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BPHCT-143
DIGITAL AND ANALOG CIRCUITS AND INSTRUMENTATION

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Volume – II Blocks 3 & 4

Volume II

Block 3	**ANALOG CIRCUITS**
Block 4	**OPERATIONAL AMPLIFIER AND INSTRUMENTATION**

Indira Gandhi National
Open University
School of Sciences

BPHET-143
DIGITAL AND ANALOG CIRCUITS AND INSTRUMENTATION

Block

3

ANALOG CIRCUITS

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CONTENTS

BLOCK 3 : ANALOG CIRCUITS

In the previous blocks of this course you learnt about various semiconductor devices like diodes, transistors and their applications in digital circuits.

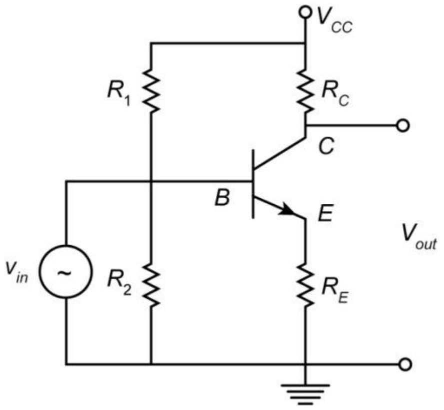
The most important property of the semiconductors is their ability to function as amplifiers of electrical voltage, current or power. When voltage or current signals are applied to the input terminals of an amplifier, larger voltage or current signals are available at the output terminals. In **Unit 10** we will introduce you to different types of amplifiers and their classification based on their applications, frequency range of operation, the position of operating point (*Q*) on the transistor output characteristics etc. The audio circuits require a distortion-free amplification of input signal for satisfactory listening experience. Class A amplifiers are the most commonly used amplifiers for such applications. We will analyse the class A amplifier and its frequency response. In order to enhance the gain of the circuit, it is common practice to cascade multiple amplifiers together. Various methods to couple different stages of amplifiers will be described. You will also learn to estimate the performance of a power amplifier and get familiar with push-pull amplifier.

Feedback in electronic circuits plays a very important role. The negative feedback in an amplifier enhances its stability and bandwidth (range of operating frequency). On the other hand a positive feedback gives rise to oscillations in the circuits.

Sometimes, it becomes necessary to generate alternating currents of high frequencies (ranging upto millions and even billions of cycles per second). Transistors together with associated components, may be used to generate these alternating signals using proper feedback network. We call such generators as oscillators. **Unit 11** discusses a variety of sinusoidal oscillators include *RC* oscillators and *LC* oscillators.

In all previous units, the voltages and currents required to operate the analog and digital circuits were assumed to be available. We will examine how necessary voltages are generated and the means by which they are regulated. Most electronic circuits need a dc voltage in order to work properly. Since line voltage is alternating, the first thing that has to be done in any electronic equipment is to convert ac voltage to dc voltage. In **Unit 12** we explain how well-regulated dc power supplies for electronic circuits can be derived from the ac mains.

We wish you all the best in your studies.



Amplifiers are used to enhance the signals. Class A amplifier shown in this figure is used in audio circuits because of its low distortion, as you will learn in this unit.

UNIT 10

AMPLIFIERS

Structure

STUDY GUIDE

In this course you have so far learnt about the semiconductor devices and their electrical characteristics. Most of the electronics systems use these devices for their functioning. The most prominent use of transistors is in amplifier circuits that enlarge the input voltage signal or amplify the power (voltage × current product) for driving the loads like speakers or transmitter antenna in communication circuits. In this unit you will learn the use of transistor in different types of amplifiers. To understand these circuits, you should revise the transistor input-output characteristics discussed in Unit 4 and the transistor equivalent circuits described in Unit 5. You should solve all the SAQs and Terminal Questions on your own to have better understanding of the topic.

"Negative feedback effected amplifier performance significantly."

Harold Stephen Black

10.1 INTRODUCTION

You are familiar with an 'audio system' which is used to play CDs, cassettes and receive radio broadcasts. Fig. 10.1a shows a simple diagram for such a system. It consists of various input devices connected to the input of an amplifier whose output is connected to the loudspeaker. The microphone and other input devices convert sound into electrical signals. The loudspeaker carries out the reverse process by converting electrical signals into sound. The electrical output from the input devices is too weak to provide an adequate sound level in the loudspeaker. The amplifier is used to convert the input signal into a sufficiently powerful electrical signal for the loudspeaker.

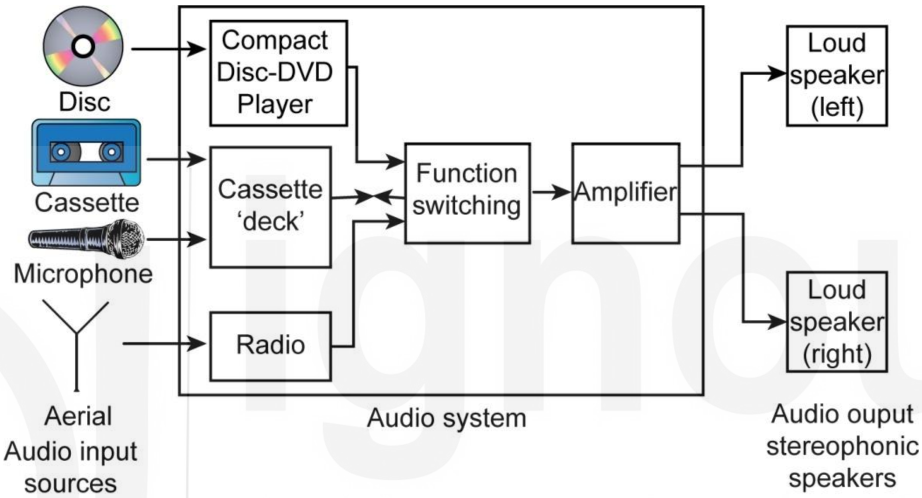


Fig. 10.1: **A block diagram for an audio system.**

In Fig. 10.1 we have not shown a power supply but you must remember that all the electronic systems need such supply. It may either be provided with batteries or plugged into the mains supply. In Fig. 10.2 we have shown a signal from a microphone given to an amplifier. Here the amplifier controls the flow of power from the power supply to the loudspeaker in response to the electrical signal received from the microphone. In this way amplifier supplies much stronger signal power to the loudspeaker than the microphone can provide.

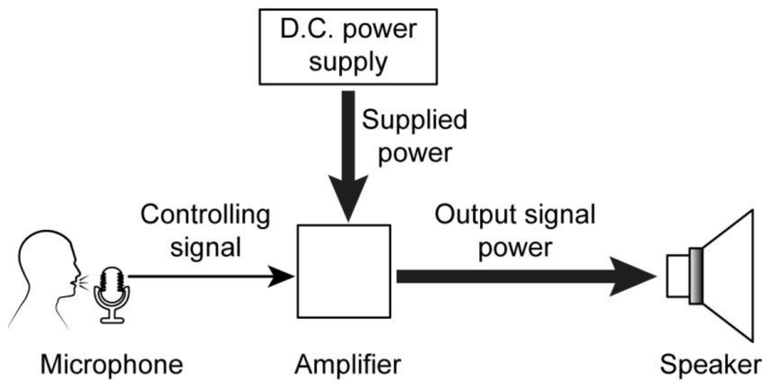


Fig. 10.2: **Power flow in the audio system.**

The function of an amplifier is to increase (boost) the level of the signal. The amplifier circuits use transistors or integrated circuits (ICs) as amplifying devices.

The amplifier circuits can be classified in a wide variety of ways as discussed in Sec. 10.2. The amplifiers used for handling small amplitude and low frequency signals are discussed in Sec. 10.3. You will also learn about their frequency response.

There are certain conditions when a single amplifier is not enough for providing the necessary voltage/current/power output. In such cases the amplifying action can be augmented by connecting more than one amplifier in succession or cascade. You will learn about such multistage amplifiers in Sec. 10.4. Many a times we need high power output from an amplifier to drive certain loads like radio transmitters. You will learn about such high power amplifiers in Sec. 10.5.

By sampling a part of output signal and providing it at the input of an amplifier, we can improve the quality of amplifier performance significantly. This is essentially done with the help of negative feedback. You will study the effects of negative feedback on the amplifier performance in Sec. 10.6.

Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ state the classification of amplifiers on the basis of applications, operating point, coupling, circuit configuration, bandwidth and frequency;
- ❖ explain the variation of *Q*-point in a small signal class A amplifier;
- ❖ describe the frequency response curve of an *RC*-coupled amplifier;
- ❖ calculate the overall gain of multistage amplifier;
- ❖ draw and explain the working of single ended and push pull amplifier circuits;
- ❖ calculate the output ac power delivered by a single-ended power amplifier; and
- ❖ explain the advantages of negative feedback in amplifiers.

10.2 CLASSIFICATION OF AMPLIFIERS

Amplifier circuits can be classified in a wide variety of ways. They can be classified according to their use, the type of bias used, the frequency or bandwidth of the signals they amplify, the type of coupling used to join two stages and their circuit configuration.

Amplifiers according to use: They fall into two main groups – voltage amplifiers and power amplifiers. Voltage amplifiers increase the voltage level of an applied signal. Since the output voltage of an amplifier is determined by the voltage drop across the output load, the impedance of the load is made as large as is practical in most voltage amplifiers.

Power amplifiers are also called current amplifiers. They deliver a large amount of current to the output load so that large power can be delivered to the loads like speaker, transmitters etc.

Amplifiers according to bias: Amplifiers are also classified according to their biasing conditions, or, in other words, according to the portion of the input signal voltage cycle during which output current flows. You have learnt about the loadline and operating point of a transistor based on the biasing conditions in Unit 4. There are four classes of amplifiers according to bias: class A, class B, class AB and class C.

Class A amplifiers are biased such that the *Q* point is in the centre of their operating curve so that output current flows during the entire cycle of the input voltage (see Fig. 10.3a). This results in minimum distortion of the signal at the output and as a result, class A amplifiers are widely used in audio system, where low distortion is important. However, these amplifiers are not energy efficient because, even for no input signal, the transistor always conducts current at its quiescent value.

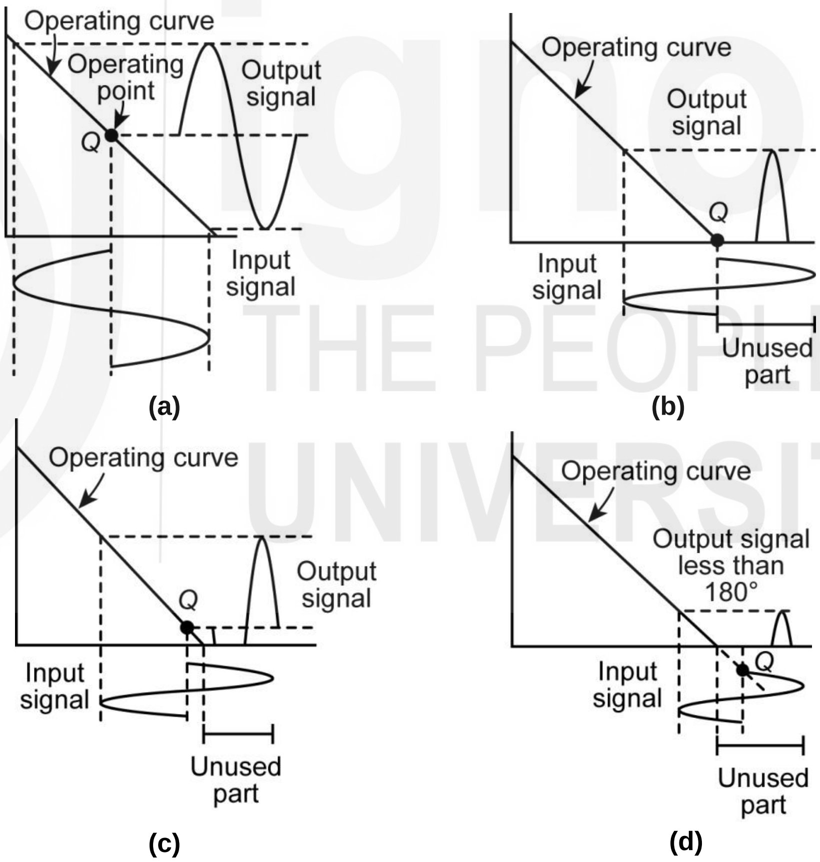


Fig. 10.3: **Classification of amplifier according to bias.**

Class B amplifiers are biased such that the operating point is at the cutoff, so output current flows for approximately one-half of the input signal voltage cycle as shown in Fig. 10.3b. In effect, a class B amplifier cuts off one half of the ac input signal waveform. When no input signal is present, no output current flows, hence it is very efficient with low power consumption.

Class AB amplifiers are biased so that output current flows for appreciably more than one half of the input cycle, but for less than the entire cycle as shown in Fig. 10.3c. Essentially, class AB amplifiers are a compromise between the low distortion of class A amplifiers and the high efficiency of class B amplifiers.

