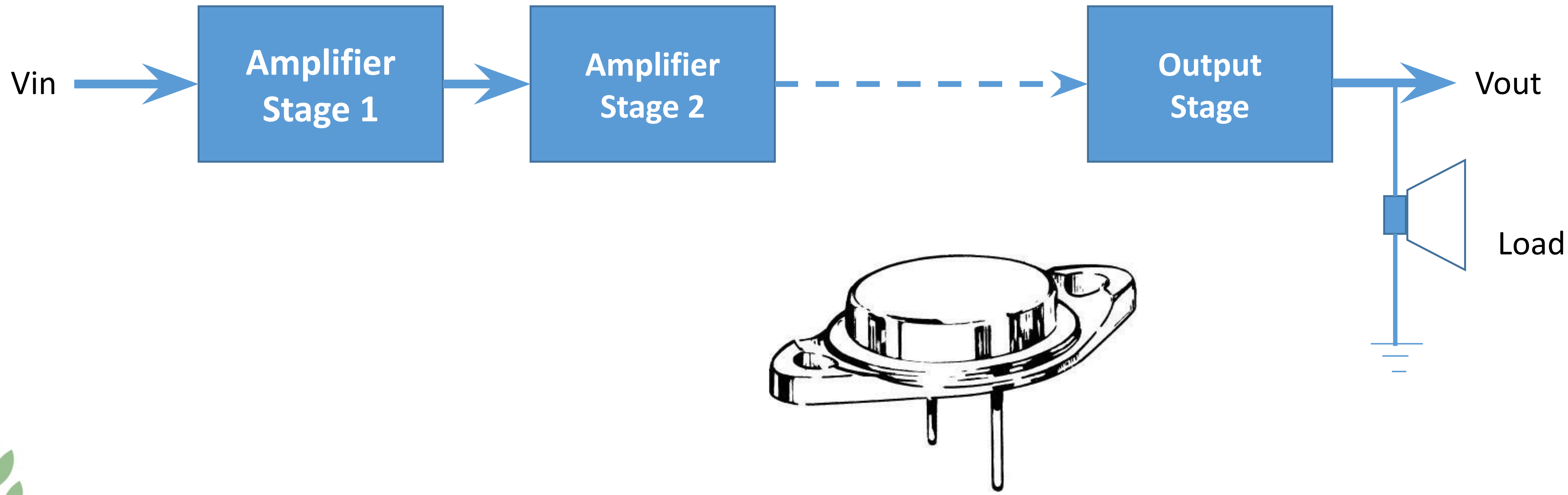
Electronic III

Lecture (8)

Power Amplifiers (I)

Power Amplifiers

- A power amplifier is simply an amplifier with a high-power output stage.
- The power Amplifier has a unity voltage gain while it has a high current gain.
- It is connected in the multistage amplifier as the last stage (Output Stage) to provide the load with high power.



power transistors

Classification Of Amplifiers

1. According to frequency capabilities.

Amplifiers are classified as audio amplifiers , radio frequency amplifiers

- **<u>AF Amplifier</u>** are used to amplify the signals lying in the audio range (i.e. 20 Hz to 20 kHz)
- **<u>RF amplifiers</u>** are used to amplify signals having very high frequency.

2. According to coupling methods.

- R-C coupled amplifiers,
- Transformer coupled amplifiers
- Direct Coupled

3. According to use.

a. Voltage amplifiers

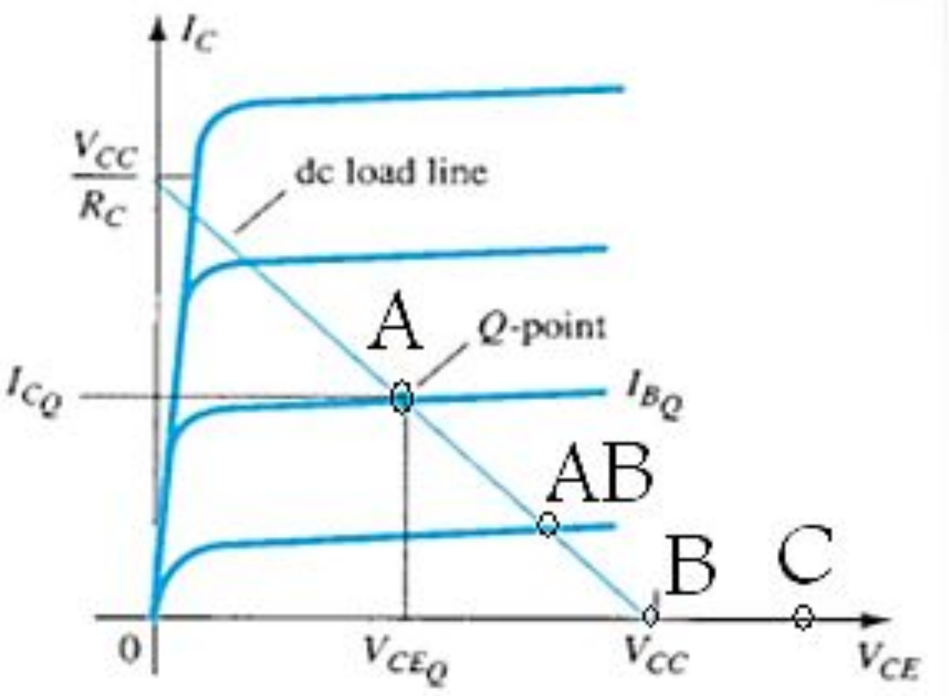
- Amplify the input voltage, if possible with minimal current at the output.
- The power gain of the voltage amplifier is low.
- The main application is to strengthen the signal to make it less affected by noise and attenuation.
- Ideal voltage amp. have infinite input impedance & zero output impedance.

a. Power amplifiers

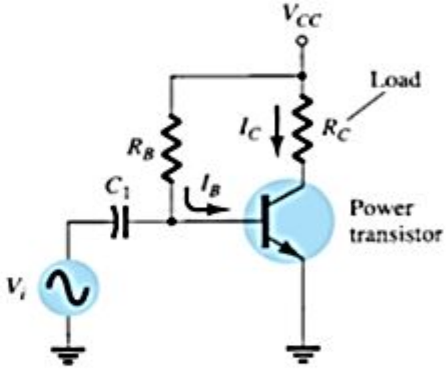
- Amplify the input power, if possible with minimal change in the output voltage
- Power amp. are used in devices which require a large power across the loads.
- In multi stage amplifiers, power amplification is made in the final stages
  - ✔ Audio amplifiers and RF amplifiers use it to deliver sufficient power the load.
  - ✔ Servo motor controllers use it to drive the motors.

