Module 5: Power Amplifiers and Voltage Regulators

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Syllabus:

Power Amplifiers: Definition and amplifier types, Series fed class A amplifier, Transformer coupled class A amplifier, Class B amplifier operation and circuits, Amplifier distortion, Class C and Class D amplifiers. Voltage regulators: Discrete transistor voltage regulation - Series and Shunt Voltage regulators.

Courtesy:

Robert L. Boylestad and Louis Nashelsky, "Electronics Devices and Circuit Theory", Pearson, 10th Edition, 2012, ISBN: 978-81-317-6459-6.

Adel S. Sedra and Kenneth C. Smith, "Micro Electronic Circuits Theory and Applications," Oxford University Press, 5th Edition, ISBN:0198062257.

J.Millman & C.C.Halkias, "Integrated Electronics", 2nd edition, 2010, TMH. ISBN 0-07-462245-5.

U A Bakshi & A P Godse,"Analog Electronics",1st Edition-2009, Technical Publications, Pune

5.1 Introduction

When the power requirement to drive the load is in terms of several Watts rather than mili-watts the power amplifiers are used. Power amplifiers form the last stage of multistage amplifiers. If we consider the example of Public address systems where, microphone output or a CD player output is to be driven across loudspeakers then these signals undergo series of small signal amplifiers. The output of small signal amplifiers intern acts as input to Power amplifiers. The output of Power amplifier drives the loudspeaker.

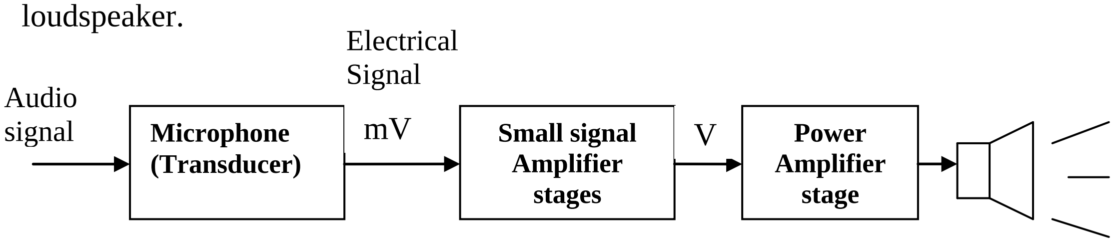


Figure 5.1 Public Address Systems

The power amplifier makes use of power transistors for signal amplification. Power amplifiers are classified depending upon the operating point (Q point) of operation and nature of output waveforms they produce. Basically, amplifier classes represent the amount the output signal variation over one cycle of operation for a full cycle of input signal. Power amplifiers are classified as CLASS A, CLASS B, CLASS AB, CLASS C and CLASS D Power amplifiers.

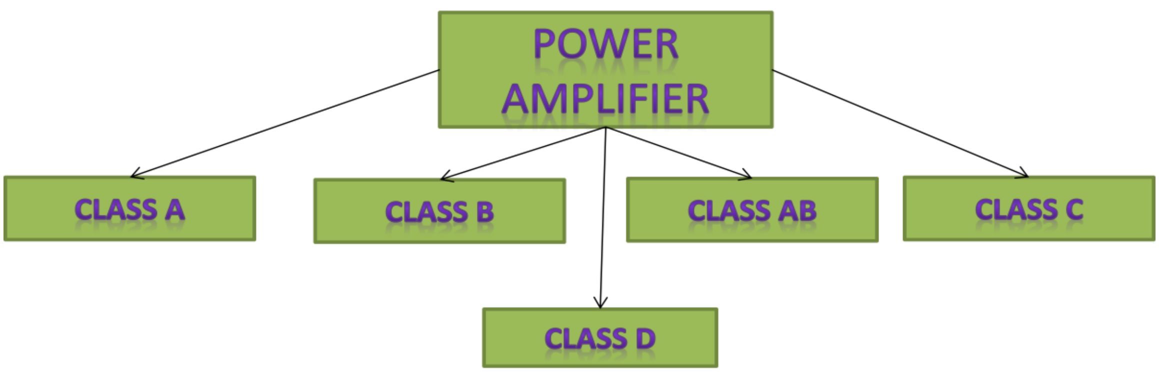


Figure 5.2 Classification of power amplifiers

5.2 Classification of Power Amplifiers:

5.2.1 CLASS A Power Amplifier

Here the Q pt & input signal are selected such that the output signal is entire 360^o amplified version of the input. This power amplifier is widely used for amplification of audio signals. Here Q pt is selected such that both Positive & Negative half cycle of the ac input are amplified. The efficiency of class A Power amplifies is between 25% to 50%.

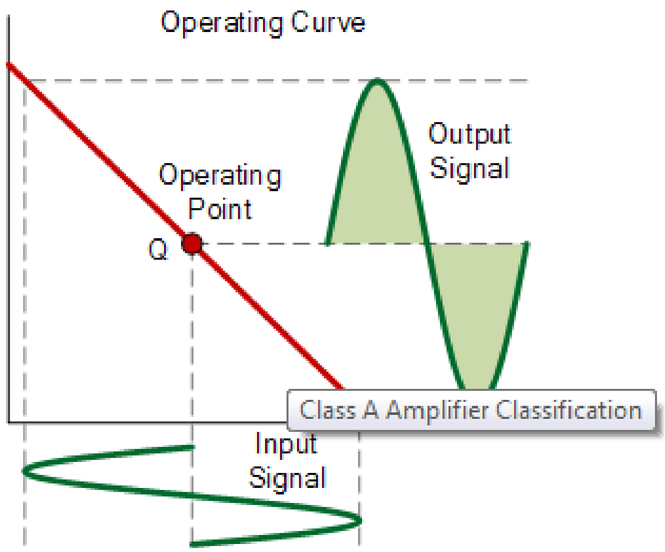


Figure 5.3 CLASS A Power Amplifier

5.2.2 CLASS B Power Amplifier

Here Q pt & input signal are selected that output signal is obtained for only one half of input signal. Usually class B operation is very much necessary for large signal amplification. Here Q pt is set at the x-axis. To have full cycle output, two class B operations—one to provide output on the positive output half-cycle and another to provide operation on the negative-output half-cycle are necessary. The combined half-cycles then provide an output for a full 360° of operation. This type of connection is referred to as push-pull operation, which is discussed later in this section. Efficiency of class B power amplifiers is more than 75%.

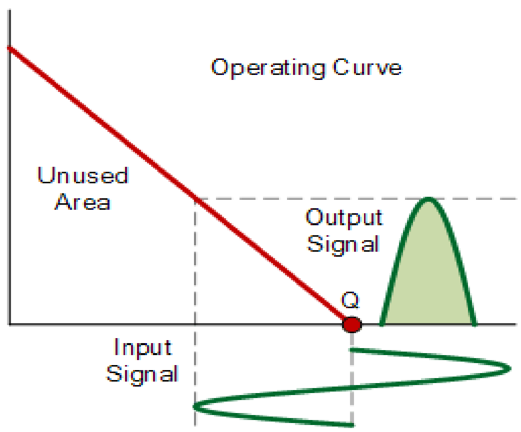


Figure 5.4 Class B Operation

5.2.3 CLASS AB Power Amplifier

Here Q pt & input signal are selected such that output signal is obtained for more than 180^o but less than 360^o. The 'Q' pt of class AB amplifiers is above the x-axis but below the midpoint of operation. Efficiency of class AB power amplifiers is more than class A & less than class B.

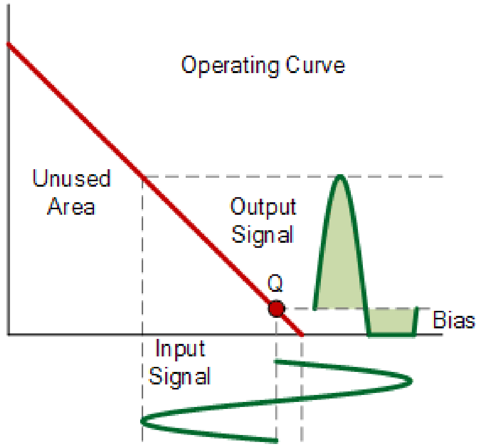


Figure 5.5 Class AB Operation

5.2.4 CLASS C Power amplifiers

Here 'Q' pt & input signal are selected such that output signal is present for less than 180o of input cycle. Class C power amplifies are not suitable for audio frequency amplification. These are useful in tuned circuits of all communication transmitters & receivers.

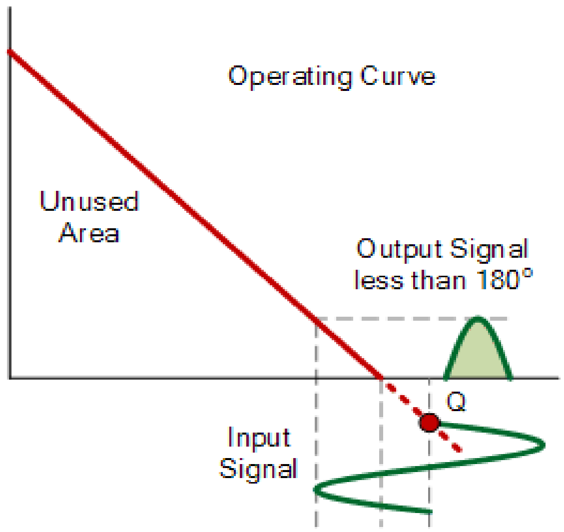


Figure 5.6 Class C operation

5.2.5 CLASS D power amplifiers

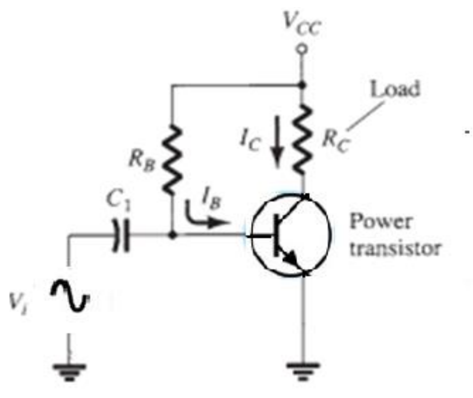
The class D amplifiers make use of digital signals to provide power amplification. The major advantage of class D operation is that the amplifier is on (using power) only for short intervals and the overall efficiency can practically be very high, as described in the next sections.

5.3CLASS A Power amplifiers

Class A power amplifiers can be classified as Directly coupled CLASS A power amplifiers & transformer coupled CLASS A power amplifiers

5.3.1 Directly coupled class A power amplifiers

The Figure 5.7 shows directly coupled class A amplifier. Where load resistance Rc to be driven is present at collector of the transistor amplifier. The Common Emitter Amplifier Circuitry is modified to act as class A power amplifier.