Class C amplifiers are biased beyond the cutoff so that output current only flows during the small part of positive going peak of the input cycle (see Fig. 10.3d). Such, amplifiers have high power outputs but they have a high degree of distortion, which prevents their use in audio applications.

Amplifiers according to coupling: When large amplification is required, it is practical to use cascade (or multi-stage) amplifiers. Such amplifiers are often classified according to the way in which they are coupled. The basic coupling methods are: resistance-capacitance (*RC*) coupling, transformer coupling and direct coupling. In *RC* coupling, the output of first stage is coupled to the input of next stage through a capacitor. In transformer coupling, the output of one circuit is coupled to the input of the next by means of a transformer. In direct coupling, the output of one stage is applied directly to the input of the next stage.

Amplifiers according to circuit configuration: Amplifiers are also classified on the basis of transistor configuration used. These are:

i) grounded base or common base (CB) amplifier.

ii) grounded emitter or common emitter (CE) amplifier.

iii) grounded collector or common collector (CC) amplifier.

Amplifiers according to frequency: They are classified as direct current (dc) amplifier, audio frequency (af) amplifier, radio frequency (rf) amplifier and video frequency (vf) amplifier. As their names imply, dc amplifiers amplify signals of very low frequency. Audio amplifiers operate in the audio frequency range i.e. from 20 to 20,000 Hz. Video amplifiers amplify signals from the lower audio frequencies to as high as 4 or 5 MHz.

You must have noticed that these classifications are somewhat overlapping. For instance, audio amplifiers may also be voltage or power amplifiers. Similarly, an rf amplifier at the same time may be a common emitter or common base amplifier.

SAQ 1 – **Classification of amplifiers**

Why are class C amplifiers preferred for amplifying the oscillator outputs?

10.3 SMALL SIGNAL LOW FREQUENCY AMPLIFIER

In Unit 4 of this course we discussed the biasing of transistor for linear operation. After the transistor has been biased with a *Q* point near the middle of the dc load line we can couple a small ac signal into the transistor. This produces fluctuations in the collector current of the same frequency and shape. For example, if the input is a sine wave with a frequency of 1 kHz, the output will be an enlarged sine wave with a frequency of 1 kHz. The amplifier is called a linear amplifier if it does not change the shape of the signal. As long as the amplitude of the input signal is small, the transistor will use only a small portion of the load line and the operation will be linear. For this purpose, a class A amplifier shown in Fig. 10.4a with universal bias is used.

Look at the output characteristics of a transistor shown in Fig. 10.4b. The operating point Q is defined by I_{CQ}, V_{CEQ} and I_{BQ}.

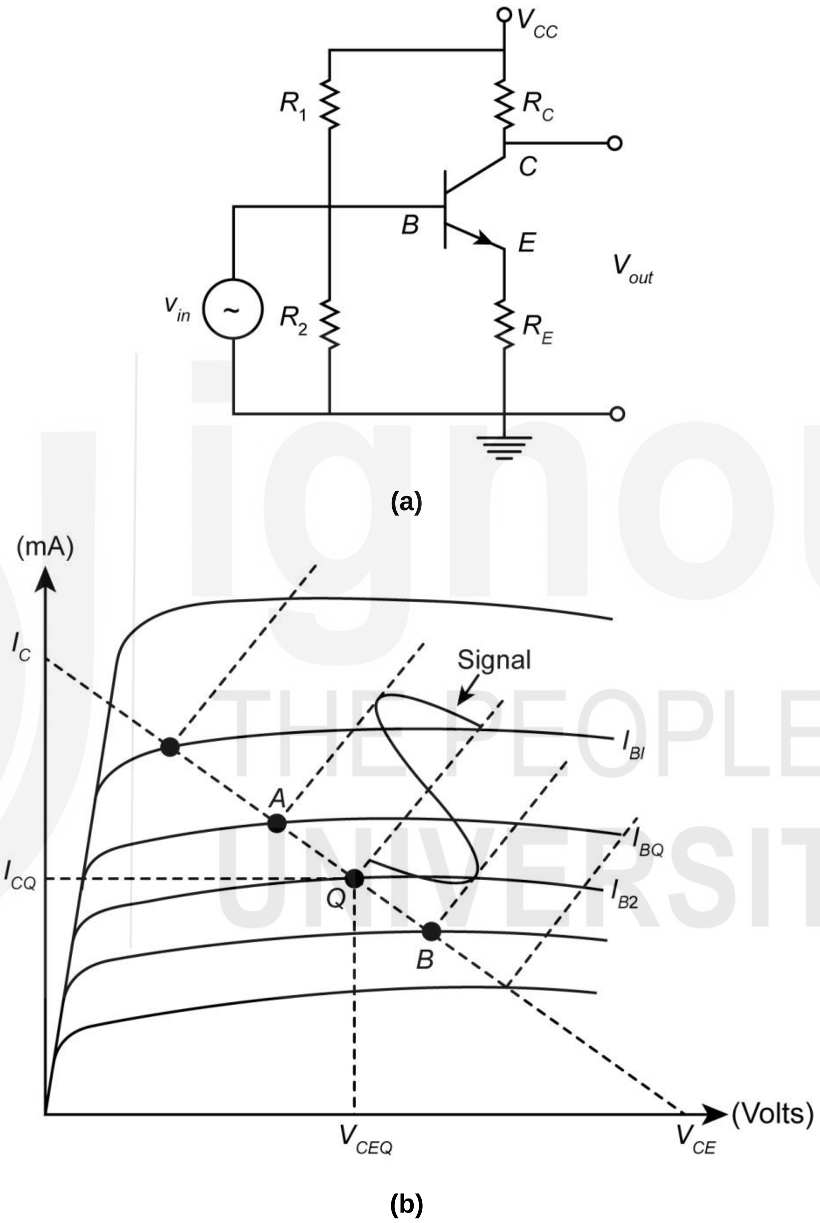


Fig. 10.4: a) Class A amplifier circuit; b) swing of *Q*-point for a sinusoidal input.

When a sinusoidal signal is applied to the base, the base current changes to I_{B_1} during positive half-cycle of the signal and to I_{B_2} during the negative half. The Q-point swings from Q to A and Q to B during this time. You can observe that under all circumstances the operating point remains on the linear portion of the characteristics. So an amplifier in which the operation is linear for the applied signal, is called a small signal amplifier.

Now we will get familiar with some concepts required to analyze small signal amplifier. We will begin with coupling capacitors, devices that allow us to couple ac signals into and out of a transistor stage without changing the dc bias voltages.

10.3.1 Coupling and Bypass Capacitors

In Fig. 10.5 we show a small signal (class A) amplifier. The output is taken between point *D* and ground. The coupling capacitor (C_C) passes (couples) an ac signal from collector *C* to output *D*. For this to happen, the capacitive reactance X_C must be very small at the frequency of signal being amplified.

A bypass capacitor (C_E) is similar to a coupling capacitor, except that it couples an ungrounded emitter (*E*) to a grounded point. The bypass capacitor ideally looks like a short to an ac signal. Because of this, point *E* is shorted to ground as far as the ac signal is concerned. This is why we have labelled the emitter (point *E*) as ac ground. A bypass capacitor will not disturb the dc voltage at point *E* because it looks open to dc current and keeps the dc operating point *Q* in the middle of the loadline.

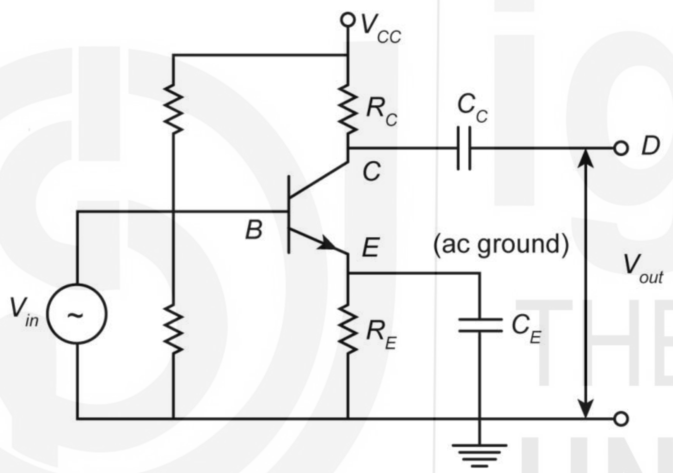


Fig. 10.5: **Small signal amplifier with coupling and bypass capacitors.**

10.3.2 Frequency Response of an *RC*-Coupled Amplifier

A practical amplifier circuit is meant to raise the voltage level of the input signal. This signal may be obtained from the CD player or the microphone in case of a public address (PA) system. Such a signal is not of a single frequency, but it consists of a band of frequencies. For example, the electrical signal produced by our speech or by a musical orchestra may contain frequencies as low as 30 Hz and as high as 15 kHz. If the loudspeakers are to reproduce the original sound faithfully, the amplifier used must amplify all the frequency components of the signal equally well. If it does not do so, the output of the loudspeaker will not be an exact replica of the original sound.

The performance of an amplifier is judged by observing whether all frequency components of the signal are amplified equally well. This information is provided by its frequency response curve. This curve illustrates how the magnitude of the voltage gain of amplifier (A_V) varies with the frequency of the input signal.

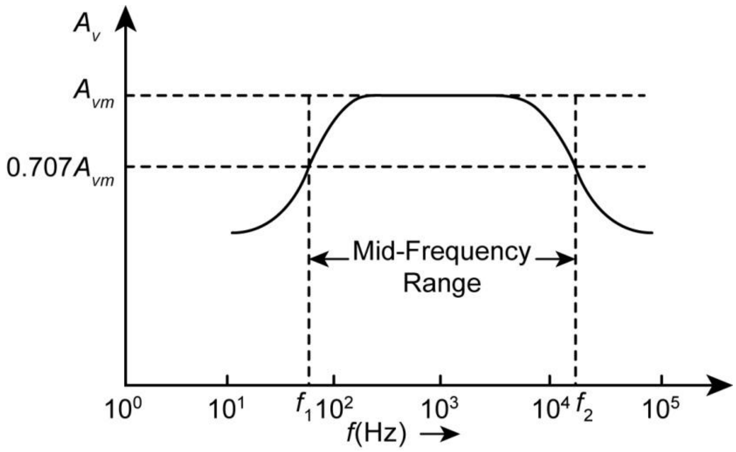


Fig. 10.6: **Frequency response curve of an *RC*-coupled amplifier.**

Fig. 10.6 shows a frequency response curve of a typical *RC*-coupled amplifier. You will observe that the gain is constant only for a limited band of frequencies. This range of frequencies is called the mid-frequency range and the gain is called mid-band gain, A_{vm}. On both sides of the mid-frequency range, the gain decreases. For very low and for very high frequencies, the gain of the amplifier reduces significantly.

Low Frequency Range

In Unit 5, we analysed an amplifier circuit to determine its voltage gain. This was the mid-frequency gain. In mid-frequency range, the coupling and bypass capacitors are as good as short circuits. But, when the frequency is low, these capacitors can no longer be replaced by the short circuit approximation. The lower the frequency, the greater is the value of reactance of these capacitors, since

$$X_C = \frac{1}{2\pi fC}$$

This causes a significant voltage drop across C_C. The lower the frequency of the signal, higher will be the reactance of the capacitor C_C and more will be the reduction in output voltage. At zero frequency (dc signals), the reactance of capacitor C_C is infinitely large (an open circuit). The effective output voltage then reduces to zero. Thus, we see that the output voltage (and hence the voltage gain) decreases as the frequency of the signal decreases below the mid-frequency range.

In practical circuits, the value of the bypass capacitor C_E is very large (= 100 μF) hence its effect is not significant at low frequencies. Effectively, it is the coupling capacitor that has more pronounced effect in reducing the gain at low frequencies.

High Frequency Range

As the frequency of the input signal increases beyond mid frequency range, the gain of the amplifier reduces. Several factors are responsible for this reduction in gain. Firstly, the beta (β) of the transistor is frequency dependent. Its value decreases at high frequencies. Because of this, the voltage gain of the amplifier reduces as the frequency increases.

When depletion layer is formed, it has a barrier potential across it due to ions present there. This potential acts as a parallel plate capacitor with charge accumulation across the junction.

Another important factor responsible for the reduction in gain of the amplifier at high frequencies is the presence of the semiconductor device itself. In a transistor, there exist some capacitance due to the formation of a depletion layers at the junctions. These inter-electrode capacitance C_{bc}, C_{be}, C_{ce} are shown in Fig. 10.7. Note that the connection for these capacitances are shown by dotted lines to indicate that these are not physically present in the circuits, but are inherently present within the device.

