Analog Circuits

Day-9

Power Amplifiers

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- Class A Power amplifier and its Analysis
  - Example
- Harmonic Distortions
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- Complementary Symmetry push-pull Amplifier
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Introduction

- Power amplifiers are used to deliver a relatively **high amount of power**, usually **to** a **low resistance load**.
- Typical load values range from 300W (for transmission antennas) to 8W (for audio speaker).
- Although these load values do not cover every possibility, they do illustrate the fact that power amplifiers **usually drive low-resistance loads**.
- Typical output power rating of a power amplifier will be **1W or higher**.
- **Ideal** power amplifier will deliver **100%** of the power it draws from the supply to load. In **practice**, this can never occur.
- The reason for this is the fact that the components in the amplifier will all **dissipate** some of the power that is being drawn form the supply.

Concept of Power Amplifier

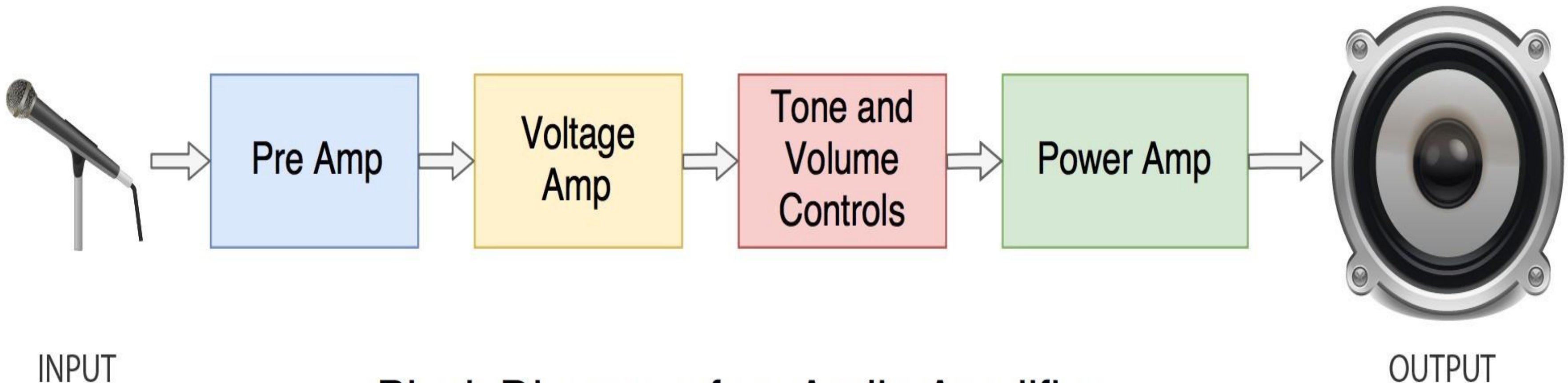
- Provide ***sufficient power*** to an output load to drive other power device.

- To deliver a large current to a small load resistance e.g. audio speaker;

- To deliver a large voltage to a large load resistance e.g. switching power supply;

- To provide a low output resistance in order to avoid loss of gain and to maintain linearity (to minimize harmonic distortion)

- To deliver power to the ***load efficiently***

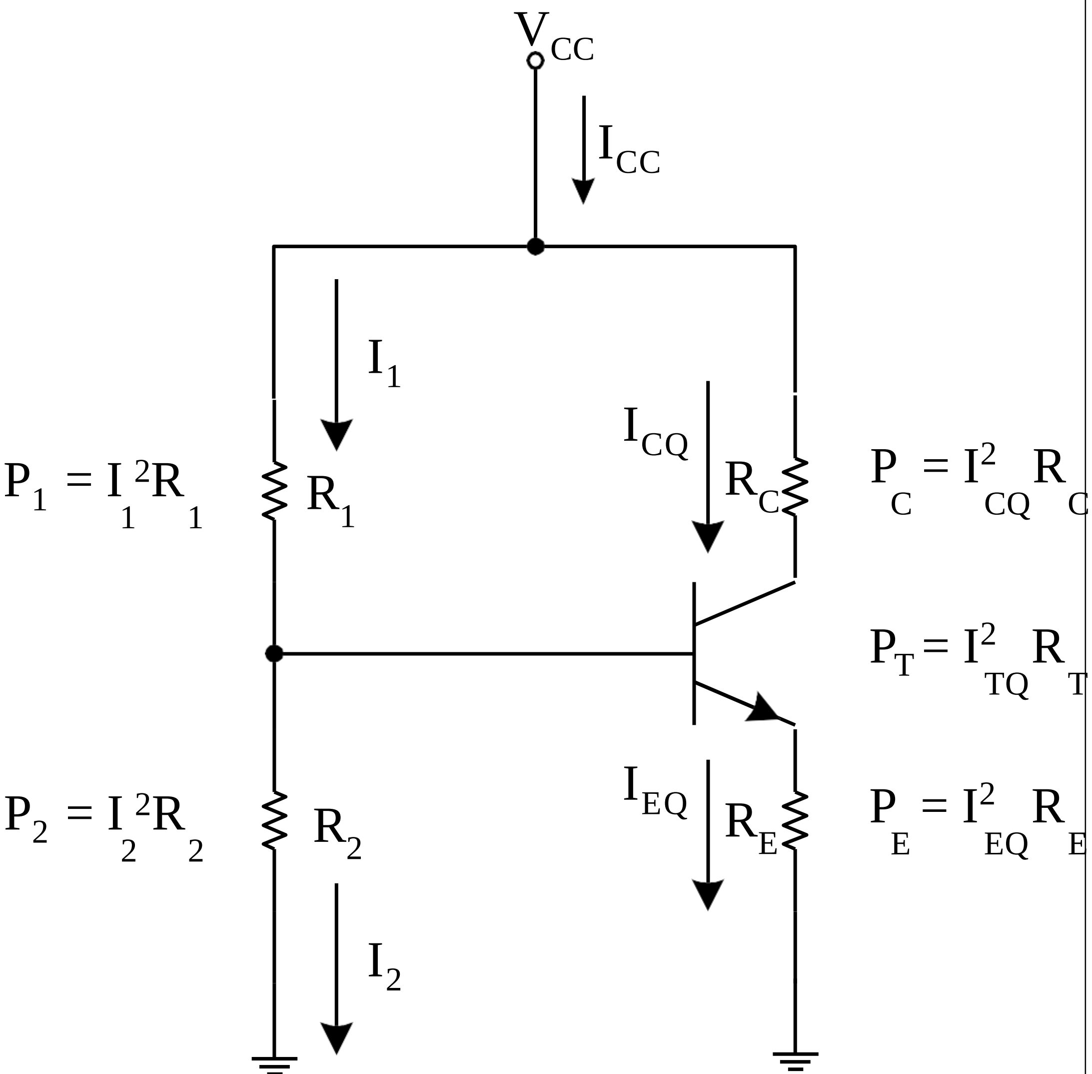


Block Diagram of an Audio Amplifier

Power Amplifier Power Dissipation

The **total** amount of power being dissipated by the amplifier, $\boldsymbol{P_{tot}}$, is

$$P_{tot} = P_1 + P_2 + P_C + P_T + P_E$$



The difference between this total value and the total power being drawn from the supply is the power that actually goes to the **load** – **i.e. output power**.

Power Amplifier Efficiency η

- A **figure of merit** for the power amplifier is its efficiency, η .

- **Efficiency (η)** of an amplifier is defined as the ratio of ac output power (power delivered to load) to dc input power .

- By formula: $\eta = \dfrac{ac\ \ output\ \ power}{dc\ \ input\ \ power} \times 100\% = \dfrac{P_o(ac)}{P_i(dc)} \times 100\%$

- As we will see, certain amplifier configurations have much higher efficiency ratings than others.

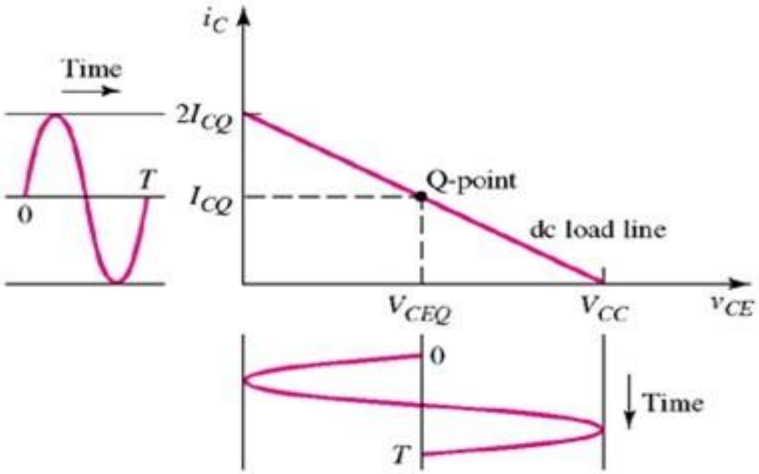
- This is primary consideration when deciding which type of power amplifier to use for a specific application.

Power Amplifiers Classification
(Depending on Type of output load)

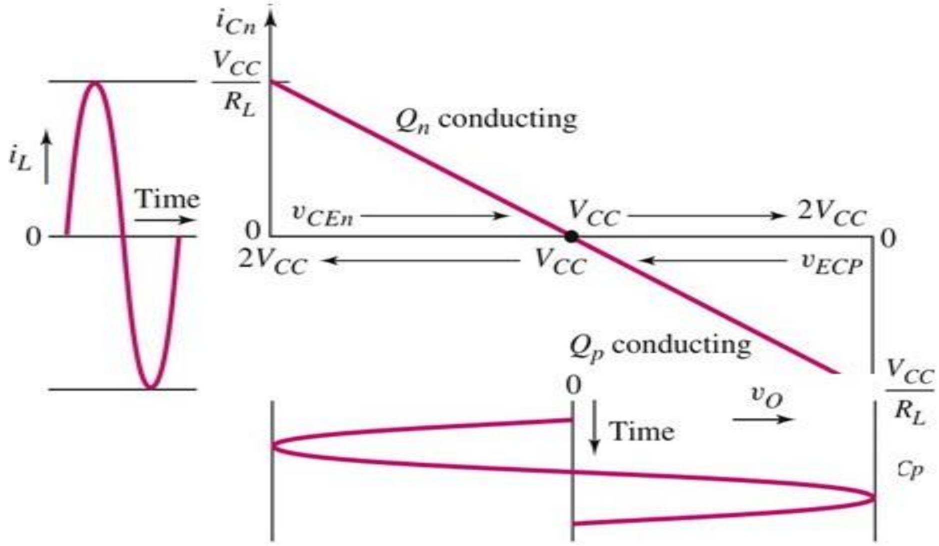
- AUDIO AMPLIFIERS
- RADIO FREQUENCY AMPLIFIERS
- D C POWER AMPLIFIERS

Power Amplifiers Classification

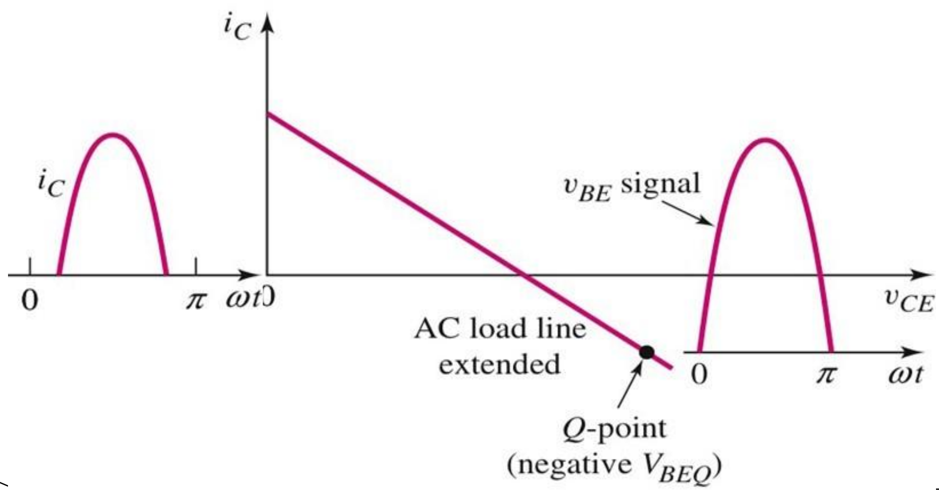
Class-A Power Amplifier:



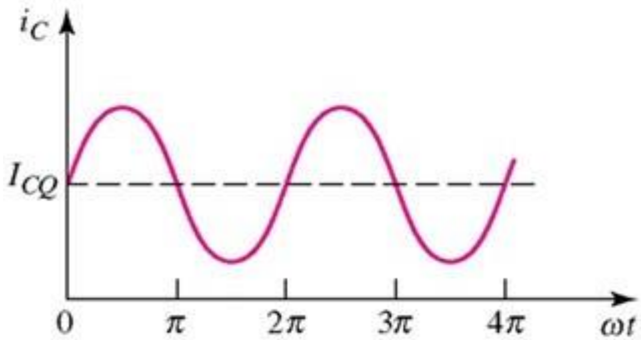
Class-B Power Amplifier:



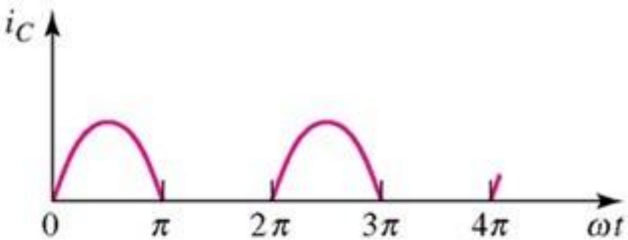
Class-C Power Amplifier:



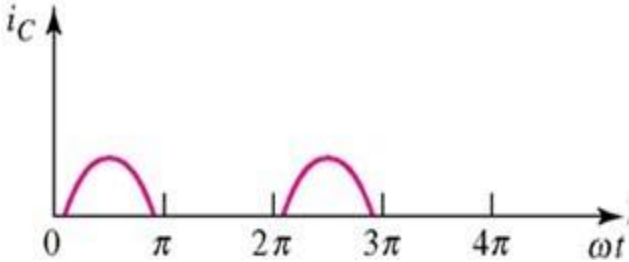
Class A - The transistor conducts during the whole cycle of sinusoidal input signal



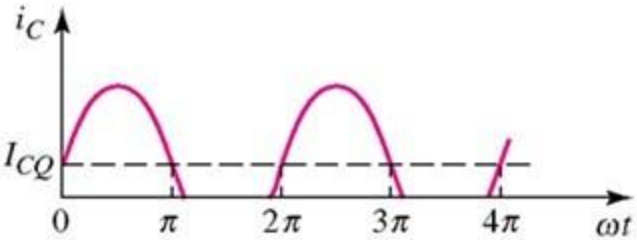
Class B - The transistor conducts during one-half cycle of input signal



Class C - The transistor conducts for less than half a cycle of input signal



Class AB - The transistor conducts for slightly more than half a cycle of input signal



Class	A	B	C	AB
Conduction Angle	360^o	180^o	Less than 90^o	180 to 360^o
Position of the Q-point	Centre Point of the Load Line	Exactly on the X-axis	Below the X-axis	In between the X-axis and the Centre Load Line
Overall Efficiency	Poor 25 to 30%	Better 70 to 80%	Higher than 80%	Better than A but less than B 50 to 70%
Signal Distortion	None if Correctly Biased	At the X-axis Crossover Point	Large Amounts	Small Amounts

Efficiency Ratings

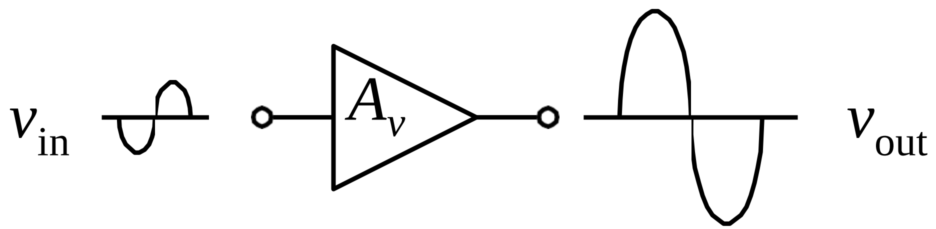
- The **maximum theoretical efficiency** ratings of class-A, B, and C amplifiers are:

Amplifier	Maximum Theoretical Efficiency, η_{max}
Class A	25%
Class B	78.5%
Class C	99%

Steps for Analysis of Power Amplifiers:

- Draw the Circuit Diagram of relevant type of Power Amplifer
- Draw the Graphical operating point representation
- Make DC analysis (AC components as 0) & Calculate 'Pdc'
- Make AC analysis (DC components as 0) & Calculate 'Pac'
- Measure the Percentage Efficiency of the amplifier (% n)
- Show the Power Dissipation
- Advantages and Disadvantages

Class A Amplifier



- v_{output} waveform → **same shape** → v_{input} waveform + π **phase shift.**

- The collector current is **nonzero** 100% of the time.

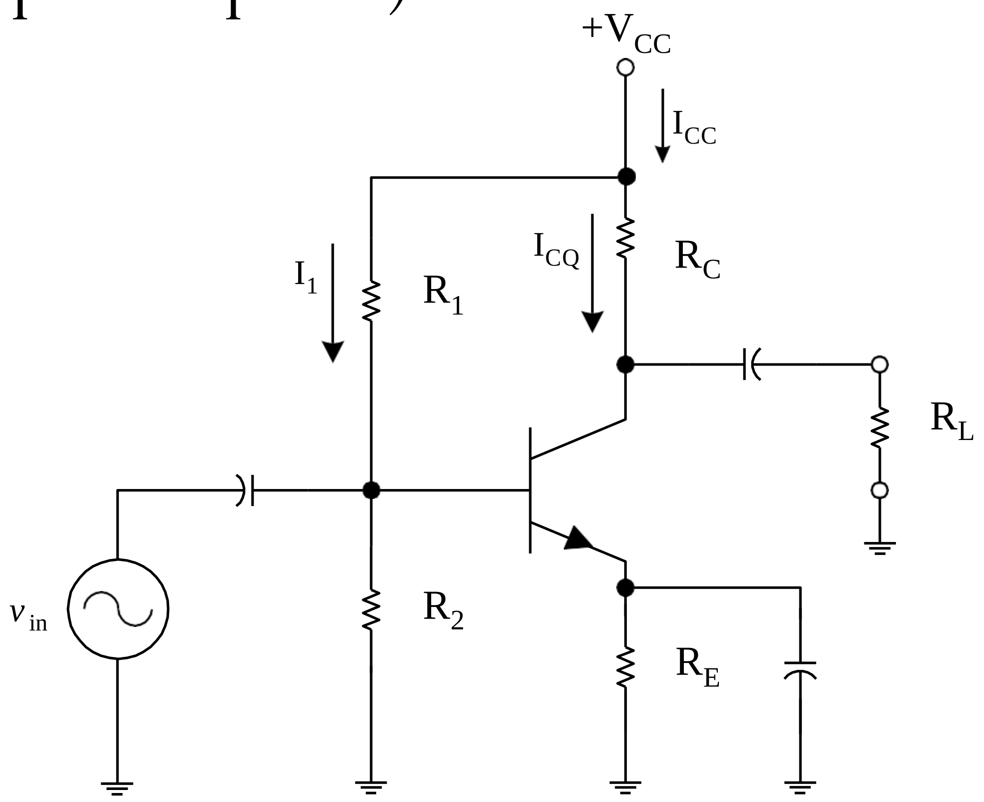
  → **inefficient**, since even with zero input signal, I_{CQ} is nonzero (i.e. transistor dissipates power in the rest, or quiescent, condition)

Class A Amplifier Classification

- RC Coupled
- Transformer Coupled

RC Coupled Class A Power Amplifier Analysis

Common-emitter (voltage-divider) configuration
(RC-coupled amplifier)

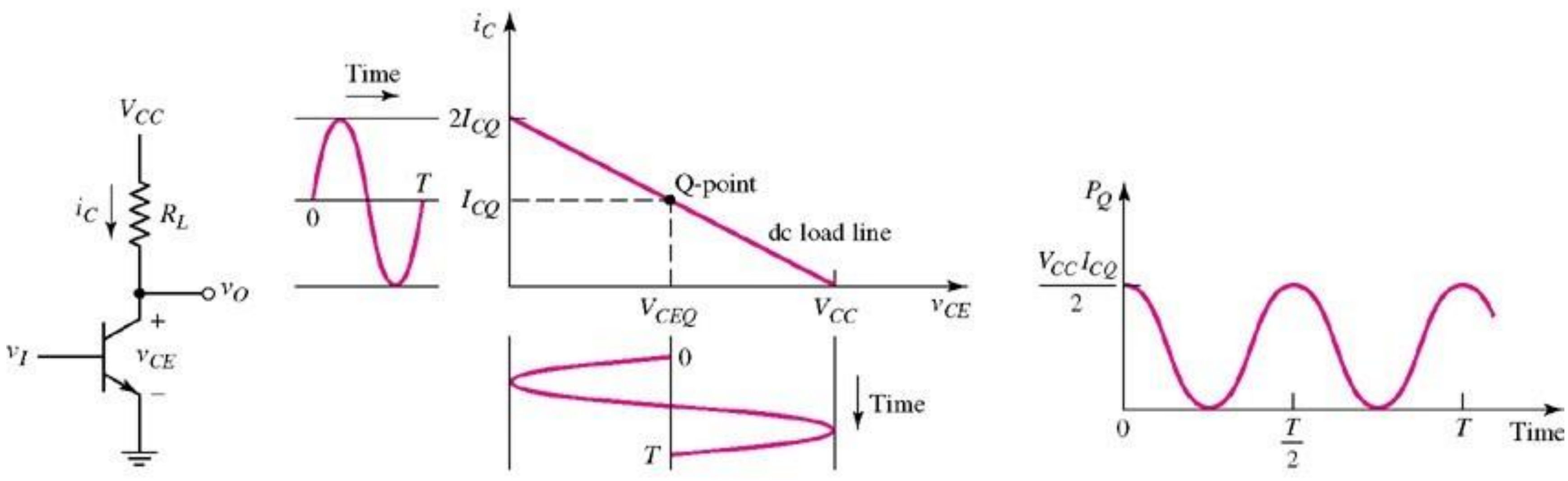


Typical Characteristic Curves for Class A Operation

(a) Common-emitter amplifier,

(b) dc load line (the Q point is at centre of the load line)

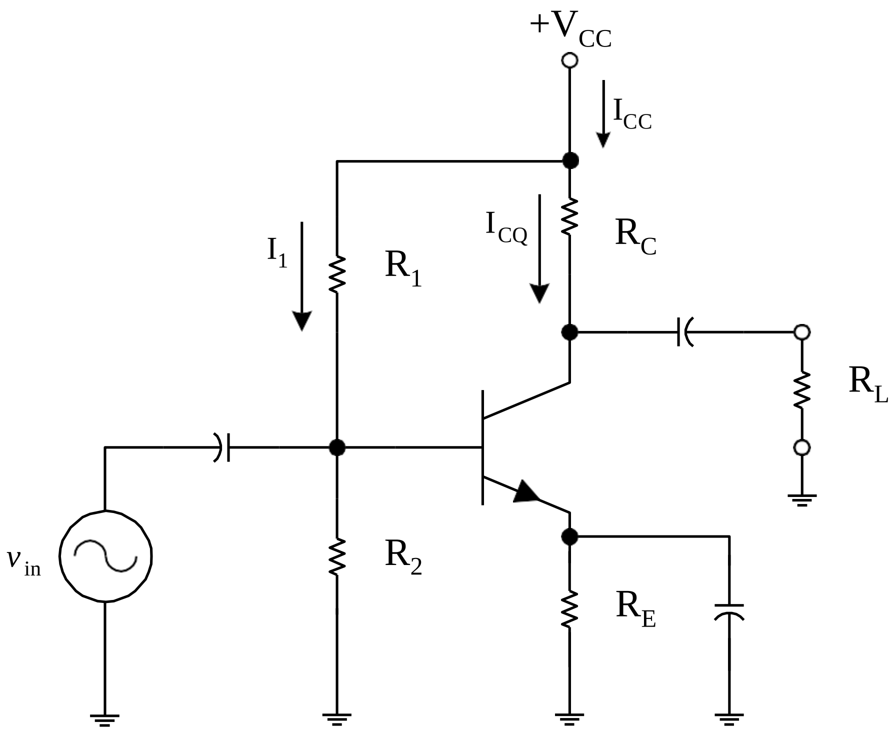
(c) instantaneous power dissipation versus time in the transistor



(a) (b) (c)