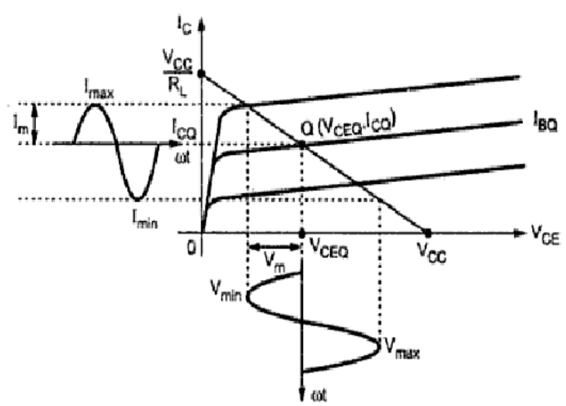


Figure 5.7 Directly coupled Class A Power Amplifiers   Figure 5.8 Output Characteristics

The design equations are shown as below:

$V_{CC}-I_BR_B-V_{BE}=0$

$I_B = \frac{Vcc-V_{BE}}{R_B}$ ------------------------------ (1)

$I_{CQ} = \beta I_B$ ------------------------------ (2)

$V_{CC}-I_CR_C-V_{CE}=0$

$V_{CEQ}= Vcc - I_CR_C$------------------------------ (3)

Derivation of Efficiency of Class A Power Amplifier

Output Power:

The ac power delivered to the load can be expressed in a number of ways. The ac power delivered to the load R_L may be expressed using rms signals as

$Pac = V_c I_c = I_c^2 R_L$ ------------------------------ (4)

Where V_c & I_c are the rms values of the output voltage

$$I_c = \frac{I_m}{\sqrt{2}} = \frac{I_{max} - I_{min}}{2\sqrt{2}} \quad \text{------------------------------ (5)}$$

$$V_c = \frac{V_m}{\sqrt{2}} = \frac{V_{max} - V_{min}}{2\sqrt{2}} \quad \text{-------------------------- (6)}$$

$$Pac = VcIc = \frac{V_m I_m}{2} = \frac{I_m^2 R_L}{2} = \frac{V_m^2}{2R_L} \quad \text{------------------------ (7)}$$

Input Power:

The power to an amplifier is provided by the DC supply. With no input signal, the dc current drawn is the collector bias current, I_{CQ}. Therefore power then drawn from the supply is

DC power $P_{dc} = V_{CC} \; I_{CQ}$ ------------------------------ (8)

Efficiency can be expressed as,

η=Output Power/Input Power

= Pac/Pdc

$$\eta = \frac{P_{ac}}{P_{dc}} = \frac{(V_{max} - V_{min})(I_{max} - I_{min})}{8V_{CC} I_{CQ}} \quad \text{------------------------------ (9)}$$

To derive maximum efficiency, it is assumed that Class A is operating at its Full efficiency, the voltage and current waveforms are as shown in figure 5.9.

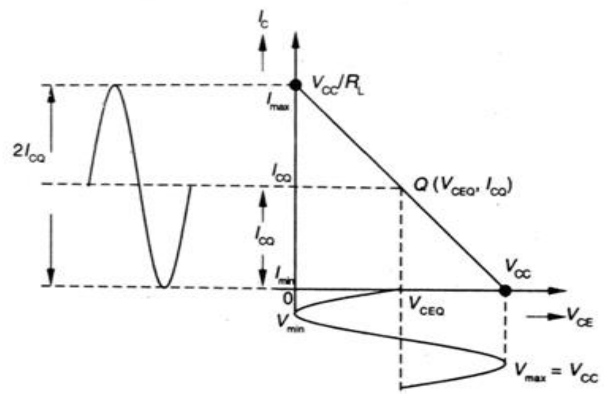


Figure 5.9 Output characteristics at maximum efficiency

We can observe from the above diagram that,
For maximum efficiency,

$$V_{max} = V_{CC} \ \& \ V_{min} = 0 \quad \text{------------------------------ (10)}$$

$$I_{max} = 2I_{CQ} \ \& \ I_{min} = 0 \quad \text{------------------------------ (11)}$$

Therefore, maximum efficiency,

$$\eta_{max} = \frac{V_{CC}\, 2I_{CQ}}{8V_{CC}\, I_{CQ}} = 25\% \quad \text{------------------------------ (12)}$$

Advantages of directly coupled class A amplifier,

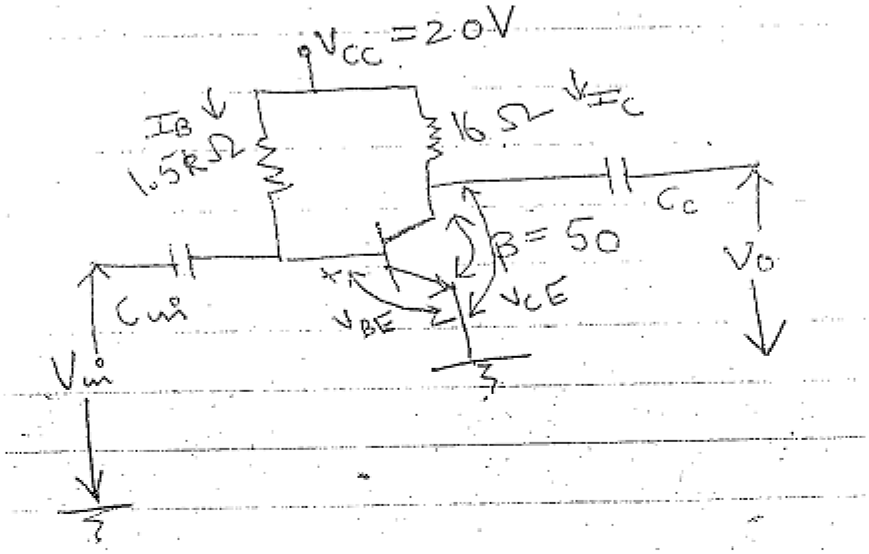
1. Circuit is simple to design.
2. Used as audio signal amplifier.
3. Less costly.

Disadvantages:

1. Efficiency is less
2. Transistor's output impedance is large.
3. Typical load impedance is very low (loud speakers having resistances only from 5-16Ω) **therefore, Impedance mismatch exists and maximum power transfer cannot be achieved. Efficiency is limited to 25%.**

Problems

1) A class A power amplifier operates from a DC source and applied sinusoidal signal generates a peak 9mA. Calculate I_{CQ}, V_{CEQ}, P_{DC}, $P_{AC,}$ η
Assume β=50, V_{BE} =0.7V. It is given that applied signal generates peak base current of 9mA .



To calculate DC Power,

Applying KVL to BE loop we get,

V_{CC}-$I_B R_B$-V_{BE}=0

$I_B = \frac{Vcc-V_{BE}}{R_B}$ =12.87mA

$I_{CQ} = \beta I_B$=643.5mA

KVL to CE loop,
V_{CC}-$I_C R_C$ -V_{CE}=0
$V_{CEQ}= Vcc - I_C R_C$ =9.704V

Therefore, DC input power, $P_{DC}=V_C I_{CQ}$

P_{DC}=12.87W

AC output power= $I^2_{RMS}.R_L$
=$i^2_{CRMS}.R_C$
It is given that,
i_{bm}= 9mA.
$i_{cm}=\beta i_{bm}$
i_{cm}=45mA
$i^2_{CRMS}=\frac{450mA}{\sqrt{2}} = 0.318A$

$P_{AC}=(0.318)^2X16=1.618W$

$\eta=\frac{P_{AC}}{P_{DC}} X100\% = \frac{1.618}{12.87} = 12.57\%$

5.3.2 Transformer Coupled Class A Power Amplifier

Disadvantages associated with directly coupled class A amplifier can be over-come by my making use of transformer at the output. In case of directly coupled class A amplifier output impedance of amplifier is large. The typical loads such as loudspeaker have very low input impedance 5 to 16Ω, due to this impedance mismatching maximum power transmission to the load cannot be achieved. If transformer is used as a impedance matching device then maximum power transfer to the load and efficiency of up to 50% can be achieved.

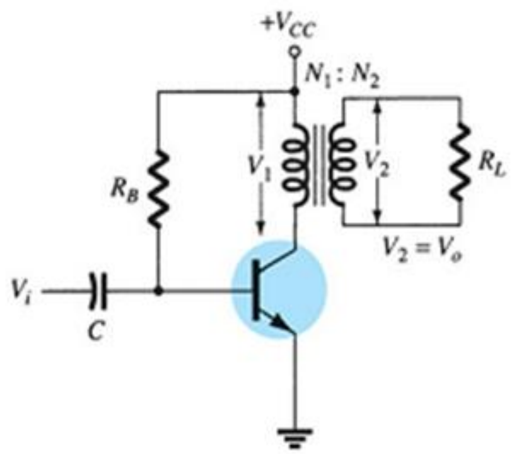


Figure 5.10 Transformer coupled class A Power amplifier

Impedance transformation property of the transformer

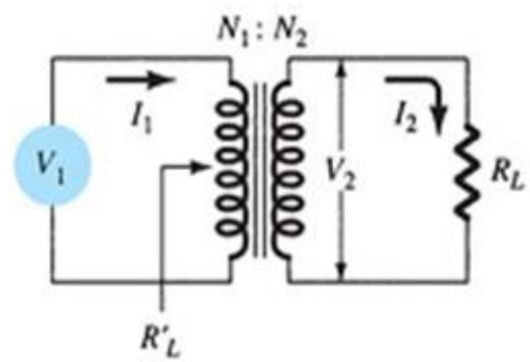


Figure: 5.11 Transformer windings

We know that Turns ratio, $\eta = \frac{V_2}{V_1} = \frac{N_2}{N_1}$ − − − − − − − − − − − − − (13)

Also, $\frac{N_2}{N_1} = \frac{I_1}{I_2}$ − (14)

At secondary, load resistance can be expressed as, $R_L = \frac{V_2}{I_2}$ − − − − (15)

Reflected impedance at the 1° side of the transformer can be expressed as

$$R^{I}_{L} = \frac{V_1}{I_1}$$

$$= \frac{\left(\frac{N1}{N2}\right)V2}{\left(\frac{N2}{N1}\right)I2} = \left(\frac{N1}{N2}\right)^2 R_L$$

$$R^{I}_{L} = \left(\frac{1}{n^2}\right)R_L \text{ ------------------------------------ } (16)$$

It can be seen that impedance at the 2° gets reflected at the 1° by the square of turn's ratio. This makes impedance matching possible.

DC operation: Applying KVL to CE loop, we get In an ideal transformer, there is no primary drop. Thus the supply voltage appears as the collector-emitter voltage of the transistor. Winding offers no resistance.

$$V_{CC} = V_{CE} \text{ ....}(17)$$

When the values of the resistance R_B and V_{CC} are known, the base current at the operating point may be calculated by the equation,

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} \approx \frac{V_{CC}}{R_B} \text{ ....}(18)$$

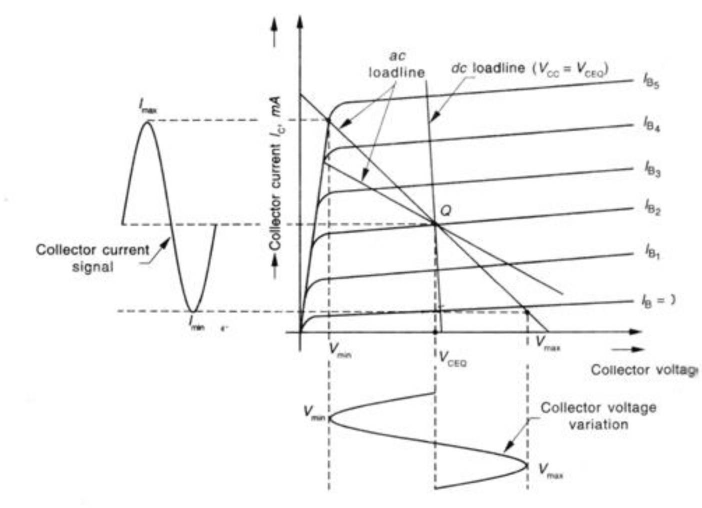


Figure 5.12 Output Characteristics of transformer coupled Power A Power Amplifiers

Efficiency of transformer coupled Class A Power Amplifier can be expressed as,

$$\text{Efficiency } \eta = \frac{\left(\frac{o}{p}\right) power}{\left(\frac{i}{p}\right) power} = \frac{P_{AC}}{P_{DC}} - - - - - - - - - - - - - - (19)$$

DC Power, $P_{DC}=V_{CC}*I_{CQ}$ -------------------------------------- (20)

AC Output power can be derived as,

$$P_{AC}(\text{primary})=I_1{}^2{}_{RMS}R^I{}_L=\frac{V_{1RMS}{}^2}{R^I{}_L}=V^2{}_{1RMS}I^1{}_{RMS}=\frac{V_{1M}}{\sqrt{2}}.\frac{I_{1M}}{\sqrt{2}}=\frac{V_{1M}I_1}{2} ....(21)$$

$$P_{AC}(2^O)=I^2{}_{2RMS}.R_L=\frac{V_{2RMS}{}^2}{R_L}=V_{2RMS}I_{2RMS}$$

$$=\frac{V_{2M}}{\sqrt{2}}.\frac{I_{2M}}{\sqrt{2}}=\frac{V_{2M}I_{2M}}{2} ....(22)$$

Assuming lossless Transformer,

AC power at 1^o=AC Power at 2^o

$P_{AC}(1^O)=P_{AC}(2^O)$

$P_{ACMAX}=\frac{V_{PP}I_{PP}}{8}$

$=(V_{CEMAX}-V_{CEMIN})(I_{CMAX}-I_{CMIN})/8$

$=\frac{(2V_{CC}-0)(2I_{CQ}-0)}{8}$

$=\frac{V_{CC}I_{CQ}}{2}$..........................(23)

Assuming that class A amplifier is operating at its full efficiency then the waveforms of current and voltages as shown in Figure 5.13.

