

Unit-IV

Output stages and Power Amplifiers:

Classification of Output stages A/B/AB, single-ended and Push-Pull Configuration, Power dissipation and Output Power conversion efficiencies, complimentary-symmetry Power Amplifier.

Power BJTs-

Junction Temperature, Thermal resistance, Transistor case and Heat sink.

MOS Power Transistors: Structure, Characteristics, Temperature Effects, Comparison with BJTs.

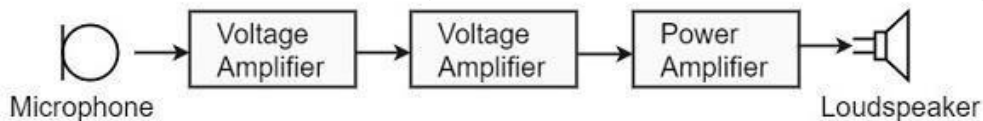
UNIT-IV

Power Amplifiers

In practice, any amplifier consists of few stages of amplification. If we consider audio amplification, it has several stages of amplification, depending upon our requirement.

Power Amplifier

After the audio signal is converted into electrical signal, it has several voltage amplifications done, after which the power amplification of the amplified signal is done just before the loud speaker stage. This is clearly shown in the below figure.



While the voltage amplifier raises the voltage level of the signal, the power amplifier raises the power level of the signal. Besides raising the power level, it can also be said that a power amplifier is a device which converts DC power to AC power and whose action is controlled by the input signal. The DC power is distributed according to the relation, DC power input = AC power output + losses

Power Transistor

For such Power amplification, a normal transistor would not do. A transistor that is manufactured to suit the purpose of power amplification is called as a **Power transistor**.

A Power transistor differs from the other transistors, in the following factors.

- It is larger in size, in order to handle large powers.
- The collector region of the transistor is made large and a heat sink is placed at the collector-base junction in order to minimize heat generated.
- The emitter and base regions of a power transistor are heavily doped.
- Due to the low input resistance, it requires low input power.

Hence there is a lot of difference in voltage amplification and power amplification. So, let us now try to get into the details to understand the differences between a voltage amplifier and a power amplifier.

Difference between Voltage and Power Amplifiers: Let us try to differentiate between voltage and power amplifier.

Voltage Amplifier

The function of a voltage amplifier is to raise the voltage level of the signal. A voltage amplifier is designed to achieve maximum voltage amplification.

The voltage gain of an amplifier is given by

$$A_v = \beta(R_c/R_{in})$$

The characteristics of a voltage amplifier are as follows –

- The base of the transistor should be thin and hence the value of β should be greater than 100.

- The resistance of the input resistor R_{in} should be low when compared to collector load R_C .
- The collector load R_C should be relatively high. To permit high collector load, the voltage amplifiers are always operated at low collector current.
- The voltage amplifiers are used for small signal voltages.

Power Amplifier

The function of a power amplifier is to raise the power level of input signal. It is required to deliver a large amount of power and has to handle large current.

The characteristics of a power amplifier are as follows –

- The base of transistor is made thicker to handle large currents. The value of β being ($\beta > 100$) high.
- The size of the transistor is made larger, in order to dissipate more heat, which is produced during transistor operation.
- Transformer coupling is used for impedance matching.
- Collector resistance is made low.

The comparison between voltage and power amplifiers is given below in a tabular form.

S.No	Particular	Voltage Amplifier	Power Amplifier
1	β	High (>100)	Low (5 to 20)
2	R_C	High (4-10 K Ω)	Low (5 to 20 Ω)
3	Coupling	Usually R-C coupling	Invariably transformer coupling
4	Input voltage	Low (a few m V)	High (2-4 V)
5	Collector current	Low (≈ 1 mA)	High (> 100 mA)
6	Power output	Low	High
7	Output impedance	High (≈ 12 K Ω)	Low (200 Ω)

The Power amplifiers amplify the power level of the signal. This amplification is done in the last stage in audio applications. The applications related to radio frequencies employ radio power amplifiers. But the **operating point** of a transistor plays a very important role in determining the efficiency of the amplifier. The **main classification** is done based on this mode of operation.

The classification is done based on their frequencies and also based on their mode of operation.

Classification Based on Frequencies

Power amplifiers are divided into two categories, based on the frequencies they handle. They are as follows.

- **Audio Power Amplifiers** – The audio power amplifiers raise the power level of signals that have audio frequency range (20 Hz to 20 KHz). They are also known as **Small signal power amplifiers**.
- **Radio Power Amplifiers** – Radio Power Amplifiers or tuned power amplifiers raise the power level of signals that have radio frequency range (3 KHz to 300 GHz). They are also known as **large signal power amplifiers**.