DC Input Power

The total dc power, $P_i(dc)$, that an amplifier draws from the power supply :



$$P_i(dc) = V_{CC} I_{CC}$$

$$I_{CC} = I_{CQ} + I_1$$

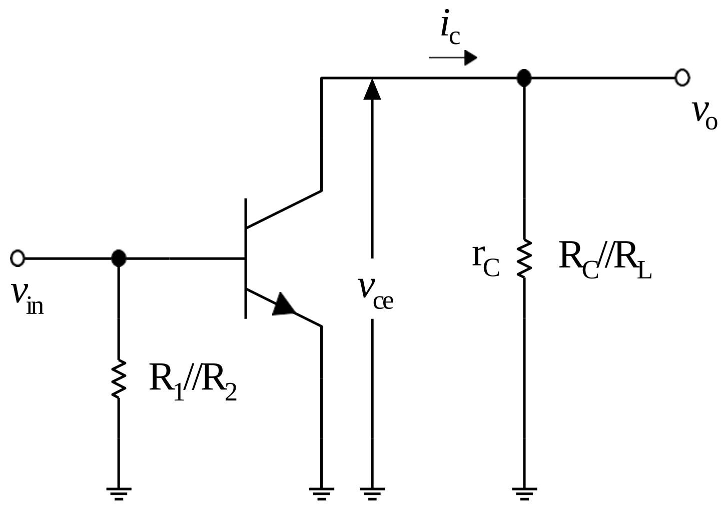
$$I_{CC} \approx I_{CQ} \qquad (I_{CQ} >> I_1)$$

$$P_i(dc) = V_{CC} I_{CQ}$$

Note : That this equation is valid for most amplifier power analyses. We can rewrite for the above equation for the **ideal** amplifier as

$$P_i(dc) = V_{CC} I_{CQ}$$

AC Output Power



$$P_o(ac) = i_{c(rms)} v_{o(rms)}$$

$$V_{o(rms)} = \frac{Vm}{\sqrt{2}} \qquad I_{o(rms)} = \frac{\mathrm{Im}}{\sqrt{2}}$$

$$P_o(ac) = \frac{Vm}{\sqrt{2}} * \frac{\mathrm{Im}}{\sqrt{2}} = \frac{Vm * \mathrm{Im}}{2}$$

$$V_m = \frac{Vpp}{2} \qquad I_m = \frac{Ipp}{2}$$

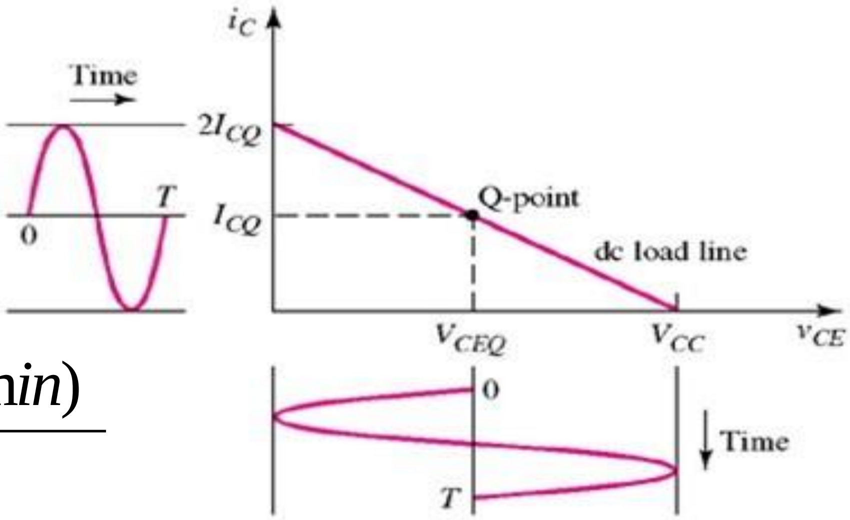
$$P_o(ac) = \frac{(V\max - V\min) * (\mathrm{Im}ax - \mathrm{Im}in)}{8}$$

$$P_o(ac) = \frac{\frac{Vpp}{2} * \frac{Ipp}{2}}{2} = \frac{Vpp * Ipp}{8}$$

$$V_{pp} = \frac{V\max - V\min}{2} \qquad I_{pp} = \frac{\mathrm{Im}ax - \mathrm{Im}in}{2}$$

Efficiency:

$$\%\eta = \frac{P_{ac}}{P_{dc}} * 100$$



$$P_o(ac) = \frac{(V\max - V\min)*(\mathrm{I}\max - \mathrm{I}\min)}{8}$$

$$P_i(dc) = V_{CC} I_{CQ}$$

$$\%\eta = \frac{(V\max - V\min)(\mathrm{I}\max - \mathrm{I}\min)}{8 * Vcc * Icq} * 100$$

Vmax=VCC & Vmin= 0

Imax=2Icq & Imin= 0

$$\%\eta = \frac{2 * Vcc * Icq}{8 * Vcc * Icq} * 100$$

$$\%\eta = 25\%$$

- **Advantages:**

1) Circuit is Simple to Design

2) Less no. of Components

- **Dis-Advantages:**

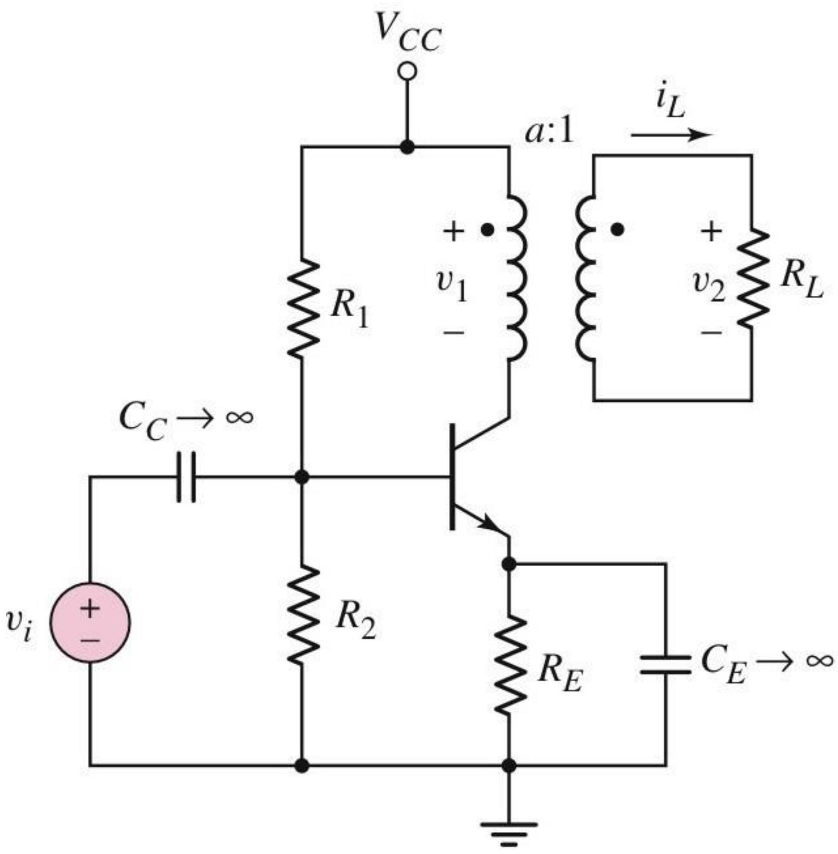
1) Load Resistor is directly connected to collector. This causes considerable wastage of Power

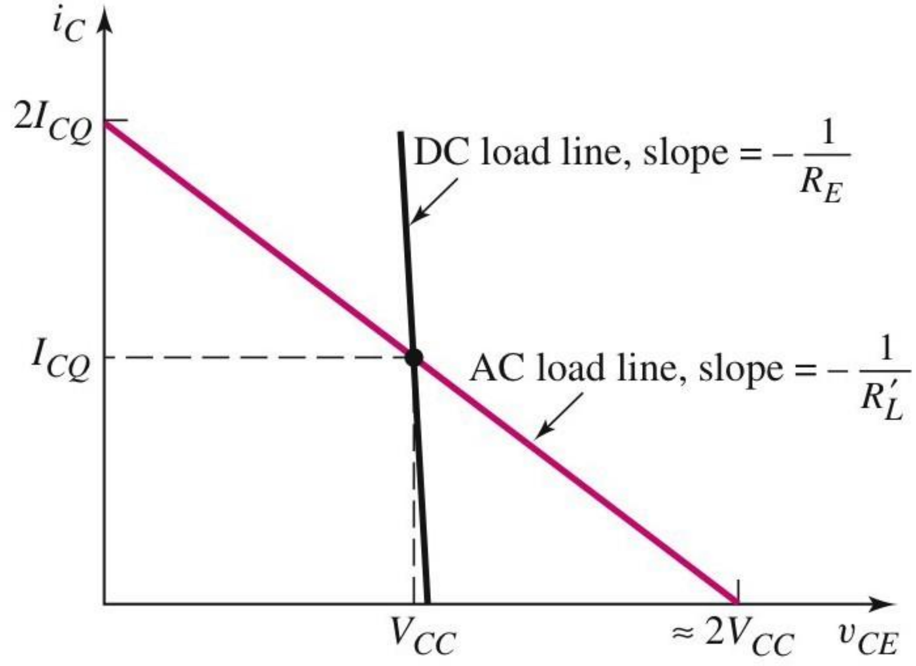
2) Power Dissipation is More

3) Efficiency is very poor, due to large power Dissipation

Transformer Coupled Amplifier

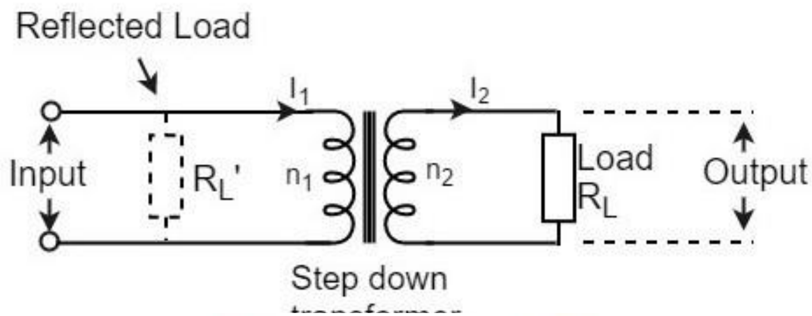
- The theoretical maximum efficiency of a basic RC-coupled class-A amplifier is limited to 25%.
- In practical circuit, the efficiency is less than 25%.
- Used for output power of about 1 W only.
- Transformer coupling can increase the maximum efficiency to 50%
- Disadvantage of transformer coupling – expensive & bulky.





Neglecting transformer resistance and assuming R_E is small;

$$V_{CEQ} \cong V_{CC}$$



$$\frac{V_1}{V_2} = \frac{n_1}{n_2} \; and \; \frac{I_1}{I_2} = \frac{n_1}{n_2}$$

Or

$$V_1 = \frac{n_1}{n_2} V_2 \; and \; I_1 = \frac{n_1}{n_2} I_2$$

Hence

$$\frac{V_1}{I_1} = \left(\frac{n_1}{n_2}\right)^2 \frac{V_2}{I_2}$$

But $V_1/I_1 = R_L'$ = effective input resistance

And $V_2/I_2 = R_L$ = effective output resistance

Therefore,

$$R'_L = \left(\frac{n_1}{n_2}\right)^2 R_L = n^2 R_L$$

Where

$$n = \frac{number\, of\, turns\, in\, primary}{number\, of\, turns\, in\, secondary} = \frac{n_1}{n_2}$$

A power amplifier may be matched by taking proper turn ratio in step down transformer.

¬ DC Input Power

The total dc power, $P_i(dc)$, that an amplifier draws from the power supply :

i_C

$$P_i(dc) = V_{CC} I_{CC}$$

$$I_{CC} \approx I_{CQ} \qquad (I_{CQ} >> I_1)$$

$$P_i(dc) = V_{CC} I_{CQ}$$

Note : That this equation is valid for most amplifier power analyses. We can rewrite for the above equation for the **ideal** amplifier as

$$P_i(dc) = V_{CC} I_{CQ}$$

¬ AC Output Power

$$P_o(ac) = i_{1(rms)} v_{1(rms)} \qquad P_o(ac) = i_{2(rms)} v_{2(rms)}$$

At Primary side A.C power generated:

i_C

$$P_o(ac) = i_{1(rms)} v_{1(rms)} = I^2{}_{1rms} R'_L = \frac{V^2_{1rms}}{R'_L}$$

$$P_o(ac) = \frac{V_1 m}{\sqrt{2}} * \frac{I_1 m}{\sqrt{2}} = \frac{V_1 m * I_1 m}{2}$$

$$V_{pp} = \frac{V\max - V\min}{2}$$

$$V_m = \frac{Vpp}{2} \qquad I_m = \frac{Ipp}{2}$$

$$I_{pp} = \frac{\mathrm{Im}ax - \mathrm{Im}in}{2}$$

ϖ We consider an idea Transformer, means Power delivered on primary side is equal to the secondary side load, and the values of currents and voltages are similar.

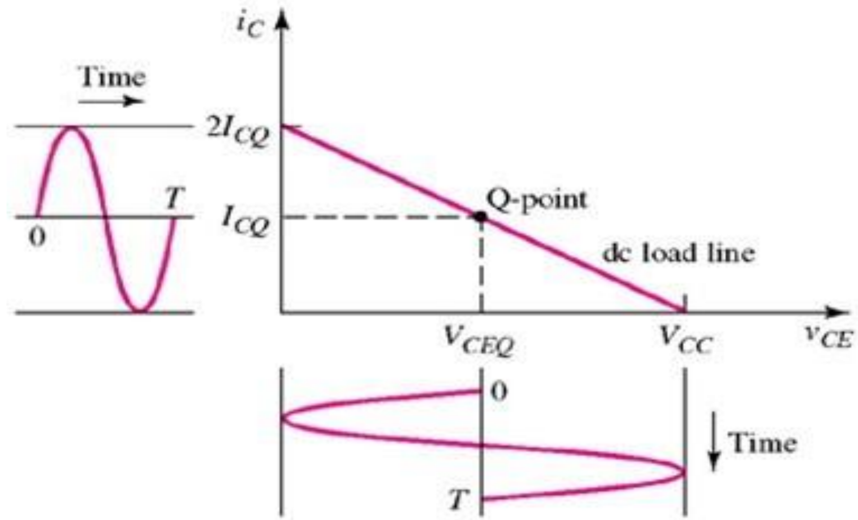
$$P_o(ac) = \frac{\frac{Vpp}{\sqrt{2}} * \frac{Ipp}{2}}{2} = \frac{Vpp * Ipp}{8}$$

$$P_o(ac) = \frac{(V\max - V\min) * (I\max - I\min)}{8}$$

$$P_i(dc) = V_{CC} I_{CQ}$$

Efficiency:

$$\%\eta = \frac{P_{ac}}{P_{dc}} * 100$$



$$P_o(ac) = \frac{(V\max - V\min)*(I\max - I\min)}{8}$$

$$P_i(dc) = V_{CC} I_{CQ}$$

Vmax=2VCC & Vmin= 0

Imax=2Icq & Imin= 0

$$\%\eta = \frac{(V\max - V\min)(I\max - I\min)}{8*Vcc*Icq} * 100$$

$$\%\eta = 50\%$$

$$\%\eta = \frac{4*Vcc*Icq}{8*Vcc*Icq} * 100$$

Power Dissipation:

$$p_d = p_{DC} - p_{AC}$$

- In case of Class A amplifiers, Power Dissipation is maximum when no input signal is applied.

