5.1. 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.

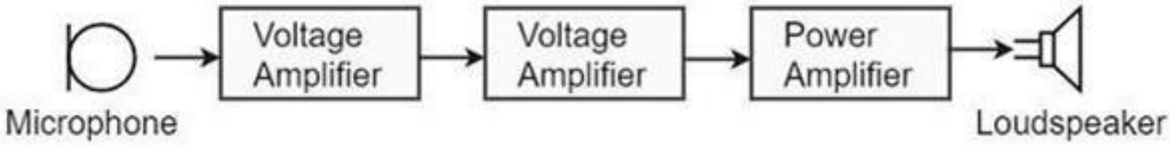
General Concepts:

- A **power amplifier** is one that is designed to deliver a large amount of power to a load. To perform this function, a power amplifier must itself be capable dissipating large amounts of power; so that the heat generated when it is operated at high current and voltage levels is released into the surroundings at a rate fast enough to prevent destructive temperature buildup.
- Power amplifiers typically contain bulky components having large surface areas to enhance heat transfer to the environment. A power transistor is a discrete device with a large surface area and a metal case.
- A power amplifier is often the last stage of an amplifier system designed to modify signal characteristics referred to as signal conditioning. It is designed at least one of its semiconductor components, typically a power transistor, can be operated over substantially the entire range of its output characteristics, from saturation to cutoff. This mode of operation is called **large-signal operation**.
- The term "large-signal operation" is also applied to devices used in digital switching circuits. In these applications, the output level switches between "high" and "low" (cutoff and saturation), but remains in those states most of the time. Power dissipation is therefore not a problem.
- On the other hand, the variations in the output level of a power amplifier occur in the active region, between the two extremes of saturation and cutoff, so a substantial amount of power is dissipated. Large signal amplifiers also known as power amplifiers are capable of providing large amount of power to the load. They are used as last

stage in electronic systems. A power amplifier takes the d.c. power supply connected to the output circuit and converts it into a.c. signal power. Output power is controlled by input signal.

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.



5.1.1 power amplification

(Source: Microelectronics byJ. Millman and A. Grabel, Page-484)

- 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 ,
  DC power i/p = AC o/p + 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 thecollector-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 betweenvoltage and power amplifier.

Voltage Amplifier

- The function of a voltage amplifier is to raise the voltage level of the signal. A voltageamplifier 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 greaterthan 100.
- The resistance of the input resistor Rin should be low when compared to collectorload RC.
- The collector load RC should be relatively high. To permit high collector load, thevoltage 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 todeliver 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 thicken to handle large currents. The value of β being(β > 100) high.
- The size of the transistor is made larger, in order to dissipate more heat, which isproduced 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	B	High (>100)	Low (5 to 20)
2	RC	High (4-10 KΩ)	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 impendence	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 modeof operation.

Classification Of Amplifiers

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**.
- **Class AB 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

η=average a.c power output / average d.c power input to transistor

- The main aim of a power amplifier is to obtain maximum collector efficiency. Hence thehigher 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.

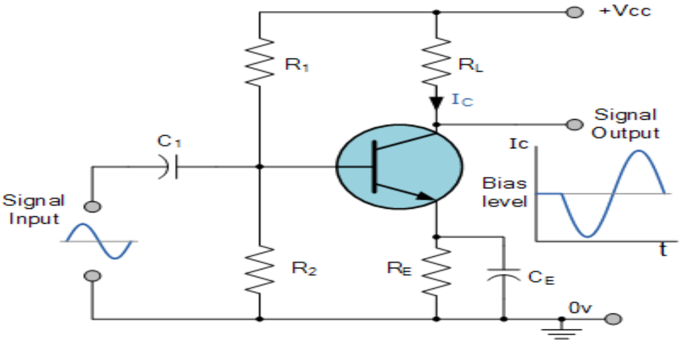
- **Power dissipation capability** can be defined as the ability of a power transistor to dissipate the heat developed in it. Metal cases called heat sinks are used in order to dissipate the heat produced in power transistors.

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.

Class A power

- 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. shows the circuit diagram

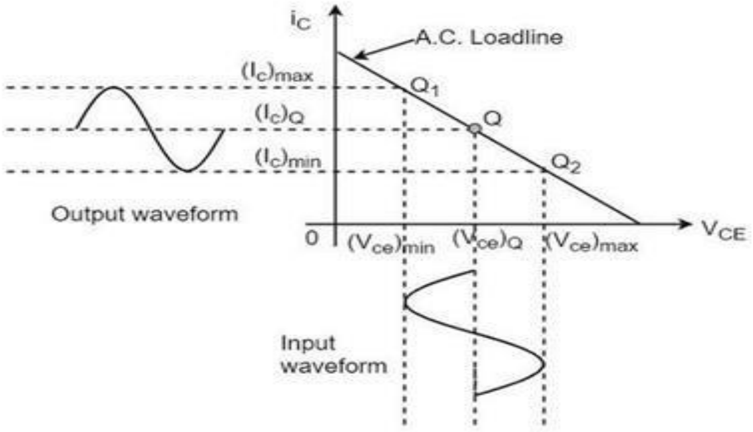


5.2.2 Class A Power amplifier.

(Source: Microelectronics byJ. Millman and A. Grabel, Page-496)

- 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.



5.1.3 AC load line

(Source: Microelectronics byJ. Millman and A. Grabel, Page-495)

- The output characteristics with operating point Q is shown in the figure above. Here (Ic)Q and (Vce)Q represent no signal collector current and voltage between collector and emitter respectively. When signal is applied, the Q-point shifts to Q1 and Q2. The output current increases to (Ic)max and decreases to (Ic)min. Similarly, the collector-emitter voltage increases to (Vce) max and decreases to (Vce) min.

D.C. Power drawn from collector battery Vcc 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

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

- Power given to transistor is given by

$$P_{tr}=P_{in}-P_{R_C}=V_{CC}-(I_C)\,2_Q R_C$$

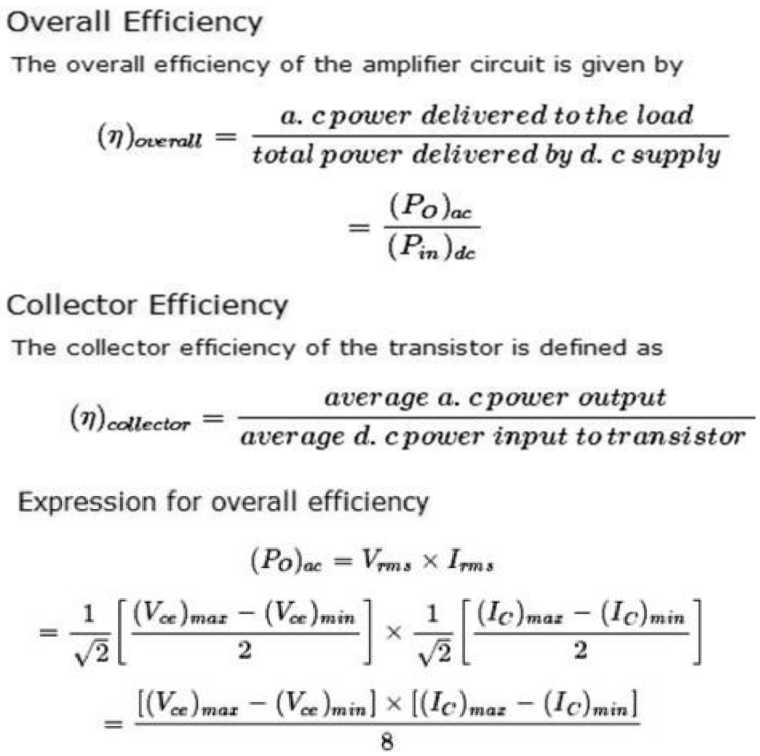
When signal is applied, the power given to transistor is used in the following two parts –

- A.C. Power developed across load resistors RC which constitutes the a.c. poweroutput.

$$(PO)ac=I^2RC=V^2 / RC=(Vm/\sqrt{2}\ ) /RC=V2m/2RC$$

- Where **I** is the R.M.S. value of a.c. output current through load, **V** is the R.M.S. valueof a.c. voltage, and **Vm** is the maximum value of V.
- The D.C. power dissipated by the transistor (collector region) in the form of heat, i.e.,(PC)dc

- This class A power amplifier can amplify small signals with least distortion and the outputwill 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

$$(\eta)_{overall} = \frac{a.c\,power\ delivered\ to\ the\ load}{total\ power\ delivered\ by\ d.c\ supply}$$

$$= \frac{(P_O)_{ac}}{(P_{in})_{dc}}$$

Collector Efficiency

The collector efficiency of the transistor is defined as

$$(\eta)_{collector} = \frac{average\ a.c\,power\ output}{average\ d.c\,power\ input\ to\ transistor}$$

Expression for overall efficiency

$$(P_O)_{ac} = V_{rms} \times I_{rms}$$

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

$$= \frac{[(V_{ce})_{max} - (V_{ce})_{min}] \times [(I_C)_{max} - (I_C)_{min}]}{8}$$

Expressions:

- $I_{BQ} = (V_{CC} - 0.7)/R_B$
- $\mathbf{I_{CQ} = \beta I_{BQ}}$
- **VEQ = VCC - ICQ RL**
- **Q point at (V_{CEQ}, I_{CQ}) Pdc = VCC ICQ**
- **$P_{ac} = ((V_{max} - V_{min})\,(I_{max} - I_{min}))/8$**
- **Efficiency %$\eta = (P_{ac}/P_{dc})*100$**

  Power dissipation $P_d = P_{dc} - P_{ac}$

Advantages of Class A Amplifiers

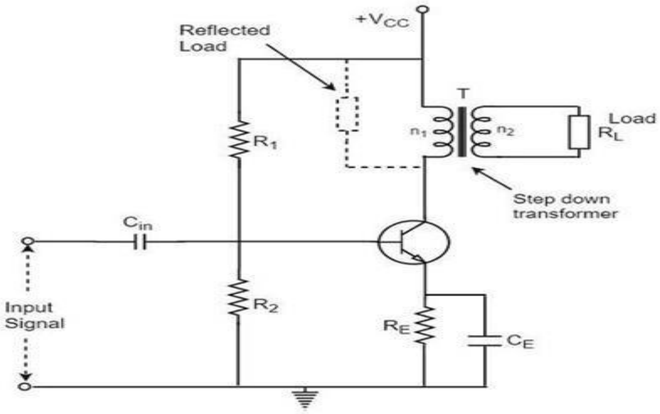
- The current flows for complete input cycle
- It can amplify small signals
- The output is same as input
- No distortion is present

Disadvantages of Class A Amplifiers

The disadvantages of Class A power amplifier are as follows

- Low power output
- Low collector efficiency

TRANSFORMER COUPLED CLASS A POWER AMPLIFIER:



51.4 Transformer coupled class A amplifier

(Source: Microelectronics byJ. Millman and A. Grabel, Page-498)

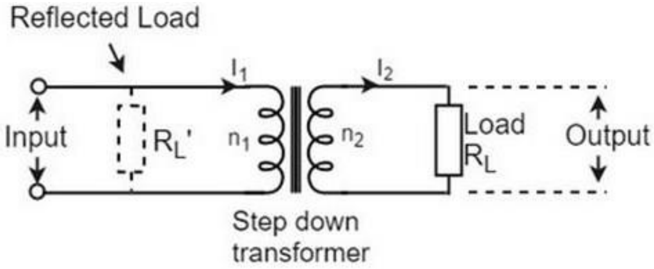
- The **construction of class A power amplifier** can be understood with the help of below figure. This is similar to the normal amplifier circuit but connected with a transformer in the collector load.

- Here R1 and R2 provide potential divider arrangement. The resistor Re provides stabilization, Ce is the bypass capacitor and Re 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. RL is the load connected in the secondary of a transformer. RL' is the reflected load in the primary of the transformer.

- The number of turns in the primary are n1 and the secondary are n2. Let V1 and V2 be the primary and secondary voltages and I1 and I2 be the primary and secondary currents respectively. The below figure shows the transformer clearly.