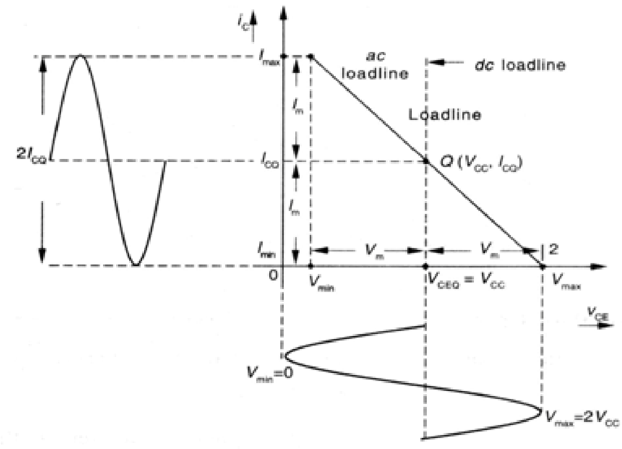


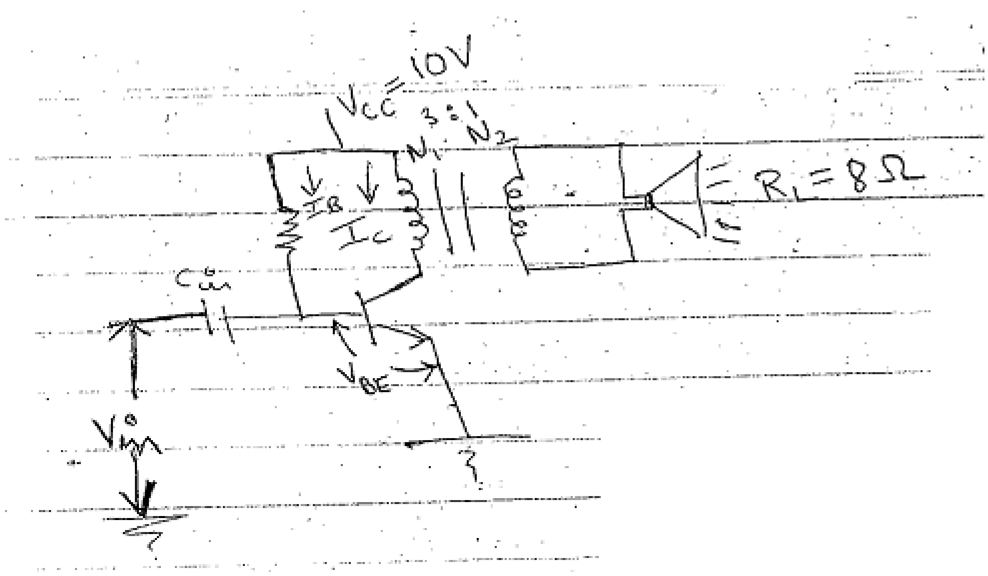
Figure 5.13 Output Characteristics of transformer coupled Power A Power Amplifiers at maximum efficiency

Maximum efficiency of class A amplifier can be expressed as

$$\eta_{max} = \frac{(2V_{CC}-0)(2I_{CQ}-0)}{8} = \frac{V_{CC}I_{CQ}}{2} \text{........(24)}$$

$$\eta_{max} = 50\%$$

1) A transformer coupled class A amplifier has a loudspeaker of 8Ω connected across its secondary. The Q pt of collector current is 140mA. The turns ratio of the transformer is 3:1. The collector supply voltage is 10V. If the transformer is lossless, calculate power delivered to the 1^{o} of the transformer, rms load current, rms 1^{0} current η and power dissipation. The power delivered to the load is 0.48W



Solution:
It is given that, P_{AC}(sec)=0.48W, I_{CQ}=140mA, R_{L}=8Ω
N2 / N1=1/3 = V2 / V1=I1 / I2
Transformer is lossless,
Therefore, $P_{AC(1*)}=P_{AC(2*)}$=0.48W

$P_{AC}(sec)=\frac{{V_{2RMS}}^2}{R_L}$

V_{2RMS}=1.96V
We know that, $\frac{V_{2RMS}}{V_{1RMS}} = \frac{N_2}{N_1}$

$V_{1RMS}=\frac{1.96*3}{1}$=5.88V

$I_{2RMS}=\frac{V_{2RMS}}{R_L} = 0.245A$

Output Power, $P_{DC}=V_{CC}I_{CQ}$

$=10*140*10^{-3}$=1.4W

Therefore, Efficiency, $\eta=\frac{P_{AC}}{P_{DC}}$
$=\frac{0.48}{1.4} * 100\%$

=34.29%

Power dissipation

It is the amount of power that is dissipated as heat across the power amplifier.
$P_D=P_{DC}-P_{AC}$ =1.4-0.48=0.92W

In Class A power amplifier, maximum power dissipation occurs when applied AC signal is zero. $P_{dmax}=P_{DC}=V_{CC}I_{CQ}$

Drawbacks of Class A power amplifier

- Less Efficiency of 25-50%.
- Power dissipation is high, therefore less reliability.
- Directly coupled class A power amplifier cannot be employed to drive low impedance loads such as loud speaker.
- Total harmonic distortion is very high.
- The output transformer is subjected to saturation problem due to the dc current in the primary.

5.4 Class B power amplifier

In class B power amplifier, output waveform is present only for 180^o of the input cycle. This is because Q pt is biased at x-axis, therefore negative half cycle is clipped and only the Positive half cycle appears at the load. If we make use of 2 class B amplifiers, each for 180^o conduction, than full power will be applies to the load. There are 2 categories of class B amplifiers. (i) Transformer coupled Push-Pull class B Power Amplifier and

(ii) Complimentary Symmetry Class B Power Amplifier

i) Transformer coupled Push-Pull class B Power Amplifier

Push-Pull Power Amplifier: These make of two identical npn or pnp transistors whereas complementary symmetry makes use of 1 pnp and 1 npn transistors. As shown in the Figure 5.14, push pull PA makes use of two centre tapped transformers, one is called as driver transformer as it drives input to the circuitry, another is a output transformer which acts a impedance matching device and couples the power to the load. The center tapped end of the driver transformer is connected to the ground and the center tapped output transformer is connected to V_{CC}. The 2 transistors Q_1 and Q_2 should be both either pnp or npn. During positive half cycle end A becomes Positive with respect to end B, therefore Q_1 gets forward biased and Q_2 gets reverse biased. Q_1 conducts and Positive half cycle is connected to the load by making use of output transformer. During negative half cycle, end B becomes positive with respect to A. therefore Q_2 gets forward biased and Q_1 gets reverse biased. Q_2 conducts and negative half cycle is connected to the load by making use output transformer. Amplified output appears for entire 360^o of the input cycle.

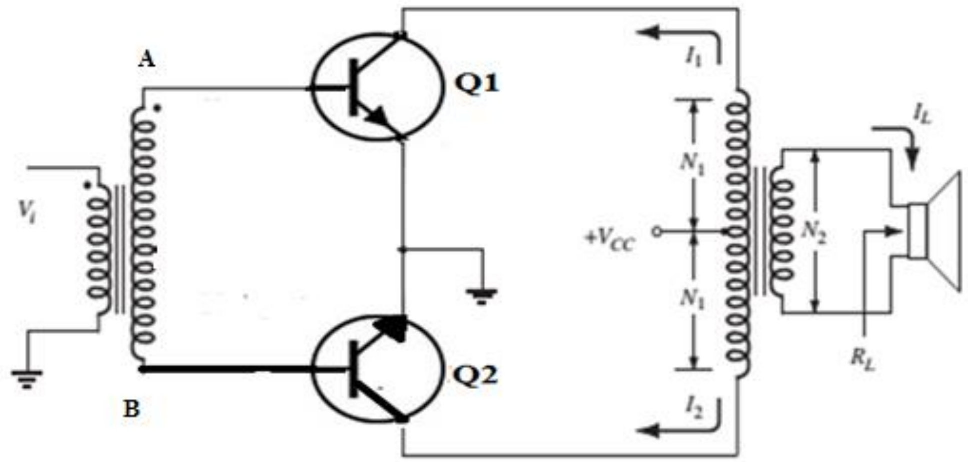


Figure 5.14 Class B Power Amplifier

Derivation of efficiency of Class B Power Amplifier

We know that Efficiency of Power Amplifier can be expressed as,

$$\eta=\frac{P_{AC}}{P_{DC}}\text{..........................}(25)$$

DC Operation

Applying KVL to output,
$V_{CC}-V_{CE}=0$
Therefore; $V_{CC}=V_{CE}$ ....(26)
DC load line is straight line as shown in the output characteristics.

Here each transistor conducts only for half cycle. Therefore it can be treated as half wave rectifier.

$P_{DC}=V_{CC}I_{DC}=V_{CC}\frac{2I_M}{\pi}=\frac{2V_{CC}I_M}{\pi}$..................(27)
Current flowing through half wave rectifier is I_{DC}, therefore overall DC current $I_{DC}=\frac{2I_M}{\pi}$
Output power, $P_{AC}(1^o)=V_{RMS}I_{RMS}$

$$=\frac{V_{1RMS}{}^2}{R_L{}^I}=I^2{}_{RMS}R_L{}^I=\frac{V_{1M}}{\sqrt{2}}\frac{I_{1M}}{\sqrt{2}}=\frac{V_{1M}I_{1M}}{2}$$

$$P_{AC}(2^O)=V_{2RMS}I_{2RMS}$$

$$=\frac{V^2{}_{2RMS}}{R_L}=I^2{}_{2RMS}R_L=\frac{V_{2M}I_{2M}}{2}$$

For a lossless transformer,
$P_{AC}(1^o)=P_{AC}(2^O)=\frac{V_{PP}I_{PP}}{8}==\frac{V_{PP}}{8}\left(\frac{V_{PP}}{R_L}\right)=\frac{V_{PP}{}^2}{8R_L}=\frac{(2V_M)^2}{8R_L}=\frac{V_M{}^2}{2R_L}$

Efficiency:

$\eta=Pac/Pdc$

$$\eta=\frac{(V^2{}_M/2R_L)}{2V_{CC}I_M V_M}=\frac{\pi}{4}\frac{V_M}{V_{CC}}$$

For max efficiency:
$V_M=V_{CC}$
$\eta_{MAX}=\frac{\pi}{4}\frac{V_{CC}}{V_{CE}}=78.55\%$

Power dissipation of class B power amplifier

We know that Power dissipation, $P_D=P_{DC}-P_{AC}=\frac{2V_{CC}I_M}{\pi}-\frac{V_M{}^2}{2R_L}$
$P_D=\frac{2V_{CC}I_M}{\pi R_L}-\frac{V_M{}^2}{2R_L}$ −−−−−−−−−−−−−(28)

To calculate the condition for max power dissipation is $\frac{dP_D}{dV_M} = 0$

$0=\frac{2V_{CC}}{\pi R_L} - \frac{2V_M}{2R_L}$

$\frac{V_M}{R_L} = \frac{2V_{CC}}{\pi R_L}$

Therefore, $V_M = \frac{2V_{CC}}{\pi}$ is the condition for max power dissipation.