Classification Based on Mode of Operation

On the basis of the mode of operation, i.e., the portion of the input cycle during which collector current flows, the power amplifiers may be classified as follows.

- **Class A Power amplifier** – When the collector current flows at all times during the full cycle of signal, the power amplifier is known as **class A power amplifier**.
- **Class B Power amplifier** – When the collector current flows only during the positive half cycle of the input signal, the power amplifier is known as **class B power amplifier**.
- **Class C Power amplifier** – When the collector current flows for less than half cycle of the input signal, the power amplifier is known as **class C power amplifier**.

There forms another amplifier called Class AB amplifier, if we combine the class A and class B amplifiers so as to utilize the advantages of both. Before going into the details of these amplifiers, let us have a look at the important terms that have to be considered to determine the efficiency of an amplifier.

Terms Considering Performance

The primary objective of a power amplifier is to obtain maximum output power. In order to achieve this, the important factors to be considered are collector efficiency, power dissipation capability and distortion. Let us go through them in detail.

Collector Efficiency

This explains how well an amplifier converts DC power to AC power. When the DC supply is given by the battery but no AC signal input is given, the collector output at such a condition is observed as **collector efficiency**.

The collector efficiency is defined as

$$\eta = \text{average a.c power output} / \text{average d.c power input to transistor}$$

The main aim of a power amplifier is to obtain maximum collector efficiency. Hence the higher the value of collector efficiency, the efficient the amplifier will be.

Power Dissipation Capacity

Every transistor gets heated up during its operation. As a power transistor handles large currents, it gets more heated up. This heat increases the temperature of the transistor, which alters the operating point of the transistor. So, in order to maintain the operating point stability, the temperature of the transistor has to be kept in permissible limits. For this, the heat produced has to be dissipated. Such a capacity is called as Power dissipation capability.

Power dissipation capability can be defined as the ability of a power transistor to dissipate the heat developed in it. Metal cases called heat sinks are used in order to dissipate the heat produced in power transistors.

Distortion

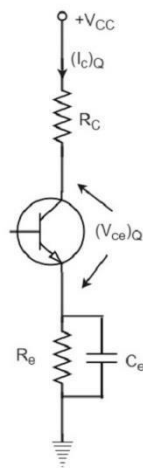
A transistor is a non-linear device. When compared with the input, there occur few variations in the output. In voltage amplifiers, this problem is not pre-dominant as small

currents are used. But in power amplifiers, as large currents are in use, the problem of distortion certainly arises.

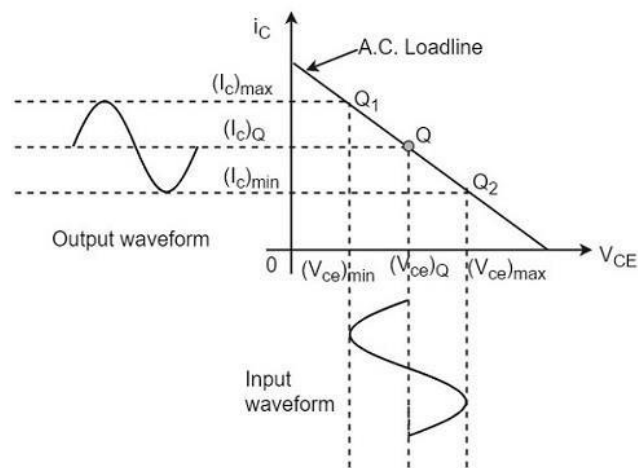
Distortion is defined as the change of output wave shape from the input wave shape of the amplifier. An amplifier that has lesser distortion, produces a better output and hence considered efficient.

We have already come across the details of transistor biasing, which is very important for the operation of a transistor as an amplifier. Hence to achieve faithful amplification, the biasing of the transistor has to be done such that the amplifier operates over the linear region.

A Class A power amplifier is one in which the output current flows for the entire cycle of the AC input supply. Hence the complete signal present at the input is amplified at the output. The following figure shows the circuit diagram for Class A Power amplifier.



From the above figure, it can be observed that the transformer is present at the collector as a load. The use of transformer permits the impedance matching, resulting in the transference of maximum power to the load e.g. loud speaker.



The operating point of this amplifier is present in the linear region. It is so selected that the current flows for the entire ac input cycle. The below figure explains the selection of operating point.

The output characteristics with operating point Q is shown in the figure above. Here $(I_c)_Q$ and $(V_{ce})_Q$ represent no signal collector current and voltage between collector and emitter respectively. When signal is applied, the Q-point shifts to Q_1 and Q_2 . The output current increases to $(I_c)_{max}$ and decreases to $(I_c)_{min}$. Similarly, the collector-emitter voltage increases to $(V_{ce})_{max}$ and decreases to $(V_{ce})_{min}$.