We know that

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

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

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

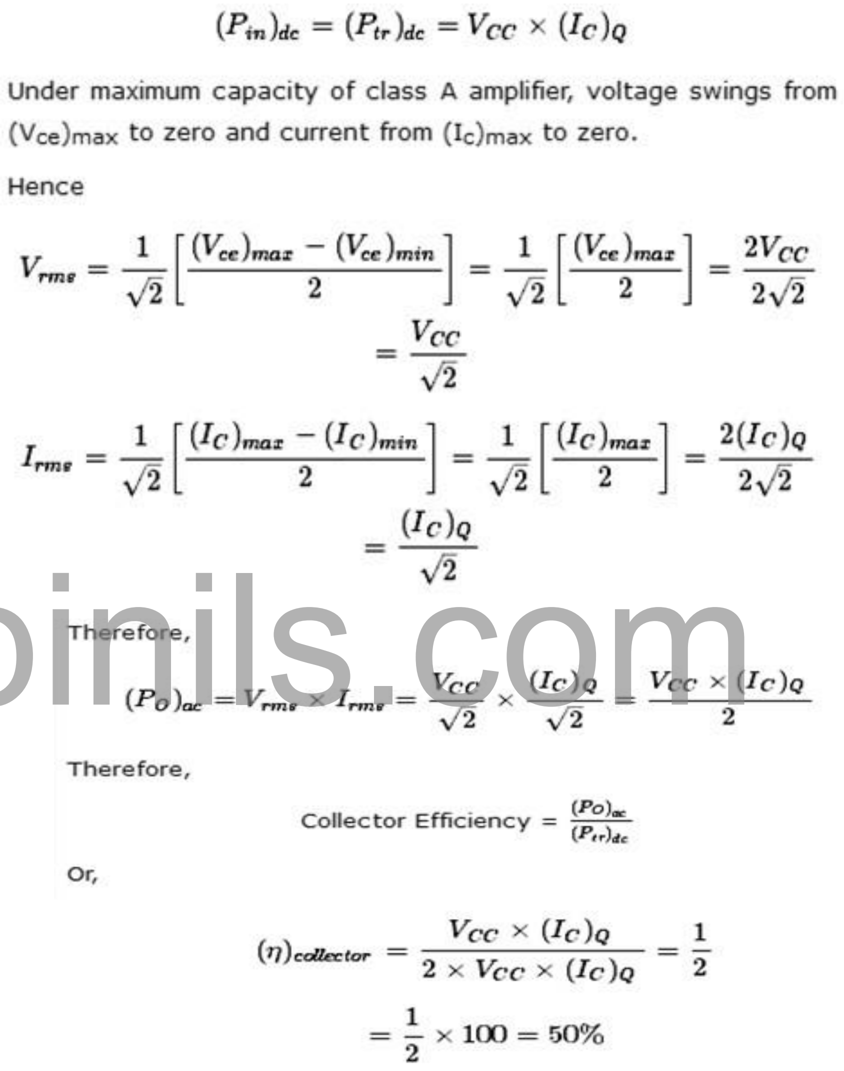
- A power amplifier may be matched by taking proper turn ratio in step down transformer.

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,

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

$$= \frac{1}{2} \times 100 = 50\%$$

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.

- **Expressions:**

$R_L' = [N_1/N_2]^2 R_L$

Q point (V_{CC}, I_{CQ}), $I_{CQ} = I_{BQ}$

$P_{dc} = V_{CC} I_{CQ}$

$P_{ac} = ((V_{max} - V_{min})(I_{max} - I_{min}))/8$

Efficiency $\%\eta = (P_{ac}/P_{dc})*100$.

$\%\eta$ max= 50%

Power dissipation $P_d = P_{dc} = V_{CC}I_{CQ}$

Impedance matching is possible

Slope of dc load line ideally ∞

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.

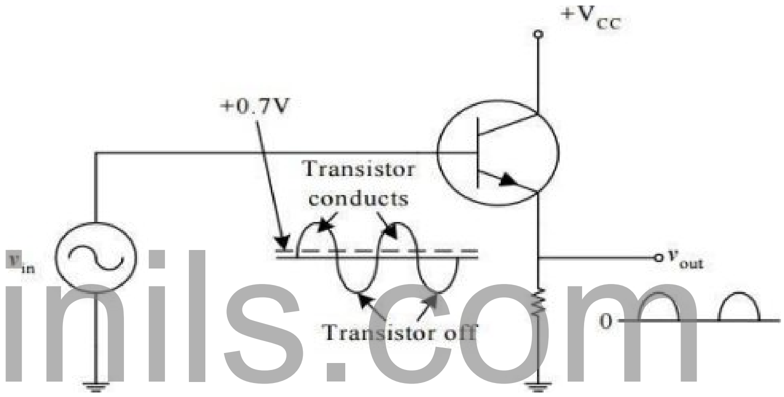
Applications

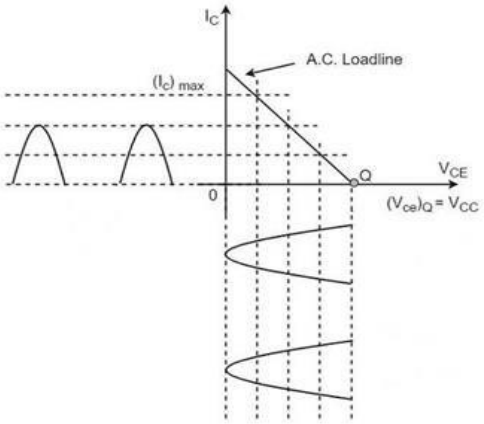
The applications of transformer coupled class A power amplifier are as follows.

- 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, thepower 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.





5.1.5 Class B Amplifier

(Source: Microelectronics byJ. Millman and A. Grabel, Page-498)

- 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.

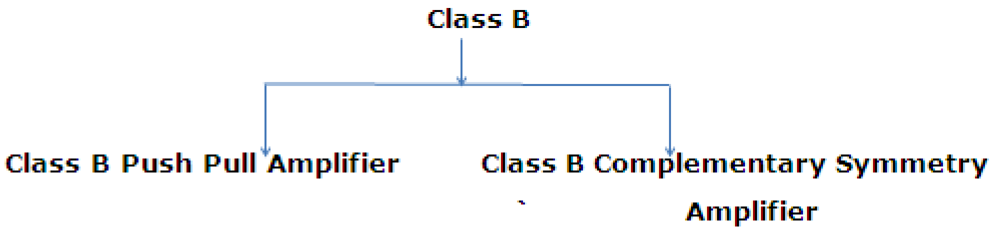
- As the negative half cycle is completely absent, the signal distortion will be high. Also, when the applied signal increases, the power dissipation will be more. But when compared to class A power amplifier, the output efficiency is increased. Well, in order to minimize the disadvantages and achieve low distortion, high efficiency and high output power, the push-pull configuration is used in this class B amplifier.
- The output power is obtained for one half cycle of input only. Refer Figure .The collector current flows for 180 degrees only. For this the Q point is adjusted so that it is in cut off region (refer figure).
- The transistor conducts one half cycle only for the positive half cycle of the input and in Negative cycle of input the transistor goes into Off state. Thus collector current flows only for one half cycle.
- Since the transistor conducts for one half cycle of the input the power dissipation of these class B amplifiers are very less. Hence efficiency gets increased.
- The class B amplifier is biased at the cutoff point so that
- It is brought out of cutoff and operates in its linear region when the input signal drives the transistor into conduction.

Advantages:

- Impedance with load is possible.
- Second harmonic get automatically cancelled.
- Zero power dissipation.
- High efficiency compared with class A amplifiers.

Disadvantage:

- Crossover distortion is present in the output waveform. Since, the transistor is biased at cut off region the waveform is distorted near zero crossings.
- Efficiency is not so high.



- **Push Pull Amplifier** - If both the transistors are of same type (NPN or PNP)

- **Complementary Symmetry**- If one of the transistors is NPN & the other one PNP or vice versa.

5.2. ***CLASS B PUSH PULL POWER 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 inclass B amplifier.
- In class B amplifier output collector current flows only for half cycle for full cycle of the input hence distortion. To get out for full input signal we use Push Pull circuit. Two transformers are used in Push pull amplifiers. one at the input and the other at the load side.

Construction:

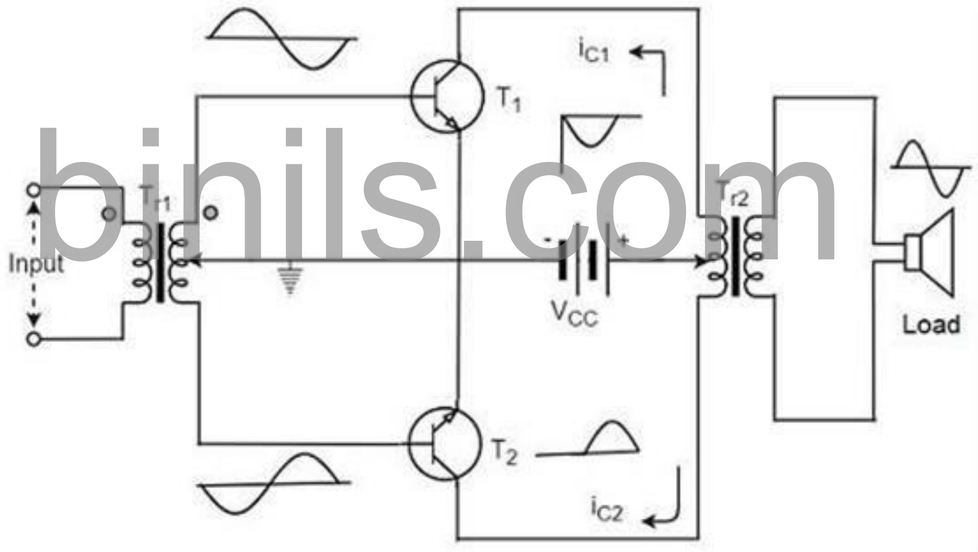


Fig 5.2.1 Push-pull class B power amplifier

(Source: Microelectronics byJ. Millman and A. Grabel, Page-483)

- The circuit of a push-pull class B power amplifier consists of two identical transistors T1 and T2 whose bases are connected to the secondary of the center-tapped input transformer Tr1. The emitters are shorted and the collectors are given the VCC supply through the primary of the output transformer Tr2.
- 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 T1 and T2 are in cut off condition and hence no collector currents flow. As no current is drawn from VCC, no power is wasted.
- When input signal is given, it is applied to the input transformer Tr1 which splits the signal into two signals that are 180^{o} out of phase with each other. These two signals are given to the two identical transistors T1 and T2. For the positive half cycle, the base of the transistor T1 becomes positive and collector current flows. At the same time, the transistor T2 has negative half cycle, which throws the transistor T2 into cutoff condition and hence no collector current flows. The waveform is produced as shown in the following figure.