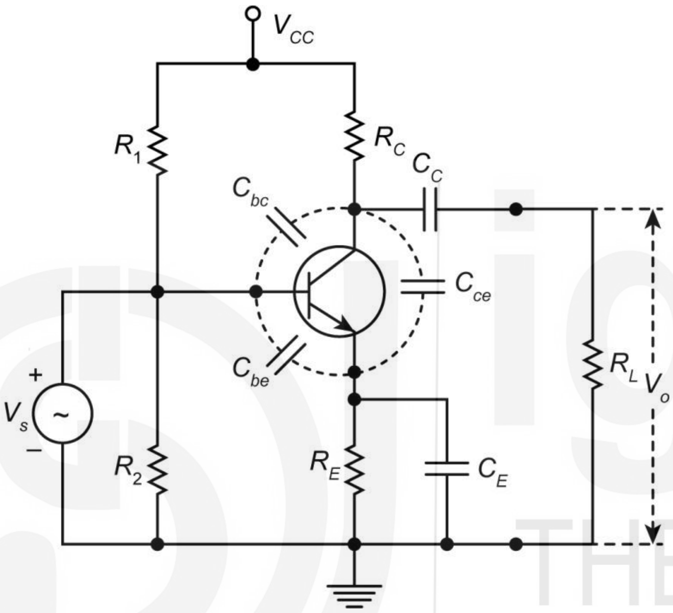


Fig. 10.7: ***RC*-coupled amplifier. Capacitances that affect high-frequency response are shown by dotted connections.**

The higher the frequency, the lower is the impedance offered by these capacitors and lower will be the output voltage.

Bandwidth of an Amplifier

Frequency response curve of an *RC*-coupled amplifier of Fig. 10.6, shows that the gain remains constant only for a limited band of frequencies. On both the low-frequency side as well as on the high frequency side, the gain falls. Now, an important question arises – where exactly should we fix the frequency limits (of input signal) within which the amplifier will have almost constant gain and may be called a good amplifier? The limit is set at those frequencies at which the voltage gain reduces to 70.7% of the maximum gain A_{vm}. These frequencies are known as the cut-off frequencies of the amplifier. These frequencies are marked in Fig. 10.6. The frequency f_1 is the lower cut off frequency and frequency f_2 is the upper cut-off frequency. The difference of the two frequencies, that is $(f_2 - f_1)$, is called the bandwidth (*BW*) of the amplifier. The mid-frequency range of the amplifier is from f_1 to f_2.

You may like to attempt an SAQ.

SAQ 2 – Class A amplifier

a) What should be the bandwidth of an amplifier used to amplify an audio signal?

b) Design a class A amplifier in Fig. 10.4a to get $V_{CEQ} = 10\,\text{V}$, $I_{CQ} = 10\,\text{mA}$. Consider $V_{CC} = 20\,\text{V}$, a silicon transistor with $\beta_{dc} = 100$ and $V_B = 4\,\text{V}$.

Let us now discuss the arrangement of amplifiers used for increasing the gain.

10.4 MULTISTAGE AMPLIFIERS AND COUPLING

An amplifier is the basic building block of most electronic systems. Just as one brick does not make a house, a single-stage amplifier is not sufficient to build a practical electronic system. In section 10.3 we discussed the single-stage amplifier. The gain of a single stage is not sufficient for some applications. The voltage level of a signal can be raised to the desired level if we use more than one stage. When a number of amplifier stages are used in succession (one after the other) it is called a **multi-stage amplifier** or a **cascaded amplifier**. Much higher gains can be obtained from the multi-stage amplifier.

Let us estimate the gain of a multistage amplifier.

10.4.1 Gain of a Multistage Amplifier

A multi-stage amplifier (n-stages) can be represented by a block diagram as shown in Fig. 10.8.

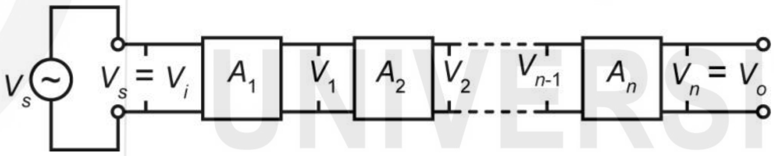


Fig. 10.8: **Block diagram of a multistage amplifier having *n* stages.**

You should note that the output of the first stage makes the input of the second stage: the output of the second stage makes the input of the third stage, …, and so on. The signal voltage v_s is applied to the input of the first stage. The final output v_o is then available at the output terminals of the last stage. The output of the first (or the input to the second stage) is

$$v_1 = A_1 v_s$$

where A_1 is the voltage gain of the first stage. Then the output of the second stage (or the input to the third stage) is

$$v_2 = A_2 v_1 = A_2(A_1 v_s)$$

Similarly, the final output v_o is given as

$$v_o = v_n = A_n v_{n-1}$$

where A_n is the voltage gain of the last (*n*th) stage.

We may look upon this multi-stage amplifier as a single amplifier, whose input is v_s and output is v_o. The overall gain A of the amplifier is then given as

$$A = \frac{v_o}{v_s} = \frac{v_1}{v_s} \times \frac{v_2}{v_1} \times \ldots \times \frac{v_{n-1}}{v_{n-2}} \times \frac{v_o}{v_{n-1}}$$

or

$$A = A_1 \times A_2 \times \ldots \times A_{n-1} \times A_n \qquad (10.1)$$

The gain of an amplifier can also be expressed in another unit called **decibel**.

Decibel

The gains of amplifiers are usually very large. While handling such large numbers it is convenient to compare two powers on a logarithmic scale rather than on a linear scale. The number of **bels** by which a power P_2 exceeds a power P_1 is defined as

$$\text{Number of bels} = \log_{10} \frac{P_2}{P_1}$$

For practical purposes it has been found that the unit bel is quite large. Another unit, one-tenth of bel, is more convenient. This smaller unit is called **decibel** (abbreviated as **dB**). Since one decibel is one-tenth of a bel, we can write

$$\text{Number of dB} = 10 \times \text{Number of bels} = 10 \log_{10} \frac{P_2}{P_1} \qquad (10.2)$$

where P_1 represents the input power and P_2 the output power of an amplifier: If V_1 and V_2 are the input and output voltages of the amplifier, then

$$P_1 = \frac{V_1^2}{R_i}$$

and

$$P_2 = \frac{V_2^2}{R_o}$$

where, R_i and R_o are the input and output impedances of the amplifier respectively. Then, Eq. (10.2) can be written as

$$\text{Number of dB} = 10 \log_{10} \frac{V_2^2 / R_o}{V_1^2 / R_I}$$

In case the input and output impedances of the amplifier are equal, i.e. $R_i = R_o = R$, then Eq. (10.2) simplifies to

$$\text{Number of dB} = 10 \log_{10} \frac{V_2^2}{V_1^2} = 10 \log_{10} \left[\frac{V_2}{V_1}\right]^2$$

$$= 10 \times 2 \log_{10} \frac{V_2}{V_1} = 20 \log_{10} \frac{V_2}{V_1} \qquad (10.3)$$

However, in general, the input and output impedances are not always equal. But the expression of Eq. (10.3) is adopted as a convenient definition of the decibel voltage gain of an amplifier, regardless of the magnitudes of the input and output impedances.

As an example, if the voltage gain of an amplifier is 100, it can be denoted on the dB scale as

$$\text{Gain in dB} = 20\log_{10}\frac{V_2}{V_1} = 20\log_{10}100$$

$$= 20 \times 2 = 40\ \text{dB}$$

Gain of Multi-Stage Amplifier in dB

The gain of a multi-stage amplifier can be easily computed if the gains of the individual stages are known in dB. The overall voltage gain in dB of a multi-stage amplifier is the sum of the decibel voltage gains of the individual stages. That is

$$A_{dB} = A_{dB1} + A_{dB2} + \ldots + A_{dBn} \qquad (10.4)$$

SAQ 3 – **Gain of a multistage amplifier**

A multi-stage amplifier consists of three stages. The voltage gains of the stages are 30, 50 and 80. Calculate the overall voltage gain. Also express the overall voltage gain in dB.

10.4.2 Coupling of Amplifier Stages

In a multi-stage amplifier, the output of one stage makes the input of the next stage (as shown in Fig. 10.8). Can we connect the output terminals of one amplifier to the input terminals of the next amplifier directly? This may not always be possible due to practical difficulties. We must use a suitable coupling network between two stages so that a minimum loss of voltage occurs when the signal passes on to the next stage. Also, the dc voltage at the output of one stage should not be permitted to go to the input of the next. If it does, the biasing conditions of the next stages are disturbed.

The coupling network not only couples two stages; it also forms a part of the load impedance of the preceding stage. Thus, the performance of the amplifier will also depend upon the type of coupling network used. The three generally used coupling schemes are:

i) Resistance-capacitance (*R*-*C*) coupling

ii) Transformer coupling

iii) Direct coupling

Resistance-Capacitance Coupling

Fig. 10.9 shows how to couple two stages of amplifier using resistance-capacitance (*RC*) coupling scheme. This is the most widely used method. In this scheme, the signal at the collector of the first stage is coupled to the base of the second stage through the capacitor C_C. The coupling capacitor C_C blocks the dc voltage of the first stage from reaching the base of the second stage. In this way, the dc biasing of the next stage is not interfered with. For this reason, the capacitor C_C is also called a *blocking capacitor*.

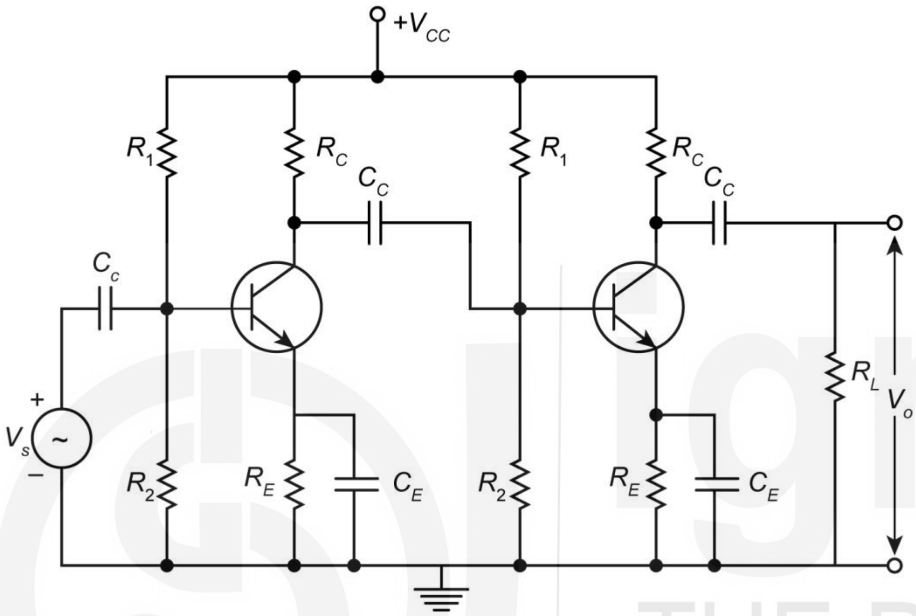


Fig. 10.9: **Two-stage *RC*-coupled amplifier using transistors.**

Transformer Coupling

In this type of coupling, a transformer is used to transfer the ac output voltage of the first stage to the input of the second stage as shown in Fig. 10.10.

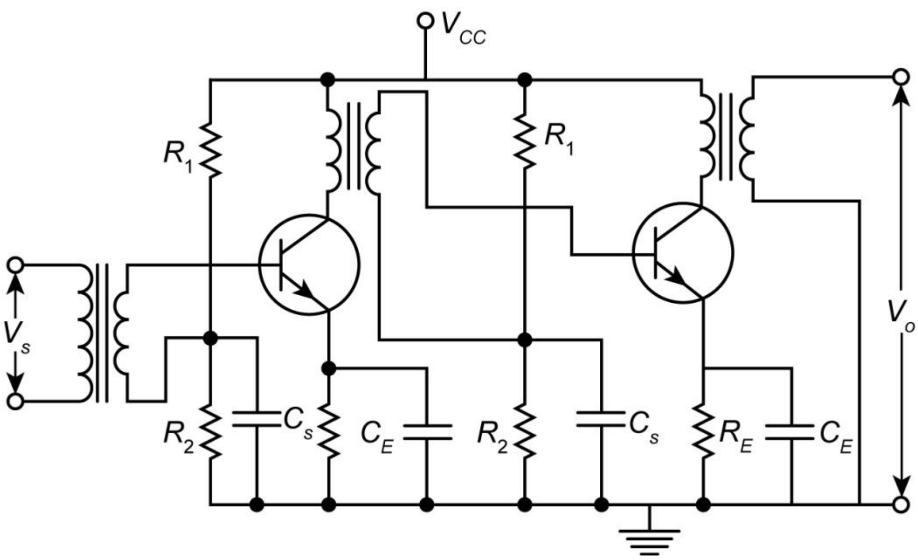


Fig. 10.10: **Two stages of amplifier are coupled by a transformer.**

Here, the resistor R_c is replaced by the primary winding of the transformer. The secondary winding of the transformer replaces the wire between the voltage divider (of the biasing network) and the base of the second stage.

Note that in this circuit there is no coupling capacitor. The dc isolation between the two stages is provided by the transformer itself. There exists no dc path between the primary and the secondary windings of a transformer. However, the ac voltage across the primary winding is transferred (with a multiplication factor depending upon the turns ratio of the transformer) to the secondary winding.