D.C. Power drawn from collector battery V_{cc} is given by

$$P_{in} = \text{voltage} \times \text{current} = V_{CC}(I_c)_Q$$

This power is used in the following two parts –

- Power dissipated in the collector load as heat is given by

$$P_{RC} = (\text{current})^2 \times \text{resistance} = (I_C)^2 R_C$$

- Power given to transistor is given by

$$P_{tr} = P_{in} - P_{RC} = V_{CC} - (I_C) R_C$$

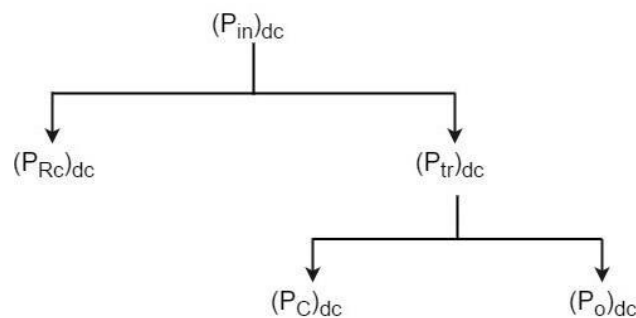
When signal is applied, the power given to transistor is used in the following two parts –

- A.C. Power developed across load resistors R_C which constitutes the a.c. power output.

$$(P_o)_{ac} = I^2 R_C = V^2 / R_C = (V_m / \sqrt{2})^2 / R_C = V_m^2 / 2R_C$$

- Where I is the R.M.S. value of a.c. output current through load, V is the R.M.S. value of a.c. voltage, and V_m is the maximum value of V .
- The D.C. power dissipated by the transistor (collector region) in the form of heat, i.e., $(P_C)_{dc}$

We have represented the whole power flow in the following diagram.



This class A power amplifier can amplify small signals with least distortion and the output will be an exact replica of the input with increased strength.

Let us now try to draw some expressions to represent efficiencies.

Overall Efficiency

The overall efficiency of the amplifier circuit is given by

$$\begin{aligned} (\eta)_{overall} &= \frac{\text{a. c power delivered to the load}}{\text{total power delivered by d. c supply}} \\ &= \frac{(P_O)_{ac}}{(P_{in})_{dc}} \end{aligned}$$

Collector Efficiency

The collector efficiency of the transistor is defined as

$$\begin{aligned} (\eta)_{collector} &= \frac{\text{average a. c power output}}{\text{average d. c power input to transistor}} \\ &= \frac{(P_O)_{ac}}{(P_{tr})_{dc}} \end{aligned}$$

Expression for overall efficiency

$$\begin{aligned} (P_O)_{ac} &= V_{rms} \times I_{rms} \\ &= \frac{1}{\sqrt{2}} \left[\frac{(V_{ce})_{max} - (V_{ce})_{min}}{2} \right] \times \frac{1}{\sqrt{2}} \left[\frac{(I_C)_{max} - (I_C)_{min}}{2} \right] \\ &= \frac{[(V_{ce})_{max} - (V_{ce})_{min}] \times [(I_C)_{max} - (I_C)_{min}]}{8} \end{aligned}$$

Advantages of Class A Amplifiers

The advantages of Class A power amplifier are as follows –

- The current flows for complete input cycle
- It can amplify small signals
- The output is same as input
- No distortion is present

Disadvantages of Class A Amplifiers

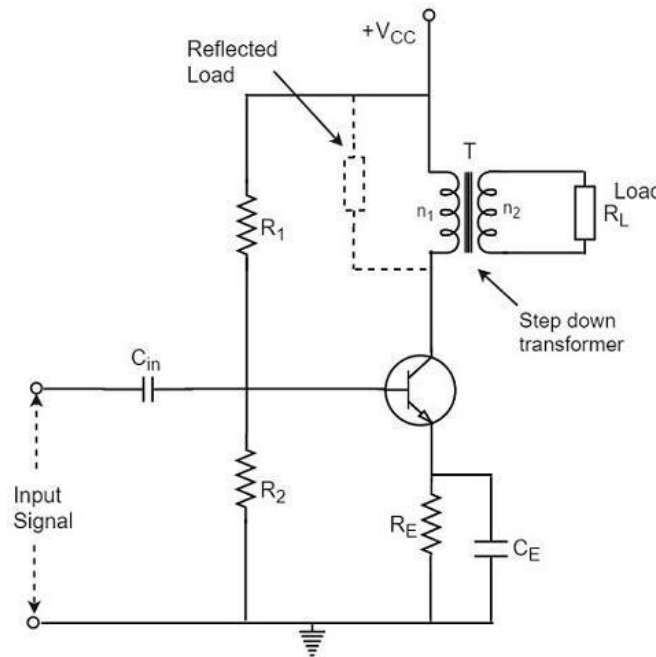
The advantages of Class A power amplifier are as follows –

- Low power output
- Low collector efficiency

The class A power amplifier as discussed in the previous chapter, is the circuit in which the output current flows for the entire cycle of the AC input supply. We also have learnt about the disadvantages it has such as low output power and efficiency. In order to

minimize those effects, the transformer coupled class A power amplifier has been introduced.