ϖ Advantages:

1) Efficiency be somewhat high compared to series fed Class A

2)Impedance matching is required for maximum power transfer is possible

ϖ Dis-Advantages:

1) Due to Transformer, the circuit becomes bulkier, heavier and costlier compared to series fed type

2) Frequency response of the circuit is poor

3) Circuit is complicated to design and implementation compared to series fed type

Class A advantages:

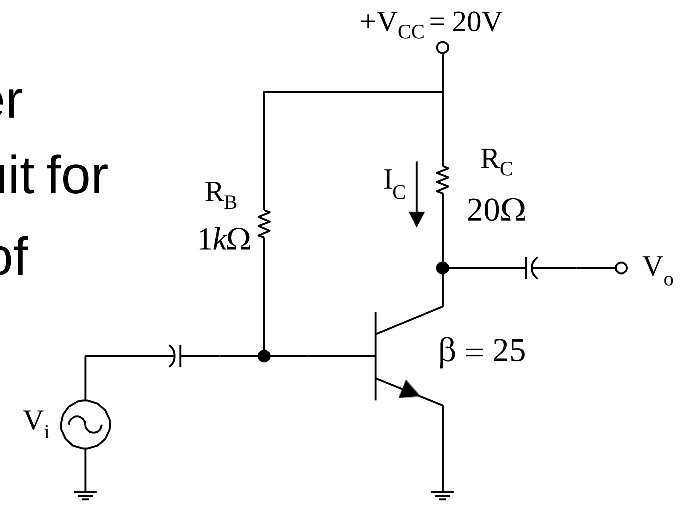
- No cross over distortion
- No switching distortion
- Lower harmonic distortion in the voltage amplifier
- Lower harmonic distortion in the current amplifier
- No signal dependent distortion from the power supply
- Constant and low output impedance
- Simpler design

Class A dis-advantages:

- Low Efficiency
- Power Dissipation more
- Wastage of Power

Example

Calculate the input power [$P_i(dc)$], output power [$P_o(ac)$], and efficiency [η] of the amplifier circuit for an input voltage that results in a base current of 10mA peak.



$$I_{BQ} = \frac{V_{CC} - V_{BE}}{R_B} = \frac{20V - 0.7V}{1k\Omega} = 19.3mA$$

$$I_{CQ} = \beta I_B = 25(19.3mA) = 482.5mA \cong 0.48A$$

$$V_{CEQ} = V_{CC} - I_C R_C = 20V - (0.48A)(20\Omega) = 10.4V$$

$$I_{c(sat)} = \frac{V_{CC}}{R_C} = \frac{20V}{20\Omega} = 1000mA = 1A$$

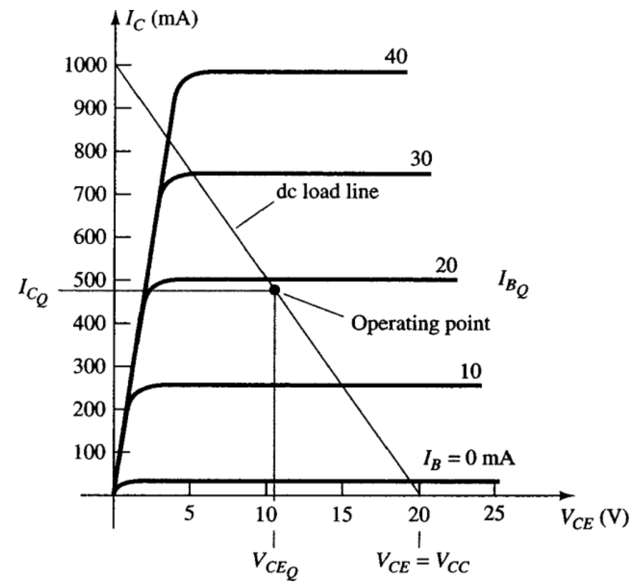
$$V_{CE(cutoff)} = V_{CC} = 20V$$

$$I_{C(peak)} = \beta I_{b(peak)} = 25(10mA\ peak) = 250mA\ peak$$

$$P_{o(ac)} = \frac{I^2_{C(peak)}}{2} R_C = \frac{\left(250 \times 10^{-3} A\right)^2}{2}(20\Omega) = 0.625W$$

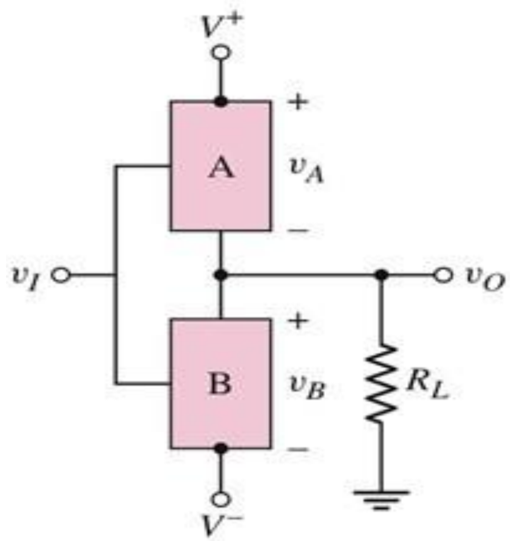
$$P_{i(dc)} = V_{CC} I_{CQ} = (20V)(0.48A) = 9.6W$$

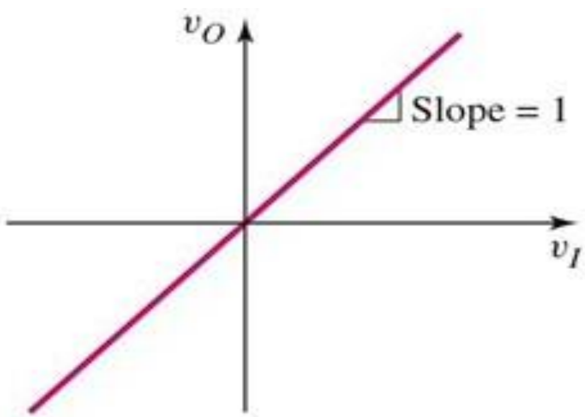
$$\eta = \frac{P_{o(ac)}}{P_{i(dc)}} \times 100\% = 6.5\%$$



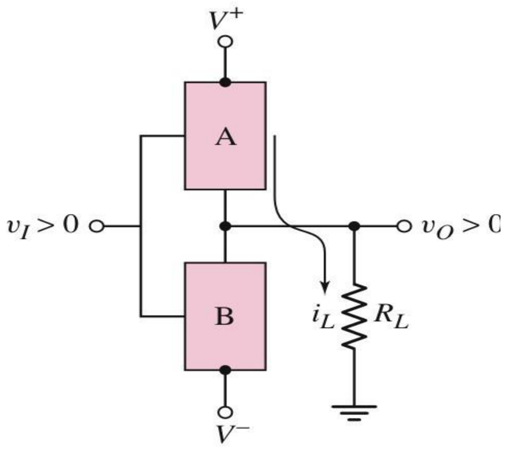
Class B Power Amplifier

- Consists of **<u>Push-Pull</u>** & **<u>complementary pair</u>** electronic devices
- One conducts for **one half cycle** of the input signal and the other **conducts** for **another half** of the **input signal**
- When the input is zero, both devices are off, the bias currents are zero and the output is zero.
- Ideal voltage gain is unity

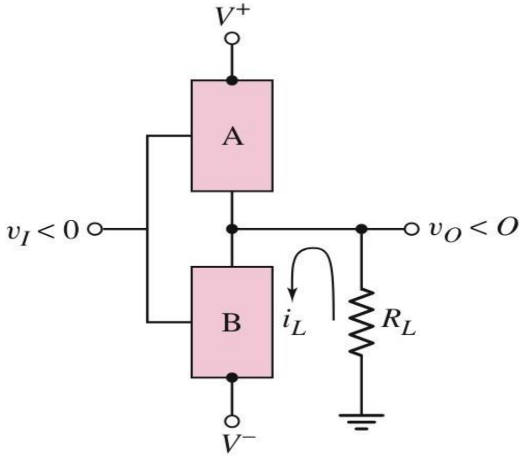




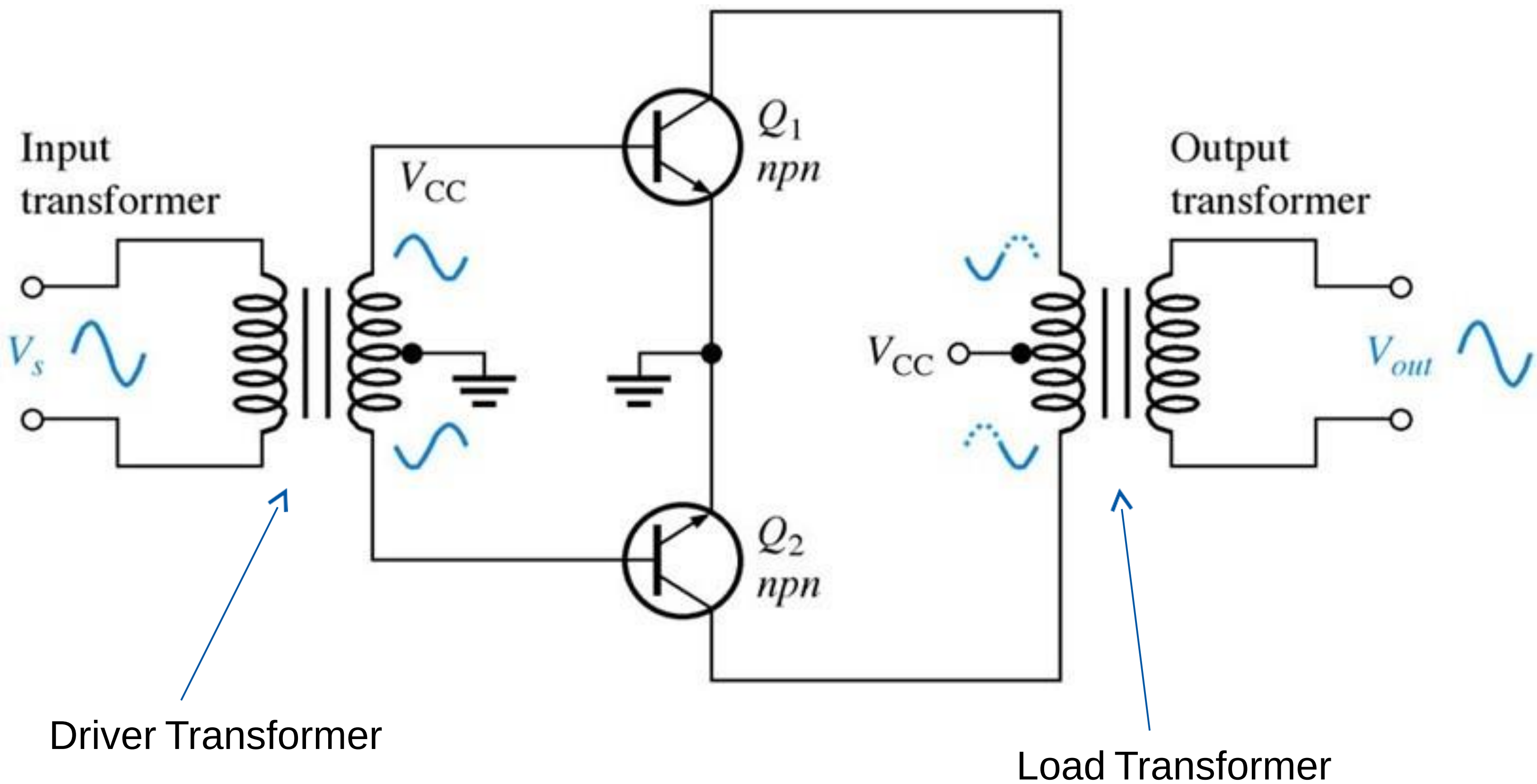
- For input larger than zero, A turn ON and supplies current to the load.