4. According to the Operating point (Q-Point)

- Class A amplifier: Q-point located at the middle of the load line.
- Class B amplifier: Q-point located at the lower point (Ic=0) of the load line.
- Class AB amplifier: Q-point located at the mid-point between class A and B on the load line.
- Class C amplifier: Q-point located out of the load line.



The Operating point (Q-Point)



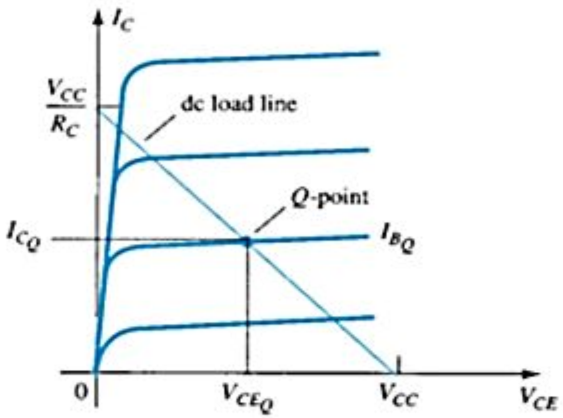
Series-fed class A large-signal amplifier.

- DC Bias Operation

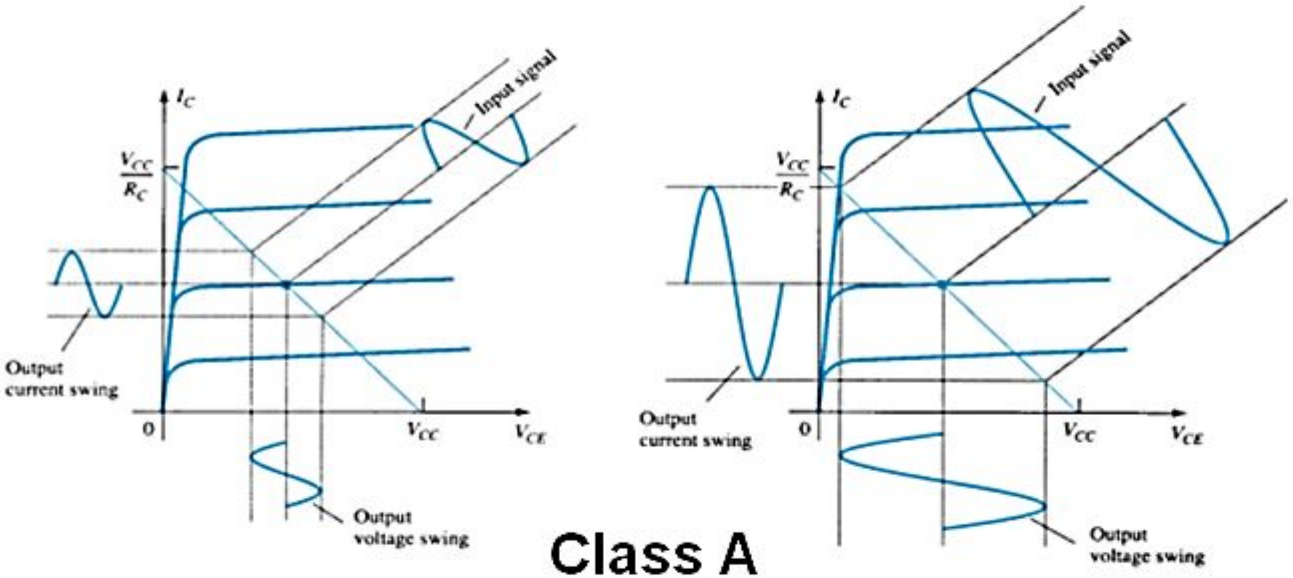
$$I_B = \frac{V_{CC} - 0.7\text{ V}}{R_B}$$

$$I_C = \beta I_B$$

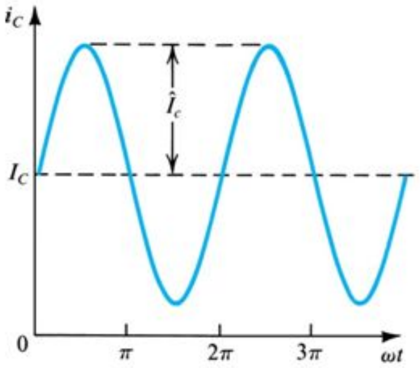
$$V_{CE} = V_{CC} - I_C R_C$$



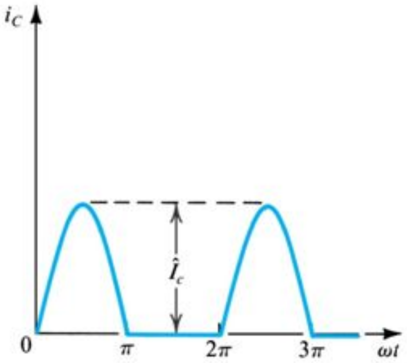
AC Operation



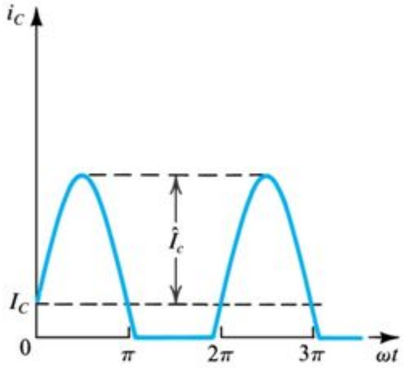
Class A



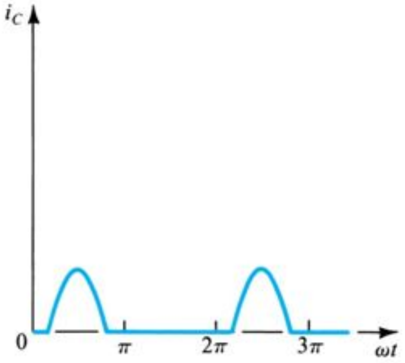
Class A



Class B

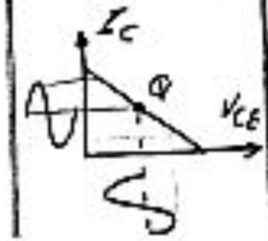
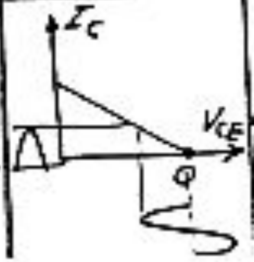
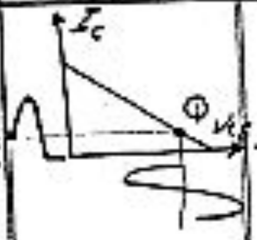
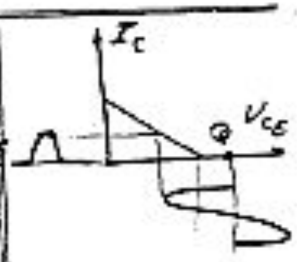