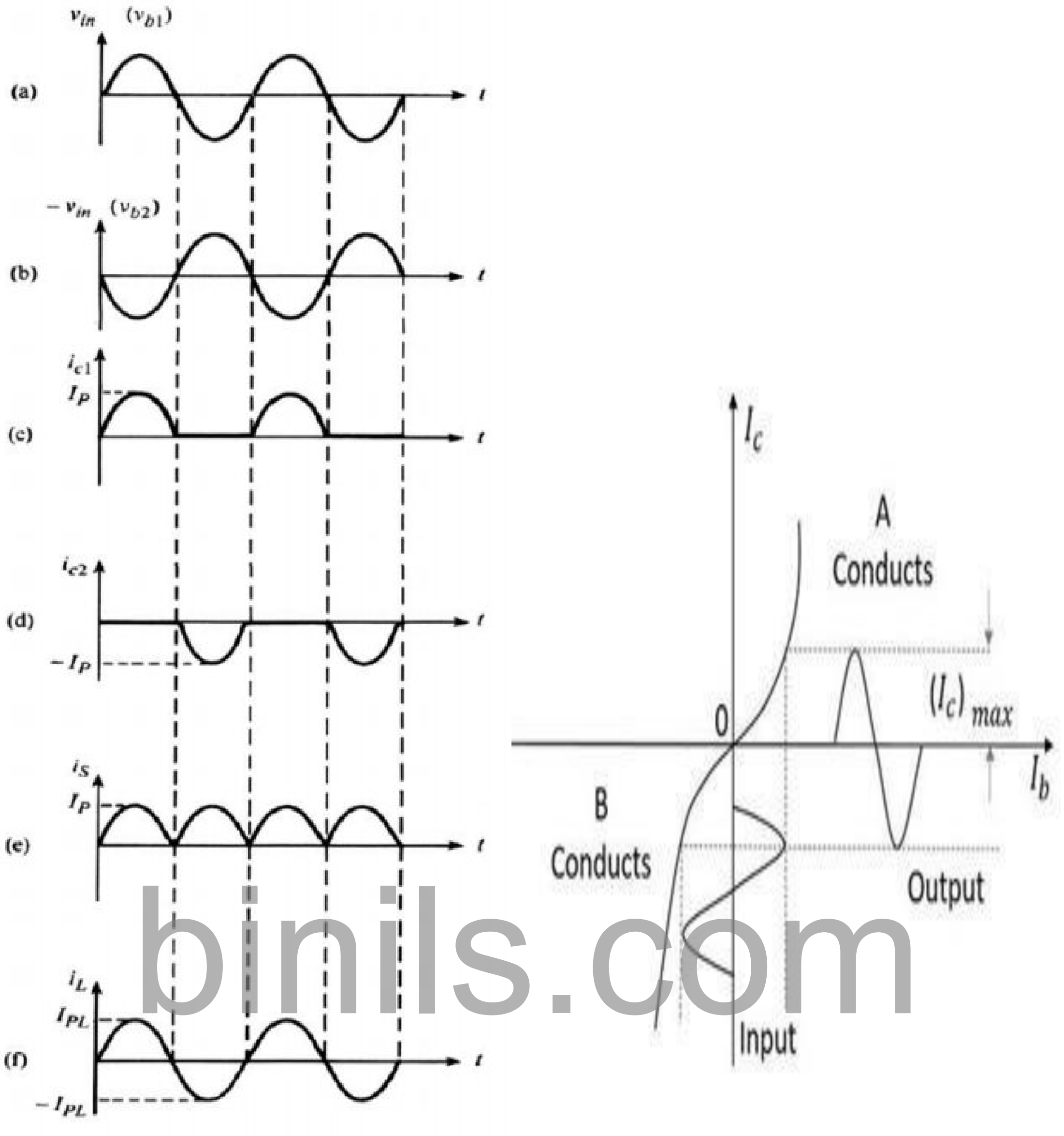


Fig.5.2.2 Push-pull class B power amplifier wave forms

(Source: Microelectronics byJ. Millman and A. Grabel, Page-489)

- For the next half cycle, the transistor T1 gets into cut off condition and the transistor T2 gets into conduction, to contribute the output. Hence for both the cycles, each transistor conducts alternately. The output transformer Tr3 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,

- Idc 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

$$\eta_{overall} = \frac{(P_O)_{ac}}{(P_{in})_{dc}}$$

$$= \frac{(I_C)_{max} \times V_{CC}}{2} \times \frac{\pi}{2(I_C)_{max} \times V_{CC}}$$

$$= \frac{\pi}{4} = 0.785 = 78.5\%$$

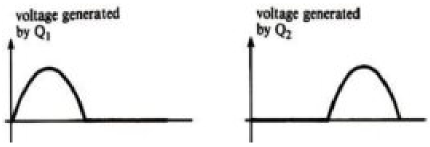
- The collector efficiency would be the same.
- Hence the class B push-pull amplifier improves the efficiency than the class A push-pullamplifier.

Distortion in Push-Pull Amplifiers:

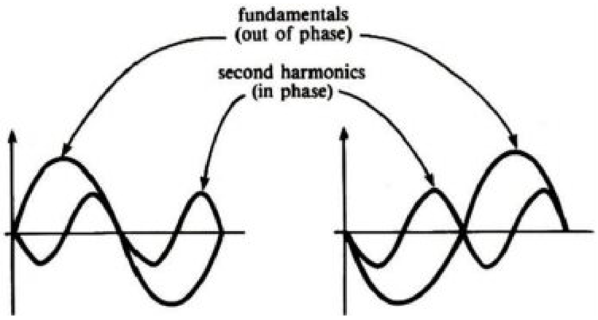
Cancellation of Even Harmonics:

- Recall that push-pull operation effectively produces in a load a waveform proportional to the difference between two input signals. Under normal operation, the signals are out of phase, so their waveform is reproduced in the load. If the signals were in phase, cancellation would occur. It can be shown that a half-wave-rectified sine wave contains only the fundamental and all even harmonics.

- Fig. (a) shows the two out-of-phase half-wave-rectified sine waves that drive the load, and Fig. (b) shows the fundamental and second-harmonic components of each. The fundamental components are out of phase. Therefore, the fundamental component is reproduced in the load, as we have already seen (Fig.). However, the second-harmonic components are in phase, and therefore cancelin the load.
- an important property of push-pull amplifies: even harmonics are cancelled in push-pull operation. The cancellation of even harmonics is an important factor in reducing distortion in push-pull amplifiers. However, perfect cancellation would occur only if the two sides were perfectly matched and perfectly balanced: identical transistors, identical drivers, and a perfectly center-tapped transformer. Of course, this is not the case in practice, but even imperfect push-pull operation reduces even harmonic distortion. Odd harmonics are out of phase, so cancellation of those components does not occur.



(a)



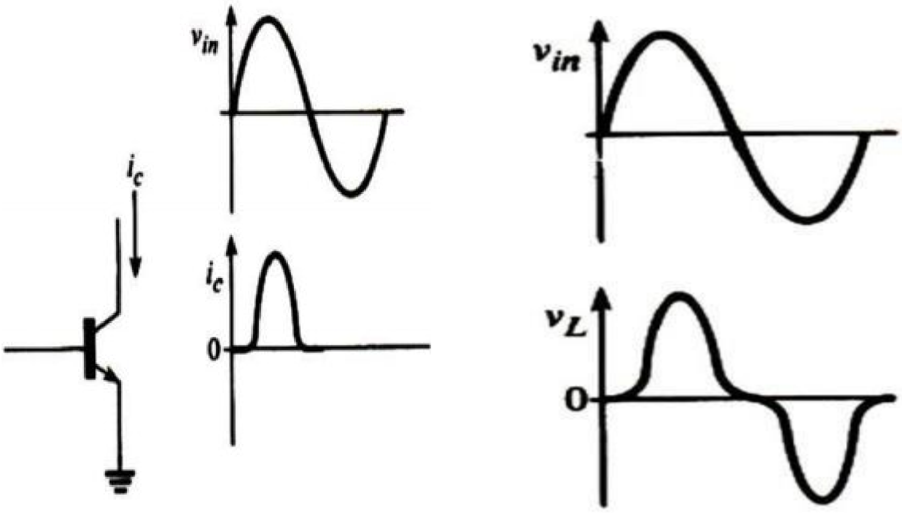
5.2.3 Cross over Distortion

(Source: Microelectronics byJ. Millman and A. Grabel, Page-493)

Crossover Distortion:

- A forward-biasing voltage applied across a PN junction must be raised to a certain level (about 0.7 V for silicon) before the junction will conduct any significant current.
- Similarly, the voltage across the base-emitter junction of a transistor must reach that level before any appreciable base current, and hence collector current, can flow.
- As a consequence, the drive signal applied to a class-B transistor must reach a certain minimum level before its collector current is properly in the active region. This fact is the principal source of distortion in a class-B, push-pull amplifier, as illustrated in Fig.
- Fig. shows that the initial rise of collector current in a class-B transistor lags the initial rise of input voltage, for the reason we have described.
- Also, collector current prematurely drops to 0 when the input voltage approaches 0.
- Fig. (b) shows the voltage wave form that is produced in the load of a push-pull amplifier when the distortion generated during each half-cycle by each class-B transistor is combined. This distortion is called ***crossover distortion***, because it occurs where the composite waveform crosses the zero voltage axes.

- Clearly, the effect of crossover distortion becomes more serious as the signal level becomes smaller.



(a) (b)

Fig. 5.2.4 Cross over distortion

(Source: Microelectronics byJ. Millman and A. Grabel, Page-495)

This results in one main fundamental problem with push-pull amplifiers in that the two transistors do not combine together fully at the output both halves of the waveform due to their unique zero cut-off biasing arrangement.

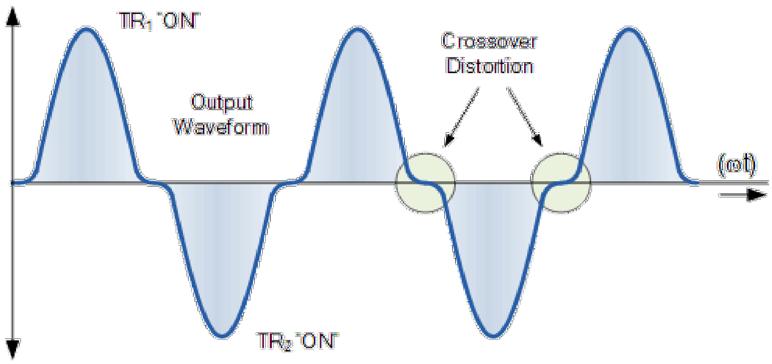
As this problem occurs when the signal changes or "crosses-over" from one transistor to the other at the zero voltage point it produces an amount of "distortion" to the output wave shape. This results in a condition that is commonly called **Crossover Distortion**.

Crossover Distortion produces a zero voltage "flat spot" or "deadband" on the output wave shape as it crosses over from one half of the waveform to the other.

The reason for this is that the transition period when the transistors are switching over from one to the other, does not stop or start exactly at the zero crossover point thus causing a small delay between the first transistor turning "OFF" and the second transistor turning "ON".

This delay results in both transistors being switched "OFF" at the same instant in time producing an output wave shape as shown below.

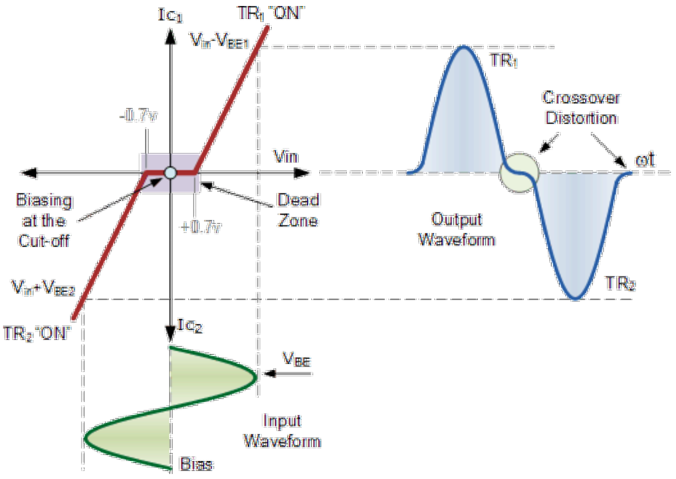
Crossover Distortion Waveform



(Source: Microelectronics byJ. Millman and A. Grabel, Page-495)

In order that there should be no distortion of the output waveform we must assume that each transistor starts conducting when its base to emitter voltage rises just above zero, but we know that this is not true because for silicon bipolar transistors, the base-emitter voltage must reach at least 0.7v before the transistor starts to conduct due to the forward diode voltage drop of the base-emitter pn-junction, thereby producing this flat spot. This crossover distortion effect also reduces the overall peak to peak value of the output waveform causing the maximum power output to be reduced as shown below.

Non-Linear Transfer Characteristics



5.2.5 Non linear Transfer Characteristics

(Source: Microelectronics byJ. Millman and A. Grabel, Page-493)

This effect is less pronounced for large input signals as the input voltage is usually quite large but for smaller input signals it can be more severe causing audio distortion to the amplifier.

Pre-biasing the Output

The problem of **Crossover Distortion** can be reduced considerably by applying a slight forward base bias voltage (same idea as seen in the **Transistor** tutorial) to the bases of the two transistors via the center-tap of the input transformer, thus the transistors are no longer biased at the zero cut-off point but instead are "Pre-biased" at a level determined by this new biasing voltage.