The main advantage of the transformer coupling over *RC* coupling is that all the dc voltage supplied by V_{cc} is available at the collector. There is no voltage drop across the collector resistor R_c (of *RC*-coupled amplifier). The absence of resistor R_c in the collector circuit also eliminates the unnecessary power loss in the resistor.

The transformer coupling scheme is not used for amplifying low frequency (audio) signals. However, these are widely used in radio-frequency (rf) amplifiers. In radio receivers, the rf ranges from 550 kHz to 3 MHz, while in TV receivers it ranges from 54 MHz to 216 MHz. The transformer coupling provides high gain at the desired rf frequency.

The use of a transformer for coupling also helps in proper impedance matching. By suitably selecting the turns ratio of the transformer, we can match any load with the output impedance of the amplifier. This help in transferring maximum power from the amplifier to the load. This is discussed in more details in Section 10.5 on power amplifier.

Direct Coupling

In certain applications, the signal voltages are of very low frequency. The amplifier used for the amplification of such slowly varying signals makes use of direct coupling. In this type of coupling scheme, the output of one stage of the amplifier is connected to the input of the next stage by means of a simple connecting wire.

However, the direct coupling scheme has one serious drawback. The transistor parameters like V_{BE} and β vary with temperature. This causes the collector current and voltage to change. Because of the direct coupling, this voltage change appears at the final output.

For applications where the signal frequency is below 10 Hz, coupling capacitors and bypass capacitors cannot be used. At low frequencies, these capacitors can no longer be treated as short circuits, since they offer sufficiently high impedance. Fig. 10.11 shows a two stage direct coupled amplifier.

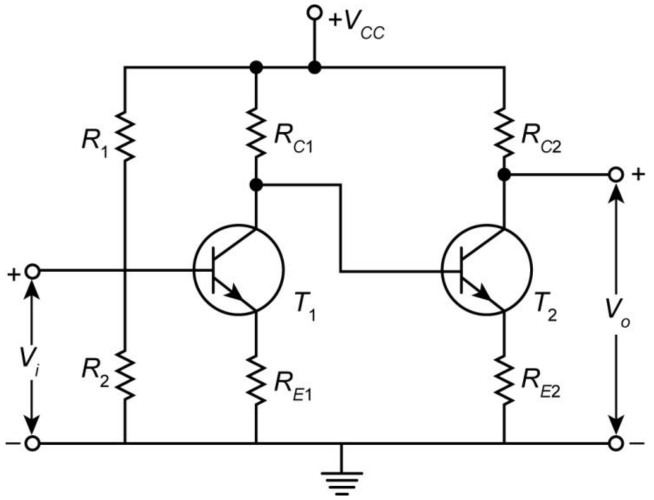


Fig. 10.11: **Direct-coupling of two stages of amplifier.**

Before proceeding further, you should solve an SAQ.

SAQ 4 – **Direct coupled amplifier**

In the circuit given in Fig. 10.11, if $V_{CC} = 20\,\text{V}$, $R_1 = 15\,\text{k}\Omega$, $R_2 = 5\,\text{k}\Omega$, collector current in T_1 is $10\,\text{mA}$, $V_{CE_1} = 8\,\text{V}$, $V_{BE_1} = 0.6\,\text{V}$ and its dc current gain is 80, calculate R_{C1}, R_{E1} and the dc voltage at the base of T_2.

Now, let us consider same high power amplifiers.

10.5 POWER AMPLIFIERS

In almost all electronic systems, the last stage has to be a power amplifier. For example, in a public address system, it is the power amplifier that drives the loudspeakers. When a person speaks into a microphone, the sound waves are converted by it into electrical signal. This electrical signal is of very low voltage (a few mV). This signal, if fed directly, cannot drive the loudspeakers, to give sound (audio) output. The voltage level of this signal is first raised to sufficiently high values (a few V) by passing it through a multi-stage voltage amplifier. This voltage is then used to drive (or excite) the power amplifier. The power amplifier amplifies the current and hence delivers higher power to the loudspeakers. The loudspeakers finally convert the electrical energy into sound energy. Thus, a large audience can hear the speech (or music from the orchestra).

A voltage amplifier increases the voltage level of the input signal, but does not increase its current. A power amplifier may not increase the voltage level, but increase the current output. Effectively power (i.e. current multiplied by voltage) is large, although there is no increase in the voltage level.

In this way, a power amplifier is an essential part of most of the electronic systems.

The primary function of the voltage amplifier is to raise the voltage level of the signal. It is designed to achieve the largest possible voltage gain. Only very little power can be drawn from its output. On the other hand, a power amplifier is meant to boost the power level of the input signal. This amplifier can feed a large amount of power to the load. To obtain large power at the output of the power amplifier, its input-signal voltage must be large. That is why, in an electronic system, a voltage amplifier precedes the power amplifier, and the power amplifiers are called **large-signal amplifiers**.

Now the question arises that why a voltage amplifier cannot work as a power amplifier or in other words what is the difference between a voltage amplifier and a power amplifier. Refer to Fig. 10.5 in Section 10.3.1.

The total dc power drawn from the supply is $V_{CC}\, I_{CQ}$. Out of this, only $(V_{CEQ}\, I_{CQ})$ is the effective dc input power to the amplifier because, at best, that is the power that could be converted into useful ac power. The difference of power dissipated in R_C and R_E which is

$$I_{CQ}^2 (R_C + R_E)$$

goes waste in unnecessarily heating the resistors.

We can attempt to reduce this wastage of power. The resistor R_E has to be there in the circuit, because it is a part of the biasing network. If R_E is absent, the stabilisation of the operating point becomes poor. However, we can do something about the resistance R_C.

We can replace R_C by a component whose dc resistance is zero, but ac impedance is very high. We can do this by replacing R_C by a choke (an inductor). Two things are achieved by doing this. First, no dc voltage drop occurs across the choke (since the dc resistance is almost zero). So we can use a lower voltage supply V_{CC} for the same amplifier. Second, the dc power loss in the choke is almost nil. Thus, this circuit is much efficient as compared to the one in Fig. 10.9.

Still more improvements can be made in this circuit so that it works as a better power amplifier. Let is discuss it now.

10.5.1 Class A Power Amplifier

Fig. 10.12 shows a typical Class A transistor power amplifier which operates linearly throughout the full cycle of the signal. In many electronic systems, such as radio, television, tape recorder, public address system, etc. the final output is in the form of sound. In such systems, the loudspeaker is the load for the power amplifier. The power amplifier makes the final stage and it drives the loudspeaker. In place of choke we have used a transformer in the circuit because it provides impedance matching.

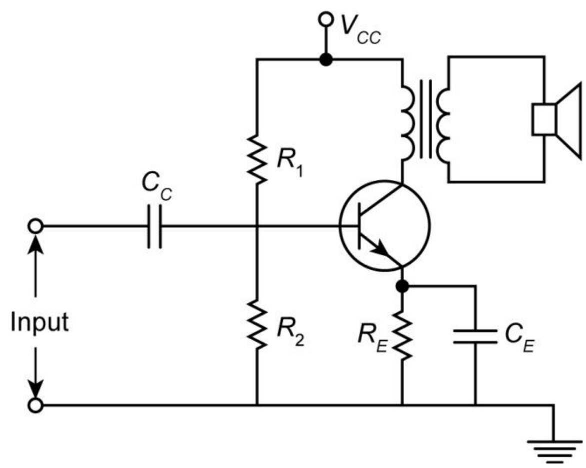


Fig. 10.12: **Class A power amplifier**

In a power amplifier, the ac output power is sufficiently high, whereas the power in the base circuit is quite low. The question naturally arises where the power comes from. The only source of power in a power amplifier is the dc supply, V_{CC}. A portion of this dc input power appears as useful ac power across the load R_L. The rest of it is lost in the circuit. That is

dc input power = ac output power + losses in devices

or

$$P_i(\text{dc}) = P_o(\text{ac}) + \text{Power losses} \quad (10.5)$$

In Eq. (10.5), the input dc power is obtained from the battery or a dc power supply. It is given by the product of voltage V_{CC} and the average current drawn from the supply. If the amplifier is working in class A configuration, the average collector current will be the same as the quiescent collector current I_{CQ}. Therefore, the dc input power is

$$P_i = V_{CC}\, I_{CQ} \quad (10.6)$$

For the transformer coupled amplifier, the only power lost is P_D which is dissipated by the transistor (other losses are negligible). We can now write Eq. (10.5) as

$$P_D = P_i - P_o(\text{ac}) \quad (10.7)$$

or

$$P_D = V_{CC}\, I_{CQ} - P_o \quad (10.7a)$$

This equation is very significant in the operation of a power amplifier. The maximum power dissipation in the transistor occurs when the ac output power is zero, in which case

$$P_{D(\max)} = V_{CC}\, I_{CQ} \quad (10.8)$$

Now let us understand this with an example. Fig. 10.13 shows output characteristics of a power transistor. Assume that its power dissipation rating is 3.5 W, then we must ensure that P_D does not exceed 3.5 W. We first plot its collector dissipation curve. For this, we take some arbitrary values of V_{CE} and calculate corresponding values of I_C so that we always have $V_{CE} I_C = P_D = 3.5$ W. The curve obtained from these values is a hyperbola, as shown in Fig. 10.13. If this transistor is used in a power amplifier, its Q point must lie below this curve.

A power amplifier is said to have high efficiency, if it can convert a greater portion of the dc input power drawn from the supply into the useful ac output power. We define circuit efficiency as the ratio of ac power to dc input power supplied to the collector-emitter circuit.

$$\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} = \frac{P_o}{V_{CC}\, I_{CQ}} \quad (10.9)$$

Efficiency is a measure of how well an amplifier converts dc power from the supply into useful ac output power.

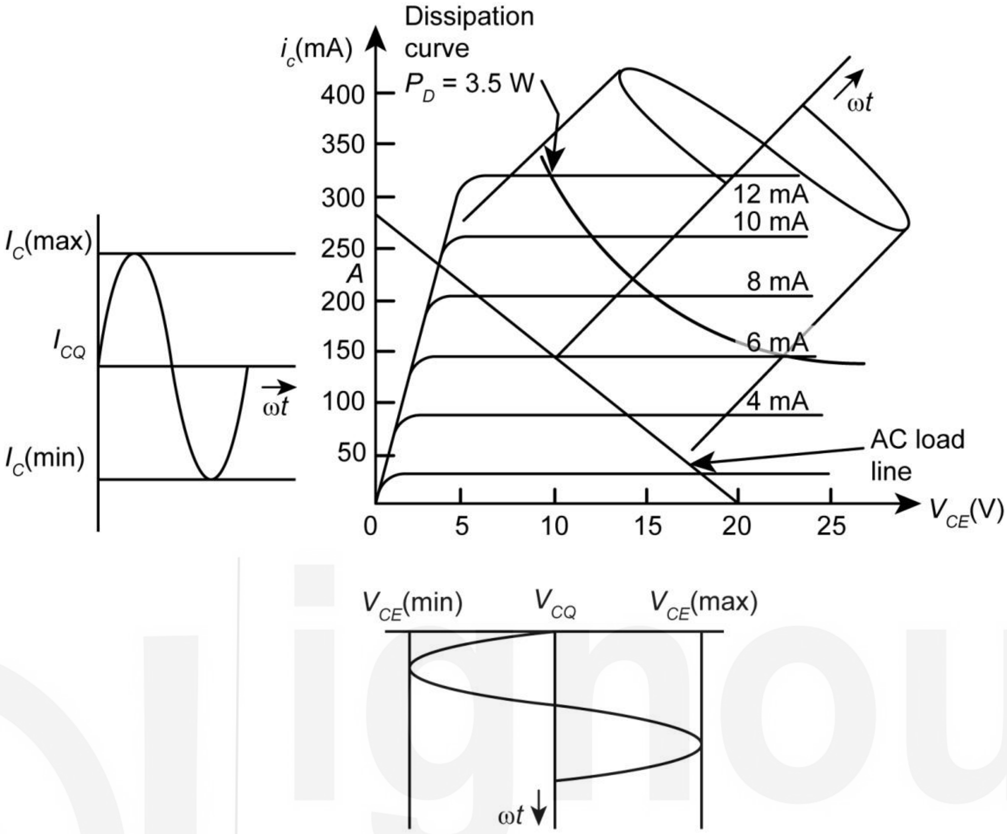


Fig. 10.13: **Characteristics of a power transistor with its collector dissipation curve.**

Let us now analyse the circuit shown in Fig. 10.14. The output characteristics of the transistor are given in Fig. 10.13. We shall find, for this circuit, the rms values of collector current and voltage, and the ac power developed at the collector and the amplifier efficiency.