Sub $V_M=\frac{2V_{CC}}{\pi}$ $in\ (28) to\ get$ max $power\ dissipation$

$P_D=\frac{2V_{CC}}{\pi R_L} * \frac{2V_{CC}}{\pi} - (\frac{2V_{CC}}{\pi})^2 \frac{1}{2\pi R_L}$

$=\frac{V^2{}_{CC}}{\pi^2 R_L} - \frac{4V^2{}_{CC}}{\pi^2 R_L}$

Therefore, Maximum Power dissipation, $P_{DMAX}=\frac{2V^2{}_{CC}}{\pi^2 R_L} - - - - - - - - -(29)$

Power dissipation of each transistor is $P_D=\frac{V^2{}_{CC}}{\pi R_L{}^2}$......................(30)

Problems:

1) Calculate the efficiency of class B amplifier for a supply voltage of V_{CC}=24V with the output load of i) V_L(p)=22V ii) V_L(p)=6V

Solution: Efficency, (i) η=78.5($\frac{V_M}{V_{CC}}$) =78.5(22/24)=71.95%

V_M=6V, (ii) η =78.5*6/24=19.625%

2) For a class B amplifier providing a 20 V peak signal to a 16Ω loud speaker and a power supply of V_{CC}=30V. Calculate DC input power, AC output power and its efficiency.

Solution: V_M=20V; R_L=16 Ω

DC input power =$\frac{2V_{CC}V_M}{\pi_{RL}}$=$\frac{2*30*20}{\pi*16}$=23.87W

$P_{AC}=\frac{V^2{}_M}{2R_L}$=12.5W

η =$\frac{P_{AC}}{P_{DC}} = 52.37\%$

3) For a class B PA using a supply voltage of V_{CC}=30V and driving a load of rR_L=16 Ω, determine max power dissipation and power dissipation of each transistor

Solution: Maximum efficiency, $V_{CC}=V_M$

P_{DC}(max)=$\frac{2V_{CC}V_M}{\pi R_L} = 35.81W$

P_{AC}(max)=$\frac{V^2{}_M}{2R_L} = 28.125W$

P_D(max)=$\frac{2V^2{}_{CC}}{\pi R^2{}_L} = 11.396W$

Each transistor, P_D(max)=5.698W

ii) Complimentary-Symmetry Class B Power Amplifier

Complimentary-symmetry makes use of npn and pnp transistors. Compared to a push pull configuration, this circuitry provides many advantages.

1) No transformers are used; hence circuitry is less bulky and less costly.

2) Matched pair of npn and pnp are used in common collector configuration. CC configuration has high input impedance; therefore impedance matching is achieved in the circuitry itself.

3) Frequency response is improved as transformers are absent.

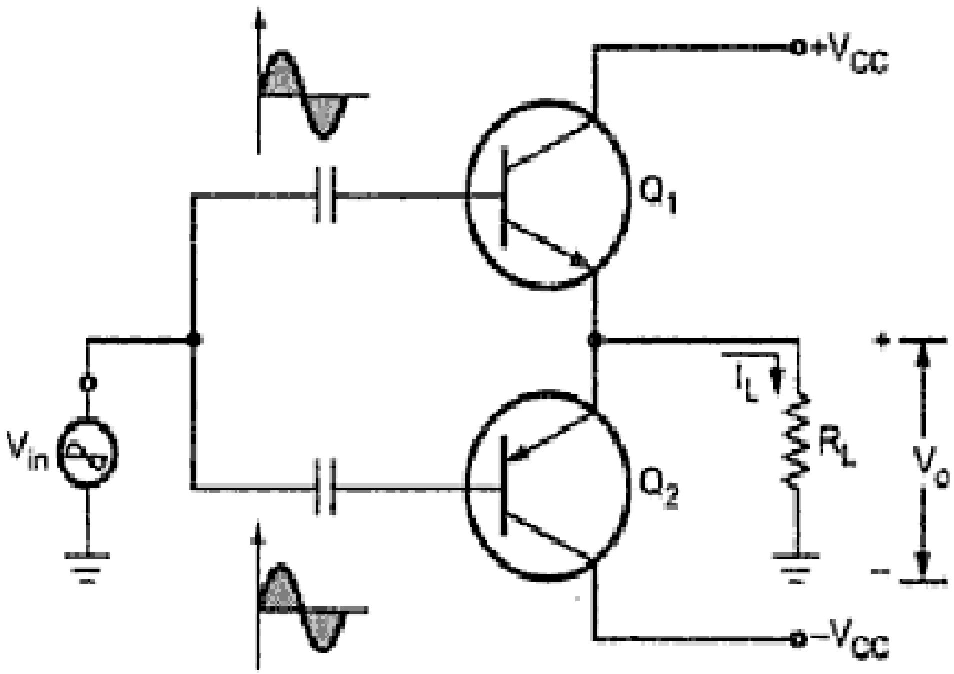


Figure 5.15 Complimentary Symmetry Class B Power Amplifier

Operation:

The basic circuitry of Complimentary-symmetry configuration is driven by dual power supply of +Vcc and –Vcc. Here Q1 is an npn and Q2 is pnp transistor. During Positive half cycle Q1 gets forward biased and conducts when input voltage becomes >0.7V, Q1 conducts and Positive half cycle appears across the load. During negative half cycle Q2 gets forward biased when the applied voltage becomes more negative than -0.7V, Q2 conducts and negative half cycle appears across the load, therefore output is present for entire 360^o of the input cycle.

There are 2 disadvantages associated with circuitry
1) Circuitry requires dual power supply.
2) Cross over distortion is present in the output.

Cross over distortion:

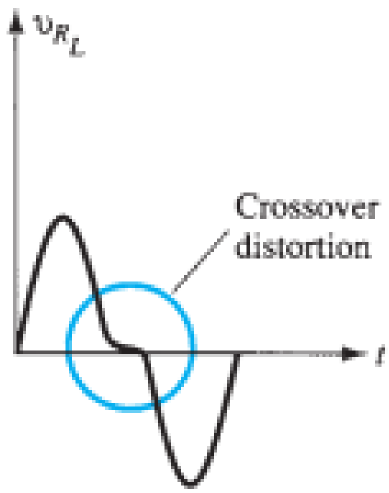


Figure 5.16 Cross over distortion in Class B Power Amplifier

In both transformers coupled push pull and complimentary symmetry configurations distortion is present at the zero crossings of the half cycle. This itself is termed as cross over distortion. In class B, There is no biasing done to ensure that transistor are on before an AC signal is applied. Typically transistors require a forward bias of 0.7V to turn on, therefore none of the transistors are on during zero crossing of half cycle.

Elimination of Cross over distortion:
To eliminate cross over distortion, some modifications are done in the basic circuits of class B amplifier circuit.

i) **Transformer coupled Push-pull Configuration:**

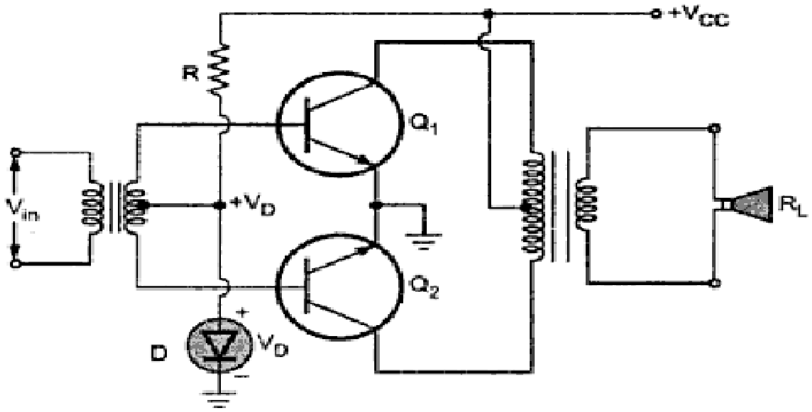


Figure 5.17 Transformer coupled Class B Power Amplifier free from Cross over distortion

Here push pull configuration is modified with the biasing circuitry so that it is free from cross over distortion. The forward bias of base to emitter junctions for both the transistors is provided by making use of a diode. The voltage drop across diode is equal to cut-in voltage of both the transistors. Therefore both the transistors conduct for full cycle making the circuit free from distortion.

Shift in Q pt: Due to forward bias supply Q pt shifts upwards on the DC load line characterizes. The circuit operation will be class AB instead of a class B operation. But shifts in Q pt can be neglected as it is very small.

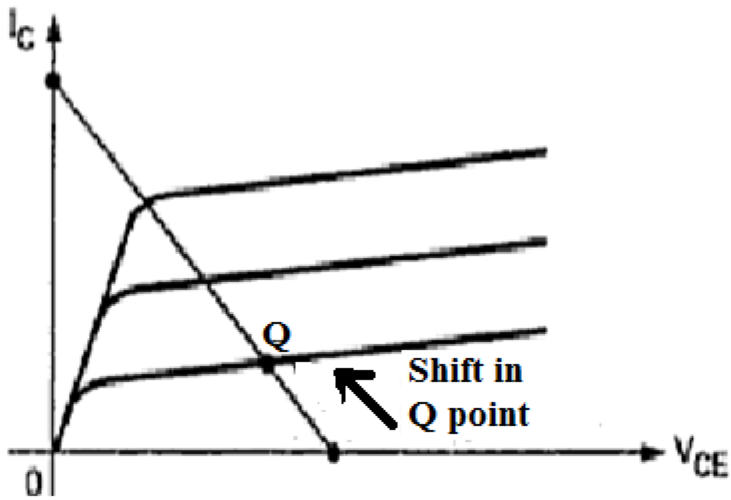


Figure 5.18 Change in Output characteristics of Class B Power Amplifier

5.4.1 Complimentary-Symmetry Circuits free from cross over distortion:

Here, Complimentary-Symmetry circuit is modified so that it is free from cross over distortion. The transistor Q1 should be provided with 0.7V across to its Base to emitter terminals and Q2 is -0.7V. This can be achieved by making value of resistances adjusting such that voltage drop across R2 is 1.4V therefore both the transistors conduct for full cycle eliminating cross over distortion at the output. The circuitry is show in Figure 5.19. It has a disadvantage with respect to change in temperature i.e. as the temperature increases, resistance associated with R2 increases and behavior of base to emitter junctions of Q1 and Q2 is opposite to it. This can be further nullified by making use of 2 diodes. The behavior of diode and p-n junction with respect to temperature and other external factors remains same. The modified circuitry is shown in Figure 5.20.

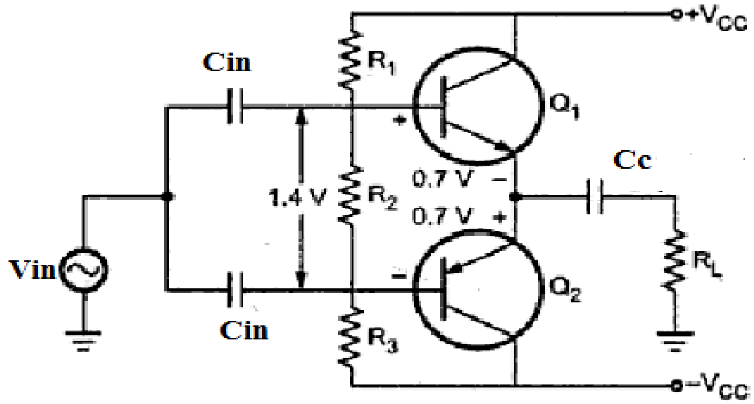


Figure 5.19 Class B Power Amplifier free from cross-over distortion

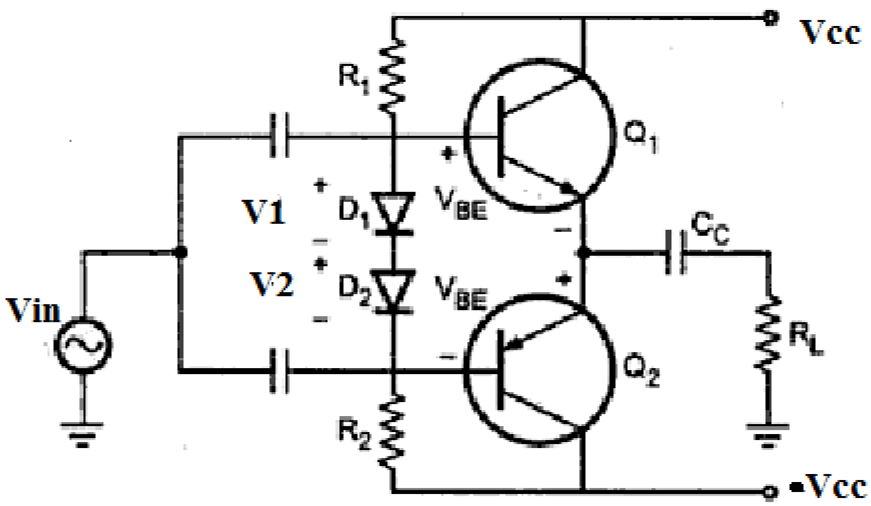


Figure 5.20 Modified Class B Power Amplifier free from cross-over distortion

Complimentary–symmetry circuit with single supply version

The drawback of dual power supply of Complimentary–symmetry configuration can be removed by making use of single supply. But fixed power supply of VCC is shared as VCC/2 by both the transistors.