Push-pull Amplifier with Pre-biasing

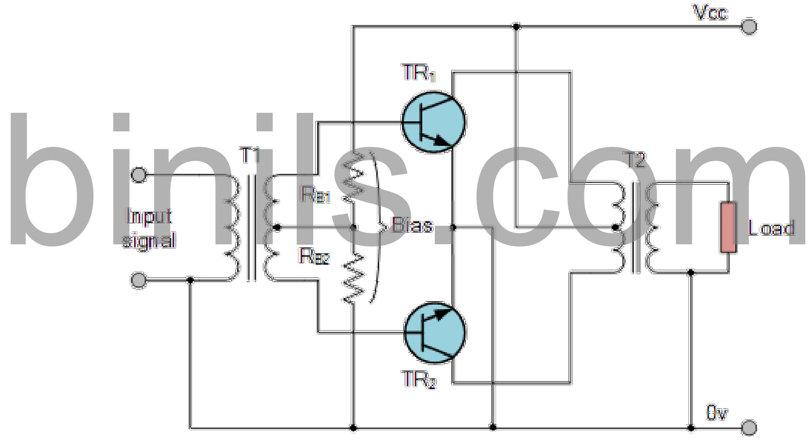


Fig 5.2.6 Push pull amplifier with pre biasing

(Source: Microelectronics byJ. Millman and A. Grabel, Page-498)

This type of resistor pre-biasing causes one transistor to turn "ON" exactly at the same time as the other transistor turns "OFF" as both transistors are now biased slightly above their original cut-off point. However, to achieve this the bias voltage must be at least twice that of the normal base to emitter voltage to turn "ON" the transistors. This pre-biasing can also be implemented in transformerless amplifiers that use complementary transistors by simply replacing the two potential divider resistors with **Biasing Diodes** as shown below.

Pre-biasing with Diodes

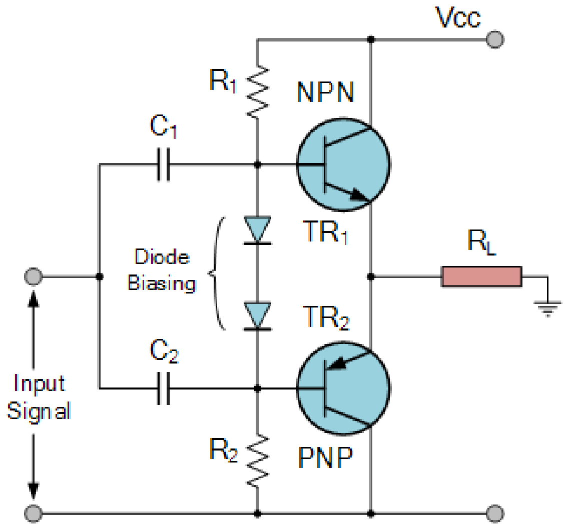
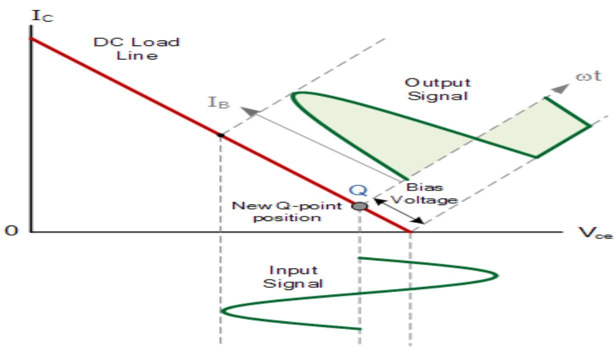


Fig 5.2.6 Push pull amplifier with pre biasing with diodes

(Source: Microelectronics byJ. Millman and A. Grabel, Page-499)

This pre-biasing voltage either for a transformer or transformerless amplifier circuit, has the effect of moving the amplifiers Q-point past the original cut-off point thus allowing each transistor to operate within its active region for slightly more than half or 180° of each half cycle. In other words, 180° + Bias. The amount of diode biasing voltage present at the base terminal of the transistor can be increased in multiples by adding additional diodes in series. This then produces an amplifier circuit commonly called a **Class AB Amplifier** and its biasing arrangement is given below.

Class AB Output Characteristics



5.2.6 Out put Characteristics

(Source: Microelectronics byJ. Millman and A. Grabel, Page-498)

Crossover Distortion Summary

Then to summarise, **Crossover Distortion** occurs in Class B amplifiers because the amplifier is biased at its cut-off point. This then results in BOTH transistors being switched “OFF” at the same instant in time as the waveform crosses the zero axis. By applying a small base bias voltage either by using a resistive potential divider circuit or diode biasing this crossover distortion can be greatly reduced or even eliminated completely by bringing the transistors to the point of being just switched “ON”.

The application of a biasing voltage produces another type or class of amplifier circuit commonly called a **Class AB Amplifier**. Then the difference between a pure Class B amplifier and an improved Class AB amplifier is in the biasing level applied to the output transistors. One major advantage of using diodes over resistors is that their PN-junctions compensate for variations in the temperature of the transistors.

Therefore, we can correctly say that the Class AB amplifier is effectively a Class B amplifier with added “Bias” and we can summarise this as follows:

- Class A Amplifiers – No Crossover Distortion as they are biased in the center of the load line.
- Class B Amplifiers – Large amounts of Crossover Distortion due to biasing at the cut-off point.
- Class AB Amplifiers – Some Crossover Distortion if the biasing level is set too low.

As well as the three amplifier classes above, there are a number of high efficiency Amplifier Classes relating to switching amplifier designs that use different switching techniques to reduce power loss and increase efficiency. Some of these amplifier designs use RLC resonators or multiple power-supply voltages to help reduce power loss and distortion.

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.

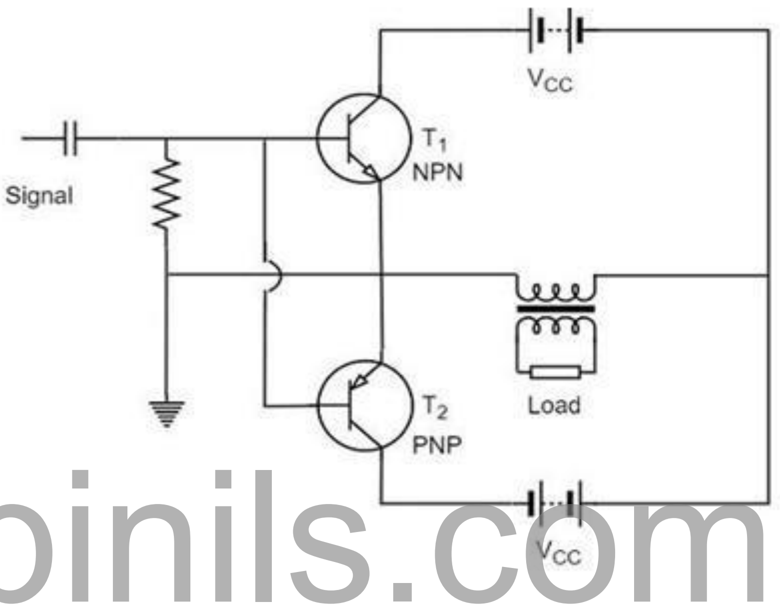


Fig 5.2.7.Complementary Symmetry Push-Pull Class B Amplifier

(Source: Microelectronics byJ. Millman and A. Grabel, Page-498)

- 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 Bamplifier**.
- The circuit diagram for complementary symmetry type is shown in

Figure**.** This circuit uses two transistors of different type. One is NPN and another PNP. It is a transformer less circuit. For better impedance matching the tow transistors Q1 & Q2 are connected as emitter follower configuration. Positive half cycle Q1 is in Active region so ON & Q2 in cut off So OFF. In negative half cycle Q2 is ON & Q1 is OFF. Thus for a complete input cycle output is developed as shown in fig.The difference between complementary symmetry and push pull models is in complementary model there is no output transformer.

Analysis:

- All results for push pull amplifiers are applicable for complementary symmetry model. Only change is replace R_L' with real load R_L value. (Since, no output transformer is used).

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.

S.N	Parameter	Push Pull	Complementary Symmetry
1	Type of Transistor	Both should be of NPN or PNPtype	One is PNP and other NPN
2	Use of transformers	Used at both i/p & o/p side	Not needed
3	Impedance matching	Possible due to use of twotransformers	Possible due to operation oftransistors in CC configuration
4	Transistor Configuration	Both transistors Operates inCE mode	Both transistors Operates inCC mode
5	Conduction Angle	180°	180°
6	Power dissipation when no input is present	Zero	Zero
7	Efficiency	Low	Higher than Push Pull type.

Comparison of Push Pull & Complementary Symmetry circuits:

5.3. Class C Power Amplifier

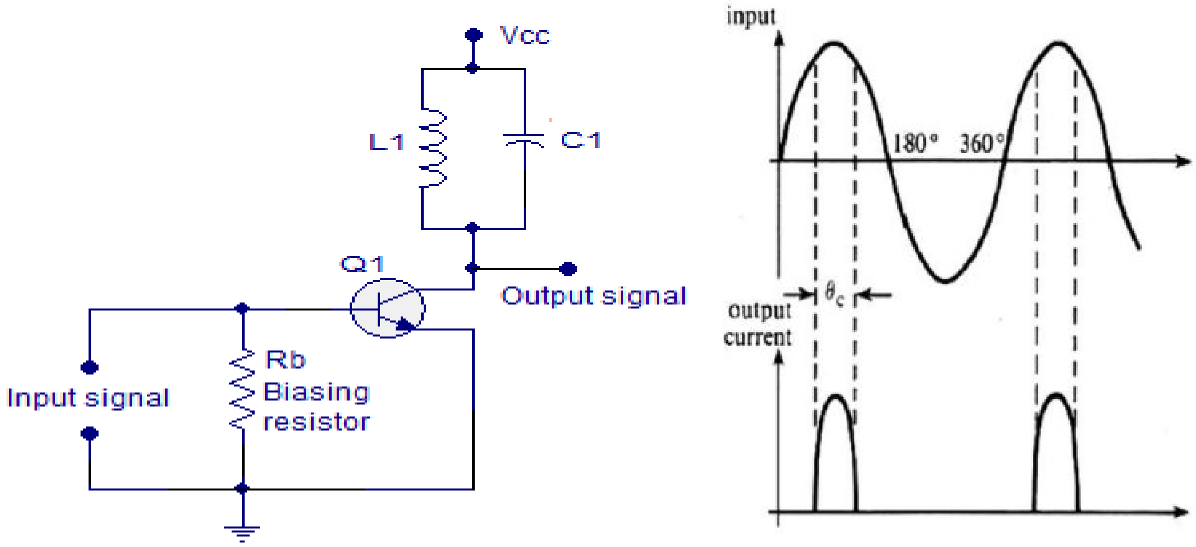


Fig 5.3.1 Class C amplifier

(Source: Electronic Circuit Analysis- K.LalKishore, Page-205)

- 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.

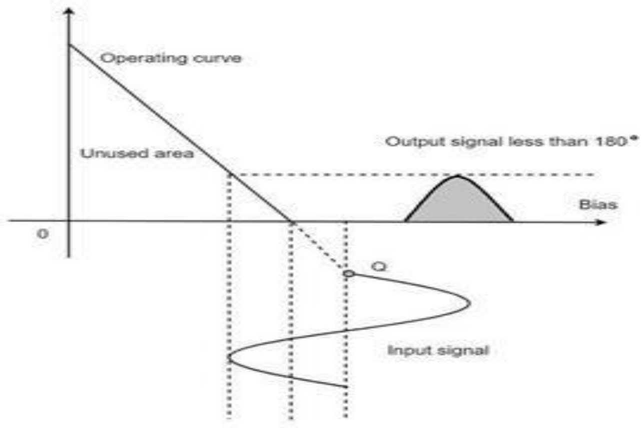


Fig 5.3.2 Class C amplifier wave forms

(Source: Electronic Circuit Analysis- K.LalKishore, Page-210)

- 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 radiofrequencies, 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.
- When the input signal is applied the tuned circuit starts resonating at the frequency of the input signal. Transistor produces a series of current pulses based on the input.
- By selecting Proper L1, C1 resonance can be achieved. This resonance frequency is extracted by the tuned load at the output. Harmonics can be eliminated by adding filters to the circuit shown in figure .
- The biasing resistance pulls the q point below Cut off region. Hence the transistor conducts only after the input amplitude is greater than the base emitter voltage.