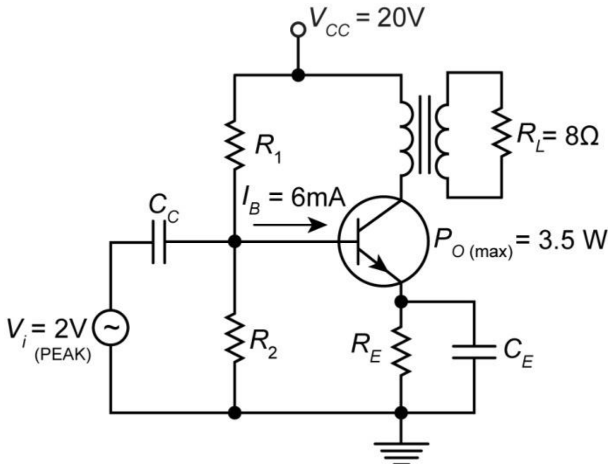


Fig. 10.14: **A practical class A power amplifier.**

From the graph in Fig. 10.13, we can find the maximum and minimum values of the collector current and voltage between which the signal swings. The ac power developed across the transformer primary can be calculated to be

$$P_o(\text{ac}) = V_{CE}(\text{rms}) \times I_C(\text{rms}) = \frac{V_{CE}(\text{peak})}{\sqrt{2}} \times \frac{I_C(\text{peak})}{\sqrt{2}}$$

But

$$V_{CE}(\text{peak}) = \frac{V_{CE}(\max) - V_{CE}(\min)}{2}$$

And

$$I_C(\text{peak}) = \frac{I_C(\max) - I_C(\min)}{2}$$

$$\therefore \quad P_0(\text{ac}) = \frac{(V_{CE(\max)} - V_{CE(\min)})}{2\sqrt{2}} \times \frac{(I_{C(\max)} - I_{C(\min)})}{2\sqrt{2}}$$

or

$$P_0(\text{ac}) = \frac{[V_{CE(\max)} - V_{CE(\min)}]\,[I_{C(\max)} - I_{C(\min)}]}{8} \qquad (10.10)$$

The same power appears across the load R_L, if the transformer is 100% efficient. Assuming the losses in the transformer to be negligible, we can now calculate the ac power delivered to the loudspeaker R_L from Eq. (10.10).

In this case, if we consider

$$V_{CE(\max)} = 18.0\text{ V};\ V_{CE(\min)} = 2.0\text{ V}$$

$$I_{C(\max)} = 245\text{ mA};\ I_{C(\min)} = 25\text{ mA}$$

then,

$$P_0(\text{ac}) = \frac{(18.0 - 2.0) \times (245 - 25) \times 10^{-3}}{8}$$

$$= \frac{16.0 \times 0.220}{8}$$

$$= 0.44\text{ W}$$

The quiescent collector current, from the graph, is $I_{CQ} = 135$ mA. The dc input power to the amplifier is given by Eq. (10.6) and in this case

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

$$= 20 \times 0.135 = 2.7\text{ W}$$

The output circuit efficiency can now be calculated by using Eq. (10.9)

$$\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} = \frac{0.44}{2.70} \times 100\% = 16.3\%$$

We can use Eq. (10.7) to determine the power dissipated by the transistor.

$$P_D = P_i(\text{dc}) - P_o = 2.70 - 0.44 = 2.26\text{ W}$$

From the above calculations we see that, under the conditions specified, the collector-circuit efficiency of the single-ended power amplifier circuit is 16.3%. This, in fact, is quite low. A large part of the net input dc power is dissipated by the transistor as heat. By increasing the signal at the input we could obtain more output power. This way, the efficiency also goes up. But then the amplifier is driven into saturation (or into cut-off, or both) during a part of the ac cycle. This will cause a large distortion in the output. To keep the distortion minimum, the amplifier has to work under class A operation. For this operation, the maximum theoretical efficiency is 50%. In practical circuits, the efficiency is much less than 30%.

It is possible to have higher efficiency by working the amplifier under class B, class AB, or even class C operation; and yet keep the distortion low. This is achieved by a circuit called a push-pull amplifier. We shall discuss this circuit in the next sub-section.

10.5.2 Push-Pull Amplifier

A push-pull amplifier circuit uses two transistors as shown in Fig. 10.15. This circuit can work in class B, class AB or class A operation. Because of the special circuit connection, it provides a low distortion, and at the same time a highly efficient operation (class AB or class B).

The dots marked on the primary and secondary winding of the transformer are the points with same phase of signal.

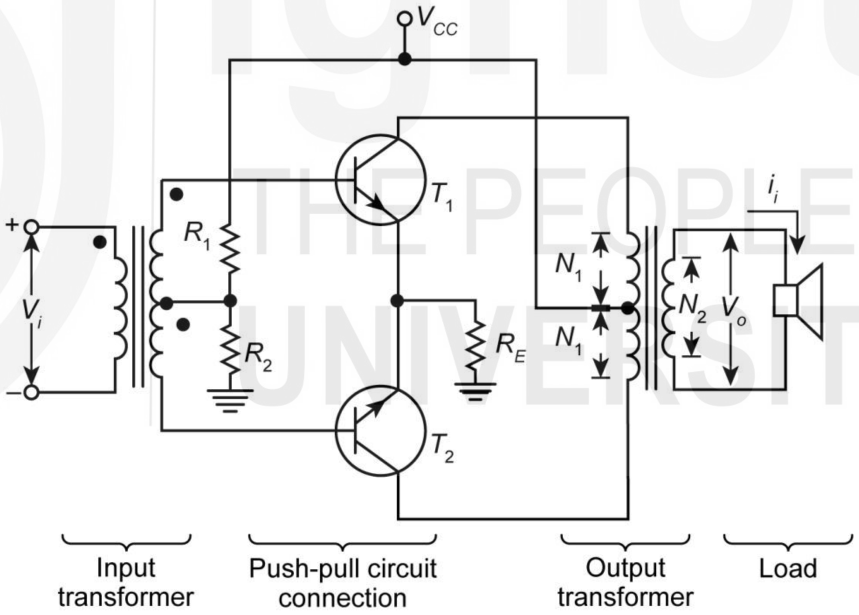


Fig. 10.15: **Push pull amplifier circuit using transistors.**

The matched transistors have identical characteristics like α, β, temperature drift etc.

Here we use two matched transistors, T_1 and T_2, with their emitter terminals connected together. The circuit has two transformers – one at the input and the other at the output. The input transformer has a centre-tapped secondary winding. It provides opposite polarity signals to the two transistor inputs. The primary of the output transformer is also centre-tapped. The collector terminals of the two transistors are connected to the supply V_{CC} through the primary of this transformer, that is, this primary acts as the choke in the collector circuits.

The load resistance (usually a loudspeaker) is connected across the secondary of the output transformer. Note that the resistors R_1, R_2 and R_E form the biasing network of both the transistors.

To understand how opposite polarity signals appear at the two transistor inputs when we apply a signal V_i to the amplifier inputs, refer to Fig. 10.16. Assume that when we apply a sinusoidal signal V_i at the input, it induced voltage of 20 V (peak) across the secondary winding (i.e. across the terminals *AB*). Point *C* is the centre-tap of the secondary. This point is at ground (0 V potential) for ac.

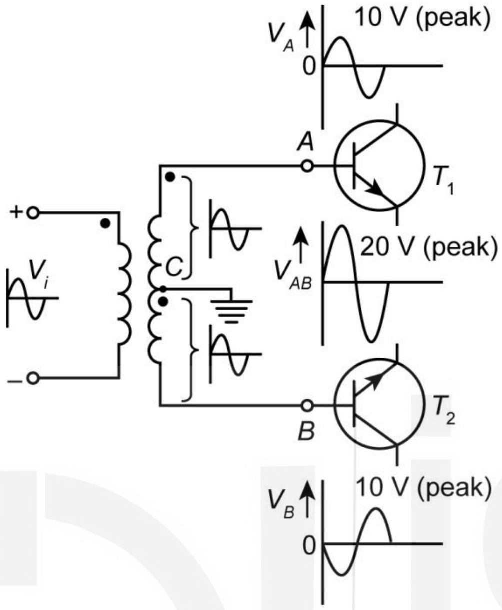


Fig. 10.16: **Opposite-polarity inputs to the two transistors obtained by using a centre-tapped transformer.**

The voltages across each half of the secondary are 10 V (peak). The two voltages add upto a total of 20 V across the whole winding. Let us consider the instant at which the voltage at point *A* is 20 V with respect to point *B*, i.e. when $V_{AB} = 20\,\text{V}$. At this instant, the voltage at point *A* with respect to point *C* is 10 V, i.e. $V_{AC} = V_A = 10\,\text{V}$. At the same time, the voltage at point C with respect to point *B* is also 10 V, i.e. $V_{CB} = 10\,\text{V}$. That is $V_{BC} = -V_{CB} = -10\,\text{V}$. This is the voltage at point *B* with respect to the ground, and this voltage V_B is appearing at the input of the transistor T_2. Thus, the signals appearing at the base of the two transistors are of opposite polarity. It can also be said that, they are in opposite phase (phase difference of π radians). The resulting base current of the two transistors can then be written as

$$i_{b1} = I_b \sin \omega t \qquad (10.11)$$

$$i_{b2} = I_b \sin(\omega t + \pi) \qquad (10.12)$$

We shall now see what happens at the output of the amplifier. We first consider class A operation (although push-pull connection can be more efficiently used in class B or class AB operation). As shown in Fig. 10.17, under no input signal, the quiescent collector currents (I_{CQ}) of the two transistors flow in opposite directions through the two halves of the primary winding. These currents produce opposite flux through the magnetic core of the output transformer. If the two transistors are perfectly matched, the net flux in the core is zero.

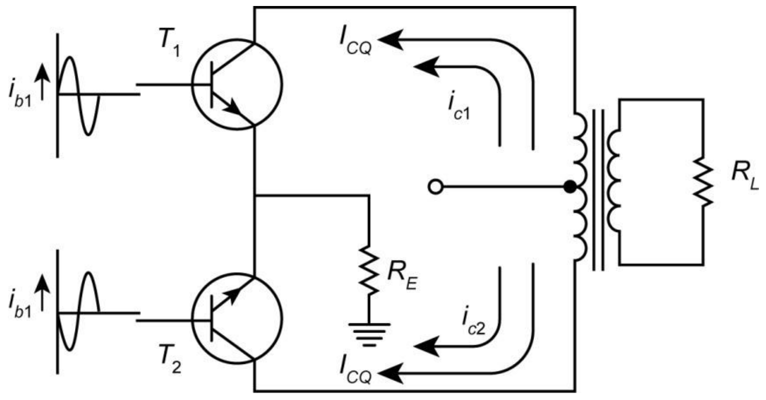


Fig. 10.17: **Details of push pull operation at the output.**

When an ac signal is applied to the input, opposite phased, varying base currents flow in the two transistors. As a result, the ac collector currents in the two transistors are also in opposite phase. The total current i_{c1} in transistor T_1 and the total current i_{c2} in transistor T_2 varies as shown in Fig. 10.18a and b, respectively. These currents flow in opposite directions in two halves of the primary winding. The flux produced by these currents will also be in opposite directions. The next flux in the core will be the same as that produced by the difference of the currents i_{c1} and i_{c2}. To find the difference i_{c1} and i_{c2}, we first find the negative of i_{c2}. This is done in Fig. 10.18c. We can now add the currents of Fig. 10.18a and c to get the difference, since

$$i_{c1} - i_{c2} = i_{c1} + (-i_{c2})$$

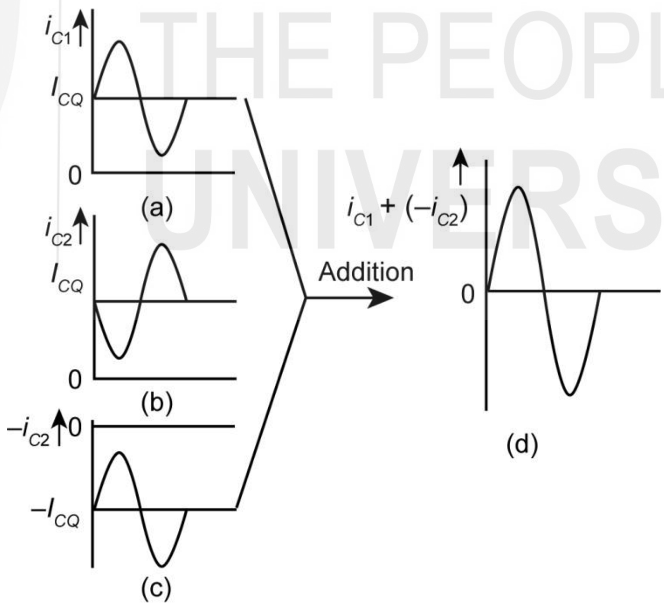


Fig. 10.18: **a) Collector current i_{c1} in transistor T_1; b) Collector current i_{c2} in transistor T_2; c) The negative of i_{c2}; d) the difference $(i_{c1} - i_{c2})$.**

The difference of the two collector currents is obtained in Fig. 10.18d. Note that during this process the quiescent currents (I_{CQ}) of the two transistors get cancelled, but the ac currents get added up. The overall operation results in a net ac current flow through the primary of the transformer. This results in a varying flux in the core. An ac voltage is induced in the secondary, and the ac power is delivered to the load resistor R_L.