Class AB



Class C

Comparison of Amplifier Classes:-

	Class A	Class B	Class AB	Class C
operating cycle	360°	180°	180° to 360°	Less than 180°
Power effeciency	25% to 50%	78.5%	between 25% and 78.5%	(not used for delivering power)
D.C bias current	$I_{D.C} = I_C$	$I_{D.C} = 0$	$I_{D.C} <<$	$I_{D.C} = 0$
operating point				

Power Amplifiers

1. Emitter Follower Class A Amplifier:

Transfer Characteristic

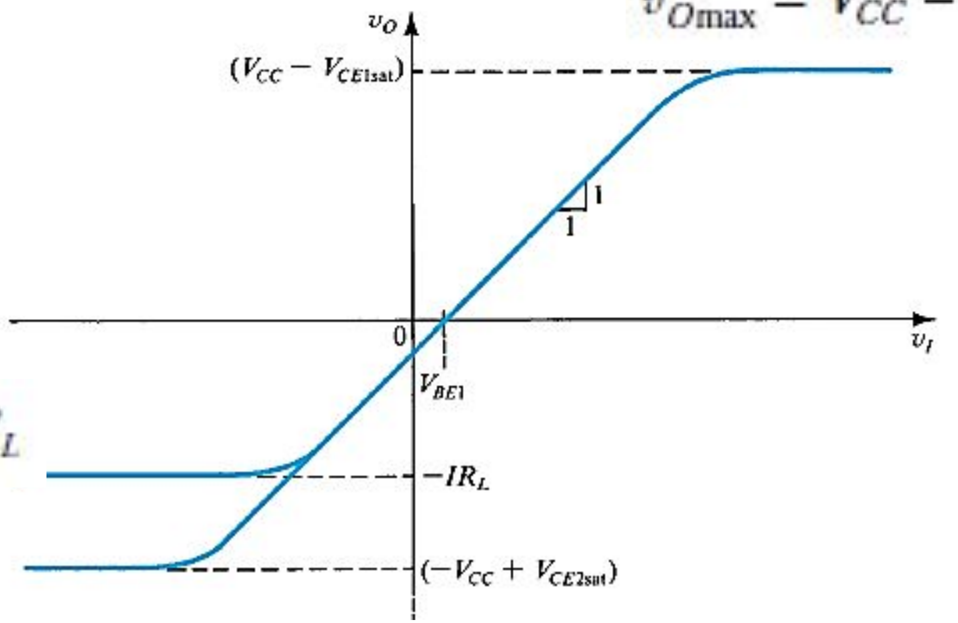
Figure shows an emitter follower Q_1 biased with a constant current I supplied by transistor Q_2. Since the emitter current $I_{E1} = I + I_L$, the bias current I must be greater than the largest negative load current; otherwise, Q_1 cuts off and class A operation will no longer be maintained.

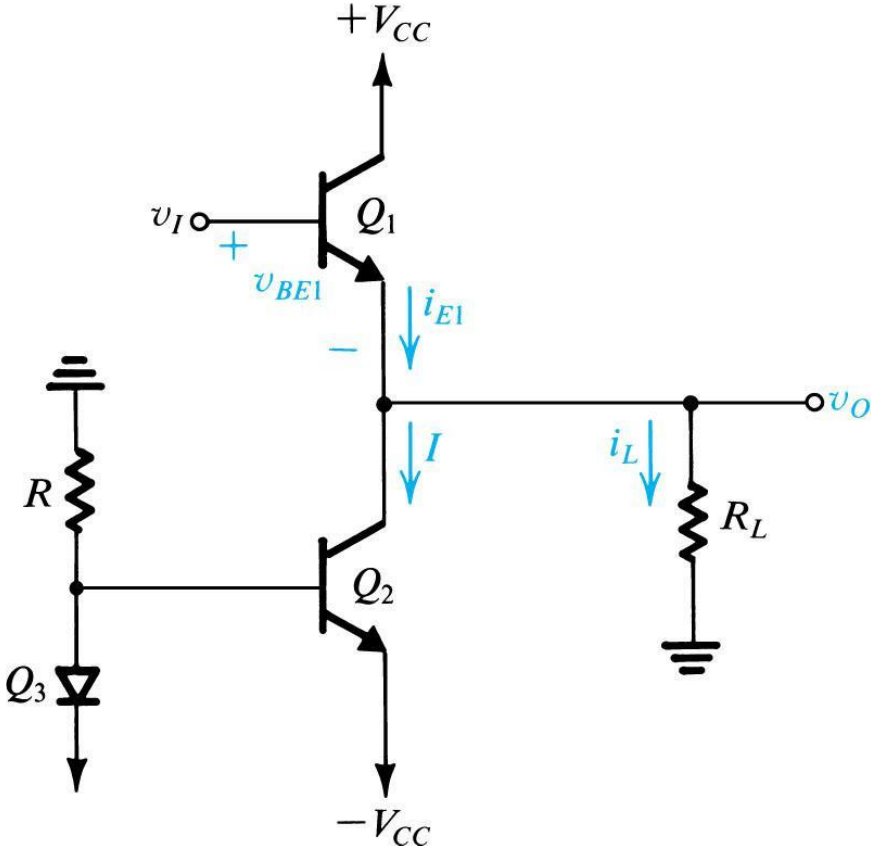
The transfer characteristic of the emitter follower of Fig. is described by

$$v_O = v_I - v_{BE1}$$

$$v_{Omax} = V_{CC} - V_{CE1sat}$$

$$v_{Omin} = -IR_L$$





* Q_1 biased with Constant current (I) supplied by Q_2. (Q_2, Q_3 → current source)

$$\boxed{i_{E_1} = I + i_L}$$

$$\boxed{v_o = v_{in} - v_{BE_1}}$$

* As v_{in} goes +ve, v_o goes +ve till Q_1 saturates.