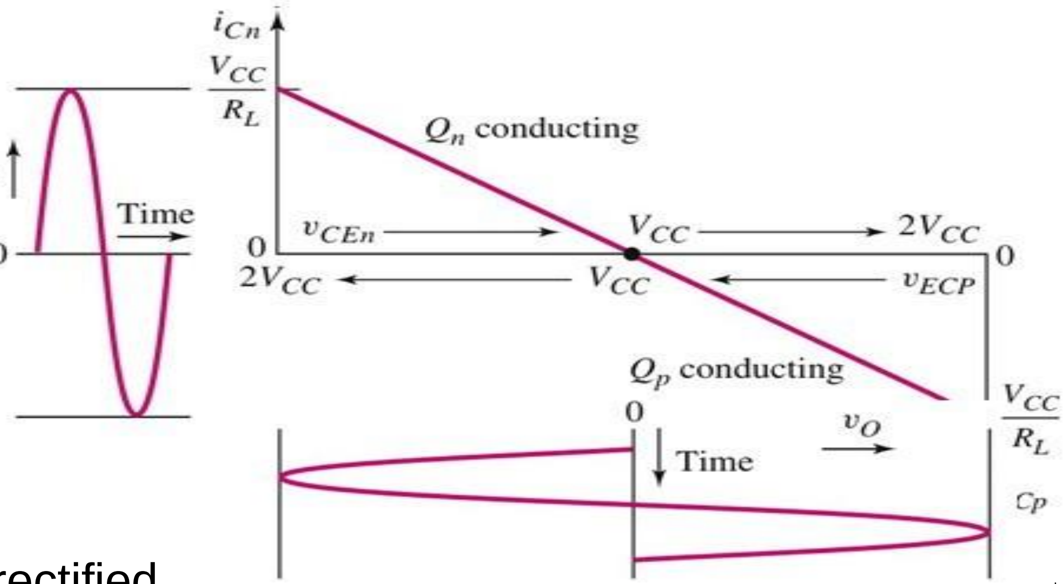
- For input less than zero, B turn ON and sinks current from the load



Class-B transformer coupled push pull amplifier



¬ DC Input Power



•DC biasing point is on the X-axis so the Vceq=VCC. And Iceq becomes 0. hence Q-point (Vcc,0).

• Each Transformer output is an Half-rectified Waveform. Then peak value of the output current is the average d.c current

$$I_1(dc) = \frac{I_m}{\pi} \qquad I_2(dc) = \frac{I_m}{\pi}$$

$$I(dc) = \frac{I_m}{\pi} + \frac{I_m}{\pi} = \frac{2I_m}{\pi}$$

$$P(dc) = V_{CC} I_{dc} = \frac{2}{\pi} V_{CC} I_m$$

¬ AC Output Power

$$P_o(ac) = i_{1(rms)} v_{1(rms)} \qquad P_o(ac) = i_{2(rms)} v_{2(rms)}$$

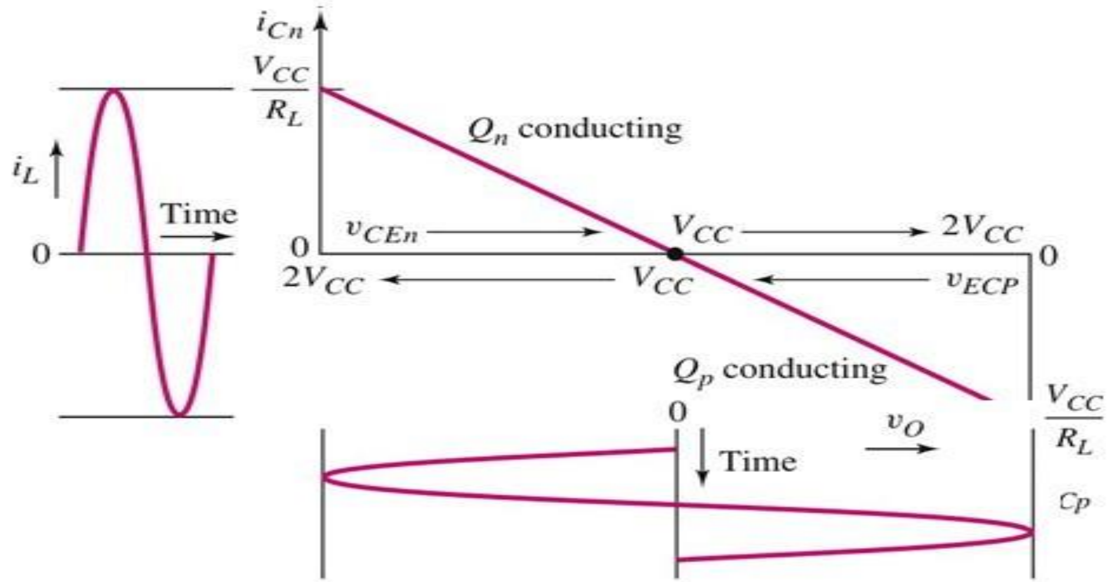
At Primary side A.C power generated:

$$P_o(ac) = i_{1(rms)} v_{1(rms)} = I^2_{1rms} R'_L = \frac{V^2_{1rms}}{R'_L}$$

$$P_o(ac) = \frac{Vm}{\sqrt{2}} * \frac{\mathrm{Im}}{\sqrt{2}} = \frac{Vm * \mathrm{Im}}{2} = \frac{I_m^2 R_L'}{2} = \frac{V_m^2}{2 R_L'}$$

Efficiency:

$$\boxed{\%\eta = \frac{P_{ac}}{P_{dc}} * 100}$$



$$P_o(ac) = \frac{Vm * \text{Im}}{2}$$

$$P(dc) = \frac{2}{\pi} V_{CC} I_m$$

$$\boxed{\%\eta = \frac{\pi}{4} * \frac{Vm}{V_{CC}} * 100}$$

- Vm = VCC

$$\%\eta = \frac{\pi}{4} * \frac{V_{CC}}{V_{CC}} * 100$$

$$\%\eta = 78.5\%$$

Power Dissipation:

$$p_d = p_{DC} - p_{AC}$$

$$p_d = \frac{2}{\pi} V_{cc} I_m - \frac{V_m * I_m}{2}$$

- In case of Class A amplifiers, Power Dissipation is maximum when no input signal is applied. But in Case of Class B, when input is 0 then Vm=0. Hence Power dissipation is very less compared to Class A.

ϖ Advantages:

1) Efficiency is much higher than Class A operation.

2) When there is no input signal, the power dissipation is zero.

3) Harmonics get cancelled. This reduces the harmonic distortion.

4) Ripples present in supply voltage also get eliminated.

5) Due to the Transformer impedence Matching is possible.

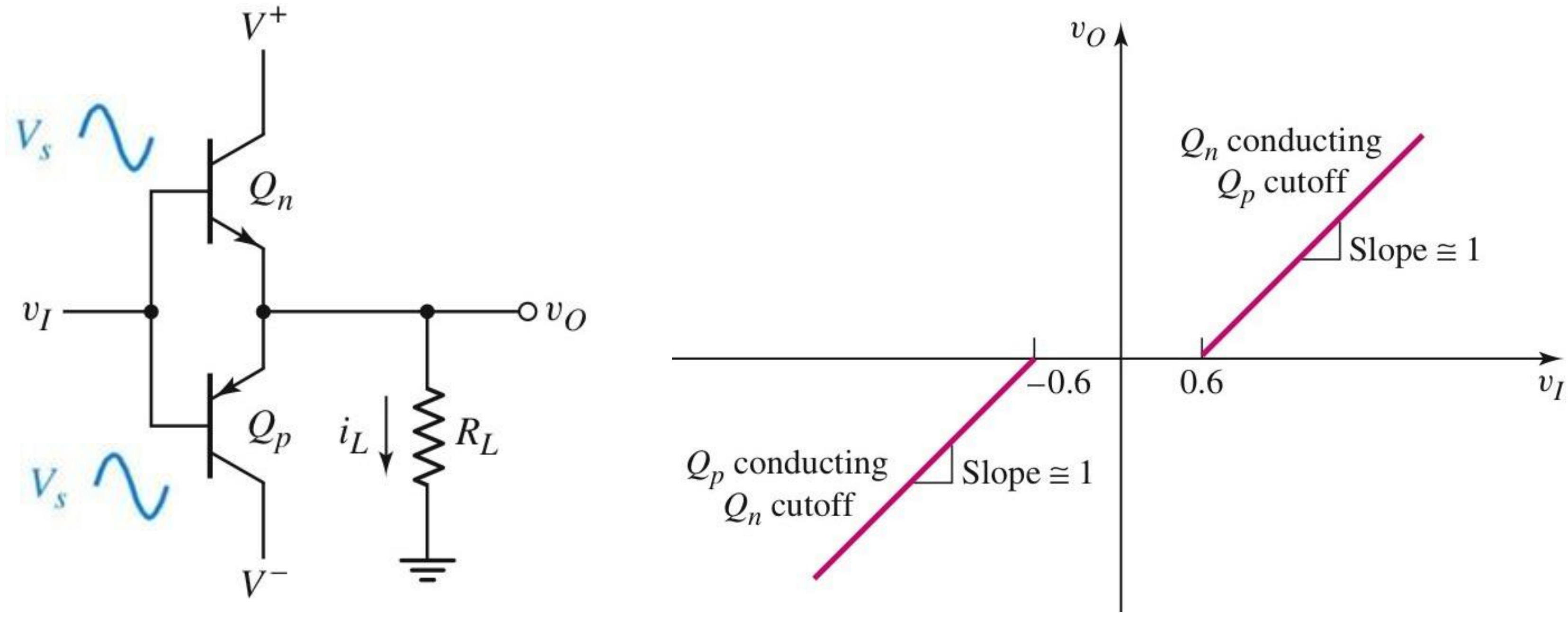
Dis-Advantages:

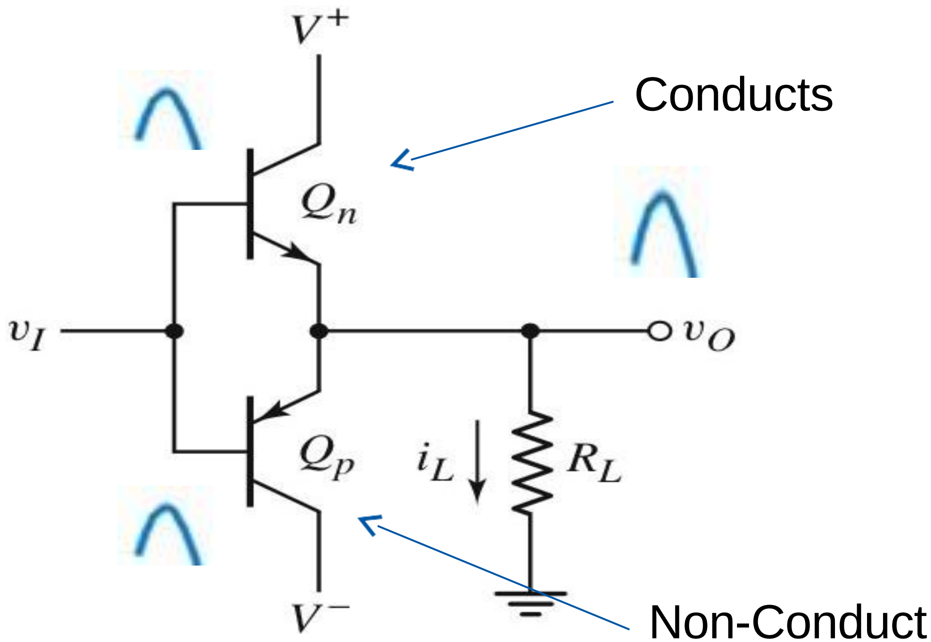
1) Frequency response of the circuit is poor

2) Center Tap transformers are necessary.

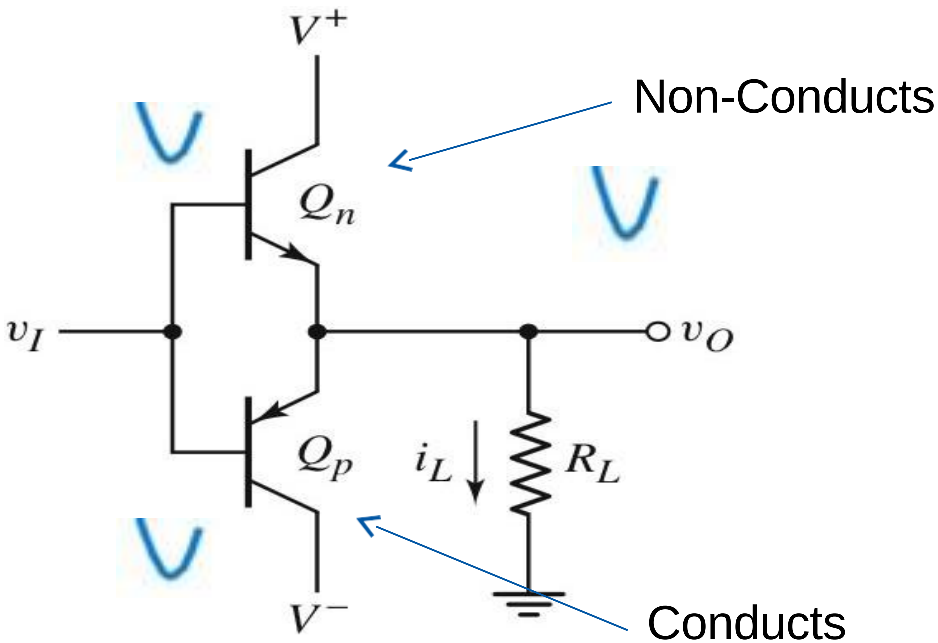
3) Transformers make the circuit bulky and hence costlier

Complimentary Symmetry Class B Circuit

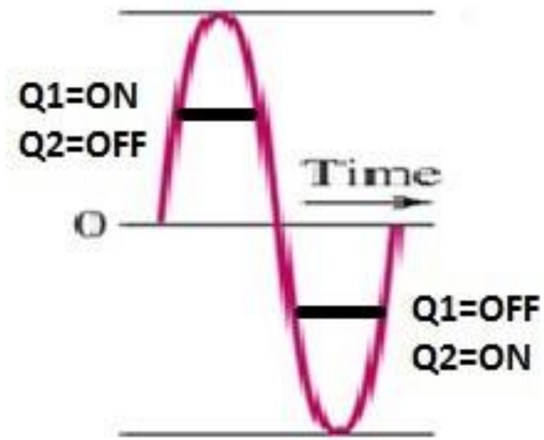




V^+
Conducts
Q_n
v_I
v_O
Q_p
i_L
R_L
V^-
Non-Conduct



V^+
Non-Conducts
Q_n
v_I
v_O
Q_p
i_L
R_L
V^-
Conducts



Q1=ON
Q2=OFF
Time
0
Q1=OFF
Q2=ON

ϖ **Advantages:**

1) As the circuit is transformer less, its weight, size and cost are less.