The **construction of class A power amplifier** can be understood with the help of below figure. This is similar to the normal amplifier circuit but connected with a transformer in the collector load.

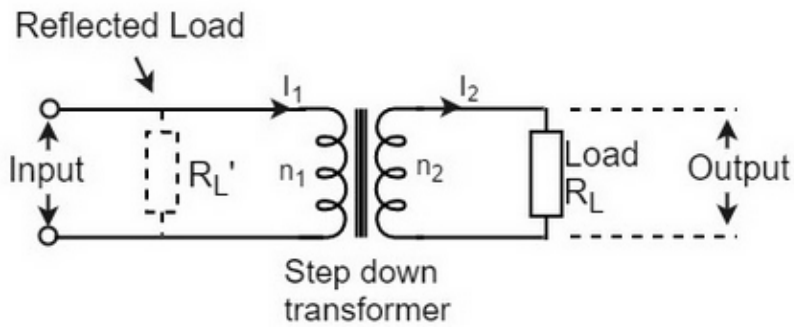


Here R_1 and R_2 provide potential divider arrangement. The resistor R_e provides stabilization, C_e is the bypass capacitor and R_e to prevent a.c. voltage. The transformer used here is a step-down transformer. The high impedance primary of the transformer is connected to the high impedance collector circuit. The low impedance secondary is connected to the load (generally loud speaker).

Transformer Action:

The transformer used in the collector circuit is for impedance matching. R_L is the load connected in the secondary of a transformer. R_L' is the reflected load in the primary of the transformer.

The number of turns in the primary are n_1 and the secondary are n_2 . Let V_1 and V_2 be the primary and secondary voltages and I_1 and I_2 be the primary and secondary currents respectively. The below figure shows the transformer clearly.



We know that

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

Or

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

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

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

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

Circuit Operation

If the peak value of the collector current due to signal is equal to zero signal collector current, then the maximum a.c. power output is obtained. So, in order to achieve complete amplification, the operating point should lie at the center of the load line.

The operating point obviously varies when the signal is applied. The collector voltage varies in opposite phase to the collector current. The variation of collector voltage appears across the primary of the transformer.

Circuit Analysis

The power loss in the primary is assumed to be negligible, as its resistance is very small.

The input power under dc condition will be

$$(P_{in})_{dc} = (P_{tr})_{dc} = V_{CC} \times (I_C)Q$$

Under maximum capacity of class A amplifier, voltage swings from $(V_{ce})_{max}$ to zero and current from $(I_C)_{max}$ to zero.

Hence

$$V_{rms} = \frac{1}{\sqrt{2}} \left[\frac{(V_{ce})_{max} - (V_{ce})_{min}}{2} \right] = \frac{1}{\sqrt{2}} \left[\frac{(V_{ce})_{max}}{2} \right] = \frac{2V_{CC}}{2\sqrt{2}} \\ = \frac{V_{CC}}{\sqrt{2}}$$

$$I_{rms} = \frac{1}{\sqrt{2}} \left[\frac{(I_C)_{max} - (I_C)_{min}}{2} \right] = \frac{1}{\sqrt{2}} \left[\frac{(I_C)_{max}}{2} \right] = \frac{2(I_C)Q}{2\sqrt{2}} \\ = \frac{(I_C)Q}{\sqrt{2}}$$

Therefore,

$$(P_O)_{ac} = V_{rms} \times I_{rms} = \frac{V_{CC}}{\sqrt{2}} \times \frac{(I_C)Q}{\sqrt{2}} = \frac{V_{CC} \times (I_C)Q}{2}$$

Therefore,

$$\text{Collector Efficiency} = \frac{(P_O)_{ac}}{(P_{tr})_{dc}}$$

Or,

$$(\eta)_{collector} = \frac{V_{CC} \times (I_C)Q}{2 \times V_{CC} \times (I_C)Q} = \frac{1}{2}$$

The efficiency of a class A power amplifier is nearly than 30% whereas it has got improved to 50% by using the transformer coupled class A power amplifier.

Advantages

The advantages of transformer coupled class A power amplifier are as follows.

- No loss of signal power in the base or collector resistors.
- Excellent impedance matching is achieved.
- Gain is high.
- DC isolation is provided.

