc as well as ac input signals.

2.6.1 Block diagram of Op-Amp (RGPV June-16, Dec-16)

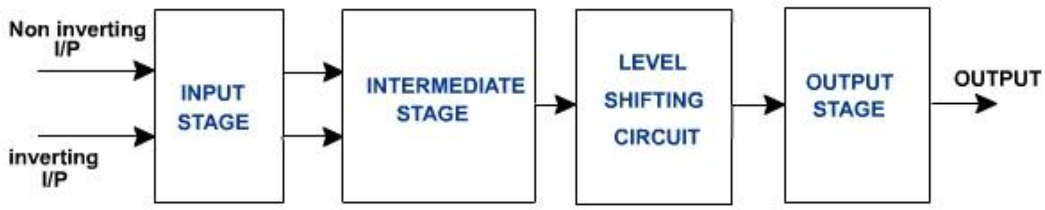


Figure 2.16 Block diagram of Operational Amplifier

As shown in figure 2.16, input stage is a dual input balanced output differential amplifier. This stage provides most of the voltage gain of the amplifier and also establishes the input resistance of the Op-Amp. The intermediate stage of Op-Amp is dual input unbalanced output differential amplifier which is driven by the output of the first stage. Because direct coupling is used, the dc voltage level at the output of intermediate stage is well above ground potential. Therefore level shifting circuit is used to shift the dc level at the output of the intermediate stage downward to zero with respect to ground. The output stage is generally a push pull complementary amplifier. The output stage increases the output voltage swing and raises the current supplying capability of the Op-Amp. It also provides low output resistance.

2.6.2 Symbol of Op-Amp

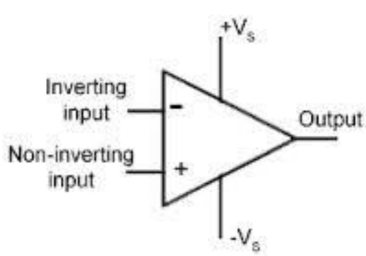


Figure 2.17 Symbol of Op-Amp

The symbolic diagram of an Op-Amp is shown in figure 2.17. The (+) input is the non-inverting input. Signal applied to this terminal produce an in-phase signal at output. On the other hand, the (-) input is the inverting input because any input applied to this terminal produces an 180° out of phase signal at output.

2.6.3 PIN Diagram of Op-Amp

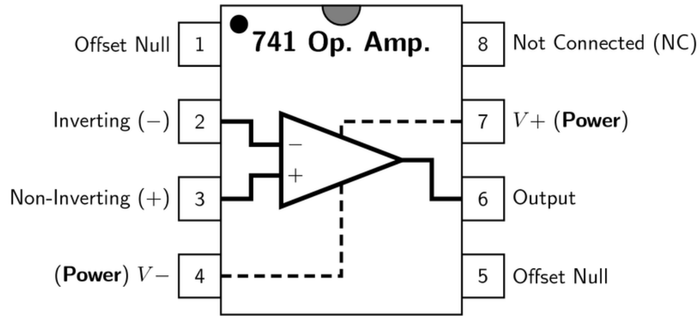


Figure 2.18 PIN Diagram of Op-Amp

As shown in PIN diagram of Op-Amp 741, it is a 8 PIN flat pack linear IC. It is also available in Metal can and Dual In Package (DIP). As we see that PIN no.1 and 5 are used for offset null, PIN no. 2 and 3 are used for inverting and non-inverting input, PIN 4 and 7 are used for supply voltage, and output is taken from PIN no. 6. PIN number 8 is not in use.

2.6.4 Ideal Characteristics of Op-Amp

An ideal Op-Amp would exhibit the following electrical characteristic.

1. Infinite voltage gain A.
2. Infinite input resistance R_i, so as to reduce loading effect of the preceding stage.
3. Zero output resistance R_O, so that output can drive an infinite number of other devices.
4. Zero output voltage when differential input voltage is zero.
5. Infinite bandwidth ***(BW)*** so that any frequency signals from 0 to infinite Hz can be amplified without attenuation.
6. Infinite common mode rejection ratio ***(CMRR)*** so that the output common mode noise voltage is zero.
7. Infinite slew rate ***(SR)***, so that output voltage changes occur simultaneously with input voltage changes.

2.6.5 Equivalent Circuit of an Op-Amp (RGPV Dec-16)

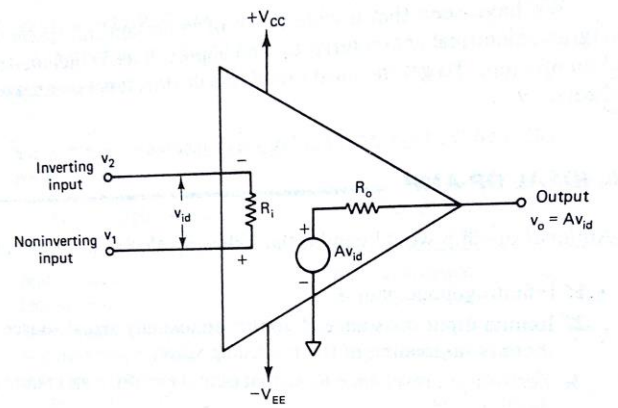


Figure 2.19 Equivalent Circuit of an Op-Amp

Figure 2.19 shows an equivalent circuit of an Op-Amp. v_1 and v_2 are the two input voltages, R_i is the input impedance of Op-Amp. Av_{id} is an equivalent Thevenin voltage source and R_O is the Thevenin equivalent impedance looking back into the terminal of an Op-Amp. This equivalent circuit is useful in analyzing the basic operating principles of Op-Amp and in observing the effects of standard feedback arrangements. For the circuit shown output voltage is given by

$$v_o = Av_{id} = A(v_1 - v_2)$$

Where A = large signal voltage gain

v_{id} = differential input voltage

v_1 = non-inverting input voltage

v_2 = inverting input voltage

This equation indicates that the output voltage v_o is directly proportional to the algebraic difference between the two input voltages. The polarity of the output voltage depends on the polarity of the difference voltage v_{id}.

Tutorials

1. The following specifications are given for the dual input, balanced-output differential amplifier R_C = 2.2 kΩ, R_E = 4.7 kΩ, $R_{in\ 1} = R_{in\ 2}$ = 50 Ω , +V_{CC} = 10V, -V_{EE} = -10 V, β_{dc} =100 and V_{BE} = 0.715V.Determine the operating points (I_{CQ} and V_{CEQ}) of the two transistors. ***(0.988mA, 8.54V)***

2. The following specifications are given for the dual input, balanced-output differential amplifier: R_C = 2.2 kΩ, R_E = 4.7 kΩ, $R_{in\ 1}$ = $R_{in\ 2}$ = 50Ω, +V_{CC}= 10V, -V_{EE} = -10 V, β_{dc} =100 and V_{BE} = 0.715V. Determine:

   (i) Voltage gain (A_d).

   (ii) Input resistance (R_i).

   (iii) Output resistance (R_o) ***(86.96, 5.06k, 2.2k)***