Advantages:

- Less Physical size.
- Used in RF applications.
- High Efficiency (higher than 95%)
- Low power loss in power transistors

Disadvantage:

- Creates lot of RF Interference.
- Selection of ideal Inductors is problem.
- Not suitable in Audio applications.

Applications:

- Tuned amplifiers, RF amplifiers, oscillators, Booster amplifiers, and High Frequency repeaters.

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 ofboth 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.

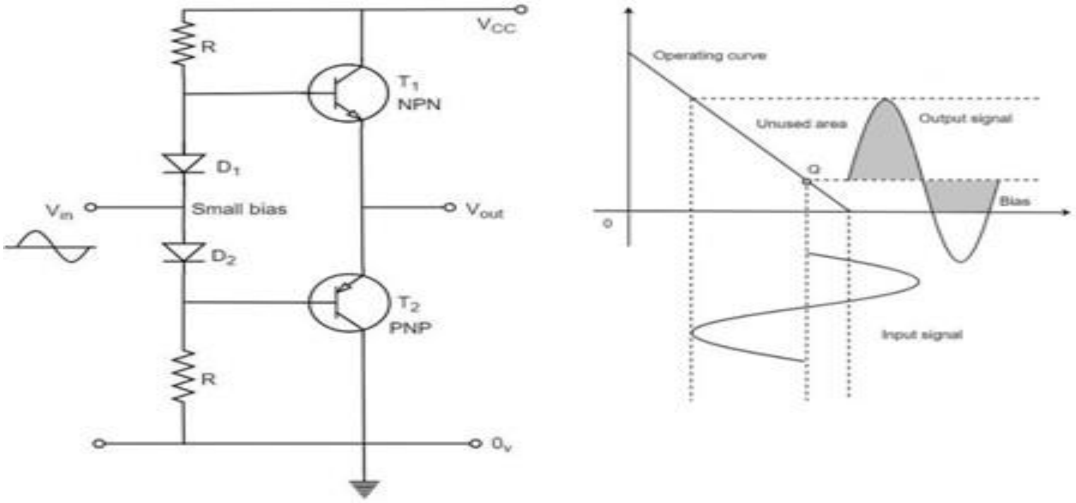


Fig 5.3.3 Class AB amplifier circuit and waveforms

(Source: Electronic Circuit Analysis- K.LalKishore, Page-212)

- 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 above figure.
- The small bias voltage given using diodes D1 and D2, 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.

Distortions in amplifiers:

- If the output of an amplifier is not a complete sine wave, then it is distortion. It can be analysed by using Fourier analysis.in this method any distorted periodic waveform can be broken down into different frequencycomponents. These components are harmonics of the fundamentalfrequency.Harmonics are integer multiples of a fundamentalfrequency (F). For example, 1st harmonic is 1 x F kHz.

TYPES OF DISTORTION

Amplitude or Non Linear distortion:

- Due to the non-linearity of transistor (nonlinear dynamic characteristics of transistor) the output is different from the input.

This kind of distortion is known as amplitude distortion or harmonic or non-linear distortion.

Harmonic distortion %D = (A_n/A_1)*100

Frequency Distortion:

- When different frequency components of the input signal are amplified differently frequency amplification takes place.This is mainly due to the internal capacitance effect of the transistors.

Delay or Phase shift distortion:

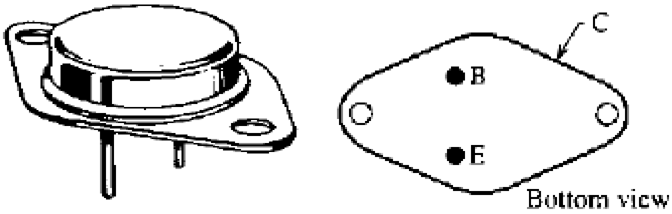
- If the phase shift introduced by amplifier is not proportional to the frequency then phase distortion takes place.

THERMAL STABILITY:

- Average power of a transistor depends on the collector base junction. It is around 150 to 200°. If the temperature exceeds this limit then transistor get physically damaged.Performance of transistor depends on the ability of transistor to dissipate the heat generated in base collector junction. This can be achieved by
- ✓ Operating the transistor in safe region (proper biasing).
- ✓ By effectively removing the heat to the surrounding air quickly.
- ✓ To remove the heat we use Heat sinks. The concept of Heat Sink is to keep the junction of the power device (transistor) to below a maximum operating temperature.

Heat sinks:

- All power devices come in complete package where there is a metal contact which connects the external heat sink to the metal surface of the device.(Usually to the collector terminal)



- Fig5.3.4 :Heat Sink(a) Top view (b) Bottom view

(Source: Electronic Circuit Analysis- K.LalKishore, Page-216)

- In Fig5.3.4 B – Base , E – Emitter & C – Collector terminal. From the above figure 14(b) we can notice that the Collector is connected to the metal top (chasis or heat sink) which has more area than Base & Emitter. So the heat generated at the output junction(collector junction) is dissipated fast. If more number of devices are connected to the same sink the INSULATORS are needed to shield individually. Usually Nylon material is used to ensure.

CLASS D AMPLIFIERS:

- Class D type is designed to work with pulse or digital input signals. The Input V_{in} is compared with saw tooth wave (known as chopping wave) and accordingly a pulse waveform is generated which is fed to the amplifier.

- The circuit diagram of class D amplifier is shown in Figure .Input is applied to the non-inverting terminal of the comparator and the saw tooth wave is applied to the inverting terminal.

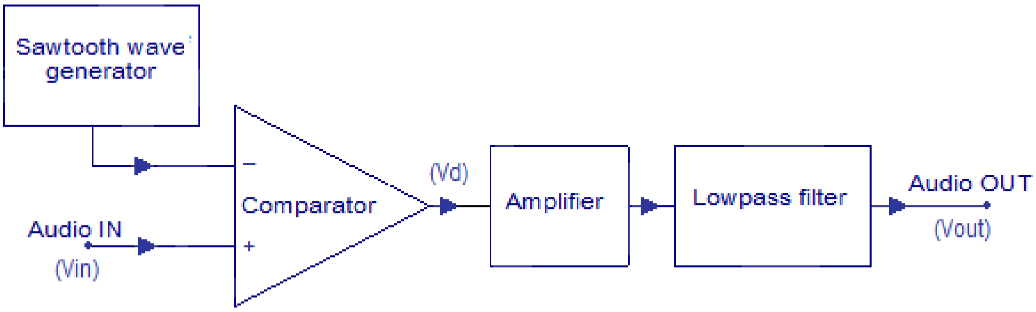


Fig 5.3.5: Class D amplifier

(Source: Electronic Circuit Analysis- K.LalKishore, Page-217)

- Based on this the comparator produces an output pulse width modulated waveform and this PWM wave is amplified by the amplifier as shown in figure . Transistor in the amplifier circuit just acts as a switch and hence the power loss is very less. Low pass filter converts the pulse wave back into sinusoidal signal.At the output thus we have sinusoidal signal.

Efficiency:

- Transistor operates in saturation region when turned on .So V_{ce} is small. This is the reason for class D amplifiers have very high efficiency (Around90%).

Advantages:

- High efficiency
- Possible to amplify the digital signals and analog signals as well.

5.4 Power MOSFET

Power MOSFETs are well known for superior switching speed, and they require very little gate drive power because of the insulated gate. In these respects, power MOSFETs approach the characteristics of an “ideal switch”. The main drawback is on-resistance RDS(on) and its strong positive temperature coefficient. This application note explains these and other main features of high voltage N-channel power MOSFETs, and provides useful information for device selection and application. All the transistors e.g. bipolar, Jn-FET, MESFET, are three terminal devices, with substrate isolated in Jn-FET and MESFET, while in bipolar transistor, the substrate is the collector itself bonded on the header directly. Thus MOSFET is a four-terminal device where substrate is 4th terminal normally connected to the source and is grounded. Rest of the three terminals being source, drain, and gate. In Jn-FET the p–n junction is at the gate while in MOSFET, there are two p–n junctions at source and drain itself. The MOSFET, because of its simpler structure and lower losses, has superseded the junction transistors (BJT and Jn-FET). MOSFET is generally used as power amplifiers as they have some advantages over BJT, Jn-FET, and MESFET,

A power MOSFET is a specific type of metal–oxide–semiconductor field-effect transistor (MOSFET) designed to handle significant power levels. Compared to the other power semiconductor devices, such as an insulated-gate bipolar transistor (IGBT) or a thyristor, its main advantages are high switching speed and good efficiency at low voltages. It shares with the IGBT an isolated gate that makes it easy to drive. They can be subject to low gain, sometimes to a degree that the gate voltage needs to be higher than the voltage under control. The design of power MOSFETs was made possible by the evolution of MOSFET and CMOS technology, used for manufacturing integrated circuits since the 1960s. The power MOSFET shares its operating principle with its low-power counterpart, the lateral MOSFET. The power MOSFET, which is commonly used in power electronics, was adapted from the standard MOSFET and commercially introduced in the 1970s.

The power MOSFET is the most common power semiconductor device in the world, due

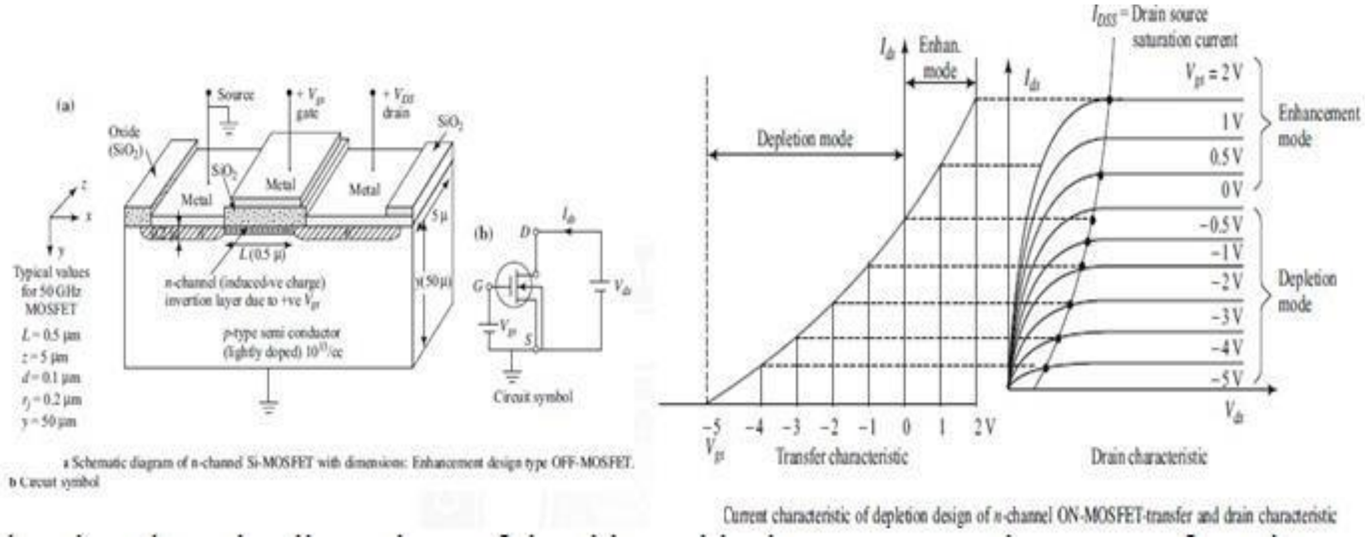


Fig:5.4.1 Power MOSFET and Drain Characterist

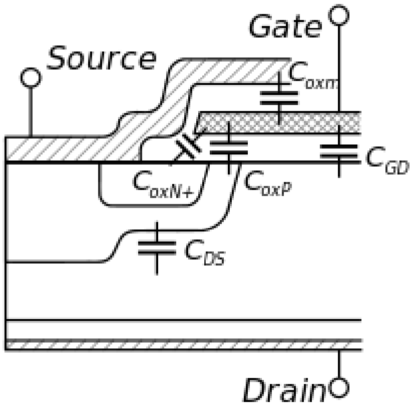
to its low gate drive power, fast switching speed, easy advanced paralleling applied to the gate with respect to source, i.e. vgs, (with substrate and source grounded), then −ve charges are induced in the channel (like a capacitor) and this provides current flow in the channel. As this MOSFET (Fig.) is with p-substrate, the channel region forms −ve carrier channel for current flow and therefore called nchannel MOSFET. The structure given in Fig. also gives the dimensions of the chip and its layers. In practice on a wafer, a large number of such chips are fabricated and chips diced out of it. A MOSFET can be a partof a circuit on a chip also and in such cases the MOSFET is normally surrounded by a thick oxide to isolate it from the adjacent device in a microwave I.C. Two designs of MOSFET are used, e.g. enhancement design (OFF-MOSFET), where n-channel region being very lightly p–type doped (10^{13}/cc), it has very less carriers therefore even with Vds bias Id = 0 for Vg 0. But by Vg = +ve n carriers are induced in the channel region, then Id starts (Fig.): The other is depletion type depletion design(ON-MOSFET), where n type (10^{15}/cc) doping is already done in the channel region, giving enough n carriers. Therefore with Vds bias Id 6¼ 0, whether Vg 0 or Vg 0 and hence ON-type the name is given.