$$\boxed{v_{omax} = V_{CC} - V_{CE_1(sat)}}$$

* As v_{in} goes -ve, Q_1 may cuts-off, then,

$$\boxed{v_{omin} = -I R_L}$$

or Q_2 saturated → $\boxed{v_{omin} = -V_{CC} + V_{CE_2 sat}}$

For symmetrical output,

$$-IR_L \geq -V_{CC} + V_{CEsat}$$

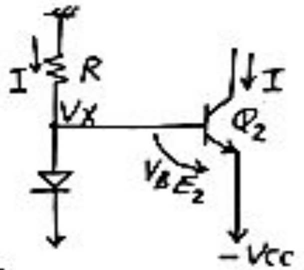
$$IR_L \geq V_{CC} - V_{CEsat}$$

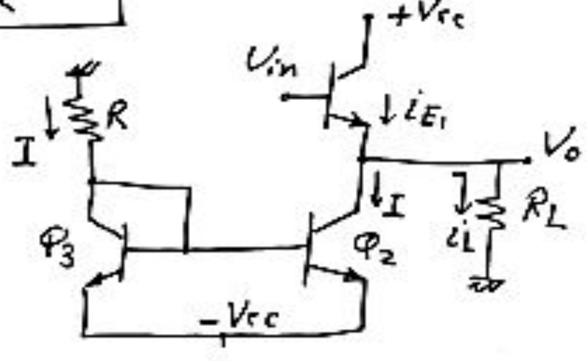
$$\boxed{I \geq \frac{V_{CC} - V_{CEsat}}{R_L}}$$

Note:-

$$I = \frac{0 - V_X}{R} = \frac{0 - (V_{BE_2} - V_{CC})}{R}$$

$$\boxed{I = \frac{V_{CC} - V_{BE_2}}{R}}$$





EXERCISES

D11.1 For the emitter follower in Fig. 11.2, $V_{CC} = 15$ V, $V_{CEsat} = 0.2$ V, $V_{BE} = 0.7$ V and constant, and β is very high. Find the value of R that will establish a bias current sufficiently large to allow the largest possible output signal swing for $R_L = 1$ kΩ. Determine the resulting output signal swing and the minimum and maximum emitter currents for Q_1.

Ans. 0.97 kΩ; –14.8 V to +14.8 V; 0 to 29.6 mA

11.2 For the emitter follower of Exercise 11.1, in which $I = 14.8$ mA, consider the case in which v_O is limited to the range –10 V to +10 V. Let Q_1 have $v_{BE} = 0.6$ V at $i_C = 1$ mA, and assume $\alpha \simeq 1$. Find v_I corresponding to $v_O = -10$ V, 0 V, and +10 V. At each of these points, use small-signal analysis to determine the voltage gain v_o/v_i. Note that the incremental voltage gain gives the slope of the v_O-versus-v_I characteristic.

Ans. –9.36 V, 0.67 V, 10.68 V; 0.995 V/V, 0.998 V/V, 0.999 V/V

Solution(11.1):

$V_{CC} = 15V$, $V_{CEsat} = 0.2V$, $V_{BE} = 0.7V$, $\beta \gg$

$R_L = 1K\Omega$

[a] Find R

$$I = \frac{V_{CC} - V_{CEsat}}{R_L} = \frac{15 - 0.2}{1}$$

$$\boxed{I = 14.8\ mA}$$

Also $I = \frac{V_{CC} - V_{BE}}{R}$

$$\therefore R = \frac{V_{CC} - V_{BE}}{I} = \frac{15 - 0.7}{14.8}$$

$$\boxed{R \doteq 0.97\ K\Omega}$$

[b] output signal swing $\mapsto$ (V_{omax}, V_{omin})

* $V_{omax} = V_{CC} - V_{CEsat} = 15 - 0.2 = 14.8V$

* $V_{omin} = -V_{CC} + V_{CEsat} = -15 + 0.2 = -14.8V$

$\therefore$ output signal swing ($-14.8V$ to $+14.8V$)

[c] $i_{Emin} = 0$ (when Q_1 cut-off)

* $i_{E1} = I + i_L$

$\therefore i_{E1max} = I + i_{Lmax}$

$$= I + \frac{V_{omax}}{R_L}$$

$$= 14.8 + \frac{14.8}{1}$$

$$\therefore \boxed{i_{E1max} = 29.6\ mA}$$

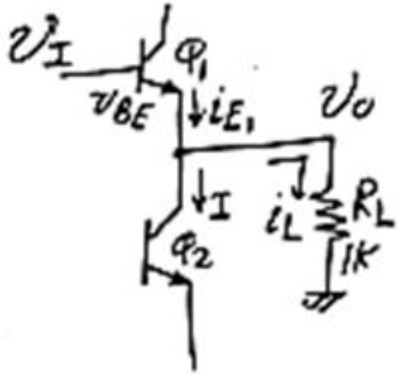
Solution(11.2):

$I = 14.8\,mA$

$v_O = -10V \xrightarrow{to} +10V$

$V_{BE} = 0.6V$ at $i_C = 1mA$, $\alpha \cong 1$ (β Large)

[a] Find v_I corresponding to $v_O = -10V, 0V, +10V$



$i_{E_1} = I + i_L$

$i_{E_1} = I + \frac{v_O}{R_L}$

[1] $v_O = -10V$

$i_{E_1} = 14.8 + \frac{-10}{1} = 4.8mA \cong i_{C_1}$

* $\Delta V_{BE} = V_T \ln \frac{i_{C_2}}{i_{C_1}} = 0.025 \ln \frac{4.8}{1} = 0.0392V$

* $V_{BE_1} = 0.6 + 0.0392 = 0.6392V$

* $v_I = V_{BE_1} + v_O = 0.6392 - 10$

$$\boxed{v_I \cong -9.36V}$$

[2] $\underline{v_o = 0}$ $\rightsquigarrow$ $i_{E_1} = 14.8 + \frac{0}{1} = 14.8\,mA \cong i_{C_1}$

$* \ \Delta v_{BE} = V_T \ln \frac{i_{C_2}}{i_{C_1}} = 0.025 \ln \frac{14.8}{1} = 0.06674V$

$* \ v_{BE_1} = 0.6 + 0.06674 = 0.6674V$

$* \ v_I = v_{BE_1} + \cancel{v_o}^{\,0}$

$$\boxed{v_I = 0.6674 \cong 0.67V}$$

[3] $\underline{v_o = +10V}$ $i_{E_1} = 14.8 + \frac{10}{1} = 24.8\,mA \cong i_{C_1}$

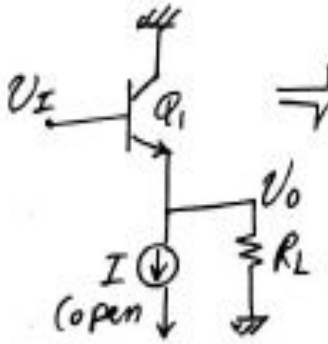
$* \ \Delta v_{BE} = 0.025 \ln \frac{24.8}{1} = 0.08V$