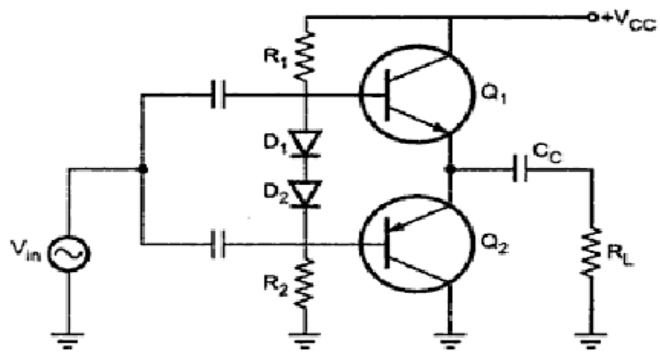


Figure 5.21 Complimentary–symmetry circuit with single supply version

Quasi – Complimentary Push pull configuration

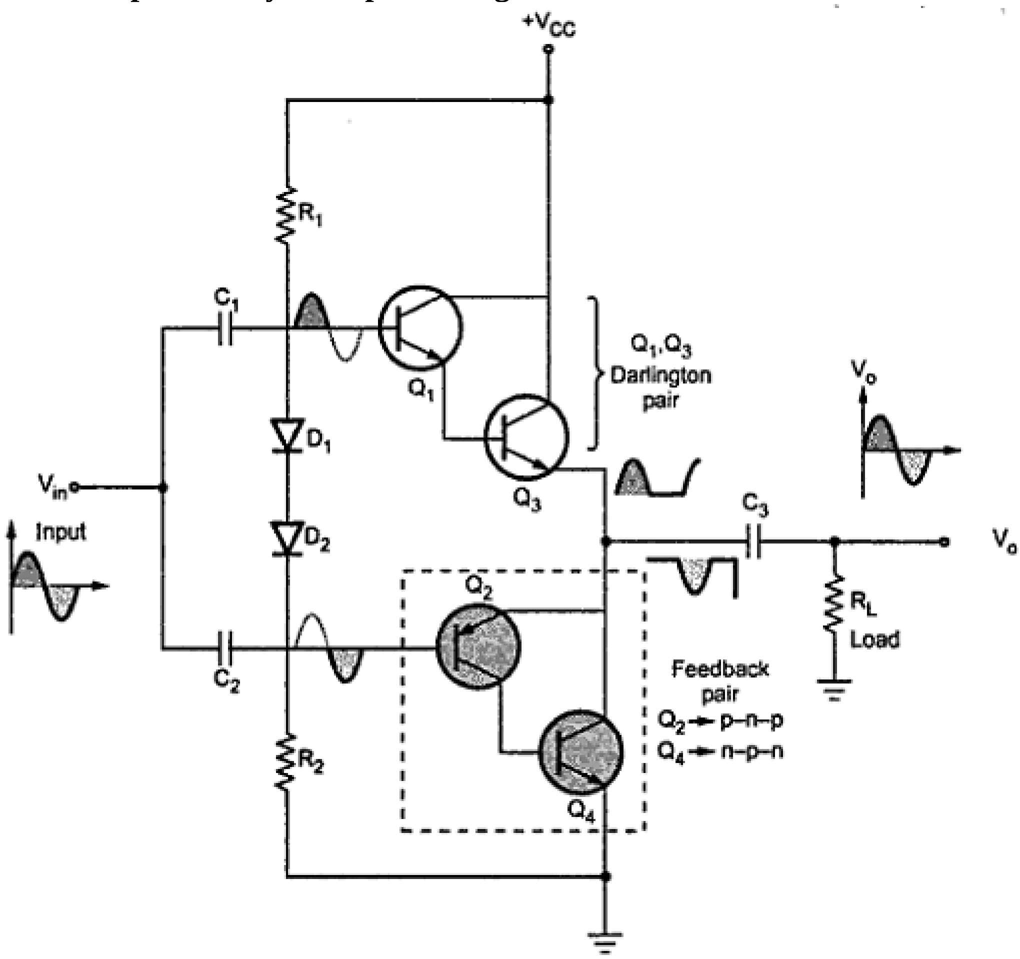


Figure 5.22 Quasi – Complimentary Push pull configuration

In order to provide high current output Complimentary–symmetry configuration can be modified by making use of additional npn transistors. So the above circuitry shows Quasi – Complimentary configuration where high gain npn transistor Q1 and Q2 are connected in a Darlington Configuration providing high current output during Positive half cycle. Q2 and Q4 forms a feedback pair providing high current output during negative half cycle. This is the most popular circuit of class B configuration.

Note: The formula derived for push pull configuration is applicable to all the circuits of class B amplifiers. In case of single supply version Vcc should be considered as Vcc/2 in all calculations.

1) Calculate output power, power dissipation, power handled by each transistor and circuit efficiency for an input of +12V_{RMS}

Solution: Peak input voltage =$\sqrt{2}$ V_{RMS}=$\sqrt{2}$*12=17V, Vcc=+25V,R_L=4Ω

DC input power, P_{DC}=VccI_{DC} =$\frac{V_{CC}2I_M}{\pi}$=$\frac{2V_{CC}V_M}{\pi R_L}$=67.63W

AC output power, P_{AC}=$\frac{V^2{}_M}{2R_L} = 36.125W$

P_D=P_{DC}-P_{AC}=31.625W

Power handled by each transistor, $P_D/2$ =15.8W

$\eta=\frac{P_{AC}}{P_{DC}}*100\%=53.4\%$

2) For the same circuit shown calculate maximum input power, max output power and power dissipation

Max input power, V_M=Vcc

$P_{DC}=\frac{2VCC^2}{\pi R_L}=99.46W$

$P_{AC}=\frac{V^2cc}{\pi^2 R_L}=31.654W$

Power dissipation, P_{DC}-P_{AC}=21.335W

5.5 Distortion in Power amplifiers

Any amplifier is subjected to three types of distortions,

1) Amplitude distortion 2) Frequency distortion and 3) Phase distortion.

Typically power amplifier should be free from all these distortions, human errors are not sensitive to phase of the signal, therefore phase distortion can be neglected as well as frequency distortion. Amplitude distortion is a major source of distortion in power amplifiers.

Amplitude distortion (Harmonic Distortion)

It is caused due to harmonics present in the output signal. Hence it is referred to as harmonic distortion. If the desired freq component is coswt, the output contains harmonics which are multiples of fundamentals at freq 'w' i.e. output contain cos 2wt, cos3wt........cosnwt. Refer Figure 5.23. As the order of harmonic increases with coswt, the amplitude of harmonics decreases. Therefore net output is resultant of all these harmonics.

Harmonic distortion caused by n^{th} harmonic component can be expressed as

$D_n=\frac{|A_N|}{|A_1|}*100\% --------(31)$

Where A_n is the amplitude of the n^{th} harmonic component and A_1 is the amplitude of fundamental harmonic component.

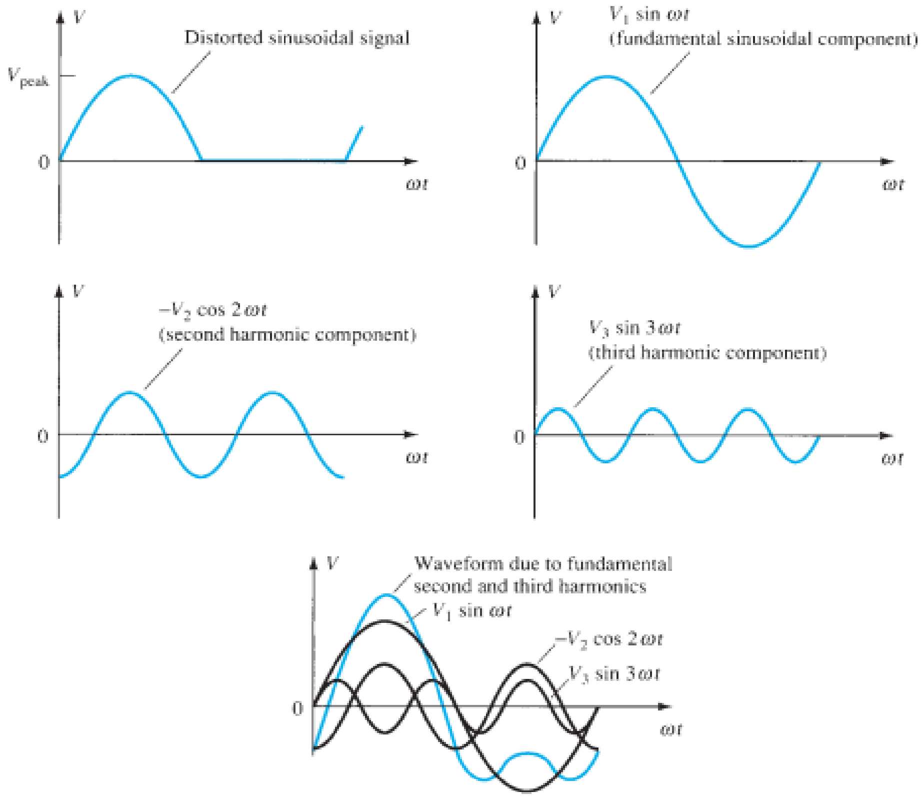
The amplitude distortion due to 2^{nd} harmonic component can be expressed as

$D_2=\frac{|A_2|}{|A_1|}*100\% --------(32)$

Where A_2 is amplitude of 2^{nd} harmonic component..