On-State Resistance:

When the power MOSFET is in the on-state (see MOSFET for a discussion on operation modes), it exhibits a resistive behaviour between the drain and source terminals. It can be seen in figure 2 that this resistance (called R_{DSon} for "drain to source resistance in on-state") is the sum of many elementary contributions:

- **R_S is the source resistance**. It represents all resistances between the source terminal of the package to the channel of the MOSFET: resistance of the wire bonds, of the source metallisation, and of the N^+ wells;
- **R_{ch}. This is the channel resistance**. It is inversely proportional to the channel width, and for a given die size, to the channel density. The channel resistance is one of the main contributors to the R_{DSon} of low-voltage MOSFETs, and intensive work has been carried out to reduce their cell size in order to increase the channel density;
- **R_a is the access resistance.** It represents the resistance of the epitaxial zone directly under the gate electrode, where the direction of the current changes from horizontal (in the channel) to vertical (to the drain contact);
- **R_{JFET} is the detrimental effect of the cell size reduction mentioned above**: the P implantations form the gates of a parasitic JFET transistor that tend to reduce the width of the current flow;
- **R_n is the resistance of the epitaxial layer**. As the role of this layer is to sustain the blocking voltage, R_n is directly related to the voltage rating of the device. A high voltage MOSFET requires a thick, low-doped layer, i.e., highly resistive, whereas a low-voltage transistor only requires a thin layer with a higher doping level, i.e., less resistive. As a result, R_n is the main factor responsible for the resistance of high-voltage MOSFETs;
- **R_D is the equivalent of R_S for the drain**. It represents the resistance of the transistor substrate (the cross section in figure 1 is not at scale, the bottom N^+ layer is actually the thickest) and of the package connections.

- **Switching Operation**



5.4.2 Switching Characteristics

(Source: Electronic Circuit Analysis- K.LalKishore, Page-285)

- Because of their unipolar nature, the power MOSFET can switch at very high speed. Indeed, there is no need to remove minority carriers as with bipolar devices. The only intrinsic limitation in commutation speed is due to the internal capacitances of the MOSFET. These capacitances must be charged or discharged when the transistor switches. This can be a relatively slow process because the current that flows through the gate capacitances is limited by the external driver

circuit. This circuit will actually dictate the commutation speed of the transistor (assuming the power circuit has sufficiently low inductance).

Capacitances

In the MOSFET the capacitances are often named C_{iss} (input capacitance, drain and source terminal shorted), C_{oss} (output capacitance, gate and source shorted), and C_{rss} (reverse transfer capacitance, source connected to ground). The relationship between these capacitances and those described below is:

Where C_{GS}, C_{GD} and C_{DS} are respectively the gate-to-source, gate-to-drain and drain-to-source capacitances (see below). Manufacturers prefer to quote C_{iss}, C_{oss} and C_{rss} because they can be directly measured on the transistor. However, as C_{GS}, C_{GD} and C_{DS} are closer to the physical meaning, they will be used in the remaining of this article.

Gate to source capacitance

- The C_{GS} capacitance is constituted by the parallel connection of C_{oxN+}, C_{oxP} and C_{oxm} (see figure 4). As the N^+ and P regions are highly doped, the two former

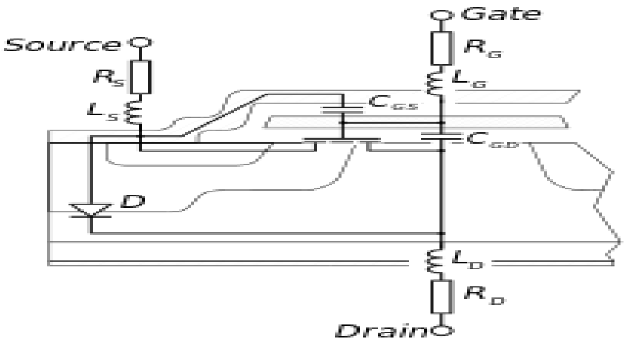
capacitances can be considered as constant. C_{oxm} is the capacitance between the (polysilicon) gate and the (metal) source electrode, so it is also constant. Therefore, it is common practice to consider C_{GS} as a constant capacitance, i.e. its value does not depend on the transistor state.

Gate to drain capacitance

The C_{GD} capacitance can be seen as the connection in series of two elementary capacitances. The first one is the oxide capacitance (C_{oxD}), constituted by the gate electrode, the silicon dioxide and the top of the N epitaxial layer. It has a constant value. The second capacitance (C_{GDj}) is caused by the extension of the space-charge zone when the MOSFET is in off-state. Therefore, it is dependent upon the drain to source voltage.

From this, the value of C_{GD} is: Where A_{GD} is the surface area of the gate-drain overlap. Therefore, it comes:

Packaging inductances



5.4.2 Packaging Inductances

(Source: Electronic Circuit Analysis- K.LalKishore, Page-291)

To operate, the MOSFET must be connected to the external circuit, most of the time using wire bonding (although alternative techniques are investigated). These connections exhibit a parasitic inductance, which is in no way specific to the MOSFET technology, but has important effects because of the high commutation speeds. Parasitic inductances tend to maintain their current constant and generate overvoltage during the transistor turn off, resulting in increasing commutation losses.

A parasitic inductance can be associated with each terminal of the MOSFET. They have different effects:

- the gate inductance has little influence (assuming it is lower than some hundreds of nanohenries), because the current gradients on the gate are relatively slow. In some cases, however, the gate inductance and the input capacitance of the transistor can constitute an oscillator. This must be avoided, as it results in very high commutation losses (up to the destruction of the device). On a typical design, parasitic inductances are kept low enough to prevent this phenomenon;
- the drain inductance tends to reduce the drain voltage when the MOSFET turns on, so it reduces turn on losses. However, as it creates an overvoltage during turn-off, it increases turn-off losses;
- the source parasitic inductance has the same behaviour as the drain inductance, plus a feedback effect that makes commutation last longer, thus increasing commutation losses.

At the beginning of a fast turn-on, due to the source inductance, the voltage at the source (on the die) will be able to jump up as well as the gate voltage; the internal V_{GS} voltage will remain low for a longer time, therefore delaying turn-on.

At the beginning of a fast turn-off, as current through the source inductance decreases sharply, the resulting voltage across it goes negative (with respect to the lead outside the package) raising the internal V_{GS} voltage, keeping the MOSFET on, and therefore delaying turn-off.

Gate Oxide Break down

The gate oxide is very thin (100 nm or less), so it can only sustain a limited voltage. In the datasheets, manufacturers often state a maximum gate to source voltage, around 20 V, and exceeding this limit can result in destruction of the component. Furthermore, a high gate to source voltage reduces significantly the lifetime of the MOSFET, with little to no advantage on R_{DSon} reduction.

To deal with this issue, a gate driver circuit is often used.

Maximum drain to source voltage

Power MOSFETs have a maximum specified drain to source voltage (when turned off), beyond which breakdown may occur. Exceeding the breakdown voltage causes the device to conduct, potentially damaging it and other circuit elements due to excessive power dissipation.

Maximum drain current

The drain current must generally stay below a certain specified value (maximum continuous drain current). It can reach higher values for very short durations of time (maximum pulsed drain current, sometimes specified for various pulse durations). The drain current is limited by heating due to resistive losses in internal components such as bond wires, and other phenomena such as electromigration in the metal layer.

Maximum temperature]

The junction temperature (T_J) of the MOSFET must stay under a specified maximum value

for the device to function reliably, determined by MOSFET die

- It can be seen that C_{GDj} (and thus C_{GD}) is a capacitance which value is dependent
- upon the gate to drain voltage. As this voltage increases, the capacitance decreases.

When the MOSFET is in on-state, C_{GDj} is shunted, so the gate to drain capacitance remains equal to C_{oxD}, a constant value.

- **Drain to source capacitance**

As the source metallization overlaps the P-wells (see figure 1), the drain and source terminals are separated by a P-N junction. Therefore, C_{DS} is the junction capacitance. This is a non-linear capacitance, and its value can be calculated using the same equation as for C_{GDj}. So far we have discussed the n-channel MOSFET only, but all these are true for pchannelMOSFET also, with n-replaced by p layout and packaging materials. The packaging often limits the maximum junction temperature, due to the molding compound and (where used) epoxy characteristics.

The maximum operating ambient temperature is determined by the power dissipation and thermal resistance. The junction-to-case thermal resistance is intrinsic to the device and package; the case-to-ambient thermal resistance is largely dependent on the board/mounting layout, heatsinking area and air/fluid flow.

The type of power dissipation, whether continuous or pulsed, affects the maximum operating temperature, due to thermal mass characteristics; in general, the lower the frequency of pulses for a given power dissipation, the higher maximum operating ambient temperature, due to allowing a longer interval for the device to cool down. Models, such as a Foster network, can be used to analyze temperature dynamics from power transients.

Safe operating area

The safe operating area defines the combined ranges of drain current and drain to source voltage the power MOSFET is able to handle without damage. It is represented graphically as an area in the plane defined by these two parameters. Both drain current and drain-to-source voltage must stay below their respective maximum values, but their product must also stay below the maximum power dissipation the device is able to handle. Thus, the device cannot be operated at its maximum current and maximum voltage simultaneously

Applications:

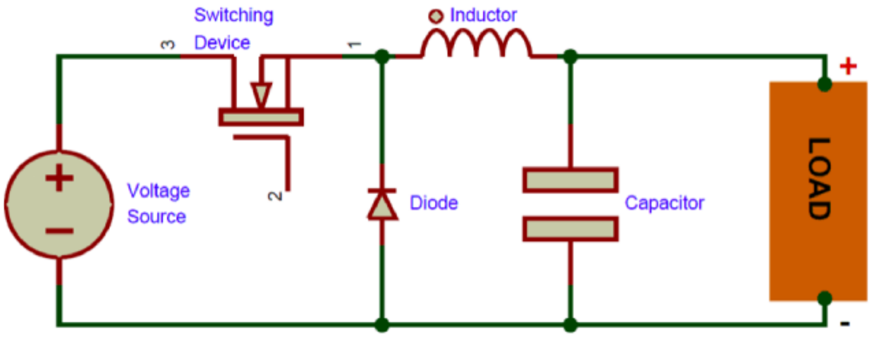
1. It can be linear power amplifier in the enhancement mode as C_{in} and g_m do not depend on V_g, while

   c_{out} is independent of v_{ds}.

2. Gate ac input signal can be quite large asn-channel depletion-type ON-MOSFET can operate fromdepletion-mode region ($-V_g$) to enhancement mode region ($+V_g$).

   Temperature Effect

5.5 .1.Buck Converter:



5.5.1 Buck Converter Circuit

Many a times in the electronics word we find the need to reduce one DC voltage to a lower one. For example we may need to power a 3.3V microcontroller from a 12V supply rail. The solution is simple, we just add a 3.3V linear regulator IC like LD1117 with the 12V rail and it regulates the voltage down to 3.3V. We have already learnt the working of Voltage regulators in our previous article.