$* \ v_I = v_{BE_1} + v_o = (0.6 + 0.08) + 10$

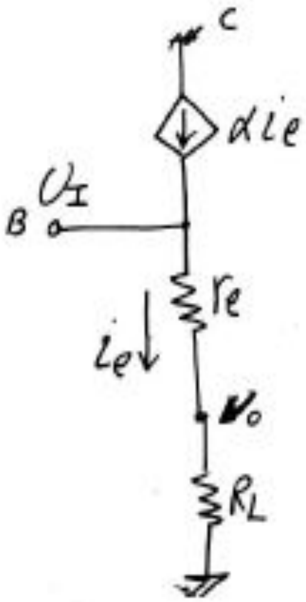
$$\boxed{v_I = 10.68V}$$

❑ Small Signal Voltage gain:

Small-signal Analysis:-



Using T-model



$$v_o = i_e . R_L = \left(\frac{v_I}{r_e + R_L}\right) . R_L$$

$$\therefore \boxed{A_v = \frac{v_o}{v_I} = \frac{R_L}{r_e + R_L}} \quad \#, \quad \boxed{r_e = \frac{V_T}{I_E}} \cong \frac{V_T}{I_C}$$

$$A_v = \frac{R_L}{\frac{V_T}{i_E} + R_L}$$

(a) $V_o = -10V$

* $i_{E1} = 4.8\ mA$

$$r_{e1} = \frac{0.025}{4.8}$$

$$A_v = \frac{R_L}{r_e + R_L} = \frac{1}{\frac{0.025}{4.8} + 1} = 0.9948$$

$$\boxed{A_v \cong 0.995}$$

(b) $V_o = 0 \quad i_{E1} = 14.8mA$

$$A_v = \frac{1}{\frac{0.025}{14.8} + 1} = 0.998$$

$$\boxed{A_v = 0.998}$$

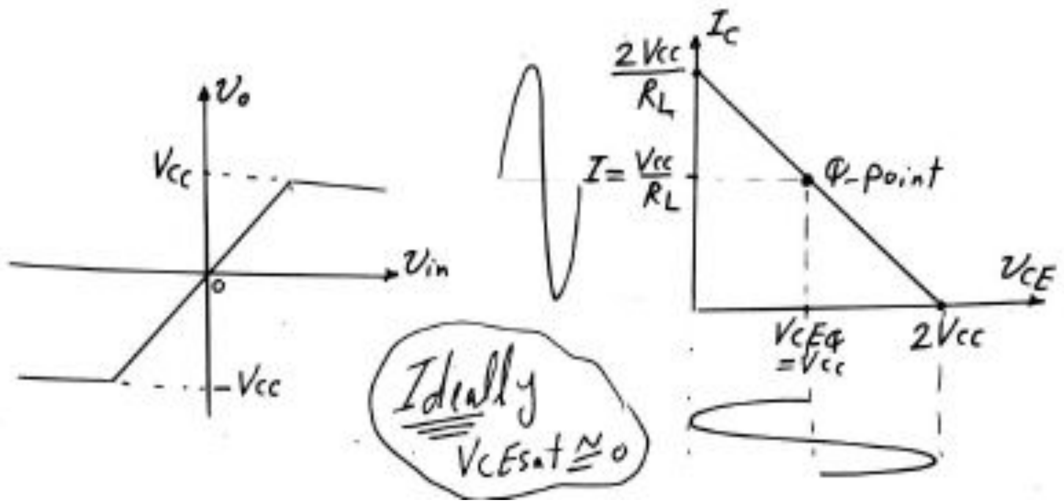
(c) $V_o = +10V$

$i_{E1} = 24.8\ mA$

$$A_v = \frac{1}{\frac{0.025}{24.8} + 1} \cong 0.999$$

$$\boxed{A_v = 0.999}$$

Power



[1] Input Power (D.c supply power)

$$\boxed{P_S = 2V_{cc} \cdot I} \neq (P_S = P_{in} = P_{D.C} = V_{d.c} \times I_{d.c})$$

$$= \frac{2V_{cc}^2}{R_L}$$

[2] Load Power (output power) (a.c Power)

$$P_L = P_o = V_{orms} \cdot I_{orms} = \frac{V_{op}}{\sqrt{2}} \times \frac{I_{op}}{\sqrt{2}}$$

$$P_L = P_o = \frac{V_{op} I_{op}}{2} \quad , \quad \boxed{I_{op} = \frac{V_{op}}{R_L}}$$

$$\therefore \boxed{P_L = P_o = \frac{V_{op}^2}{2R_L}}$$

V_{op} = output peak voltage

I_{op} = output peak current

Maximum output Power

at $V_{op} = V_{cc}$

$$\therefore \boxed{P_{Lmax} = P_{omax} = \frac{V_{cc}^2}{2R_L}}$$

3 Power conversion effeciency (η)

$$\eta = \frac{\text{Load Power } (P_L)}{\text{supply power } (P_s)}$$

$$\eta = \frac{P_L}{P_s} = \frac{V_{op}^2}{2R_L} \times \frac{1}{2V_{cc}.I} \quad , \quad I = \frac{V_{cc}}{R_L}$$

$$\eta = \frac{V_{op}^2}{2\cancel{R_L}} \times \frac{\cancel{R_L}}{2V_{cc}^2}$$

$$\eta = \frac{1}{4}\left(\frac{V_{op}}{V_{cc}}\right)^2 \quad \text{general}$$

Maximum Power effeciency at $V_{op} = V_{cc}$

$$\eta_{max} = \frac{1}{4} = 0.25 = 25\%$$

Low power effeciency due to Large d.c bias current (I).

Example

For the emitter follower class A, let *VCC* = 10 V, *I* = 100 mA, and *RL* = 100 Ω. If the output voltage is an 8-V-peak sinusoid, find the following:

(a) The power delivered to the load.

(b) The average power drawn from the supplies.

(c) The power-conversion efficiency. Ignore the loss in *Q*3 and *R*.