Disadvantages

The disadvantages of transformer coupled class A power amplifier are as follows.

- Low frequency signals are less amplified comparatively.

- Hum noise is introduced by transformers.
- Transformers are bulky and costly.
- Poor frequency response.

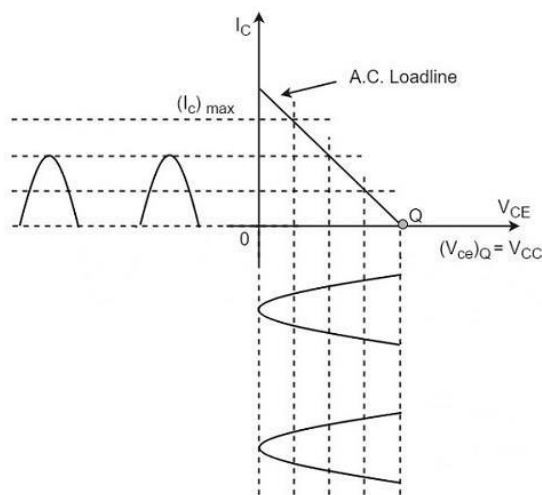
Applications

The applications of transformer coupled class A power amplifier are as follows. This circuit is where impedance matching is the main criterion. These are used as driver amplifiers and sometimes as output amplifiers. When the collector current flows only during the positive half cycle of the input signal, the power amplifier is known as **class B power amplifier**.

Class B Operation

The biasing of the transistor in class B operation is in such a way that at zero signal condition, there will be no collector current. The **operating point** is selected to be at collector cut off voltage. So, when the signal is applied, **only the positive half cycle** is amplified at the output.

The figure below shows the input and output waveforms during class B operation.



When the signal is applied, the circuit is forward biased for the positive half cycle of the input and hence the collector current flows. But during the negative half cycle of the input, the circuit is reverse biased and the collector current will be absent. Hence **only the positive half cycle** is amplified at the output.

As the negative half cycle is completely absent, the signal distortion will be high. Also, when the applied signal increases, the power dissipation will be more. But when compared to class A power amplifier, the output efficiency is increased. Well, in order to minimize the disadvantages and achieve low distortion, high efficiency and high output power, the push-pull configuration is used in this class B amplifier.

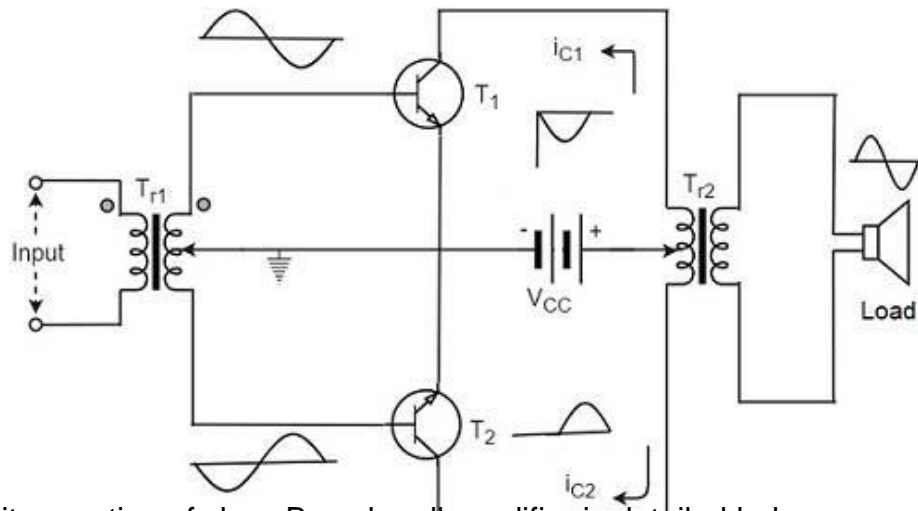
Class B Push-Pull Amplifier

Though the efficiency of class B power amplifier is higher than class A, as only one half cycle of the input is used, the distortion is high. Also, the input power is not completely utilized. In order to compensate these problems, the push-pull configuration is introduced in class B amplifier.

Construction:

The circuit of a push-pull class B power amplifier consists of two identical transistors T_1 and T_2 whose bases are connected to the secondary of the center-tapped input transformer T_{r1} . The emitters are shorted and the collectors are given the V_{CC} supply through the primary of the output transformer T_{r2} .

The circuit arrangement of class B push-pull amplifier, is same as that of class A push-pull amplifier except that the transistors are biased at cut off, instead of using the biasing resistors. The figure below gives the detailing of the construction of a push-pull class B power amplifier.