Now, suppose we have to power an LED strip from the same 3.3V rail. LEDs easily consume around 20mA each, so a long strip would easily eat up an amp or so. If we calculate the power dissipated by the regulator:

$$P = (V_{in} – V_{out}) * I_{out}$$

The power dissipated comes out to be around 8.7 Watts! Now this is a LOT of power for a little linear regulator to dissipate. If we calculate the efficiency, which is just output power divided by the input power, it comes out to be a pathetic 38%!. Normally Linear voltage regulators has very low efficiency compared with switching regulators.

Now we feel the pressing need to find something that can step DC voltages down and do it efficiently!

Introduction to Buck Converters

Luckily such a device already exists, and it's called a buck converter or step down voltage regulators. It's a type of DC-DC converter, so it accomplishes the task using a few transistor switches and an inductor. A typical buck converter circuit is shown in the above image. It's quite similar to a boost converter, but the placement of the inductor and transistor are switched. The switch shown in the above circuit will normally be a power electronics switch like MOSFET, IGBT or BJT. The switch will be switched (turned on and off) by using a PWM signal.

The working of Buck converter is slightly similar to that of PWM 'dimming'. We've all heard of lights being dimmed by a PWM signal. A small duty cycle means that the average voltage seen by the load is small and when the duty cycle is high the average voltage is high too.

But average voltage is not what we need – a raw PWN signal oscillates between high voltage level and ground, something no delicate load (like the microcontroller) would like. Of course, connecting an RC filter to a square wave source renders the output clean. The voltage level of the filter depends on the duty cycle of the PWM signal – the higher the duty cycle the higher the output voltage.

So now we have a clean output voltage. The below graph shows the raw PWM signal in blue color and the filtered outputs in red and violet color

We could now simply use this as a buck converter, but there's one major drawback –the resistor in the RC filter limits the current and wastes energy in the form of heat, which is no better than the linear voltage regulator example.

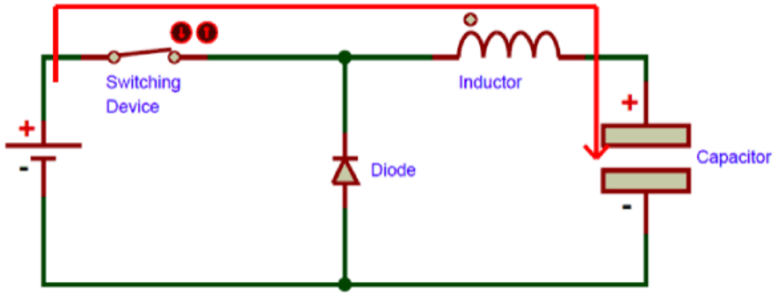
To fix this problem, we turn to another type of voltage filter, the LC filter, which does the same job as the RC filter but replaces the R with an L, in other words the resistor with an inductor. The inductor resists changes in current and the capacitor resists changes in voltage, which results in the output being smooth DC. And now we have a converter that is capable of stepping down DC voltages and doing it efficiently.

Working of a Buck Converter

The working of a buck converter can be broken down into a few steps.

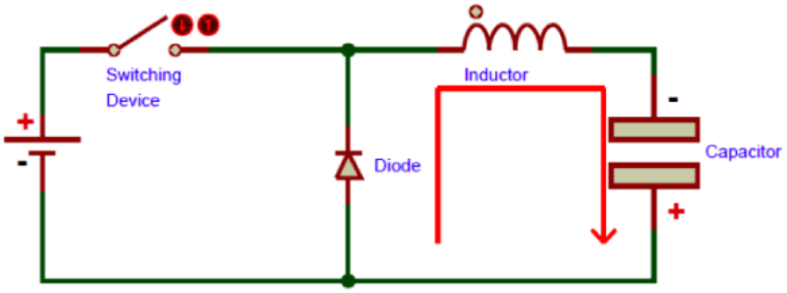
STEP – 1:

The switch turns on and lets current flow to the output capacitor, charging it up. Since the voltage across the capacitor cannot rise instantly, and since the inductor limits the charging current, the voltage across the cap during the switching cycle is not the full voltage of the power source.



STEP – 2:

The switch now turns off. Since the current in an inductor cannot change suddenly, the inductor creates a voltage across it. This voltage is allowed to charge the capacitor and power the load through the diode when the switch is turned off, maintaining current output current throughout the switching cycle.



These two steps keep repeating many thousands of times a second, resulting in continuous output.

Designing a Buck Converter

STEP – 1

Determine the input voltage and the output voltage and current.

The duty cycle of the converter is given by:

$$DC = V_{out}/V_{in}$$

STEP – 2

Determine the output power, that is, the product of the output voltage and current. This is also the input power, by the law of conservation of energy (though not exactly so – nothing is a hundred percent efficient!).

STEP - 3

Now divide the output power by the selected switching frequency in order to get the power transferred per pulse.

Since it is easier to talk about inductors in terms of energy, we can assume now that the output power is simply the output energy per second. So if the output of our converter is 30 Watts, then we can say that the output energy is thirty Joules every second.

STEP - 4

Now that we have the energy per pulse, we can calculate the inductance using the input current and the energy:

$$L = 2E/I^2$$

Where E is the energy transferred per pulse and I is the square of the input current.

Using the values of the inductance, frequency and duty cycle, we can now get to work building a simple boost converter.

Choice of Parts

MOSFET

Since the switch is on the high side, using an N channel MOSFET or an NPN bipolar wouldn’t work, unless we have a bootstrapped gate driver. Though this is possible, it is quite complicated.

Using a P channel device in these circumstances would be recommended, they greatly simplify driving requirements, but remember that they turn on when the gate is low, so an inverted signal would be necessary. One can use the IRF5210, it has a decent on resistance of 60mΩ and a V_{DS} of -100V,which should be plenty for most applications. However, there are many better devices available, the choice is entirely up to the designer based on the specific application.

Remember to use a gate driver to reduce switching losses!

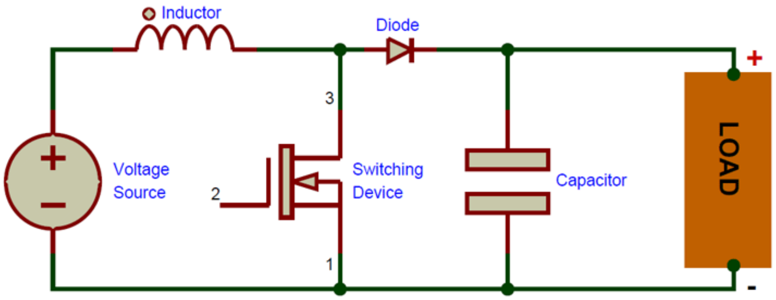
DIODE

Since this diode does not have to handle very high voltages, rather high currents, it would be a good design choice to use a Schottky diode with a low forward voltage drop to keep things efficient.

CAPACITOR

The capacitor value depends on the output voltage ripple and can be calculated using the capacitor equation, but generally a value between 100uF to 680uF for low current applications should suffice. Remember, the design process described here should not be treated as an expert rant, rather these are very simple equations to get your first buck converter up and running. Again, regulation is a topic that has not been covered here. If you want to make a regulated buck converter, it is recommended to use a dedicated buck controller IC like LM2596 designed specifically for that purpose.

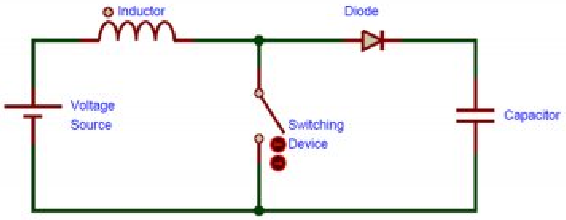
5.5.2 Boost Converter:



5.5.3.Boost Converter

(Source: Electronic Circuit Analysis- K.LalKishore, Page-235)

A boost converter is one of the simplest types of switch mode converter. As the name suggests, it takes an input voltage and boosts or increases it. All it consists of is an inductor, a semiconductor switch (these days it's a MOSFET, since you can get really nice ones these days), a diode and a capacitor. Also needed is a source of a periodic square wave. This can be something as simple as a 555 timer or even a dedicated SMPS IC like the famous MC34063A IC.



As you can see, there are only a few parts required to make a boost converter. It is less cumbersome than an AC transformer or inductor.

They're so simple because they were originally developed in the 1960s to power the electronics systems on aircraft. It was a requirement that these converters be as compact and as efficient as possible.

The biggest advantage boost converters offer is their high efficiency – some of them can even go up to 99%! In other words, 99% of the input energy is converted to useful output energy, only 1% is wasted.

Boost Converter Working:

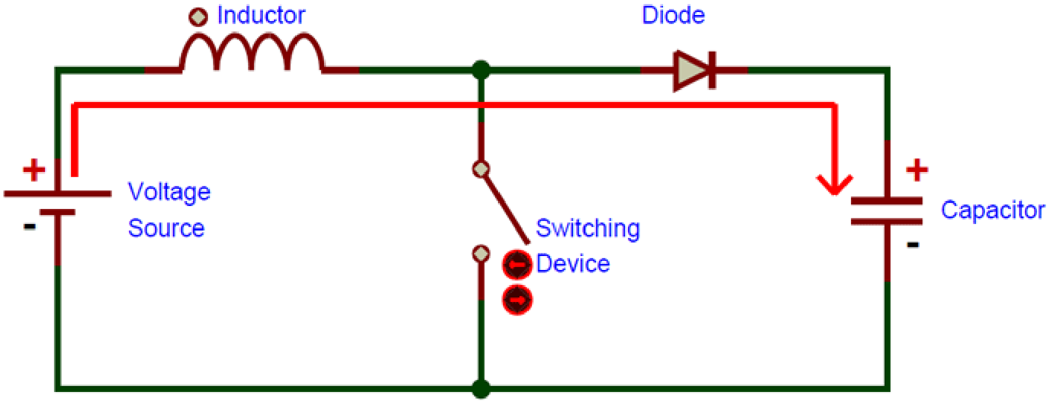
It's time to take a really deep breath, we're about to plunge into the depths of power electronics. I'll say at the outset that it is a very rewarding field.

To understand the working of a boost converter, it is mandatory that you know how inductors, MOSFETs, diodes and capacitors work.

With that knowledge, we can go through the working of the boost converter step by step.

STEP – 1

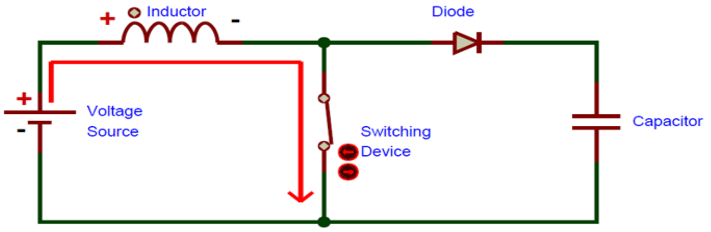
Here, nothing happens. The output capacitor is charged to the input voltage minus one diode drop.



STEP – 2

Now, it's time to turn the switch on. Our signal source goes high, turning on the MOSFET. All the current is diverted through to the MOSFET through the inductor. Note that the output capacitor stays charged since it can't discharge through the now back-biased diode.

The power source isn't immediately short circuited, of course, since the inductor makes the current ramp up relatively slowly. Also, a magnetic field builds up around the inductor. Note the polarity of the voltage applied across the inductor.



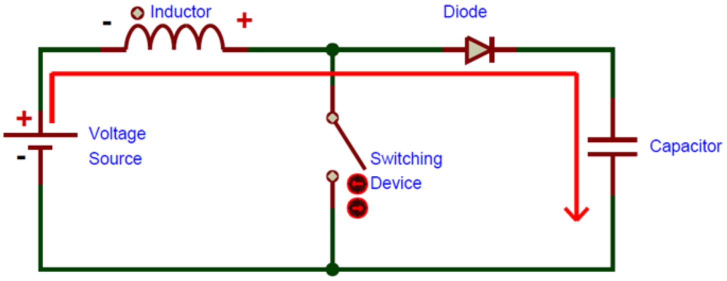
STEP – 3

The MOSFET is turned off and the current to the inductor is stopped abruptly.