Solution:

(a) Po = PL = $\frac{V_{op}^{2}}{2R_L} = \frac{8^2}{2x100}$ = 0.32 Watts

(b) Pin = PDC = 2Vcc.I = 2x10x0.1= 2 Watts

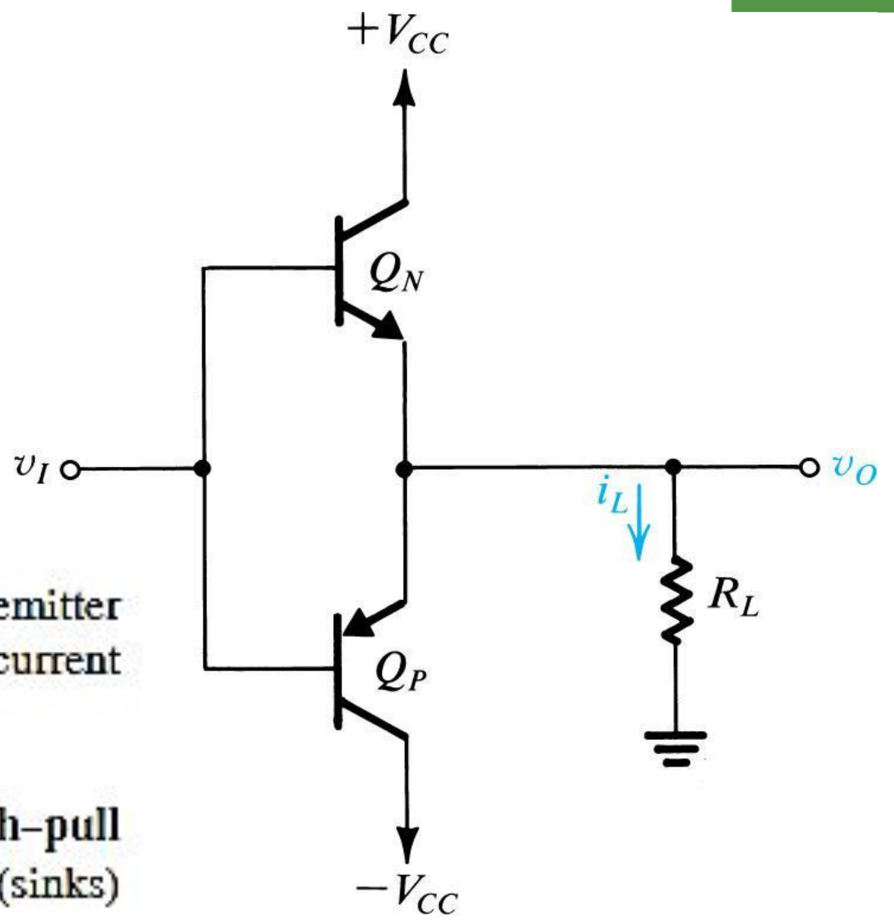
(c) power-conversion efficiency η = $\frac{Po}{Pin} = \frac{0.32}{2}$ = 0.16 = 16%

2. Class B Amplifier:

It consists of a complementary pair of transistors (an *npn* and a *pnp*) connected in such a way that both cannot conduct simultaneously.

Circuit Operation

When the input voltage v_I is zero, both transistors are cut off and the output voltage v_O is zero. As v_I goes positive and exceeds about 0.5 V, Q_N conducts and operates as an emitter follower. In this case v_O follows v_I (i.e., $v_O = v_I - v_{BEN}$) and Q_N supplies the load current. Meanwhile, the emitter–base junction of Q_P will be reverse-biased by the V_{BE} of Q_N, which is approximately 0.7 V. Thus Q_P will be cut off.



If the input goes negative by more than about 0.5 V, Q_P turns on and acts as an emitter follower. Again v_O follows v_I (i.e., $v_O = v_I + v_{EBP}$), but in this case Q_P supplies the load current and Q_N will be cut off.

We conclude that the transistors in the class B stage are biased at zero current and conduct only when the input signal is present. The circuit operates in a push–pull fashion: Q_N *pushes* (sources) current into the load when v_I is positive, and Q_P *pulls* (sinks) current from the load when v_I is negative.

Transfer Characteristic

A sketch of the transfer characteristic of the class B stage is shown in Fig. 11.6. Note that there exists a range of v_I centered around zero where both transistors are cut off and v_O is zero. This **dead band** results in the **crossover distortion** illustrated in Fig. 11.7 for the case of an input sine wave. The effect of crossover distortion will be most pronounced when the