From Fig. 10.18a and b, it may be seen that during the first half-cycle, the current i_{c1} increases, but at the same time the current i_{c2} decreases. In other words, when one transistor is being driven into more conduction, the other is driven into less conduction. The reverse happens in the next half-cycle. This amounts to saying that when the current in one transistor is "pushed-up", the current in the other transistor is "pulled down". Hence, the name **push-pull** amplifier.

Before proceeding further solve an SAQ.

SAQ 5 – **Class A power amplifier**

a) The quiescent operating collector current for the circuit shown in Fig. 10.12 is 25 mA. If $V_{CC} = 15\text{ V}$, what is the input dc power to the circuit?

b) Calculate output ac power, if the efficiency of the amplifier is 15%

The amplifier performance can improve if a feedback from its output is used to stabilize its parameters. Let us now discuss how a negative feedback achieves this.

10.6 AMPLIFIER PERFORMANCE UNDER NEGATIVE FEEDBACK

Feedback simply means transferring a portion of the energy from the output of a device back to its input. In other words, feedback is the process of taking a part of output signal and feeding it back to the input circuit. Look at the block diagram shown in Fig. 10.19. Let *A* be the gain of the amplifier when there is no feedback.

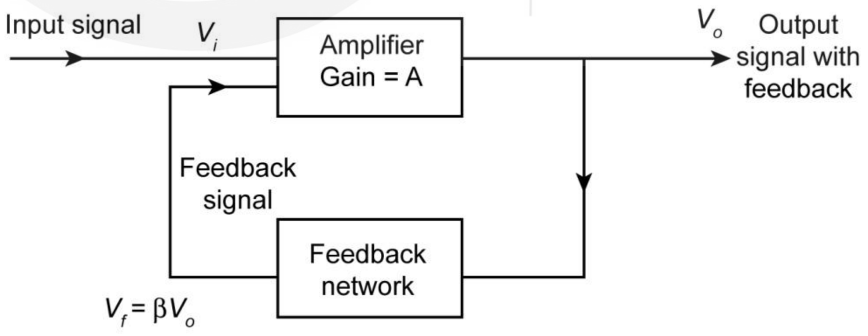


Fig. 10.19: **Schematic diagram of feedback amplifier.**

A portion βV_o where $\beta \le 1$, is then applied back to the amplifier input. The actual input to the amplifier thus consists of the sum of the signal voltage V_i plus feedback voltage, $V_f = \beta V_o$. We call β as the **feedback fraction** defined as

$$\beta = \frac{V_f}{V_o} \tag{10.13}$$

So the total input voltage with feedback $= V_i + \beta V_o$

The output voltage with this input is $V_o = (V_i + \beta V_o) A$

i.e. $V_o = AV_i + A\beta V_o$

as $V_o - A\beta V_o = AV_i$

$V_o (1 - A\beta) = AV_i$

$\therefore$ Gain with feedback, $A_f = \dfrac{V_o}{V_i} = \dfrac{A}{1 - A\beta}$ (10.14)

10.6.1 Negative Feedback and its Effect on Amplifier Performance

In Eq. (10.13) if β is negative, then the feedback signal is out of phase with the applied signal. In such a case, the net input voltage to the amplifier becomes the difference of the external input voltage and the feedback voltage. Since the net input to the amplifier is reduced, the output of the amplifier also decreases. In other words, the gain of the amplifier reduces because of the feedback. Such a feedback is called **negative** or **degenerative feedback**. By putting β as a negative quantity into Eq. (10.14) you will get the gain with negative feedback as

$$A_f = \frac{A}{1 - A(-\beta)} = \frac{A}{1 + A\beta} \qquad (10.15)$$

Since you are dividing A by a positive quantity greater than 1, obviously $A_f < A$. Thus, negative feedback reduces the gain of the amplifier.

Before moving further you may solve the following SAQ.

SAQ 6 **– Negative feedback gain**

Calculate the gain of a negative feedback amplifier with an internal gain, A = 100, and feedback factor β = 1/10.

In Sec. 10.3.2, we discussed the frequency response of an amplifier. The difference $(f_2 - f_1)$ is called the bandwidth (*BW*) of the amplifier. For an amplifier, the product of gain and *BW*, called **gain-bandwidth product**, remains constant i.e. $A \times BW$ = constant. Since the gain of the amplifier is decreased with negative feedback, to get the product $A_f \times BW$ same as before, *BW* has to increase. In other words, the bandwidth of the amplifier increases with negative feedback. Fig. 10.20 shows the frequency response of the amplifier both, with and without feedback.

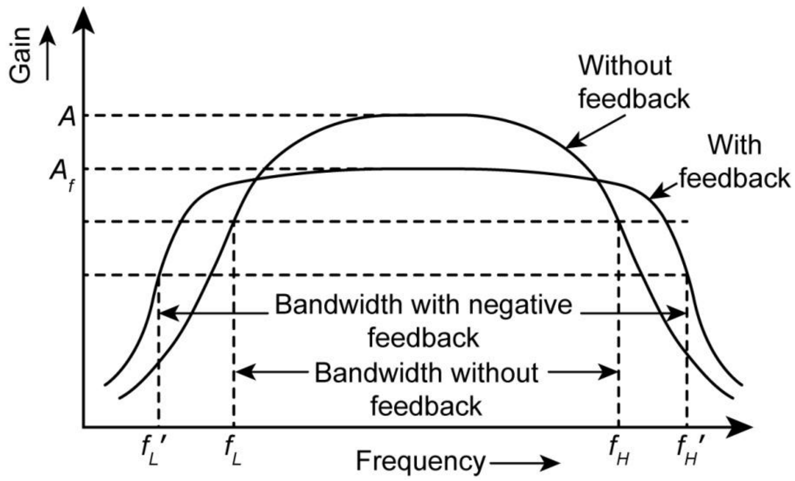


Fig. 10.20: **Frequency response of negative feedback amplifier.**

In Eq. (10.15), if $A\beta$ is very large compared to 1 in the denominator, then 1 can be neglected in comparison with $A\beta$. So Eq. (10.15) reduces to

$$A_f = \frac{A}{A\beta} = \frac{1}{\beta} \qquad (10.16)$$

Since β does not depend upon the parameters of the active device that you have used in the amplifier, such as a transistor, the gain with feedback, A_f is almost independent of the actual gain *A*. On the other hand, *A* is dependent upon the transistor parameters. Thus, by introducing negative feedback we can have the gain to be independent of transistor parameters. This is known as *stabilization of amplifier gain*.

Likewise other effects of negative feedback are, reduction in noise, modification of the input and output resistances of the amplifier etc.

Thus, we have seen that the gain of an amplifier is reduced when negative feedback is used. However, the negative feedback improves the performance of the amplifier from so many other points of view. The advantages of negative feedback are as follows:

i) It increases the bandwidth

ii) It improves the stability of amplifier gain

iii) It reduces distortion

iv) It increases the input impedance

v) It decreases the output impedance

Now we will recapitulate the points discussed in this unit.

10.7 SUMMARY

Concept	Description
Q-point	■ The operating point (*Q*-point) with fixed I_B, I_C and V_{CE} values is provided to the transistor through biasing when no signal is applied.
Small signal amplifier	■ In a small signal amplifier, the signal amplitude makes the *Q*-point to swing on the linear portion of the characteristics.
Power amplifier	■ A large signal amplifiers is the one in which the signal amplitude swings the *Q*-point even over the non-linear portion of the characteristics. This produces distortion.
Push-pull amplifier	■ In push-pull amplifier, the signal to be amplified is converted to two 180 degree out of phase signals that are applied simultaneously to the inputs of two matched transistors. The amplified output signal is obtained across a transformer connected between the collectors of two transistors.
Negative feedback	■ Negative feedback reduces the gain of the amplifier and increases its bandwidth.

10.8 TERMINAL QUESTIONS

1. Why do you select the operating point on the linear portion of the characteristics?

2. What is meant by biasing? Which biasing is the most commonly used?

3. Fill in the gap by choosing the correct option.

   a) If in an *RC* coupled amplifier the value of a coupling capacitor is increased to twice the original value, the low frequency response of the amplifiers would be ……………….. (worse/the same/better).

   b) In the above case the high frequency response would be ……………. (worse/the same/better).

4. An *RC*-coupled amplifier has a voltage gain of 100 in the frequency range of 400 Hz to 25 kHz. On either side of these frequencies, the gain falls so that it is reduced by 3 dB at 80 Hz and 40 kHz. Calculate gain in dB at cut-off frequencies and also construct a plot of frequency response curve.

5. In class B push pull amplifier battery supply is 5 volts, output power is 400 mW and maximum collector dissipation of each transistor is 100 mW. Calculate peak collector current.

10.9 SOLUTIONS AND ANSWERS

Self-Assessment Questions

1. Oscillator circuits are used for generation of a single frequency signal. It is purely sinusoidal signal of fixed frequency and hence there is no particular need of distortion-free amplification. Class C amplifier provides good results for such applications, even though it uses only a small fraction of input signal for operation.

2. a) Audio signal ranges between 20 Hz to 20 kHz. Hence audio amplifier bandwidth should be 20 kHz.

   b)

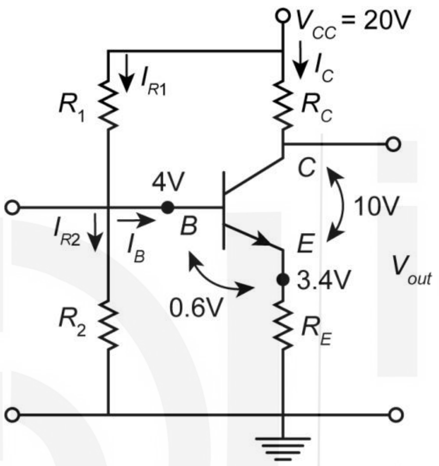


Fig. 10.21: **Class A amplifier design.**

$$I_C = 10\,\text{mA}$$

$$I_B = \frac{I_C}{\beta} = \frac{10\,\text{mA}}{100} = 100\,\mu\text{A}$$

$$V_B = 4\,\text{V}$$

$$\therefore \quad V_E = V_B - V_{BE} = 4\,\text{V} - 0.6\,\text{V} = 3.4\,\text{V}$$

Considering $I_C \approx I_E = 10\,\text{mA}$

$$R_E = \frac{3.4\,\text{V}}{10\,\text{mA}} = 340\,\Omega$$

$$V_{CC} = 20\,\text{V} \quad V_B = 4\,\text{V}$$

$$V_{R_2} = V_B = 4\,\text{V}$$

$$\therefore \quad V_{R_1} = 20 - 4 = 16\,\text{V}$$

If we wish to draw 100 μA base current, the current through the resistor R_1 should be ~ 10 times the value of I_B. Hence current through R_1,

$$I_{R_1} = 1\,\text{mA}$$

$$\therefore \quad R_1 = \frac{V_{R_1}}{I_{R_1}} = \frac{16\,\text{V}}{1\,\text{mA}} = 16\,\text{k}\Omega$$

Now current through R_2, $I_{R_2} = I_{R_1} - I_B = 1\,\text{mA} - 100\,\mu\text{A} = 0.9\,\text{mA}$

$$\therefore \quad R_2 = \frac{V_{R_2}}{I_{R_2}} = \frac{4\text{ V}}{0.9\text{ mA}} = 4.4\,\text{k}\Omega$$

Now

$$V_E = 3.4\text{ V}$$

The supply voltage V_{CC} is getting divided into voltage across R_C, V_{CE}, and voltage across R_E. It is given that $V_E = 3.4\text{ V}$ and $V_{CE} = 10\text{ V}$.