The very nature of an inductor is to maintain smooth current flow; it doesn't like sudden changes in current. So it does not like the sudden turning off of the current. It responds to this by generating a large voltage with the opposite polarity of the voltage originally supplied to it using the energy stored in the magnetic field to maintain that current flow.

If we forget the rest of the circuit elements and notice only the polarity symbols, we notice that the inductor now acts like a voltage source in series with the supply voltage. This means that the anode of the diode is now at a higher voltage than the cathode (remember, the cap was already charged to supply voltage in the beginning) and is forward biased.

The output capacitor is now charged to a higher voltage than before, which means that we have successfully stepped up a low DC voltage to a higher one!



It recommend that go through the steps once again very slowly and understand them intuitively. These steps happen many thousands of times (depending on the frequency of the oscillator) to maintain the output voltage under load.

Boost Converter Operation - The Fine Points

By now many of We have already have questions about this oversimplified explanation. There was a lot left out, but it was worth it to make the working of the boost converter absolutely clear. So now that we have that understanding, we can move on to the finer details.

1. The Oscillator. You can't keep the MOSFET output switch on forever, no inductor is ideal – they have saturation currents. If we did keep the MOSFET switch on for any longer than a few hundred microseconds max, the supply will be short circuited and the inductor insulation burns off and the MOSFET goes bust and other nasty things happen. We use our knowledge of inductors to calculate the time required to reach a sensible current (one Amp, for example) and then configure the on time of the oscillator accordingly. This results in the inductor current waveform looking like a saw edge, hence the name sawtooth.

2. The MOSFET itself. If you look closely, during step 3, the MOSFET sees a voltage that is the supply voltage plus the inductor voltage, which means that the MOSFET has to be rated for a high voltage, which again implies a rather high on resistance. Boost converter design is always a compromise between MOSFET breakdown voltage and on resistance. The switching MOSFET of the boost converter is always the

weak point, as I learned from cold, hard experience. The maximum output voltage of the boost converter is not limited by design but by the breakdown voltage of the MOSFET.

3. The inductor. Obviously, just any old inductor won't work. Inductors used in boost converters should be able to withstand the high currents and have a highly permeable core, so that the inductance for a given size is high.

Boost Converter Operation

There is yet another way of thinking about the operation of a boost converter.

We know that the energy stored in an inductor is given by:

$$\frac{1}{2} \times L \times I^2$$

Where L is the inductance of the coil and I is the maximum peak current.

So we store some energy in the inductor from the input and transfer that same energy to the output though at a higher voltage (power is conserved, obviously). This happens many thousands of times a second (depending on the oscillator frequency) and so the energy adds up in every cycle so you get a nice measurable and useful energy output, for example 10 Joules every second, i.e. 10 watts.

As the equation tells us, the energy stored in the inductor is proportional to the inductance and also to the square of the peak current.

To increase output power our first thoughts might be to increase the size of the inductor. Of course, this will help, but not as much as we think! If we make the inductance larger, the maximum peak current that can be achieved in a given time decreases, or the time taken to reach that current increases (remember the basic equation $V/L = dI/dt$), so the overall output energy does not increase by a significant amount!

However, since energy is proportional to the square of the maximum current, increasing the current will lead to a larger increase in output energy!

So we understand that choosing the inductor is a fine balance between inductance and peak current.

With this knowledge we can being to understand the formal method of designing a boost converter.

Boost Converter Design

STEP – 1

To begin with, we need a thorough understanding of what our load requires. It is highly recommended (from experience) that if you attempt to build a boost converter at the beginning it is very important to know the output voltage and current independently, the product of which is our output power.

STEP – 2

Once we have the output power, we can divide that by the input voltage (which should also be decided) to get the average input current needed. We increase the input current by 40% to account for ripple. This new value is the peak input current. Also the minimum input current is 0.8 times the average input current, so multiply the average input current by 0.8. Now that we have peak and minimum current, we can calculate the total change in current by subtracting the peak and minimum current.

STEP – 3

Now we calculate the duty cycle of the converter, i.e. the ratio of the on and off times of the oscillator.

Duty cycle is given by this textbook formula:

$$D.C. = (V_{out} - V_{in})/(V_{out})$$

This should give us a reasonable decimal value, above 0 but below 0.999.

STEP – 4

Now it is time to decide upon the frequency of the oscillator. This has been included as a separate step because the signal source can be anything from a 555 timer (where the frequency and duty cycle are completely under your control) or a fixed frequency PWM controller. Once the frequency is determined, we can find out the total time period by taking an inverse. Now the time period is multiplied by the duty cycle value to get the on time.

STEP – 5

Since we have determined the on time, input voltage and change in current, we can plug those values into the inductor formula which has been rearranged a little:

$$L = (V*dt)/dI$$

Where V is the input voltage, dt is the on time and dI is the change in current.

Don’t worry if the inductor value is not a commonly available one, use the closest standard value available. With a little tweaking, the system should work just fine.

Selection of Parts

1. Switching Transistor

It have not mentioned the type since that is completely based on the application. Of course, the MOSFET is used in all applications these days, since they are very efficient, but there may be situations where a normal bipolar transistor may suffice because of simplicity.

It might also be a good choice to look at the MOSFET datasheet and determine the input capacitance/gate capacitance. The lower this value is, the easier the driving requirements are. Anything below 3500pF is acceptable and moderately easy to drive.

My personal choice would be the IRF3205, which has an on resistance of 8 milliOhms and a breakdown voltage of 55V, with a manageable input capacitance of 3247pF, besides being an easily available part.

Also not mentioned in the schematic was a dedicated MOSFET gate driver. Again, I *highly* recommend using one. It’ll save you a lot of losses and time. My recommendation – the TC4427. It has two drivers in one DIP8 package, which can be paralleled easily for more drive current.

2. Output Diode

Though this may seem trivial, at the currents we are dealing with (or sometimes voltage) the choice of diode plays a large role in efficiency.

Unfortunately the common 1N4007 won't work, since it is too slow. Neither will the beefy 1N5408. I've tried both on designs that I worked on, both performed miserably since they were so slow. It's not worth even trying.

I use the UF4007, with the same voltage rating as the 1N4007 (1000V reverse).

If you're building a low voltage converter (say 3.3V to 5V) then the diode of choice would be a Schottky, like the 1N5822.

5.5.3 Buck Boost Converter :

The buck boost converter is a DC to DC converter. The output voltage of the DC to DC converter is less than or greater than the input voltage. The output voltage of the magnitude depends on the duty cycle. These converters are also known as the step up and step down transformers and these names are coming from the analogous step up and step down transformer. The input voltages are step-up/down to some level of more than or less than the input voltage. By using the low conversion energy, the input power is equal to the output power. The following expression shows the low of a conversion.

Input power (Pin) = Output power (Pout)

For the step up mode, the input voltage is less than the output voltage (Vin < Vout). It shows that the output current is less than the input current. Hence the buck booster is a step up mode.

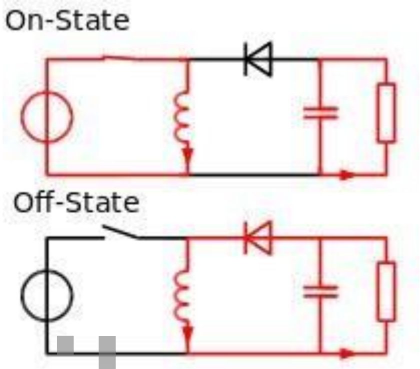
Vin < Vout and Iin > Iout

In the step down mode the input voltage is greater than the output voltage (Vin > Vout). It follows that the output current is greater the input current. Hence the buck boost converter is a step down mode.

Vin > Vout and Iin < Iout

What is a Buck Boost Converter?

It is a type of DC to DC converter and it has a magnitude of output voltage. It may be more or less than equal to the input voltage magnitude. The buck boost converter is equal to the fly back circuit and single inductor is used in the place of the transformer. There are two types of converters in the buck boost converter that are buck converter and the other one is boost converter. These converters can produce the range of output voltage than the input voltage. The following diagram shows the basic buck boost converter.



5.5.5Buck Boost Converter

(Source: Electronic Circuit Analysis- K.LalKishore, Page-245)

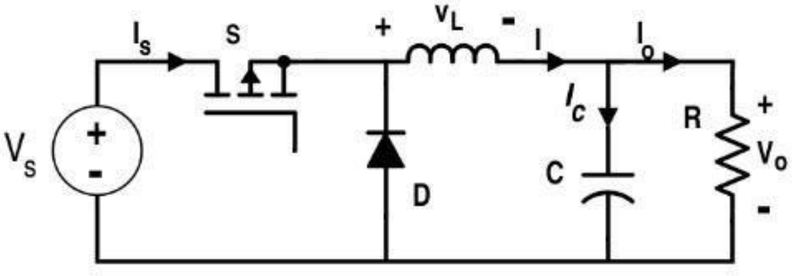
Working principle of Buck-Boost Converter

The working operation of the DC to DC converter is the inductor in the input resistance has the unexpected variation in the input current. If the switch is ON then the inductor feed the energy from the input and it stores the energy of magnetic energy. If the switch is closed it discharges the energy. The output circuit of the capacitor is assumed as high sufficient than the time constant of an RC circuit is high on the output stage. The huge time constant is compared with the switching period and make sure that the steady state is a constant output voltage Vo(t) = Vo(constant) and present at the load terminal.There are two different types of working principles in the buck boost converter.

- Buck converter. And Boost converter.

Buck Converter Working

The following diagram shows the working operation of the buck converter. In the buck converter first transistor is turned ON and second transistor is switched OFF due to high square wave frequency. If the gate terminal of the first transistor is more than the current pass through the magnetic field, charging C, and it supplies the load. The D1 is the Schottky diode and it is turned OFF due to the positive voltage to the cathode.



5.5.6.Buck Converter Working

(Source: Electronic Circuit Analysis- K.LalKishore, Page-245)

The inductor L is the initial source of current. If the first transistor is OFF by using the control unit then the current flow in the buck operation. The magnetic field of the inductor is collapsed and the back e.m.f is generated collapsing field turn around the polarity of the voltage across the inductor. The current flows in the diode D2, the load and the D1 diode will be turned ON. The discharge of the inductor L decreases with the help of the current. During the first transistor is in one state the charge of the accumulator in the capacitor. The current flows through the load and during the off period keeping Vout reasonably. Hence it keeps the minimum ripple amplitude and Vout closes to the value of Vs

Boost Converter Working

In this converter the first transistor is switched ON continually and for the second transistor the square wave of high frequency is applied to the gate terminal. The second transistor is in conducting when the on state and the input current flow from the inductor L through the second transistor. The negative terminal charging up the magnetic field around the inductor. The D2 diode cannot conduct because the anode is on the potential ground by highly conducting the second transistor.

Boost Converter Working

By charging the capacitor C the load is applied to the entire circuit in the ON State and it can construct earlier oscillator cycles. During the ON period the capacitor C can discharge regularly and the amount of high ripple frequency on the output voltage. The approximate potential difference is given by the equation below.

$$VS + VL$$

During the OFF period of second transistor the inductor L is charged and the capacitor C is discharged. The inductor L can produce the back e.m.f and the values are depending up on the rate of change of current of the second transistor switch. The amount of inductance the coil can occupy. Hence the back e.m.f can produce any different voltage through a wide range and determined by the design of the circuit. Hence the polarity of voltage across the inductor L has reversed now. The input voltage gives the output voltage and atleast equal to or higher than the input voltage. The diode D2 is in forward biased and the current applied to the load current and it recharges the capacitors to VS + VL and it is ready for the second transistor.

Modes Of Buck Boost Converters

There are two different types of modes in the buck boost converter. The following are the two different types of buck boost converters.

- Continuous conduction mode.
- Discontinuous conduction mode.

Continuous Conduction Mode

In the continuous conduction mode the current from end to end of inductor never goes to zero. Hence the inductor partially discharges earlier than the switching cycle.

Discontinuous Conduction Mode

In this mode the current through the inductor goes to zero. Hence the inductor will totally discharge at the end of switching cycles.

Applications of Buck boost converter

- It is used in the self regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Adaptive control applications.
- Power amplifier applications.

Advantages of Buck Boost Converter

- It gives higher output voltage.
- Low operating duct cycle.
- Low voltage on MOSFETs