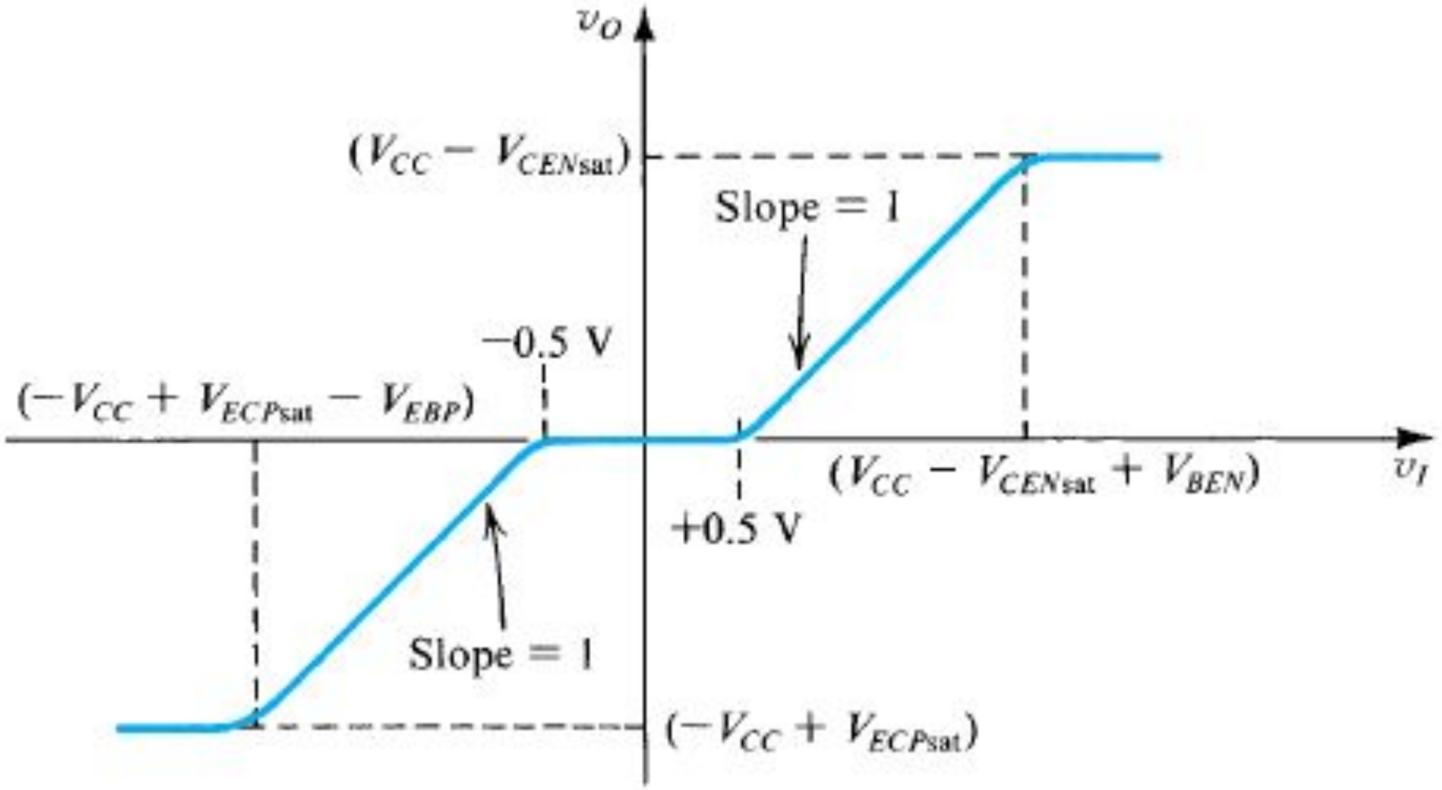


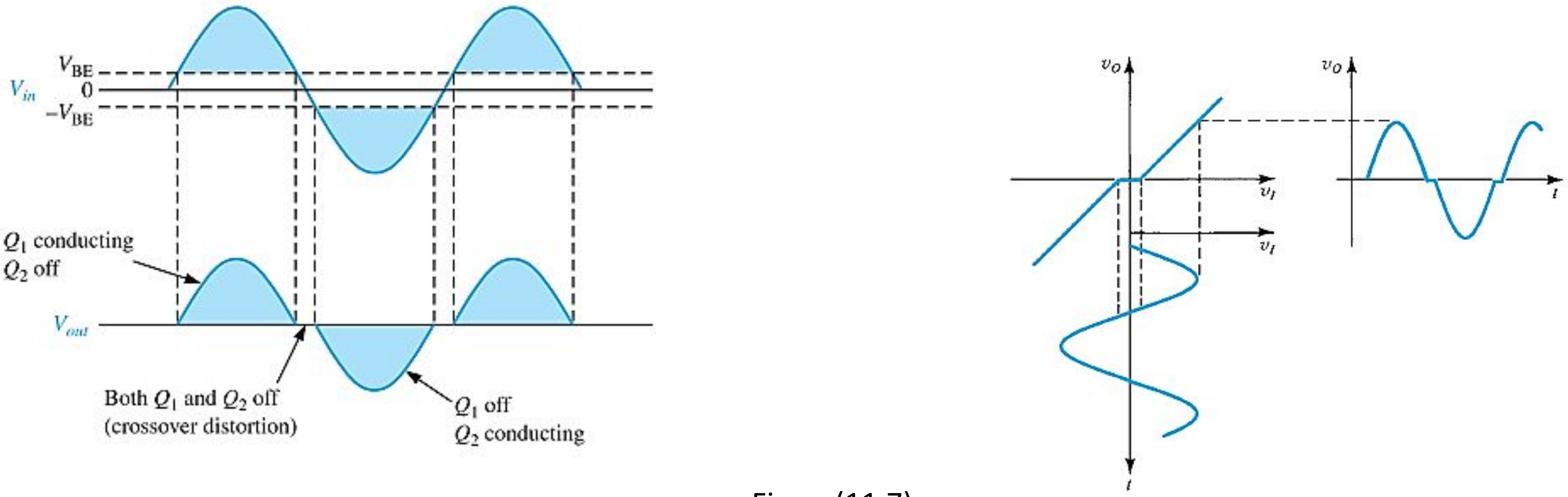
Fig. 11.6.

Voltage gain $A_v = \frac{R_L}{R_L + R_{out}}$

$R_{out} = r_{eN} \parallel r_{eP}$

Crossover Distortion

- When the dc base voltage is zero, both transistors are off and the input signal voltage must exceed V_{BE} before a transistor conducts.
- Because of this, there is a time interval between the positive and negative alternations of the input when neither transistor is conducting, as shown in Figure.
- The resulting distortion in the output waveform is called **crossover distortion**.



Figure(11.7)

Power

[1] Load Power (a.c Power) (o/p Power)

$$\boxed{P_L = P_o = \frac{V_{op}\, I_{op}}{2} = \frac{V_{op}^2}{2R_L}}, \quad P_{omax} = \frac{V_{cc}^2}{2R_L}$$

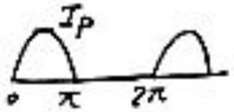
[2] Supply Power (D.C Input Power)

$$P_s = V_{D.C} \times I_{d.c}$$

$$P_S^+ = P_S^- = V_{cc} \cdot \frac{I_P}{\pi} = V_{cc}\,\frac{V_{op}/R_L}{\pi}$$

$$\boxed{P_S^+ = P_S^- = \frac{V_{cc}\, V_{op}}{\pi R_L}}$$

supply power For one BJT



$$I_{d.c} = \frac{1}{2\pi}\int_0^{\pi} I_P \sin\omega t \, d\omega t$$

$$= \frac{I_P}{2\pi}\left[-\cos\omega t\right]_0^{\pi}$$

$$= \frac{I_P}{2\pi}\left[1+1\right]$$

$$I_{dc} = \frac{I_P}{\pi} = \frac{V_{op}}{\pi R_L}$$

Total supply Power

$$\boxed{P_S = 2\,\frac{V_{cc}\, V_{op}}{\pi R_L}}$$

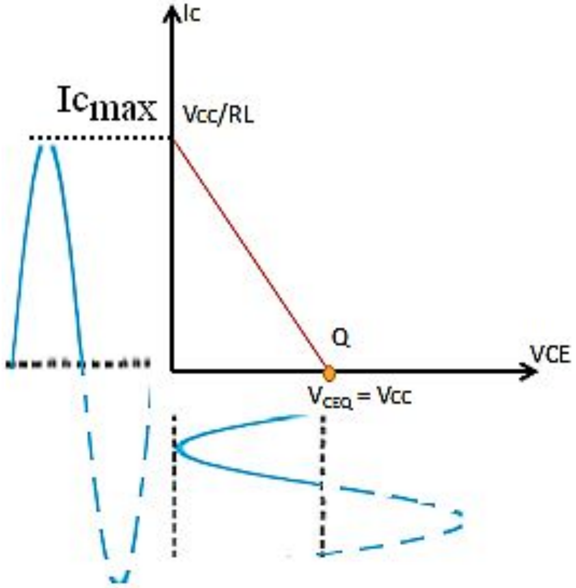
[3] Power Conversion efficiency

$$\eta = \frac{P_L}{P_S} = \frac{V_{op}^2}{2R_L} \times \frac{\pi R_L}{2V_{cc}V_{op}}$$

$$\eta = \frac{\pi}{4}\,\frac{V_{op}}{V_{cc}}$$ general

η_{max} at $V_{op} = V_{cc}$

$$\eta_{max} = \frac{\pi}{4} = 0.785 = 78.5\,\%$$



4] Power dissipation:-

$$P_D = P_S - P_L$$

$$\boxed{P_D = \frac{2\,V_{cc}\,V_{op}}{\pi R_L} - \frac{V_{op}^2}{2R_L}} \quad \text{I}$$