Harmonic distortion caused by all the harmonics can be expressed as

$D=(\sqrt{D_2^2+D_3^2+\cdots D_N^2})*100\% ----- (33)$



. Figure 5.17 Harmonic distortion in Class B Power Amplifiers

1) Calculate harmonic distortion component for an output signal having fundamental component of 2.5V, 2nd harmonic component of 0.25 and third harmonic component of 0.1V 4th harmonic component of 0.05. Also calculate total harmonic distortion

Solution: We know that harmonic distortion caused by nth component is $\frac{|A_N|}{|A_1|} * 100\%$

Distortion caused by 2nd component $\frac{|A_2|}{|A_1|} * 100\%$

i) D_2=0.25/2.5*100% =0.1=10%

ii)D3=0.1/2.5*100%=0.04=40%

iii)D4=0.05/2.5-100%=0.02=20%

Total distortion is given by,

D=$(\sqrt{D_2^2 + D_3^2 + \cdots D_N^2}) * 100\%$=$\sqrt{(0.1)^2 + (0.04)^2 + (0.02)^2}$=0.1095*100%=10.95%

5.5.1 Analysis of 2nd harmonic Distortion

2nd harmonic component has the largest amplitude of all others harmonics these is the major source of harmonic distortion. Harmonics are introduced due to non-linear behavior of transistor as shown in figure 5.18. Transistor is a non-linear device. Output quantity Ic can be related to I_B using the relation given by,

$i_c=G_1 i_b+G_2 i^2_b$-------------------------(34)

where, G1 and G2 are constants of proportionality, i_c and i_b are instantaneous collector and base currents respectively. Let $i_b= I_m coswt$---------------------(35)

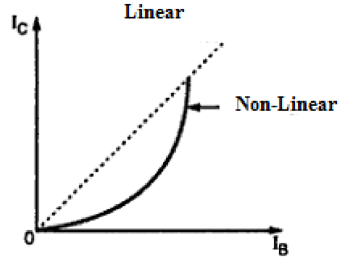


Figure 5.18 Non-linear behavior of transistor

$i_c=G_1(I_m coswt)+G_2(I_m coswt)^2$-----(36)

$=G_1 I_m coswt+\frac{G_2 I_M^2}{2}+\frac{G_2 I_M^2}{2}cos2wt$

$i_c=A_0+A_1coswt+A_2cos2wt$---------(37)

$i_c=I_{CQ}+A_0+A_1coswt+A_2cos2wt$---(38)

Where A0 is a constant which indicates a rectifying term. A_1coswt is the derived fundamental component A_2coswt is the derived harmonic component which needs to be calculated since the transistor is DC biased, the collector current can be expressed as in eq(37). Collector current can be represented as shown in the figure 5.19.

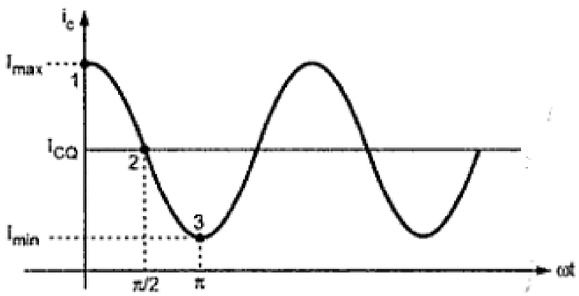


Figure 5.19 Collector current waveform

Put wt=0 in eq(37)

$I_{CMAX}=I_{CQ}+A_0+A_1+A_2$------------(39)

Putting wt=$\frac{\pi}{2}$

$ic=I_{CQ}+A_0-A_2$-------------------------(40)

Putting wt=π

$I_{CMIN}=I_{CQ}+A_0-A_1+A_2$----------------(41)

$I_{CMAX}-I_{CMIN}=8A_1$

$A_1=\frac{I_{CMAX}-I_{CMIN}}{2}$

$I_{CMAX}+I_{CMIN}=2A_0+2I_{CQ}+2A_2$

WKT at wt=$\frac{\pi}{2}$

$Ic=I_{CQ}=I_{CQ}+A_0$

$I_{CMAX}+I_{CMIN}=4A_2+2I_{CQ}$

$A_2=\frac{I_{CMAX}+I_{CMIN}+2I_{CQ}}{4}$------------------------(42)

Harmonic distortion can be expressed as

$D_2 = \frac{|A_2|}{|A_1|} = \frac{\frac{I_{CMAX}+I_{CMIN}+2I_{CQ}}{4}}{\frac{I_{CMAX}-I_{CMIN}}{2}}$

$D_2 = \frac{\frac{1}{2}(I_{CMAX}+I_{CMIN})-I_{CQ}}{I_{CMAX}-I_{CMIN}}$-------------------------(43)

In terms of collector voltages harmonics distortion can be expressed as

$D_2 = \frac{\frac{1}{2}(v_{CEMAX}+V_{CEMIN})-V_{CEQ}}{V_{CEMAX}-V_{CEMIN}}$-------------------------(44)

Power output due to harmonics:

The input power can be expressed as

$P_i = V_{RMS}I_{RMS} = \frac{V_M I_M}{2} = \frac{I_M^2 R_L}{2} - - - - - (45)$

Where, I_m is peak value of current. The fundamental components power can be expressed as $P_1 = \frac{A_1^2 R_L}{2} - - - - - - - - - - - - - - - - - - (46)$

Where A_1 is the amplitude of fundamental component. The output power includes fundamental component and all the harmonics. Therefore total output power can be expressed as

$P_0 = \frac{A_1^2 R_1}{2} + \frac{A_2^2 R_L}{2} + \cdots + \frac{A_N^2 R_L}{2}$

$= \frac{A_1^2 R_1}{2}(1 + \frac{A_1^2}{A_1^2} + \frac{A_3^2}{A_1^2} + \cdots + \frac{A_N^2}{A_1^2}$

$P_I = (1 + D_2^2 + D_3^2 + \cdots + D_N^2$

$P_0 = P_1(1+D^2)$ -------------------------(47)

Where D_n is harmonic distortion due to n^{th} harmonic distortion and D is total harmonic distortion.

Problem

Q) For an harmonic distortion reading D_2=0.1, D_3=0.02, D_4=0.01 with fundamental component of current as 4A and a load resistance of 8Ω, calculate power output due to harmonics, fundamental power and total harmonic distortion.

Solution: $I_1 = A_1$=4A, R_l=8Ω

$P_0 = P_1(1+D^2)$

$P_I = (1 + D_2^2 + D_3^2 + \cdots + D_N^2) = (0.1)^2 + (0.02)^2 + (0.01)^2 = 0.0105$

$P_0 = \frac{A_1^2 R_1}{2}(1.0105) = \frac{4^2 * 8}{2} = 64.67W$

5.6 Class C Power Amplifiers

In class C operation, the transistor is biased well beyond cutoff , therefore collector current flows for less than 180° resulting in an output of all small pulse, therefore class C is not suitable for audio frequency amplification instead it is employed as stable frequency generator in all communication transmitter and receivers. Efficiency of class C power amplifies is nearly 100%. The tuned LC circuit acts as a load for a class c power amplifiers. Class C amplifiers produce series of pulses including fundamentals and harmonics. LC circuit takes only fundamental frequency and results into oscillations; therefore output is far from harmonics.

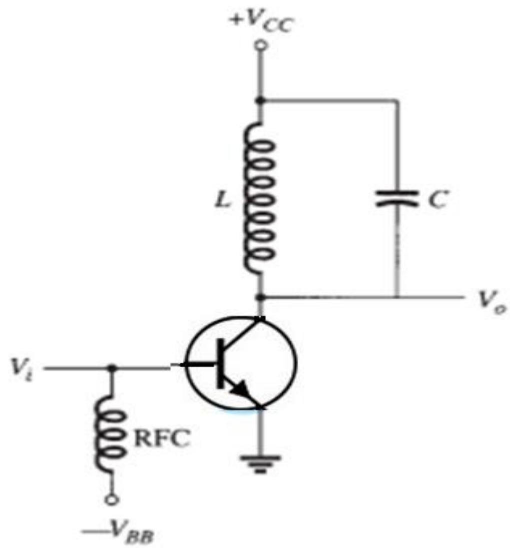


Figure 5.20 Class C Power Amplifier

5.7 Class D Power Amplifier:

Class D power amplifiers make use of digital techniques to provide amplification for Analog Signals. Typical Class D power amplifier switches are shown in Figure 5.22. Figure 5.21 shows the block diagram of Class D Power Amplifier. Comparator compares instantaneous saw tooth waveform amplitude with input signal. If difference is positive comparator output switches the Class D power amplifier. Amplifier output will be Pulse which will be on as long as comparator output being positive difference. This output is fed to low-pass filter which recovers the original signal back.

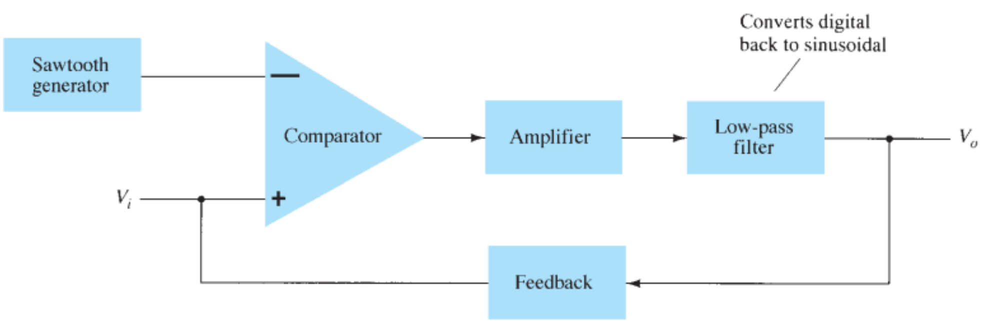


Figure 5.21 Block Diagram of Class D Power Amplifier

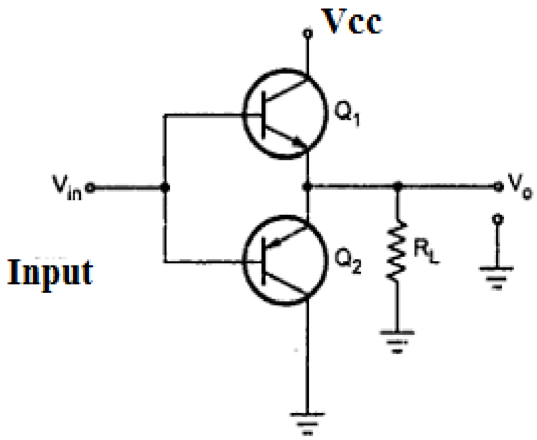


Figure 5.22 Class D Power Amplifier Switches

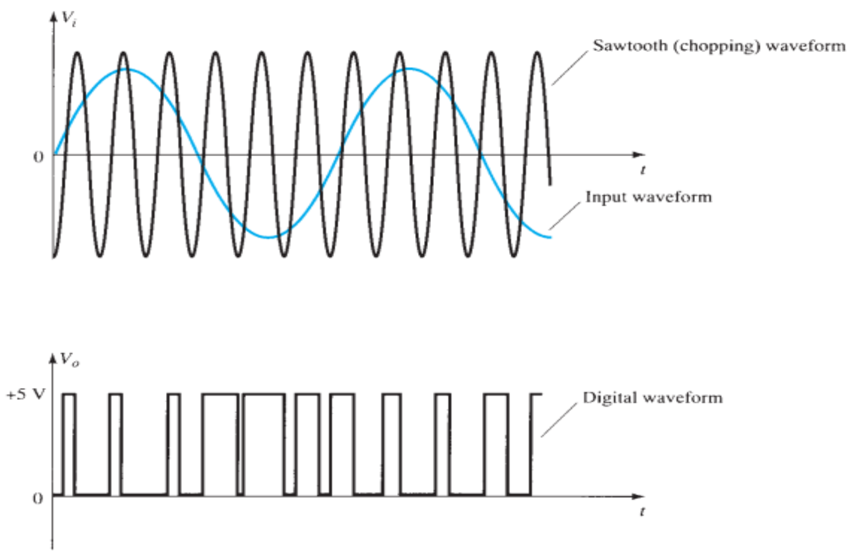


Figure 5.23 Class D Power Amplifier Waveforms

6 Voltage Regulators

6.1 Introduction

Voltage regulators are the important constituents of any power supply. All the Regulated DC Power supplies and Switched-Mode Power supplies make use of voltage regulators. Voltage regulator is used for two reasons:-

1. To regulate or vary the output voltage of the circuit.
2. To keep the output voltage constant at the desired value in-spite of variations in the supply voltage or in the load current.

Figure 6.1 shows the block diagram of typical Power supply. Input ac voltage is stepped down by making use of Transformer. Full wave rectifier converts the incoming ac into a pulsating DC. Further filter smoothens out the pulsating DC. This Pulsating DC is regulated by making use of IC regulator. Output of regulator is a constant DC which is fed to load.