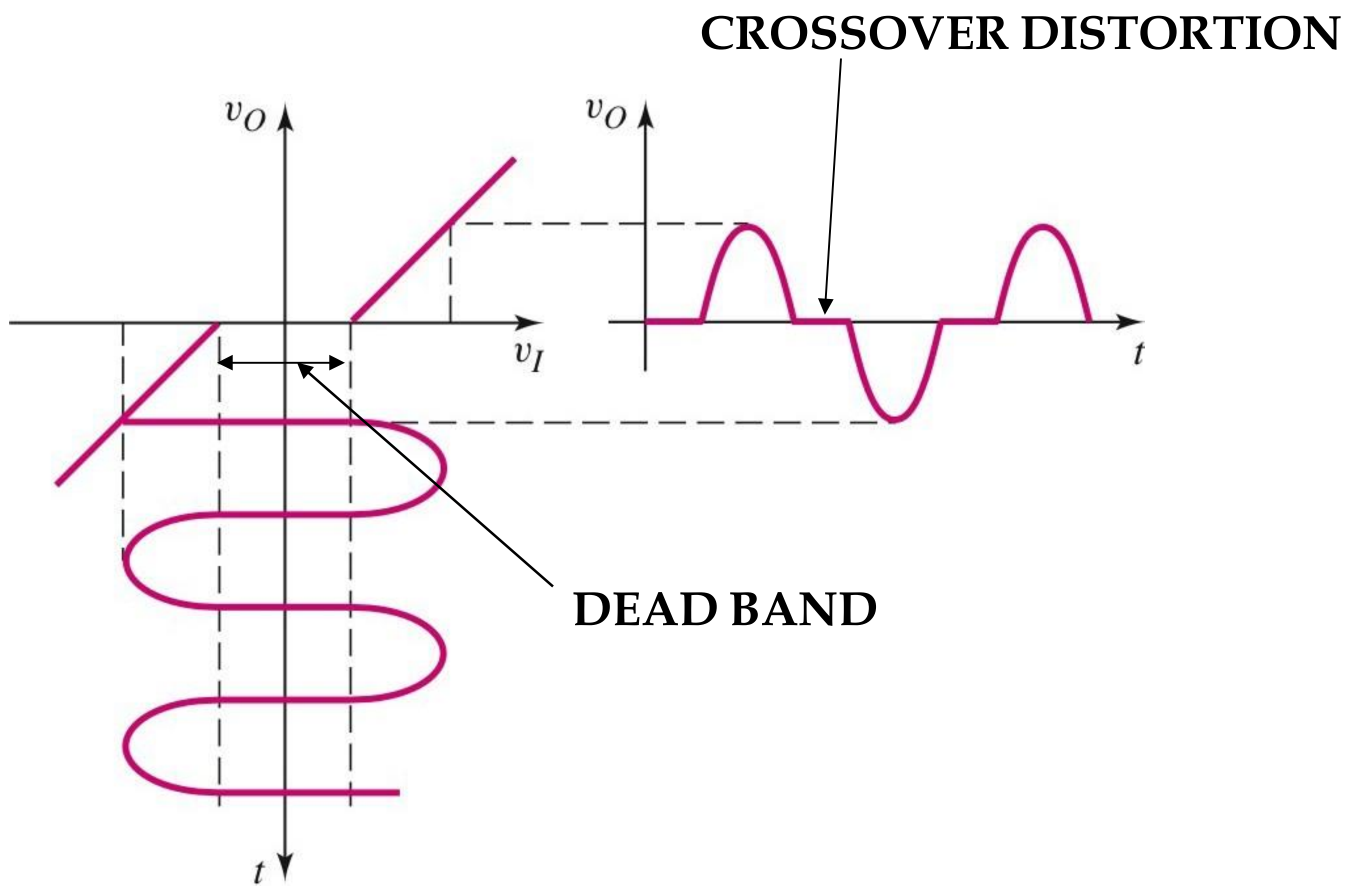
2) Due to the common collector configuration, impedance matching is possible.

3) Frequency response of the circuit is improves due to transformer less Class B amplifier circuit

Dis-Advantages:

1) Circuit needs two separate voltage supplies

2) Output suffers cross-over distortion


CROSSOVER DISTORTION
v_O
v_O
v_I
t
t
DEAD BAND

Cross-over distortion free circuits

- Push-Pull Distortion Less circuit:

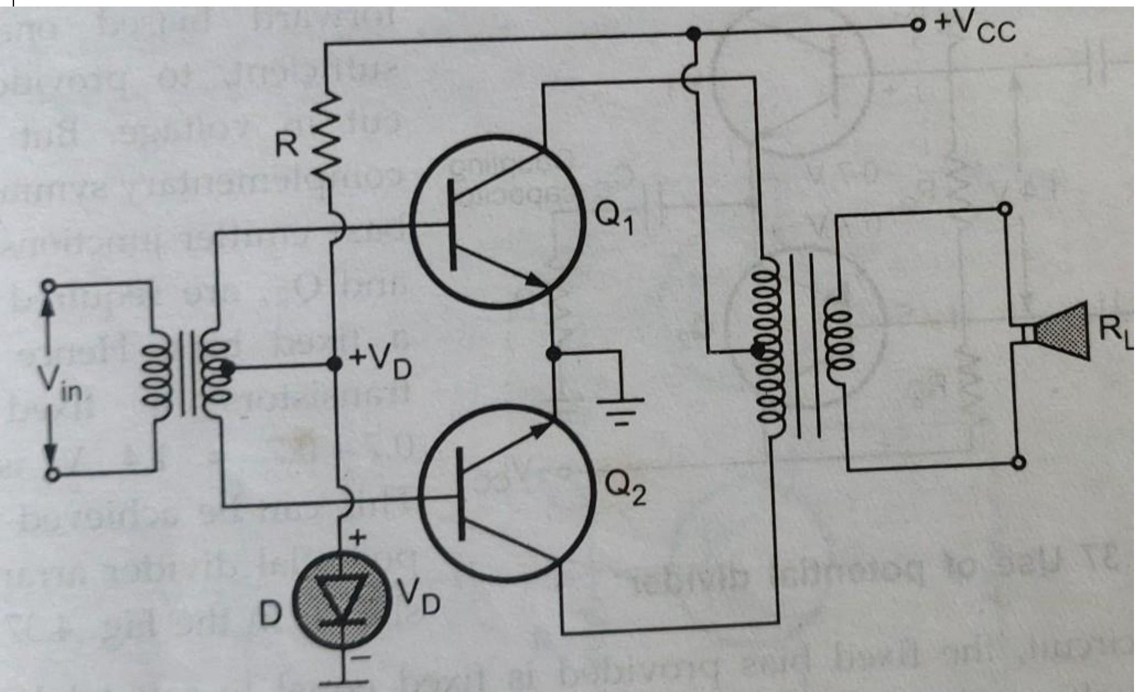
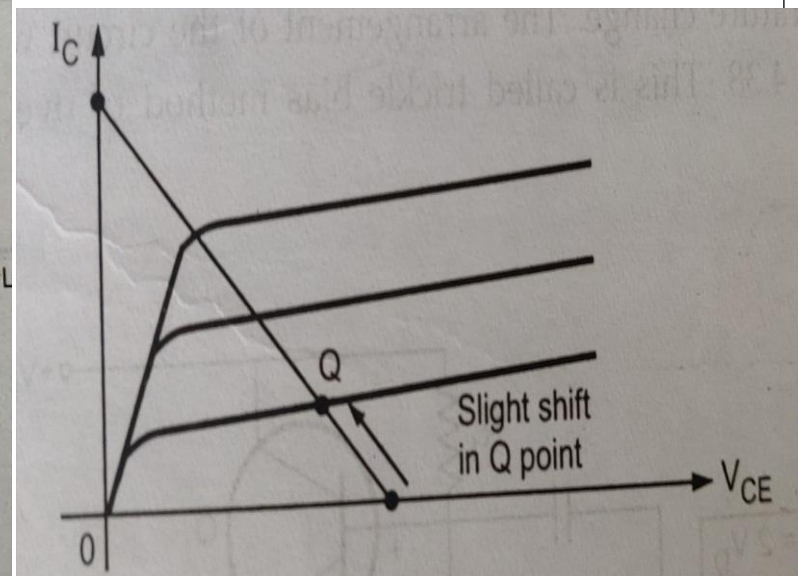
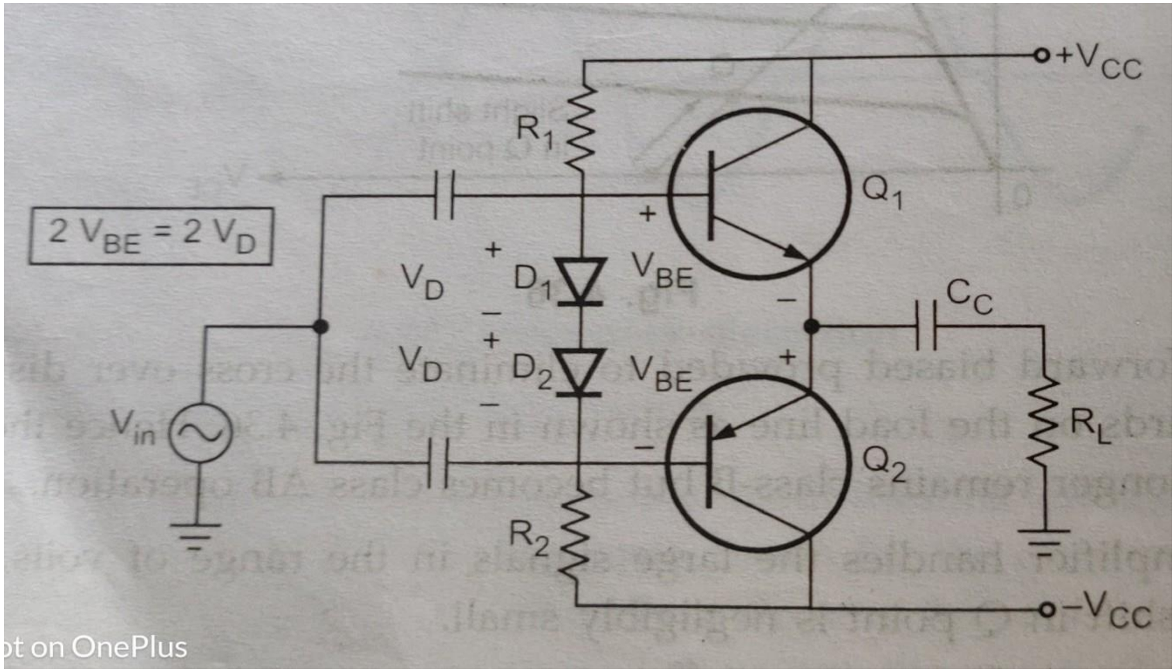


Fig. 4.35 Use of diode

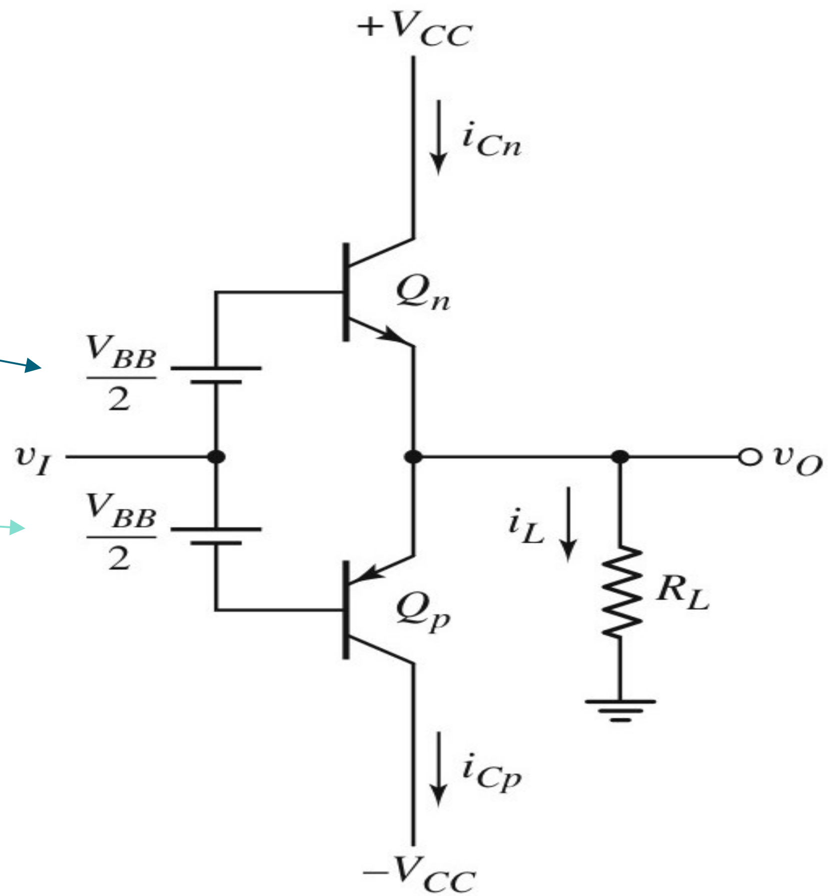


• Complementary Push-Pull Distortion Less circuit:

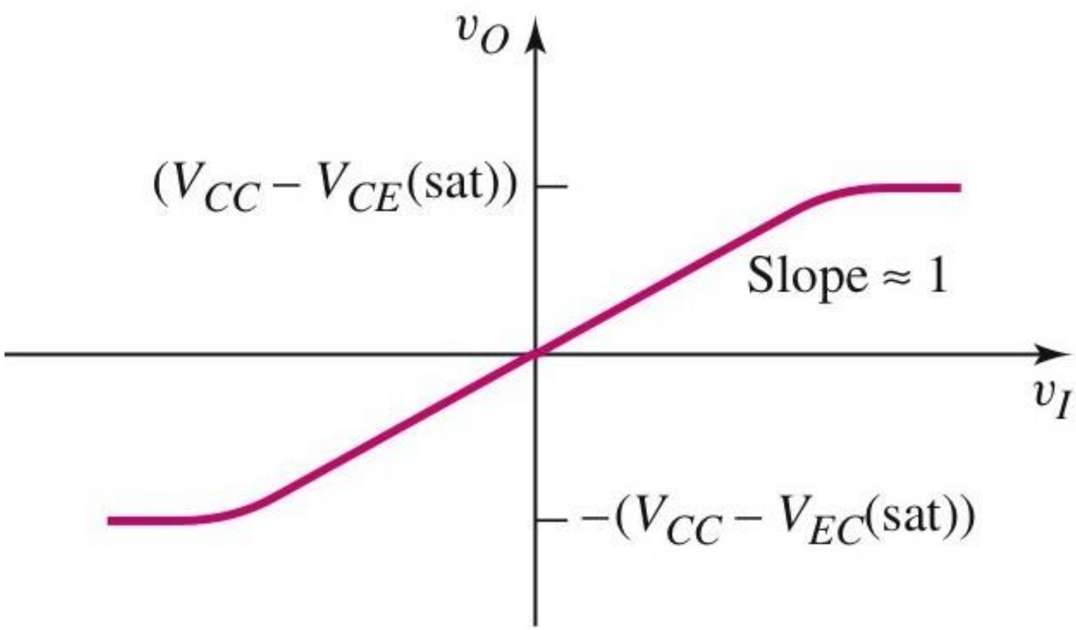


Class AB Power Amplifier

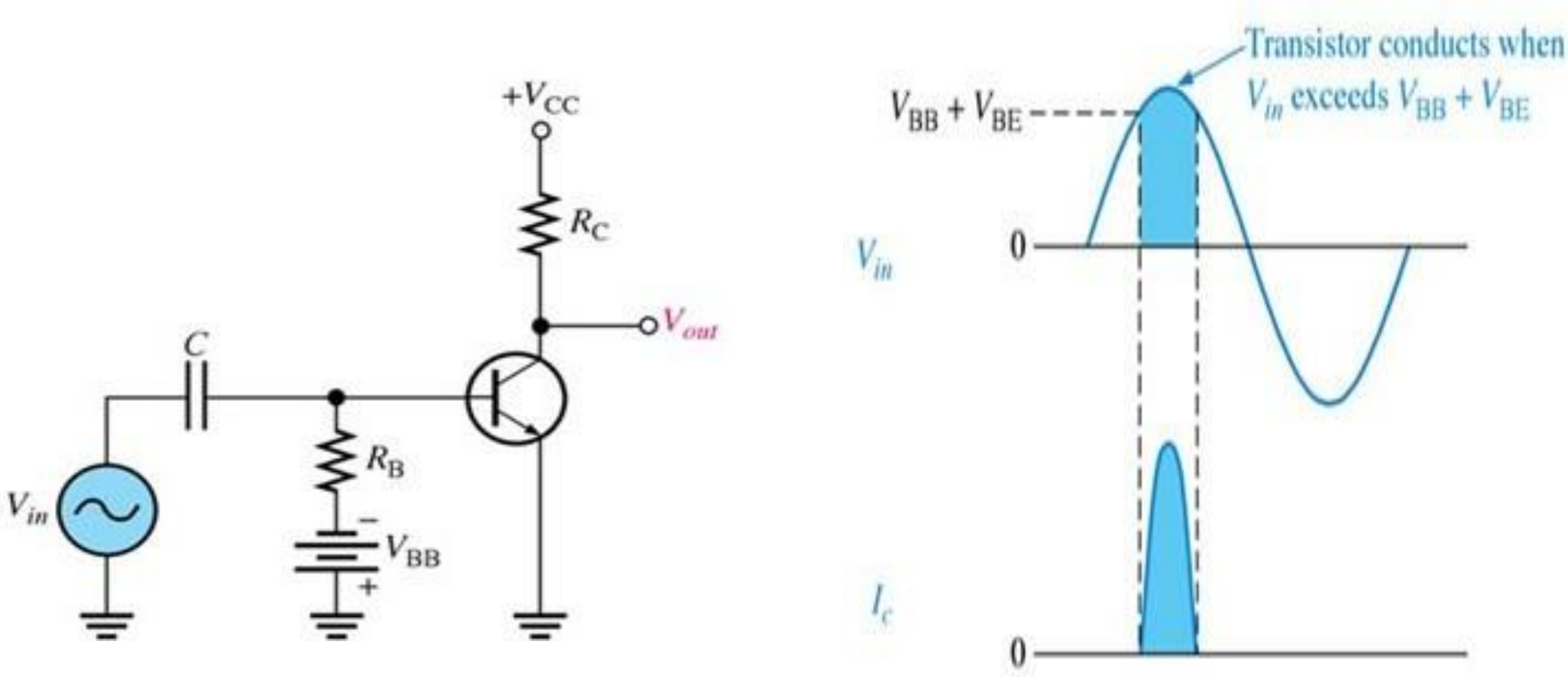
Small quiescent bias on each output transistor to eliminate *crossover distortion*



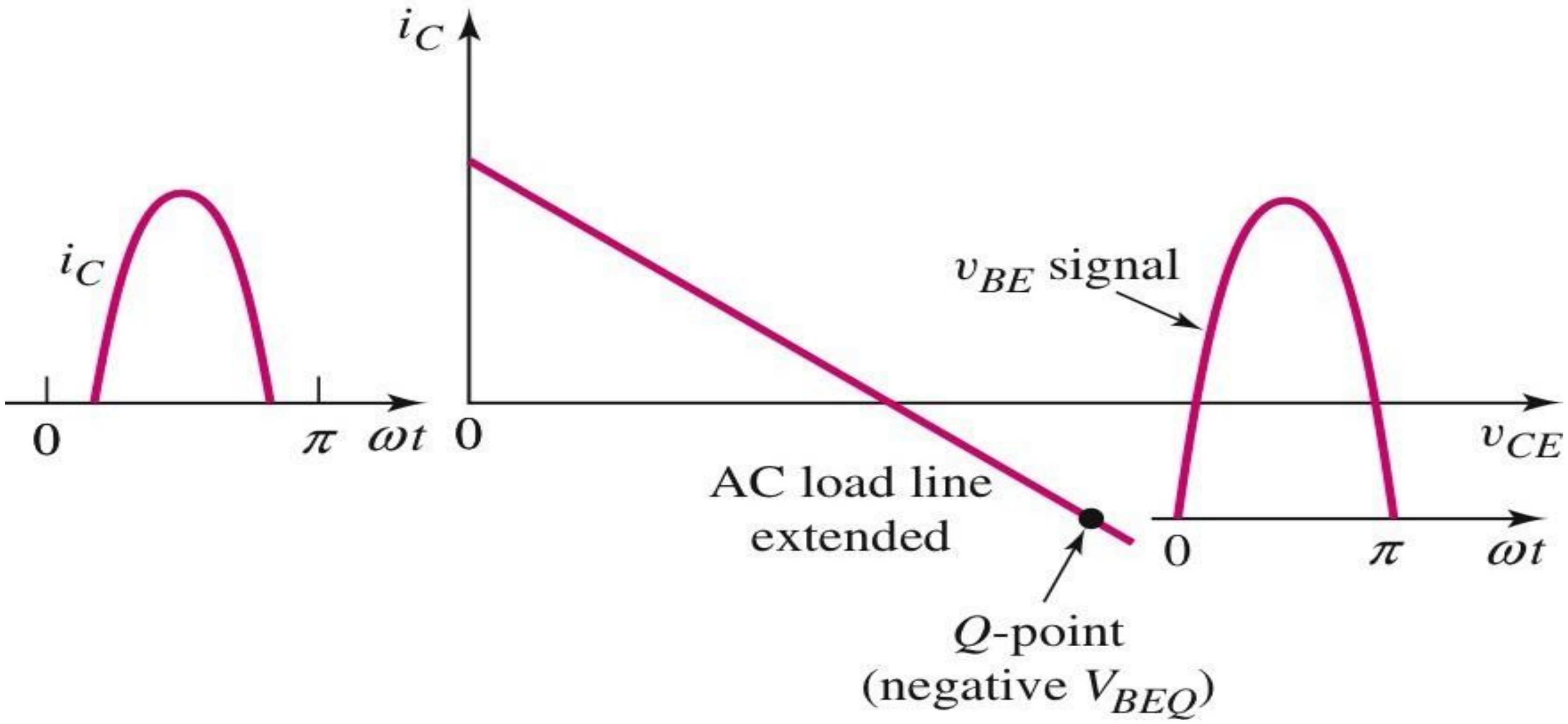
Class AB Voltage Transfer Curve



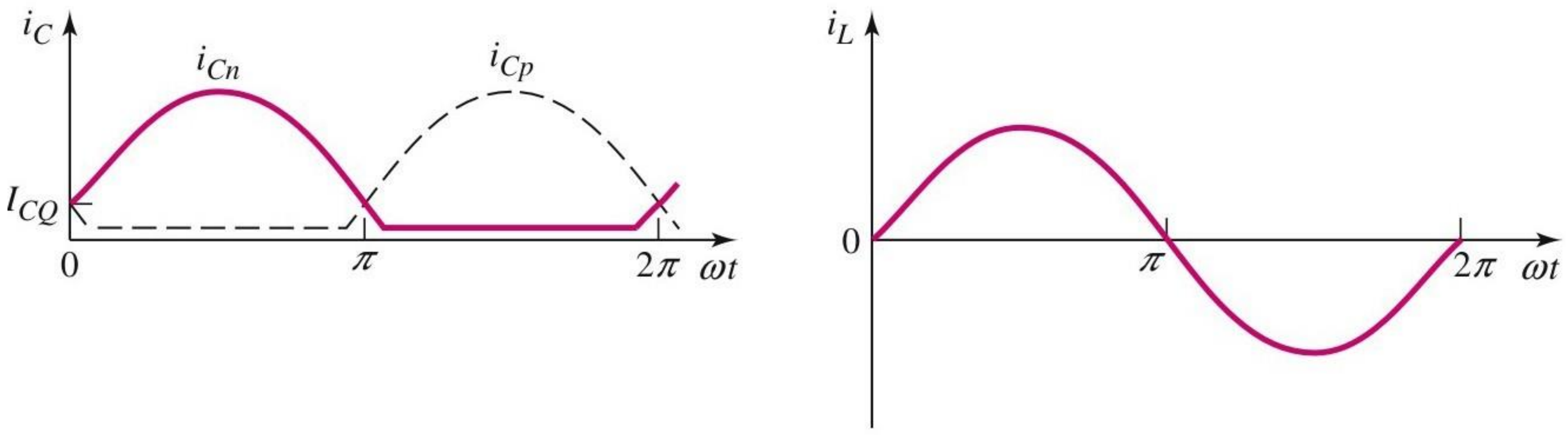
Class C Power Amplifier



Load line Operation:



Collector Currents & Output Current



$$i_{Cn} = i_L + i_{Cp}$$

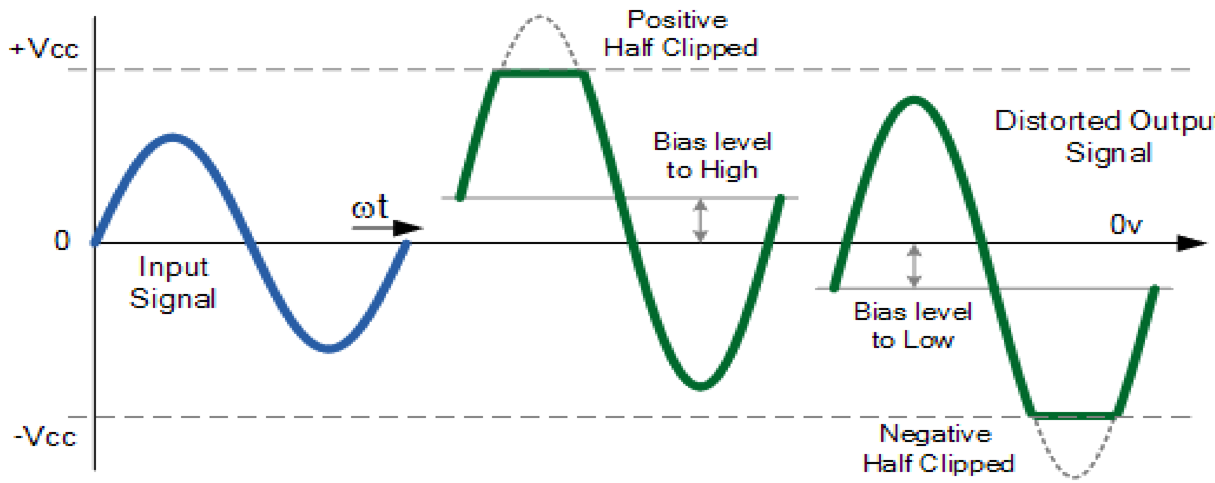
Comparison of Amplifiers

Class	A	B	C	AB
Operating Cycle	360°	180°	Less that 180°	180° to 360°
Position of Q-Point	Center of Load Line	On X-axis	Below X-axis	In between X-axis to center of Load line
Efficiency	Poor, 25% to 50%	Better, 78.5%	High	In between 78.5% to 50%
Distortion	No	Present	Highest	Present

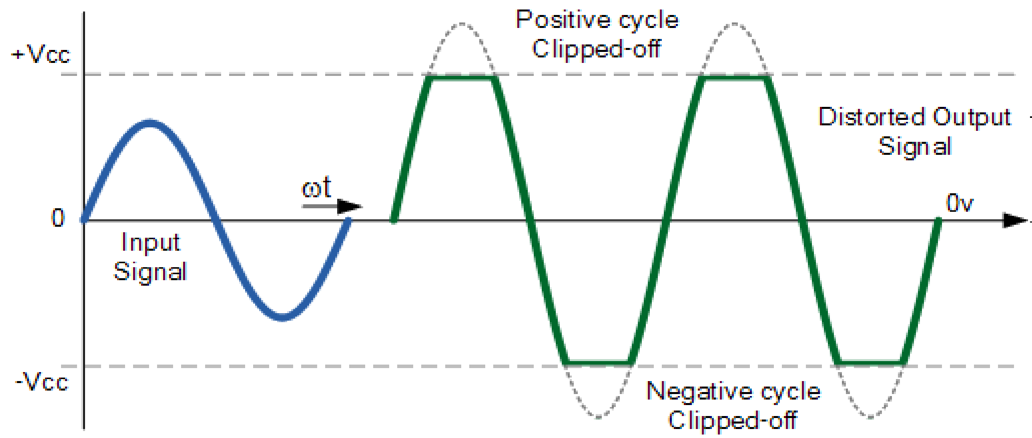
Distortion in Amplifiers

Amplifier Distortion :

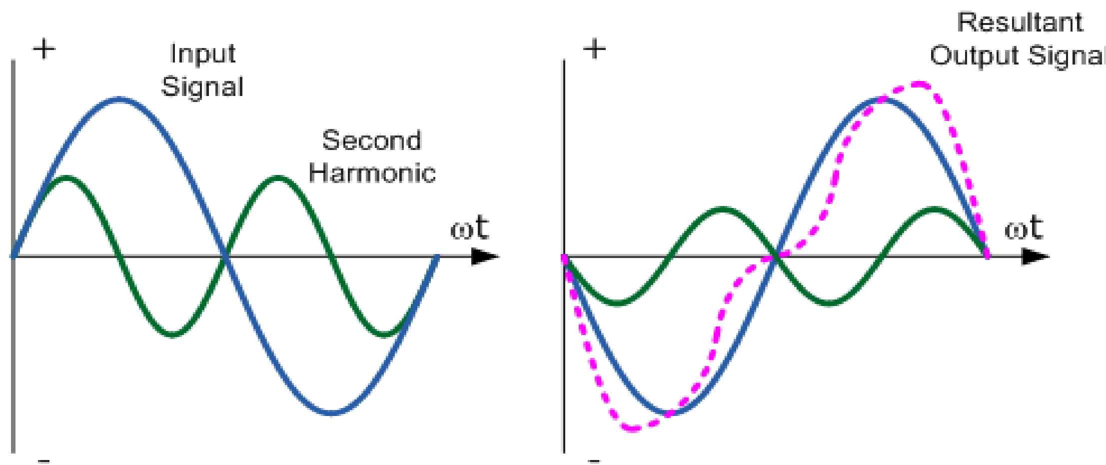
Amplifier Distortion can take on many forms such as Amplitude, Frequency and Phase Distortion due to Clipping



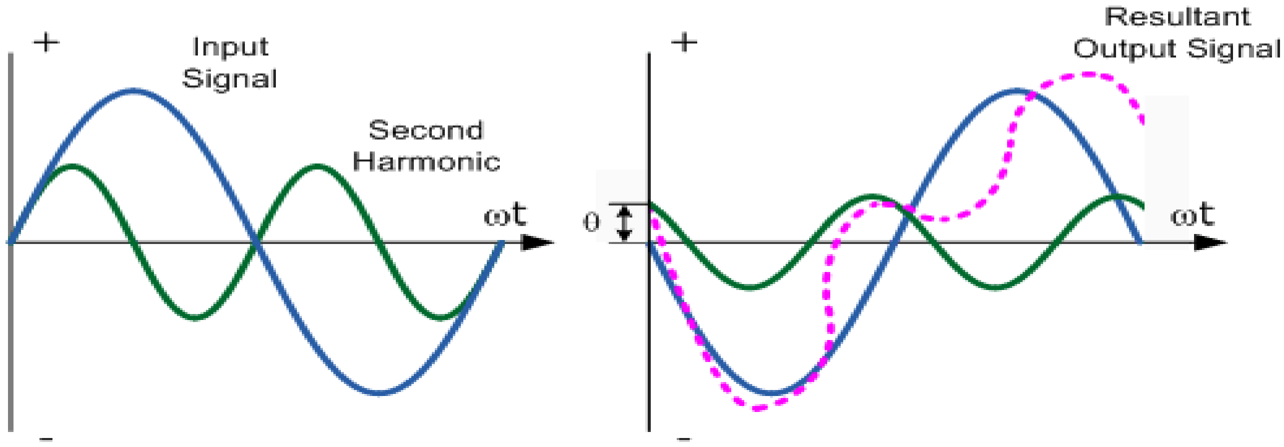
Amplitude Distortion :



Frequency Distortion :



Phase Distortion :



GATE Questions with Solutions

Example:

5.02. Calculate the effective resistance seen looking into the primary of a 15 : 1 transformer connected to an 8Ω load

(A) 2kΩ (B) 1.8kΩ

(C) 3kΩ (D) 4kΩ

Sol. $R_L{}^1 = \left(\frac{N_1}{N_2}\right)^2 R_L = (15)^2\, 8$

$R_L{}^1 = 1.8k\Omega$ Choice (B)

Examples:

5.03. Calculate the total harmonic distortion for the amplitude components as A1 = 1.5V, A2 = 0.25, A3 = 0.05

Sol. $D2 = \frac{|A_2|}{|A_1|} = \frac{0.25}{1.5} = 1/6$

$D3 = \frac{|A_3|}{|A_1|} = \frac{0.05}{1.5} = \frac{1}{30}$

$THD = \sqrt{\left(\frac{1}{6}\right)^2 + \left(\frac{1}{30}\right)^2} = 0.17\%$

5.04. Calculate the efficiency of a class 'B' amplifier for a supply voltage of 24 volts with peak voltage of 8 volts.

(A) 26.18% (B) 35.62%

(C) 40.25% (D) 52.36%

Sol. $\eta = 78.54 \frac{V_L(p)}{V_{cc}} \% = 78.54 \times \frac{8}{24}$

= 26.18 volts Choice (A)

3. The ac power output of a class A amplifier is 4w. If the collector efficiency is 45%, what is the power rating of transistor?

(A) $\geq 8.9w$ (B) $<8.9w$

(C) $\geq 4w$ (D) $<4w$

Sol. $P_{o(ac)} = 4w$

$\eta = 45\% = 0.45$

$$\Rightarrow \eta = \frac{P_{o(ac)}}{P_{in(dc)}}$$

$$P_{in(dc)} = \frac{P_{o(ac)}}{\eta} = \frac{4}{0.45} = 8.9W$$

$4\ P_{Dmax} \geq P_{in(dc)}$ for class A.

$P_{Dmax} \geq 8.9W$ Choice (A)

4. A class B push-pull amplifier uses 15V dc supply, with sinusoidal input, a max peak to peak of 24V is desired across a load of 100Ω. What is the power dissipated by each transistor?

(A) 426mW (B) 213mW

(C) 1.146W (D) 0.72W

Sol. Peak to peak value of o/p $V_{PP} = 24v$

Peak value of o/p $V_P = \frac{24}{2} = 12\,V$

$R_L = 100\Omega$

Peak value of o/p current $I_P = V_P/R_L$

$\Rightarrow I_P = \frac{12}{100} = 0.12A$

Dc current drawn from Vcc supply is

$I_{dc} = \frac{2I_P}{\pi}$ (from FWR)

$= \frac{2 \times 0.12}{\pi} = \frac{0.14}{\pi} A$

DC power drawn from battery is

$P_{dc} = V_{cc}\, I_{dc}$

$= 15 \times \frac{0.14}{\pi} = 1.146w$

AC power delivered to load is

$P_{o(ac)} = \frac{1}{2}\frac{V_P^2}{R_L} = \frac{1}{2}\frac{(12)}{100}$

$= 0.72w$

4 Power dissipated in both transistors is

$1.146 - 0.72w = 0.426w$

and power dissipated by each transistor

is $\frac{0.426}{2} w = 0.213w = 213mw$

Choice (B)

The cascade amplifier is a multistage configuration of

A)CC-CB

B)CE-CB

C)CB-CC

D)CE-CC

SOLUTION : B

cascade amplifier is a multistage configuration of CE-CB

6. A cascade connection of two voltage amplifiers A1 and A2 is shown in the figure. The open-loop gain A_{vo}, input resistance R_{in}, and output resistance R_o for A1 and A2 are as follows:

A1: $A_{vo} = 10$, $R_{in} = 10\ k\Omega$, $R_o = 1k\Omega$

A2: $A_{vo} = 5$, $R_{in} = 5\ k\Omega$, $R_o = 200\ \Omega$

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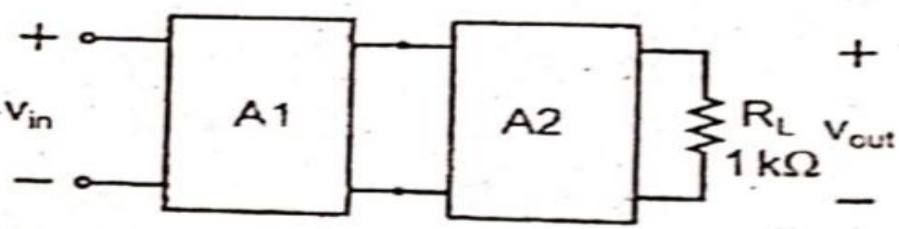
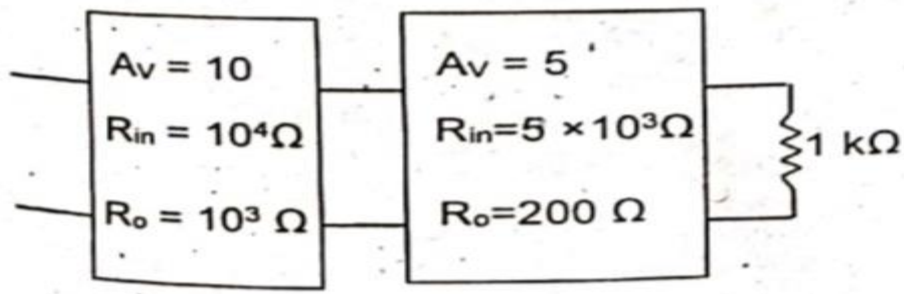
The approximate overall voltage gain v_{out}/v_{in} is ________.



(GATE 2014, Set-2)

6. $A_{V_{L_1}} = A_V \dfrac{Z_{i_2}}{Z_o + Z_{i_2}}$

$$= 10\left[\frac{5\times10^3}{10^3 + 5\times10^3}\right] = \frac{50}{6}$$



$$A_{V_{L_2}} = 5\left[\frac{1\times10^3}{200+10^3}\right] = \frac{5}{1.2}$$

$$A_{V_T} = A_{V_{L_1}} . A_{V_{L_2}} = \frac{50}{6}\times\frac{5}{1.2} = 34.7$$

Ans: 34 to 35.3

Thank you