To Find max. Power dissipation:-

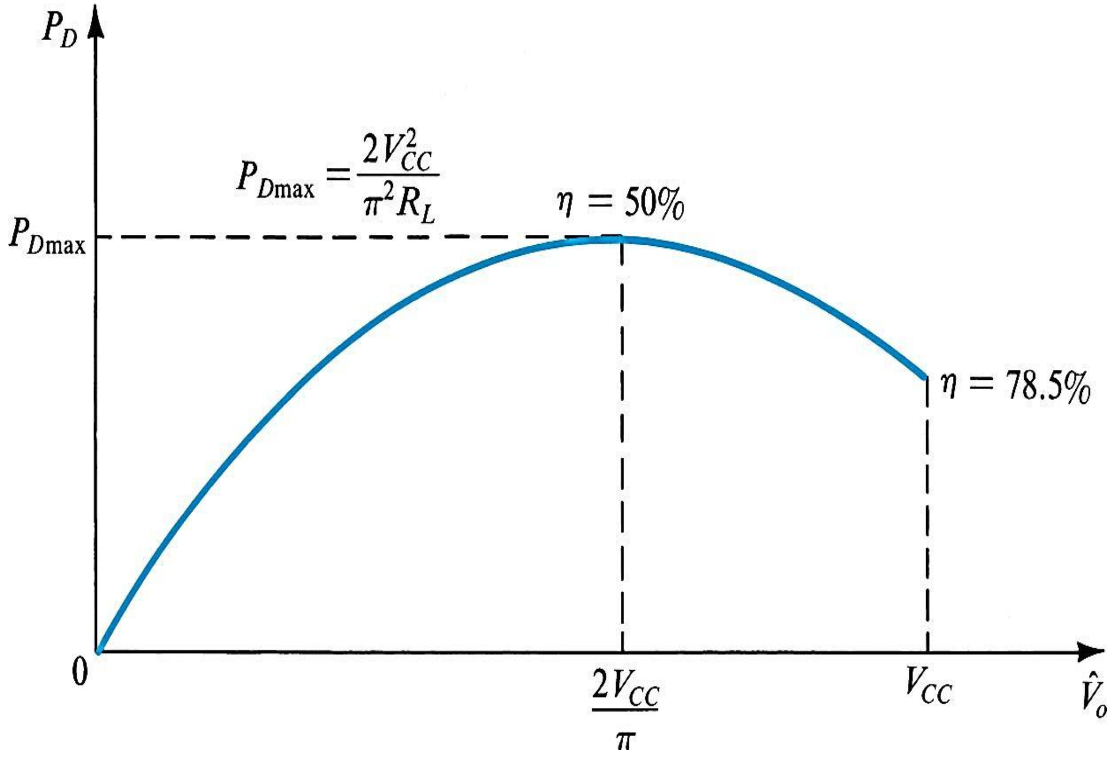
$$\frac{\partial P_D}{\partial V_{op}} = 0 \;\rightarrow\; \frac{2\,V_{cc}}{\pi R_L} - \frac{\cancel{2}V_{op}}{\cancel{2}R_L} = 0$$

$$\boxed{V_{op} = \frac{2\,V_{cc}}{\pi}}$$ at which max. power dissipation takes place.

sub. into I

$$P_{Dmax} = \frac{2\,V_{cc}^2}{\pi^2 R_L}$$ (For Q_N and Q_P)

$$P_{Dmax(N)} = P_{Dmax(P)} = \frac{V_{cc}^2}{\pi^2 R_L}$$ (one BJT)



Example

Design a class B output stage to deliver an average power of 40 watt to an 16 Ω load . The power supply is to be selected 4 voltages greater than the peak output voltage. Determine:

(1) The supply voltage Vcc.

(2) The peak current drawn from each supply.

(3) The total supply power.

(4) The power conversion efficiency.

(5) The maximum power that each transistor can dissipate safely.

Solution:

(1) The supply voltage V_{cc}.

$$P_L = \frac{V_{op}^2}{2R_L} \rightarrow V_{op} = \sqrt{2R_L P_L} = \sqrt{2 \times 16 \times 40}$$

$$V_{op} = 35.777V \cong 36V$$

$$V_{cc} = 4 + V_{op} \rightarrow \boxed{V_{cc} = 39.777V \cong 40V}$$

(2) The peak current drawn from each supply.

$$* \; I_{op} = \frac{V_{op}}{R_L} = \frac{36V}{16\Omega} = 2.25A$$

(3) The total supply power.

$$P_s = \frac{2 V_{cc} V_{op}}{\pi R_L} = \frac{2 \times 40 \times 36}{\pi \times 16} = 57.296\,W$$

(4) The power conversion efficiency.

$$\eta = \frac{P_L}{P_s} = \frac{40}{57.296} = 69.813\ \%$$

(5) The maximum power that each transistor can dissipate saf

$$P_{Dmax}(Q) = \frac{V_{cc}^2}{\pi^2 R_L} = \frac{(40)^2}{\pi^2 \times 16}$$

$$P_{D_{max}}(Q) = 10.132\,W$$

Example

Design a class B output stage to deliver a maximum average power of 40 watt to a16 Ω load. Determine:

(1) The supply voltage Vcc.

(2) The total supply power.

(3) The power conversion efficiency.

(4) The maximum power that each transistor can dissipate safely.

Solution:

(1) The supply voltage Vcc.

$$P_o(max) = \frac{V_{cc}^2}{2R_L} \sqrt{\to} \quad V_{cc} = \sqrt{2P_o(max)R_L} = \sqrt{2\times 40\times 16}$$

$$\boxed{V_{cc} = 35.777V}, \boxed{V_{op} = V_{cc} = 35.777V}$$

(2) The total supply power.

$$P_s(2Q) = \frac{2V_{cc}V_{op}}{\pi R_L} = \frac{2\times 35.777\times 35.777}{\pi\times 16}$$

$$\boxed{P_s(2Q) = 50.93W}$$

(3) The power conversion efficiency.

$$\eta = \frac{P_o}{P_s} = \frac{40}{50.93} = 0.7854$$

$$\boxed{\eta = 78.54\%}$$

(4) The maximum power that each transistor can dissipate safely. [1 Mark]

$$P_{d_{max}}(Q) = \frac{V_{cc}^2}{\pi^2 R_L} = \frac{(35.777)^2}{\pi^2\times 16}$$

$$\boxed{P_{d_{max}}(Q) \cong 8.106W}$$