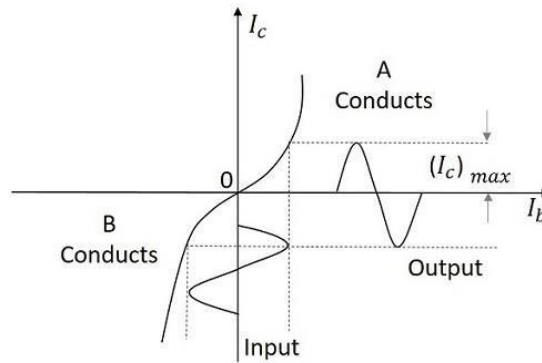


The circuit operation of class B push pull amplifier is detailed below.

Operation

The circuit of class B push-pull amplifier shown in the above figure clears that both the transformers are center-tapped. When no signal is applied at the input, the transistors T_1 and T_2 are in cut off condition and hence no collector currents flow. As no current is drawn from V_{CC} , no power is wasted.

When input signal is given, it is applied to the input transformer T_{r1} which splits the signal into two signals that are 180° out of phase with each other. These two signals are given to the two identical transistors T_1 and T_2 . For the positive half cycle, the base of the transistor T_1 becomes positive and collector current flows. At the same time, the transistor T_2 has negative half cycle, which throws the transistor T_2 into cutoff condition and hence no collector current flows. The waveform is produced as shown in the following figure.



For the next half cycle, the transistor T_1 gets into cut off condition and the transistor T_2 gets into conduction, to contribute the output. Hence for both the cycles, each transistor conducts alternately. The output transformer T_{R3} serves to join the two currents producing an almost undistorted output waveform.

Power Efficiency of Class B Push-Pull Amplifier

The current in each transistor is the average value of half sine loop. For half sine loop, I_{dc} is given by

$$I_{dc} = \frac{(I_C)_{max}}{\pi}$$

Therefore,

$$(P_{in})_{dc} = 2 \times \left[\frac{(I_C)_{max}}{\pi} \times V_{CC} \right]$$

Here factor 2 is introduced as there are two transistors in push-pull amplifier.

R.M.S. value of collector current = $(I_C)_{max} / \sqrt{2}$

R.M.S. value of output voltage = $V_{CC} / \sqrt{2}$

Under ideal conditions of maximum power

Therefore,

$$(P_O)_{ac} = \frac{(I_C)_{max}}{\sqrt{2}} \times \frac{V_{CC}}{\sqrt{2}} = \frac{(I_C)_{max} \times V_{CC}}{2}$$

Now overall maximum efficiency

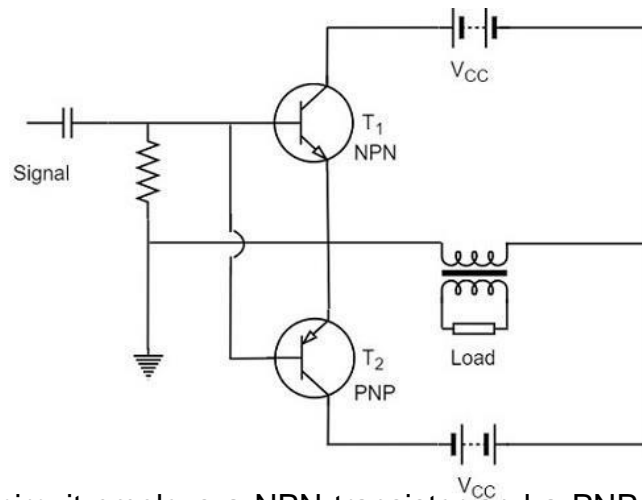
$$\begin{aligned} \eta_{overall} &= \frac{(P_O)_{ac}}{(P_{in})_{dc}} \\ &= \frac{(I_C)_{max} \times V_{CC}}{2} \times \frac{\pi}{2(I_C)_{max} \times V_{CC}} \\ &= \frac{\pi}{4} = 0.785 = 78.5\% \end{aligned}$$

The collector efficiency would be the same.

Hence the class B push-pull amplifier improves the efficiency than the class A push-pull amplifier.

Complementary Symmetry Push-Pull Class B Amplifier

The push pull amplifier which was just discussed improves efficiency but the usage of center-tapped transformers makes the circuit bulky, heavy and costly. To make the circuit simple and to improve the efficiency, the transistors used can be complemented, as shown in the following circuit diagram.



The above circuit employs a NPN transistor and a PNP transistor connected in push pull configuration. When the input signal is applied, during the positive half cycle of the input signal, the NPN transistor conducts and the PNP transistor cuts off. During the negative half cycle, the NPN transistor cuts off and the PNP transistor conducts.