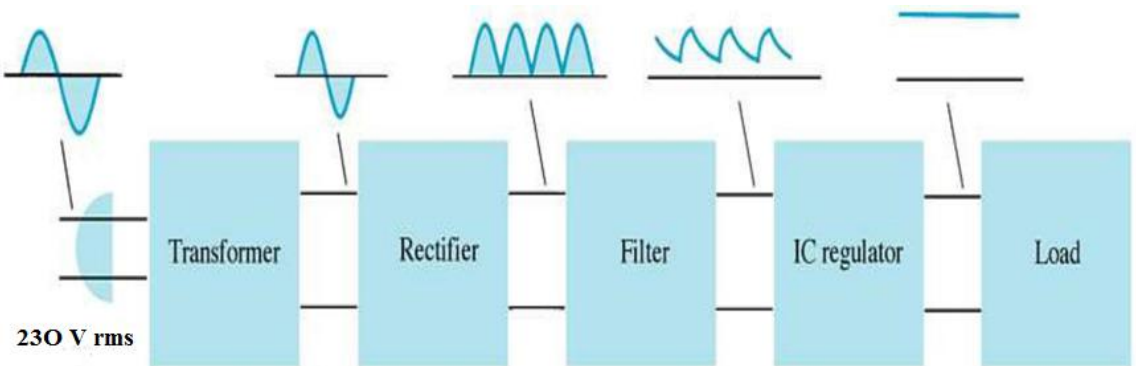


Figure 6.1 Block diagram of Power Supply

6.2 Series voltage regulator

Here the control element transistor/control element is connected in series with the input. Output is fed back to a sampling circuit which samples a part of output and couples it to comparator. Comparator compares the reference voltage with output of sampling circuit. If the output voltage increases, the comparator circuit provides a control signal to cause the series control element to decrease the amount of the output voltage there by regulating the output voltage.

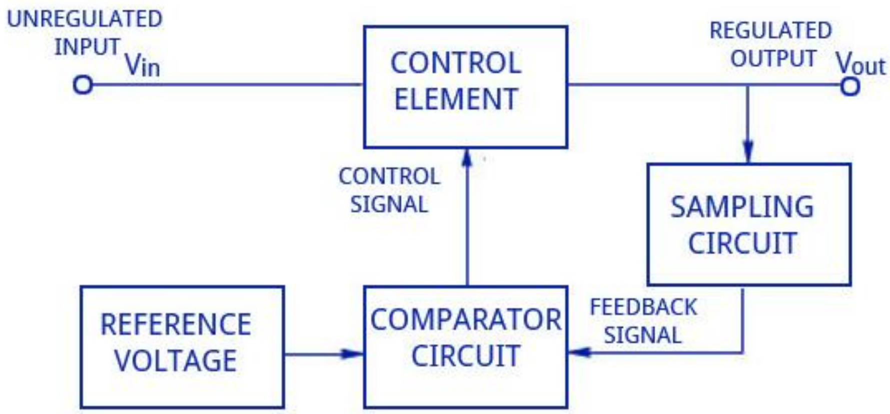


Figure 6.2 Block diagram of series voltage regulator

Courtesy: www.CircuitsToday.com

6.2.1 Simple Series Voltage Regulator Circuit

Here transistor is in series with the load. Such a circuit is also named an emitter follower voltage regulator. It is called so because the transistor used is connected in an emitter follower configuration. The circuit consists of an N-P-N transistor and a zener diode. As shown in the figure below, the collector and emitter terminals of the transistor are in series with the load. Thus this regulator has the name series in it. The transistor used is a series pass transistor. Circuitry is shown in Figure 6.3.

The output of the rectifier that is filtered is then given to the input terminals and regulated output voltage Vout is obtained across the load resistor R_L. The reference voltage is provided by the zener diode and the transistor acts as a variable resistor, whose resistance varies with the operating conditions of base current. The main principle behind the working of such a regulator is that a large proportion of the change in supply or input voltage appears across the transistor and thus the output voltage tends to remain constant. The output voltage can thus be written as,

$$V_{out} = V_z - V_{BE} \qquad (48)$$

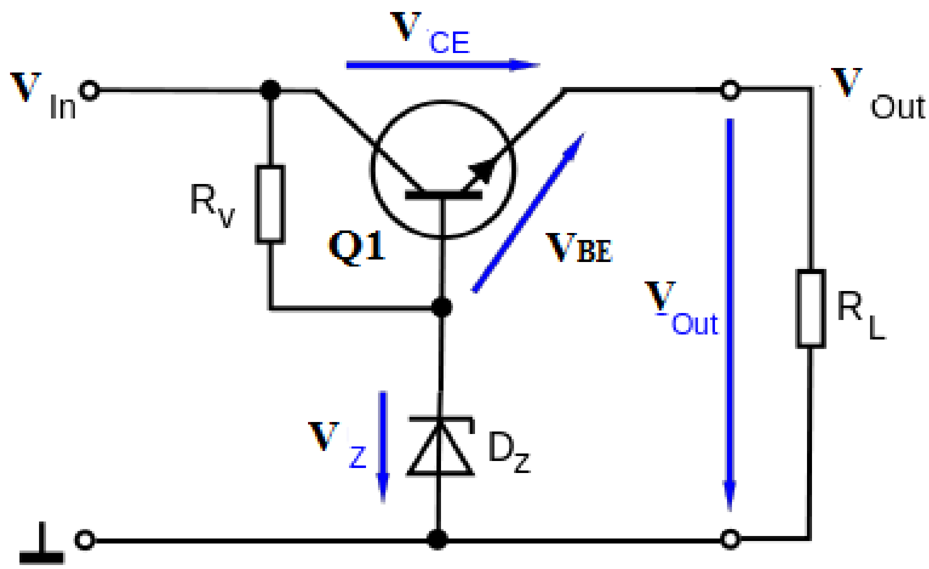


Figure 6.3 Simple Series Voltage Regulator Circuit

When the input supply voltage Vin increases the output voltage Vout also increases. This increase in Vout will cause a reduced voltage of the transistor base emitter voltage Vbe as the zener voltage Vz is constant. This reduction in V_{BE} causes a decrease in the level of conduction which will further increase the collector-emitter resistance of the transistor and thus causing an increase in the transistor collector-emitter voltage and all of this causes the output voltage Vout to reduce. Thus, the output voltage remains constant. The operation is similar when the input supply voltage decreases.

An improved series regulator circuit is shown in Figure 6.4. Resistors R1 and R2 act as a sampling circuit, with Zener diode D_Z providing a reference voltage, and transistor Q2 then controls the base current to transistor Q1 to vary the current passed by transistor Q1 to maintain the output voltage constant

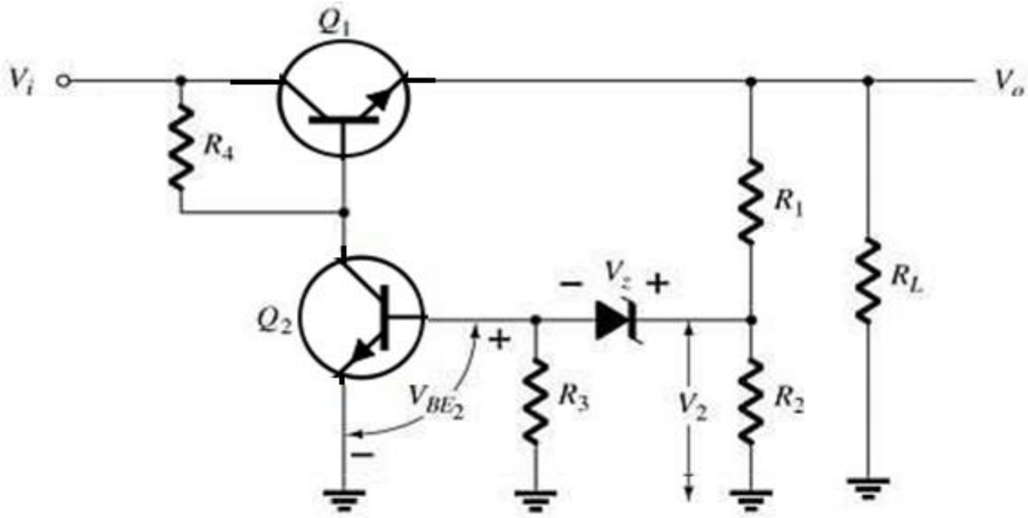


Figure 6.4 Improved Series Voltage Regulator Circuit

6.2.2 Series Voltage Regulator Circuit using op-amp

Here Zener diode provides a constant reference voltage at non-inverting terminal of op-amp. Output voltage is sampled via potential divider network and is fed to inverting terminal. Depending on variation in output voltage the output voltage of op-amp changes and in-turn transistor's control voltage changes. This ensures constant output voltage (Refer Figure 6.5).

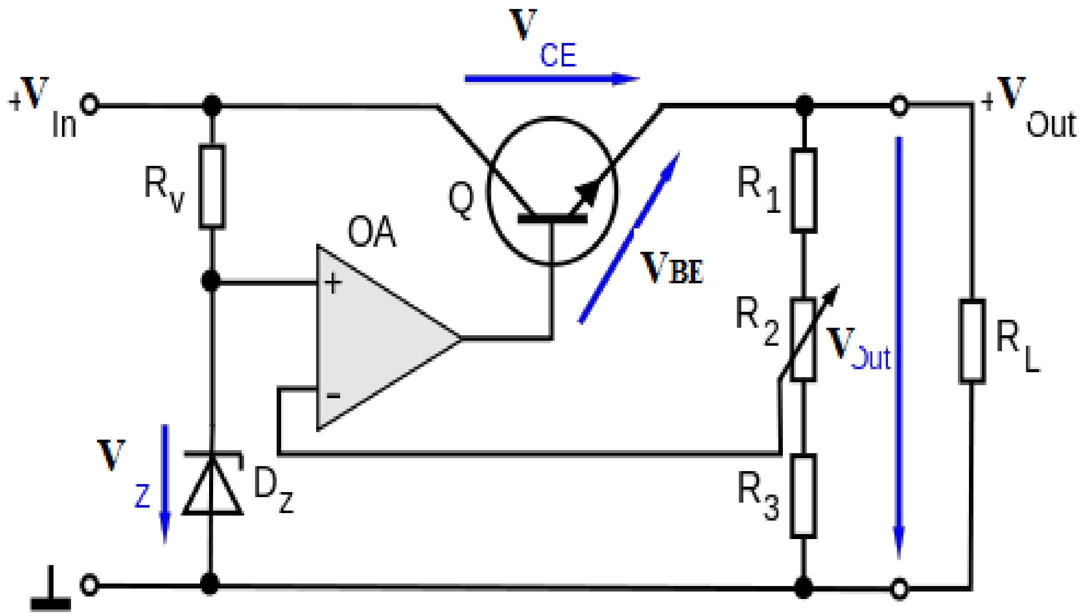


Figure 6.5 Op-amp Series Voltage Regulator

6.2.3 Over-current protection

Figure 6.6 shows how the series stabilizer can be protected against excessive current being drawn by the load. This will prevent damage to the supply in the event of too much current being drawn from the output, or even a complete short circuit across the output terminals. Two components have been added, Q2 and Rp. The resistor Rp is a very low value When the load current rises above a predetermined value, the small voltage developed across Rp will become sufficient to turn Q2 on. As Q2 is connected across the base/emitter junction of the main control transistor Q1, the action of turning Q2 on will reduce the base/emitter voltage of Q1 by an amount depending on the amount of excess current. The output current will not be allowed to increase above a predetermined amount, even if a complete short circuit occurs across the output terminals.