$\therefore$ Voltage drop across R_C

$= V_{CC} - V_{CE} - V_E$

$= 20 - 10 - 3.4 = 6.6\text{ V}$

Current through $R_C = I_C = 10\text{ mA}$

$$\therefore \quad R_C = \frac{6.6\text{ V}}{10\text{ mA}} = 660\Omega$$

With these values of R_1, R_2, R_C and R_E, we obtain operating point at $V_{CEQ} = 10\text{ V}$, $I_{CQ} = 10\text{ mA}$ and $I_{BQ} = 100\,\mu\text{A}$

3. Using Eq. (10.1), the overall voltage gain is

$$A = A_1 \times A_2 \times A_3$$

$$= 30 \times 50 \times 80 = 120000$$

The overall voltage gain in dB of three-stage amplifier is given as

$$A_{\text{dB}} = A_{\text{dB1}} + A_{\text{dB2}} + A_{\text{dB3}}$$

We are given the voltage gain of the individual stages as ratios. So, we would first find the gains of the individual stages in decibels. Thus

$$A_{\text{dB1}} = 20\log_{10} 30 = 29.54\text{ dB}$$

$$A_{\text{dB2}} = 20\log_{10} 50 = 33.98\text{ dB}$$

$$A_{\text{dB3}} = 20\log_{10} 80 = 38.06\text{ dB}$$

Therefore

$$A_{\text{dB}} = 29.54 + 33.98 + 38.06 = 101.58\text{ dB}$$

From the overall voltage gain also you can verify that the gain in dB is

$$A_{\text{dB}} = 20\log_{10} 120000 = 101.58\text{ dB}$$

4. $V_{CC} = 20\text{ V}$

$$V_{B_1} = \frac{R_2}{R_1 + R_1} V_{CC} = \frac{5\text{ k}\Omega}{(5+15)\text{ k}\Omega} \times 20\text{ V} = 5\text{ V}$$

$$V_{E_1} = V_{B_1} - V_{BE_1} = 5\text{ V} - 0.6 = 4.4\text{ V}$$

Since $I_{C_1} \cong I_{E_1} = 10\text{ mA}$,

$$R_{E_1} = \frac{4.4\text{ V}}{10\text{ mA}} = 440\ \Omega$$

$$V_{RC1} = V_{CC} - (V_{CE_1} + V_{E_1})$$

$$= 20 - (8 + 4.4) = 7.6\text{ V}$$

$$\therefore \quad R_{C_1} = \frac{7.6\text{ V}}{10\text{ mA}} = 760\ \Omega$$

and voltage at the base of Q_2

$$V_{C_1} = V_{CC} - V_{RC_1}$$

$$= 20\text{ V} - 7.6\text{ V}$$

$$= 12.4\text{ V}$$

5. a) Given that,

$V_{CC} = 15\text{ V}$, $I_{CQ} = 25\text{ mA}$

From Eq. (10.6)

$$P_i(\text{dc}) = V_{CC}\, I_{CQ} = 15\text{ V} \times 25\text{ mA}$$

$$= 0.375\text{ W}$$

b) From Eq. (10.9),

$$\eta = \frac{P_o(\text{ac})}{P_i(\text{dc})}$$

$$P_o(\text{ac}) = \eta \times P_i(\text{dc}) = (0.15 \times 0.375\text{ W}) = 0.056\text{ W} = 56\text{ mW}$$

6. For negative feedback, we use Eq. (10.15)

$A = 100; \quad \beta = 1/10.$

$$\therefore \quad A_f = \frac{A}{1 + A\beta} = \frac{100}{1 + (100 \times 0.1)} = \frac{100}{1 + 10} = 9.09$$

Terminal Questions

1. So that the change in the operating point does not introduce any distortion at the output.

2. Applying various voltages to different elements of a transistor or any device for its proper operation is called biasing. The universal or potential divider bias is the most commonly used biasing scheme.

3. a) better b) the same

4. The gain in dB is

$$A_{dB} = 20\log_{10} A = 20\log_{10}100 = 40 \text{ dB}$$

This is the mid band gain. The gain at cut-off frequencies is 3 dB less than the mid band gain, i.e.

$$(A_{dB}) \text{ (at cut-off frequencies)} = 40 - 3 = 37 \text{ dB}$$

The plot of the frequency response curve is given in Fig. 10.22.

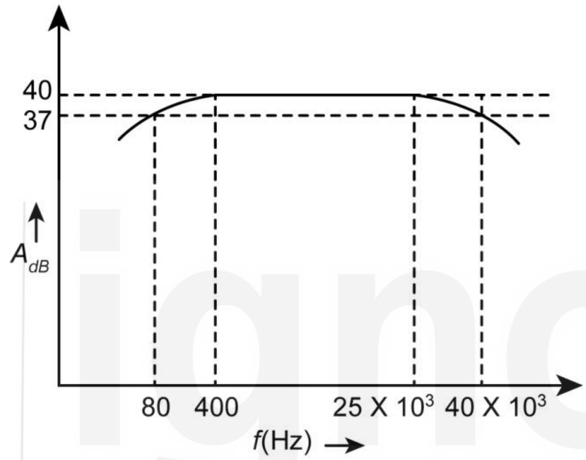


Fig. 10.22: **Frequency response of an *RC*-coupled amplifier.**

5. Given $V_{max} = V_{CC} = 5\text{ V}$.

$$P_{(out)} = 400 \text{ mW} = 400 \times 10^{-3}\text{ W}$$

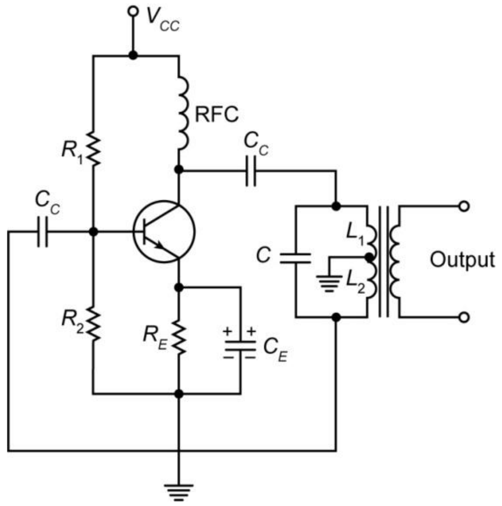
The output power is given by

$$P = \frac{I_{max}}{\sqrt{2}} \times \frac{V_{max}}{\sqrt{2}}$$

or

$$400 \times 10^{-3} = \frac{I_{max}}{2} \times 5$$

$\therefore$ $I_{max} = 160 \text{ mA}.$



Oscillators are used for generating sine waves. *LC* circuits are used for high frequency generation as you will learn in this unit.

UNIT 11

OSCILLATORS

Structure

STUDY GUIDE

In the last unit you learnt about the amplifiers required for increasing the power (or voltage / current) of a signal. You also learnt about the concept of negative feedback, and how it provides stability to the amplifier performance. In this unit, you will learn about the use of transistors for generating ac signals of desired frequency. Such circuits are called the **Oscillators**. For this you should brush up your knowledge about *RC*, *LC* and *LCR* resonant circuits you worked with in the second semester courses BPHCT-133 entitled Electricity and Magnetism and BPHCL-134 entitled Electricity and Magnetism: Laboratory.

You will also require the knowledge of transistor biasing (mostly in *CE* configuration) discussed in the earlier units of this course.

You should try to work out the SAQs, TQs and design examples given in this unit on your own in order to get complete knowledge of the topic.

> **"External interference, which can never be entirely eliminated in practice, always reduces the effectiveness of the system."**
>
> ***R.V.L. Hartley***

11.1 INTRODUCTION

Generation of high frequencies is essential in all communication systems. For example, in radio and television broadcasting, the transmitter radiates the signal using a carrier of very high frequency say from 550 kHz to 22 MHz in radio broadcasting and from 47 MHz to few GHz in TV broadcasting. In radio and TV receivers too there is an **oscillator** circuit which generates very high frequencies. Even mobile phones require oscillator circuits. The oscillators are usually transistor amplifier circuits with positive feedback. In the last unit you learnt about the concept of feedback.

If the portion of the output that is fed back is in phase with respect to the input, then the feedback is termed as **positive feedback**. With positive feedback a circuit can be made to generate an output with no external input. In this unit we will use positive feedback in building oscillators.

In Sec. 11.2 we will discuss about the positive feedback and the principle governing the oscillations. You will be able to establish the criteria for sustained oscillations in a circuit called **Barkhausen Criteria**.

Based on the principle used for generation of oscillations, the oscillators are classified as tuned circuit (*LC*) oscillators and *RC* oscillators. In Sec. 11.3 you will learn about two important *LC* oscillators viz. Hartley oscillator and Colpitts oscillator.

In Sec. 11.4 we will discuss about the *RC* oscillators, namely, Wien bridge oscillator and phase shift oscillator.

Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ workout the feedback gain in case of positive feedback;
- ❖ state the conditions under which a feedback amplifier works as an oscillator;
- ❖ state the classification of oscillators;
- ❖ draw the circuit and explain the working, state the frequency relation and design the *LC* oscillators (Hartley and Colpitt's oscillators);
- ❖ explain the working of phase shift oscillator and design its feedback *R-C* network; and
- ❖ explain the working and calculate the frequency of a Wien bridge oscillator.

Now, we begin with understanding the role of positive feedback in sustaining oscillations in an oscillator circuit.

11.2 POSITIVE FEEDBACK AND OSCILLATIONS

We had discussed the concept of feedback in the last unit. You also know the effect of negative feedback on the amplifier performance in form of reduced gain and increased bandwidth.

Now, when the feedback voltage is in phase with the input signal, then it adds to the input signal. In this case β is positive and feedback is termed as **positive** or **regenerative feedback**. You can observe that when β is positive, the gain with feedback can be written from Eq. (10.14) as

$$A_f = \frac{A}{1 - A\beta} \qquad (11.1)$$

Since A is divided by a number smaller than unity, $A_f > A$. So positive feedback increases the gain of an amplifier. This in turn reduces the bandwidth (BW) because you know that the product (Gain $\times$ BW) is constant.

In Eq. (11.1) if $A\beta = 1$, then $A_f = \infty$. In other words you have an amplifier which gives an output without an input! Such a circuit is called as an **oscillator**. You should not be under the impression that you are getting an output power without any input power. The circuit draws the power from the dc supply connected to the transistor, and converts it into ac power. So we can define an oscillator as that circuit which converts dc power into ac power. Fig. 11.1 illustrates the difference between an oscillator and an amplifier.

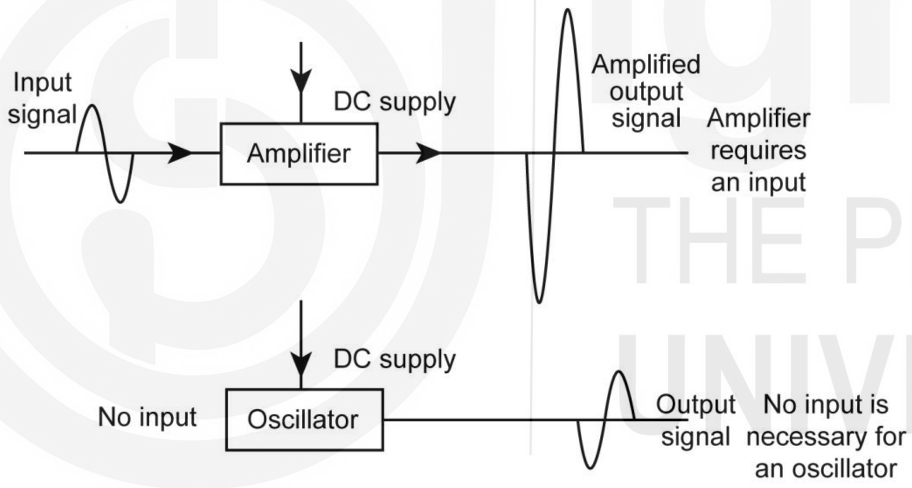


Fig. 11.1: **Comparison between an amplifier and an oscillator.**

For a circuit to work as an oscillator certain conditions have to be satisfied. They are as follows:

1. The feedback should be positive.
2. The product $A\beta$ should be unity.

   $$A\beta = 1 \qquad (11.2)$$

   This condition is known as **Barkhausen Criteria** of oscillations.
3. The circuit must amplify and the amplification should be sufficient to overcome the losses in the circuit.

The third condition is to be satisfied in order to sustain oscillations (see Fig. 11.2a) otherwise you will get the damped oscillations as shown in Fig. 11.2b.

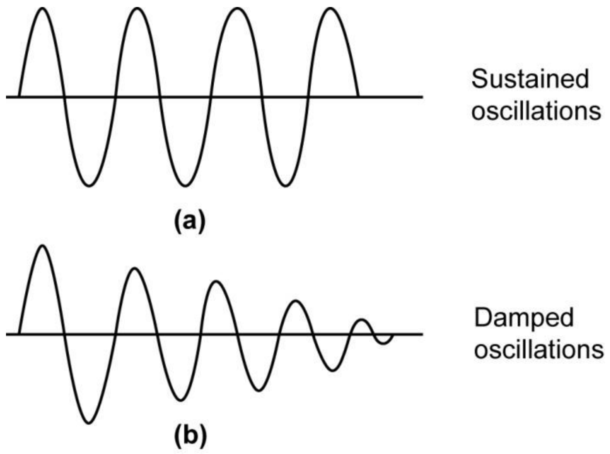


Fig. 11.2: **a) Sustained oscillations; b) damped oscillations.**

Oscillators are mainly divided into two types, namely, sinusoidal and relaxation oscillators. Sinusoidal oscillators produce continuously varying signals like sine waves with single frequency. Whereas relaxation oscillators produce non-sinusoidal signals like square waves, triangular waves etc. In this unit we will study about a few sinusoidal oscillators. Depending upon how oscillations are produced, sinusoidal oscillators are of the following type:

i) Tuned circuit (*LC*) oscillators

ii) *RC* oscillators

These two classes require different conditions to be satisfied by the feedback circuits. Let us discuss these in detail now.