In this way, the NPN transistor amplifies during positive half cycle of the input, while PNP transistor amplifies during negative half cycle of the input. As the transistors are both complement to each other, yet act symmetrically while being connected in push pull configuration of class B, this circuit is termed as **Complementary symmetry push pull class B amplifier**.

Advantages

The advantages of Complementary symmetry push pull class B amplifier are as follows.

- As there is no need of center tapped transformers, the weight and cost are reduced.
- Equal and opposite input signal voltages are not required.

Disadvantages

The disadvantages of Complementary symmetry push pull class B amplifier are as follows.

- It is difficult to get a pair of transistors (NPN and PNP) that have similar characteristics.
- We require both positive and negative supply voltages.

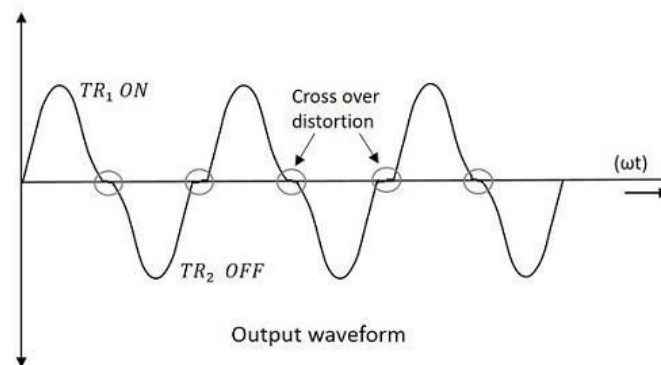
The class A and class B amplifier so far discussed has got few limitations. Let us now try to combine these two to get a new circuit which would have all the advantages of both class A and class B amplifier without their inefficiencies. Before that, let us also go through another important problem, called as **Cross over distortion**, the output of class B encounters with.

Cross-over Distortion:

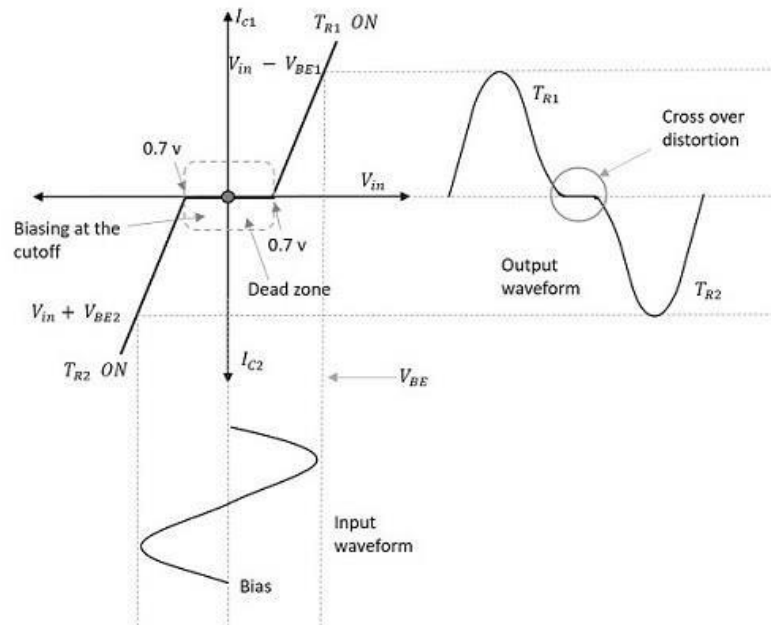
In the push-pull configuration, the two identical transistors get into conduction, one after the other and the output produced will be the combination of both.

When the signal changes or crosses over from one transistor to the other at the zero voltage point, it produces an amount of distortion to the output wave shape. For a transistor in order to conduct, the base emitter junction should cross 0.7v, the cut off voltage. The time taken for a transistor to get ON from OFF or to get OFF from ON state is called the **transition period**.

At the zero voltage point, the transition period of switching over the transistors from one to the other, has its effect which leads to the instances where both the transistors are OFF at a time. Such instances can be called as **Flat spot** or **Dead band** on the output wave shape.



The above figure clearly shows the cross over distortion which is prominent in the output waveform. This is the main disadvantage. This cross over distortion effect also reduces the overall peak to peak value of the output waveform which in turn reduces the maximum power output. This can be more clearly understood through the non-linear characteristic of the waveform as shown below.