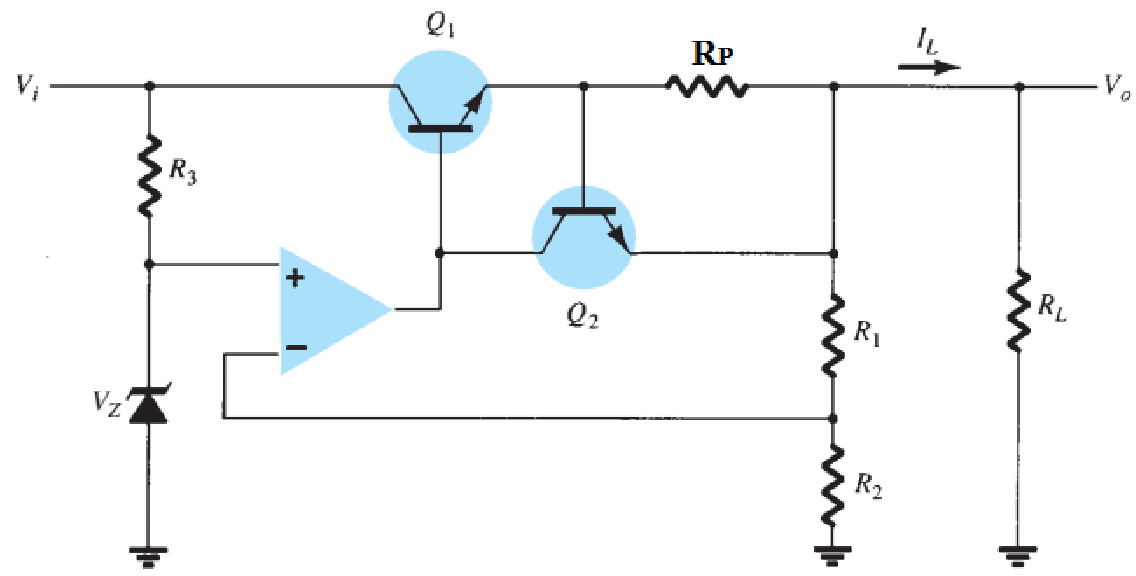


Figure 6.6 Current-Limiting Voltage Regulator Circuit

6.3 Shunt Voltage Regulator

The block diagram of a discrete transistor shunt voltage regulator is given in Figure 6.7. As the name says the voltage regulation is provided by shunting the current away from the load. The control element shunts a part of the current that is produced as a result of the input unregulated voltage that is given to the load. Thus the voltage is regulated across the load. Due to the change in load, if there is a change in the output voltage, it will be corrected by giving a feedback signal to the comparator circuit which compares with a reference voltage and gives the output control signal to the control element to correct the magnitude of the signal required to shunt the current away from the load.

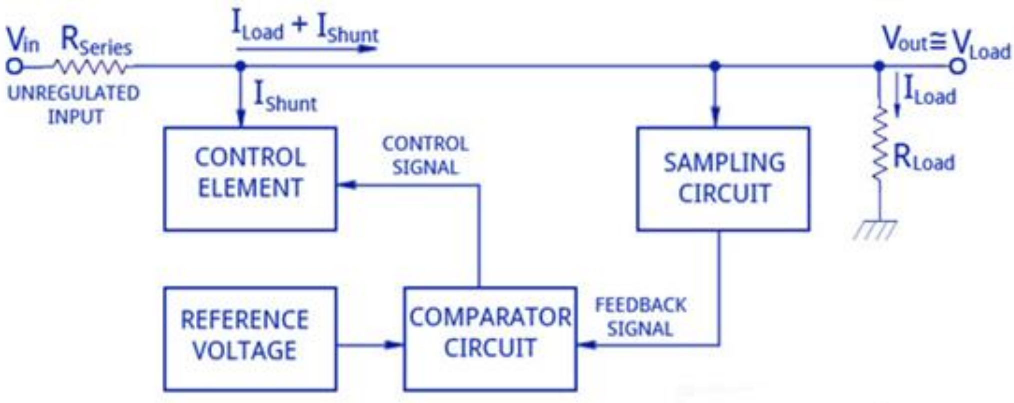


Figure 6.7 Block Diagram of Shunt Voltage Regulator

Courtesy: www.CircuitsToday.com

If the output voltage increases, the shunt current increases and thus produces less load current and maintains a regulated output voltage. If the output voltage reduces, the shunt current reduces and thus produces more load current and maintains a regulated constant output voltage. In both cases, the sampling circuit, comparator circuit and control element plays an important role.

6.3.1 Simple Shunt Voltage Regulator Circuit

The circuit consists of an NPN transistor and a zener diode along with a series resistor Rs that is connected in series with the input supply. The zener diode is connected across the base and the collector of the transistor which is connected across the output. The circuit consists of an NPN transistor and a zener diode along with a series resistor Rs that is connected in series with the input supply. The zener diode is connected across the base and the collector of the transistor which is connected across the output.

The output voltage to the load is given by,

$$V_L=V_Z+V_{BE}.......................(50)$$

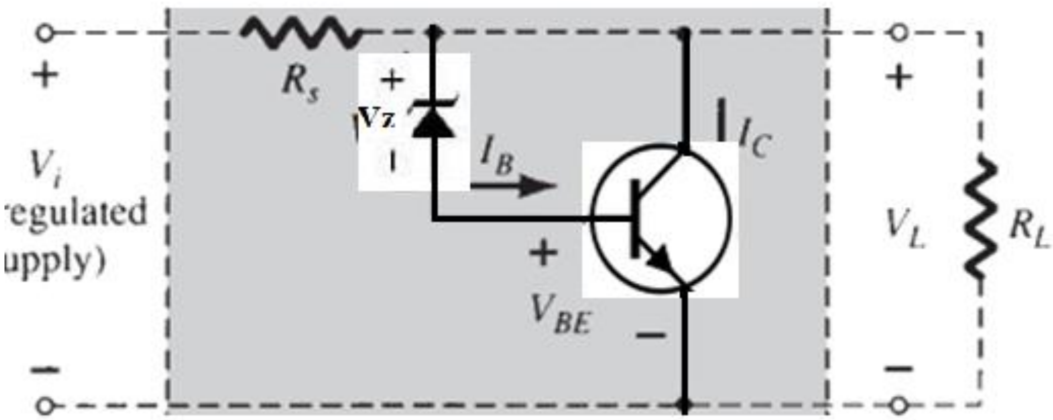


Figure 6.8 Simple Shunt Voltage Regulator Circuit

6.3.2 Improved Shunt Voltage Regulator Circuit

The circuit of Figure 6.8 can be improved as shown in Figure 6.9. As the output voltage tries to change, the current shunted by transistor Q1 is varied to maintain the output voltage constant. Transistor Q2 provides a larger base current to transistor Q1 so that larger load current can be handled.

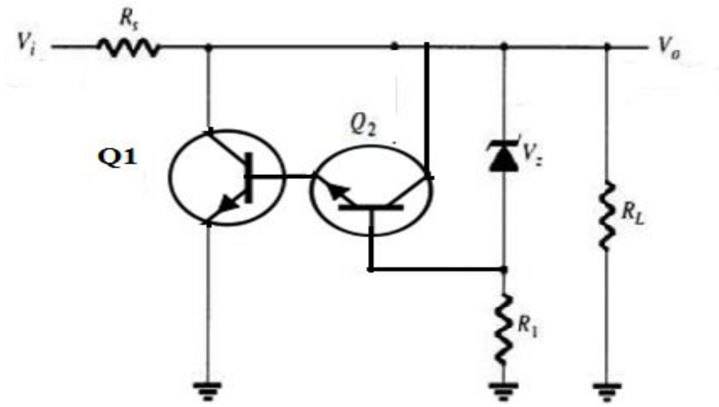


Figure 6.9 Improved Shunt Voltage Regulator Circuit

6.3.3 Shunt Voltage Regulator using op-amp

Here Zener diode provides a constant reference voltage at non-inverting terminal of op-amp. Output voltage is sampled via potential divider network and is fed to inverting terminal. Depending on variation in output voltage the output voltage of op-amp changes and in-turn transistor's control voltage changes. This ensures constant output voltage (Refer Figure 6.10).

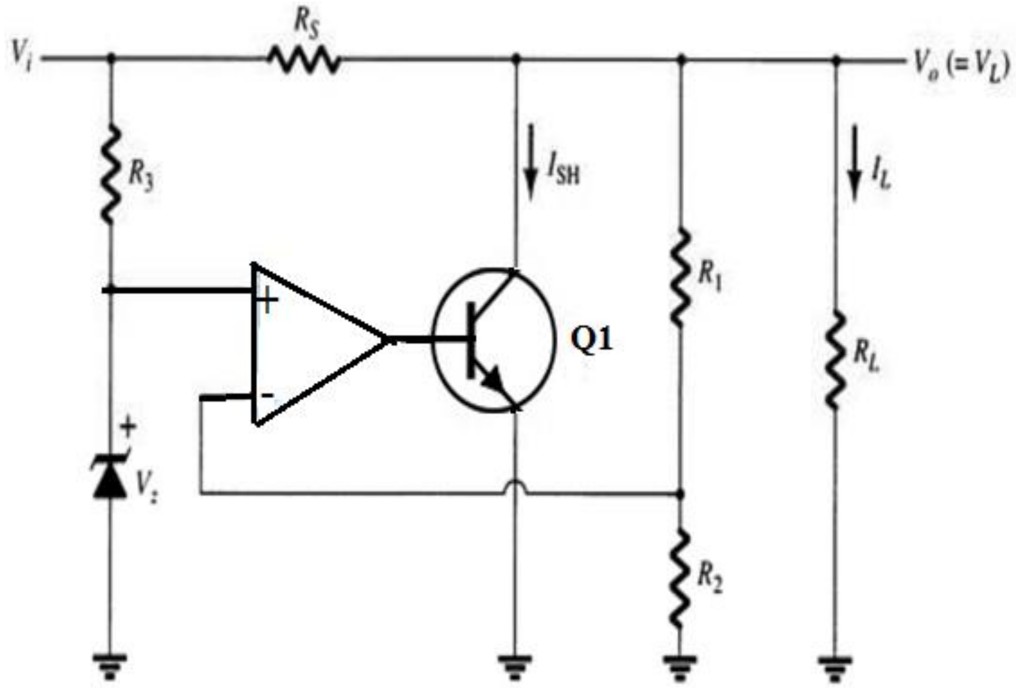


Figure 6.10 Shunt Voltage Regulator using op-amp

6.4 Switching Regulators

Switching regulators make use of power electronics devices to provide a constant and efficient dc supply. Basically, a switching regulator passes voltage to the load in pulses, which are then filtered to provide a smooth dc voltage. Block diagram of 3 terminal switching voltage regulators is shown in Figure 6.11.

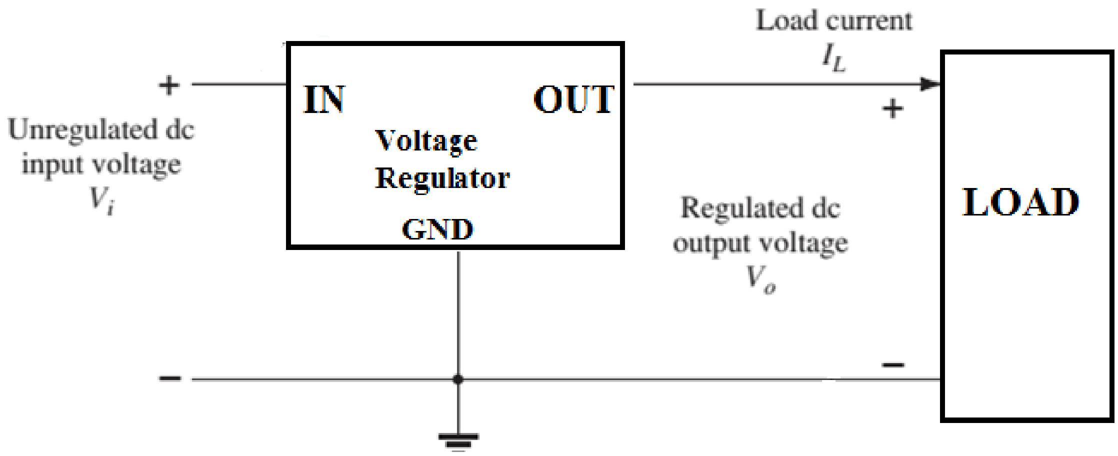


Figure 6.11 Block diagram of Switching Regulators