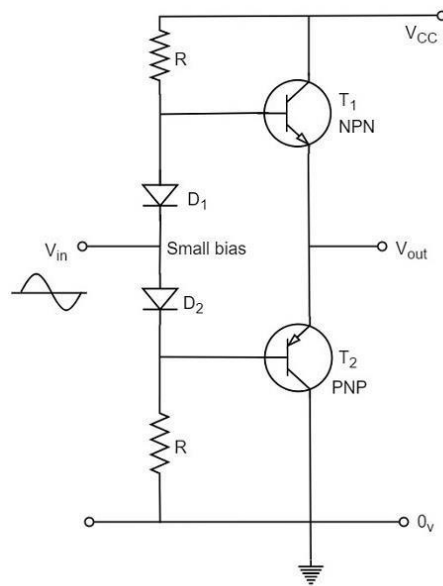
It is understood that this cross-over distortion is less pronounced for large input signals, where as it causes severe disturbance for small input signals. This cross over distortion can be eliminated if the conduction of the amplifier is more than one half cycle, so that both the transistors won't be OFF at the same time.

This idea leads to the invention of class AB amplifier, which is the combination of both class A and class B amplifiers, as discussed below.

Class AB Power Amplifier

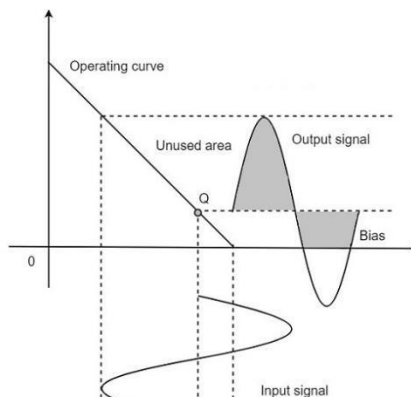
As the name implies, class AB is a combination of class A and class B type of amplifiers. As class A has the problem of low efficiency and class B has distortion problem, this class AB is emerged to eliminate these two problems, by utilizing the advantages of both the classes.

The cross over distortion is the problem that occurs when both the transistors are OFF at the same instant, during the transition period. In order to eliminate this, the condition has to be chosen for more than one half cycle. Hence, the other transistor gets into conduction, before the operating transistor switches to cut off state. This is achieved only by using class AB configuration, as shown in the following circuit diagram.



Therefore, in class AB amplifier design, each of the push-pull transistors is conducting for slightly more than the half cycle of conduction in class B, but much less than the full cycle of conduction of class A.

The conduction angle of class AB amplifier is somewhere between 180° to 360° depending upon the operating point selected. This is understood with the help of below figure.



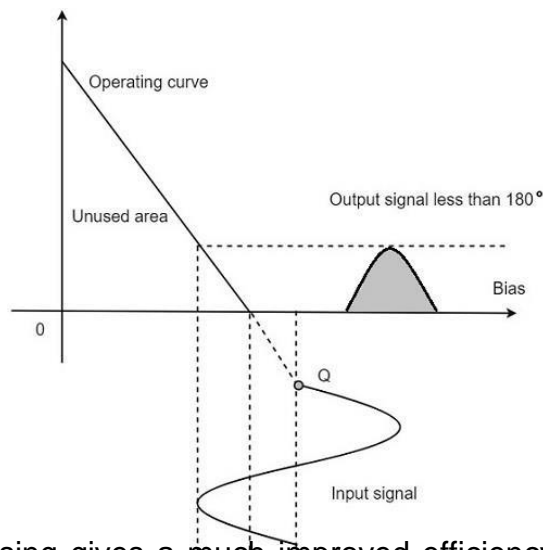
The small bias voltage given using diodes D_1 and D_2 , as shown in the above figure, helps the operating point to be above the cutoff point. Hence the output waveform of class AB results as seen in the above figure. The crossover distortion created by class B is overcome by this class AB, as well the inefficiencies of class A and B don't affect the circuit.

So, the class AB is a good compromise between class A and class B in terms of efficiency and linearity having the efficiency reaching about 50% to 60%. The class A, B and AB amplifiers are called as **linear amplifiers** because the output signal amplitude and phase are linearly related to the input signal amplitude and phase.

Class C Power Amplifier

When the collector current flows for less than half cycle of the input signal, the power amplifier is known as **class C power amplifier**. The efficiency of class C amplifier is high while linearity is poor. The conduction angle for class C is less than 180° . It is generally around 90° , which means the transistor remains idle for more than half of the input signal. So, the output current will be delivered for less time compared to the application of input signal.

The following figure shows the operating point and output of a class C amplifier.



This kind of biasing gives a much improved efficiency of around 80% to the amplifier, but introduces heavy distortion in the output signal. Using the class C amplifier, the pulses produced at its output can be converted to complete sine wave of a particular frequency by using LC circuits in its collector circuit.

The types of amplifiers that we have discussed so far cannot work effectively at radio frequencies, even though they are good at audio frequencies. Also, the gain of these amplifiers is such that it will not vary according to the frequency of the signal, over a wide range. This allows the amplification of the signal equally well over a range of frequencies and does not permit the selection of particular desired frequency while rejecting the other frequencies.