11.2.1 Oscillations in Tuned Circuits

An inductor and a capacitor connected in parallel form a tuned or tank circuit. In Fig. 11.3a, energy is introduced into this circuit by connecting the capacitor

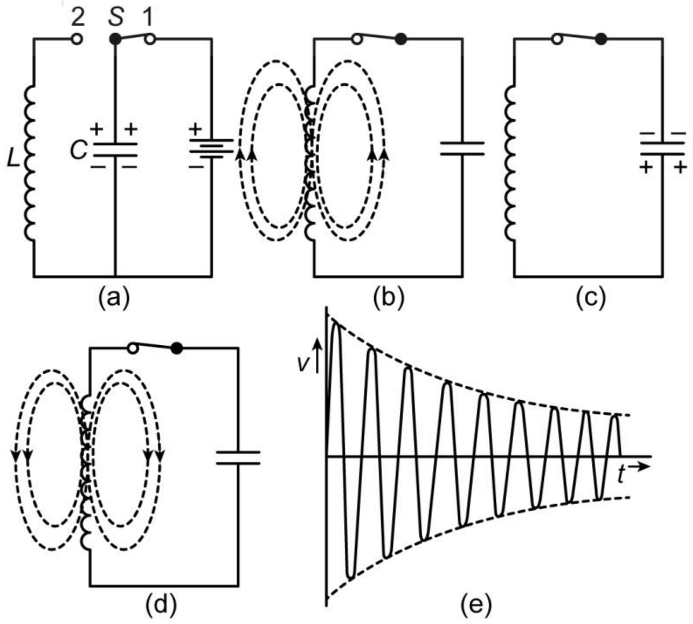


Fig. 11.3: Damped oscillation in an *LC* circuit.

to a dc voltage source, that is with switch *S* in position 1. The negative terminal of the battery supplies electrons to the lower plate of the capacitor. Because of the accumulation of electrons, the capacitor gets charged and there is a voltage across it. We say that energy is stored in the capacitor in the form of electric potential energy. When the switch *S* is thrown to position 2 as shown in Fig. 11.3b, current starts flowing in the circuit comprising the capacitor and inductor. The capacitor now starts discharging through the inductor. Since the inductor has the property of opposing any change in current, the current builds up slowly. Maximum current flows in the circuit when the capacitor is fully discharged. At this instant, the potential energy of the system is zero. But the electron motion being greatest (maximum current), the magnetic field energy around the coil is maximum.

Once the capacitor is fully discharged, the magnetic field begins to collapse. The back emf in the inductor keeps the current flowing in the same direction. The capacitor starts charging, but with opposite polarity this time, as shown in Fig. 11.3c. As the charge builds up across the capacitor, the current decreases and the magnetic field decreases. When the magnetic field energy drops to zero, the capacitor charges to the value it had in condition (a) but with opposite polarity. Once again all the energy is in the form of potential energy. The capacitor now begins to discharge again. This time current flows in the opposite direction. Fig. 11.3d shows the capacitor fully discharged, and also shows maximum current flowing in the circuit. Again, all the energy is in the magnetic field. The interchange or "oscillation" of energy between *L* and *C* is repeated again and again. This situation is similar to an oscillating pendulum, in which the energy keeps on interchanging between potential energy and kinetic energy.

In a practical pendulum, because of the friction at the pivot and the air resistance, some energy is lost during each swing. The amplitude of each cycle goes on decreasing and eventually the pendulum comes to rest, though it may take a long time. The oscillations of the pendulum are said to be damped.

An ideal *LC* circuit is expected to perform the oscillations forever, however, a practical *LC* circuit deviates from the ideal one. The inductor coil will have some resistance, and the dielectric material of the capacitor will have some finite resistance, and will have some leakage. Because of these factors, some energy loss takes place during each cycle of the oscillation. As a result of this loss, the amplitude of oscillation decreases continuously and ultimately the oscillations die down just like in case of practical pendulum. Thus, we find that a tank circuit by itself is capable of producing oscillations, but they are damped as shown in Fig. 11.3e.

Frequency of Oscillations in an *LC* Circuit

In *LC* circuit, the constants of the system are the inductance and capacitance values. The frequency of oscillation is the same as the resonant frequency of the tank circuit. It is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (11.3)$$

Sustained Oscillations

The oscillations of a pendulum can be maintained at a constant level, if we supply additional energy to it from time to time, to overcome the effect of frictional losses.

The oscillations of an *LC* circuit can also be maintained at a constant level in a similar way. For this, we have to supply a pulse of energy at the right time in each cycle. The resulting "undamped oscillations" are called sustained oscillations, as shown in Fig. 11.2a. Such sustained oscillations (or continuous waves) are generated by the electronic oscillator circuits.

There are many varieties of *LC*-oscillator circuits. All of them have following two features in common:

i) They must contain an active device (transistor) that works as an amplifier to overcome the losses.
ii) There must be positive feedback in the amplifier.

11.2.2 Positive Feedback Amplifier as an Oscillator

We discussed that an oscillator generates ac output signal without any input ac signal. A part of the output is fed back to the input; and this feedback signal is the only input to the internal amplifier.

To understand how an oscillator produces an output signal without an external input signal, let us consider Fig. 11.4a. The voltage source *v* drives the input terminals YZ of the internal amplifier (with voltage gain A). The amplified signal *Av* drives the feedback network is to produce feedback voltage $A\beta v$. This voltage returns to the point X. If the phase shift due to the amplifier and feedback network is correct, the signal at point X will be exactly in phase with the signal driving the input terminals YZ of the internal amplifier.

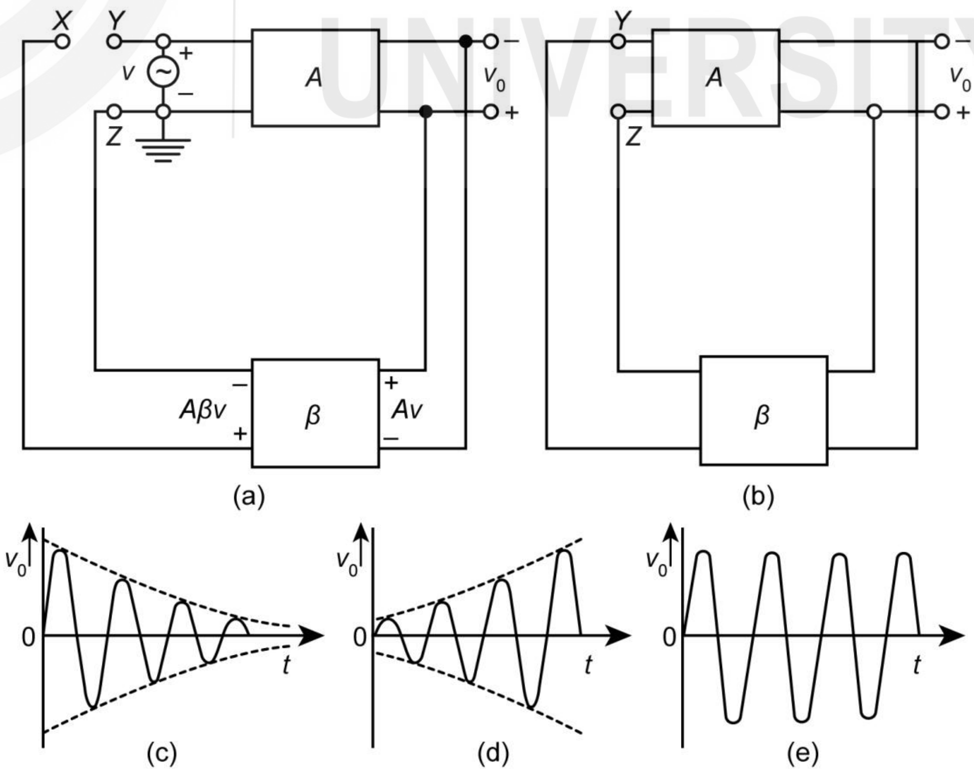


Fig. 11.4: **Proper positive feedback in an amplifier makes it an oscillator.**

Let us assume that we connect points X and Y and remove voltage source *v*. The feedback signal now drives the input terminals YZ of the amplifier (see Fig. 11.4b). If $A\beta$ is less than unity, $A\beta v$ is less than *v*, and the output signal will die out as shown in Fig. 11.4c. This happens because enough voltage is not returned to the input of the amplifier. On the other hand, if $A\beta$ is greater than unity, $A\beta v$ is greater than *v*, and the output voltage builds up as shown in Fig. 11.4d. Such oscillations are called growing oscillations. Finally, if $A\beta$ equals unity, no change occurs in the output and we get an output with constant amplitude as shown in Fig. 11.4e.

You must be wondering that how do we get the initial voltage *v*, which is required to start the oscillations, if no external source is connected. In practice, this starting voltage required to initiate the oscillations is actually generated within the circuit itself by the components like resistors used in it. Every resistor has some free electrons in it. Due to the room temperature, these electrons gain some energy to move around randomly in the resistor. This causes generation of a noise voltage across the resistor. This noise can contain many frequencies due to its random nature. So a resistor can be considered as a source of voltage generated due to thermal noise.

When we turn the power to the circuit on, the only signal existing in the circuit is this noise generated voltage. At the output of the amplifier, this noise voltage appears as an amplified voltage containing many frequencies. This voltage is fed to the input of the amplifier via the feedback network and this starts the oscillations. At this stage $A\beta$ product is little more them unity. Due to frequency selective nature of the feedback network, only single frequency oscillations sustain in the oscillator and eventually the Barkhausen Criteria ($A\beta = 1$) condition is satisfied at this frequency.

You may now like to attempt an SAQ.

***SAQ 1* – Barkhausen criteria**

For an oscillator circuit if β factor is 5% of the output voltage, what should be the gain of the amplifier in order to obtain sustained oscillations?

Now we will discuss about some tuned circuit (*LC*) oscillators.

11.3 *LC* OSCILLATORS

LC oscillators or resonant-circuit oscillators are widely used for generating high frequencies. With practical values of inductors and capacitors, it is possible to produce frequencies as high as 500 MHz. The oscillators used in rf (radio frequency) generators, radio and TV receivers etc. are *LC* oscillators. Such an oscillator has an amplifier, an *LC* resonant circuit and a feedback arrangement. There is a large variety of *LC*-oscillator circuits. Here, we shall discuss only a few important ones.

11.3.1 Tuned-Collector Oscillator

Fig. 11.5 shows a basic *LC*-oscillator circuit. It is called tuned-collector oscillator, because the tuned (*LC*) circuit is connected to the collector. We use a transformer here. The primary of the transformer and the capacitor form the tuned circuit (or tank circuit) which decides the frequency of oscillation. The secondary winding is connected to the base. You are aware that the voltage in primary and secondary winding of the transformer can have 0° or 180° phase difference depending upon the direction of windings of the primary and secondary coils. On the transformer symbol, the points of equal phase are indicated by the dots near the ends of the two windings. In present case, shown in Fig. 11.5, the primary and secondary voltages are out of phase i.e. have 180° phase difference. Since a phase difference of 180° is provided by the *CE* transistor amplifier, and an additional 180° by the transformer, the type of feedback is positive. The transistor amplifier provides sufficient gain for oscillator action to take place.

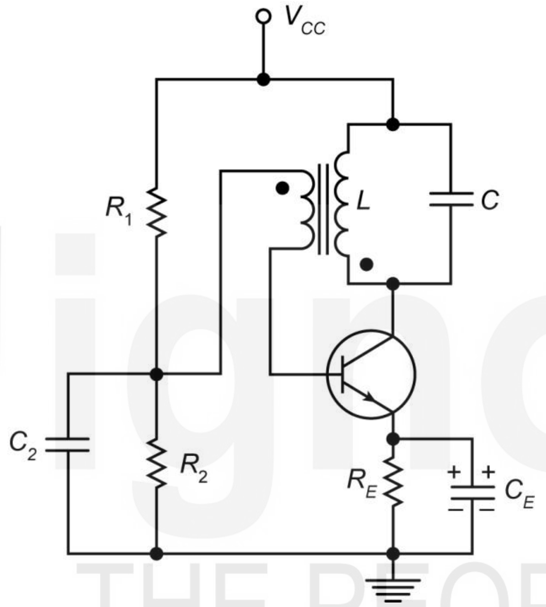


Fig. 11.5: **Tuned-collector oscillator.**

Resistors $R_1 R_2$ and R_E provide dc bias to the transistor. The capacitors C_E and C_2 bypass resistors R_E and R_2, respectively for ac signal. It is for this reason, the resistors R_E and R_2 have no effect on the ac operation of the circuit. The dc bias voltage set by the potential divider R_1 and R_2 is connected to the base through the low-resistance secondary winding of the transformer. This secondary of the transformer provides ac feedback voltage which is 180° out of phase than the output. This voltage appears across the base-emitter junction, since the junction point of R_1 and R_2 is at ac ground (due to bypass capacitor C_2).

The moment we switch on the supply, the current starts building up through the primary winding of the transformer connected to the collector. This induces a varying voltage in the secondary of the transformer. An amplified voltage again appears in the tank circuit, which responds most to its resonant frequency. Because of the sufficient gain provided by the transistor, and the proper amount of feedback in the correct phase, the oscillations grow till a certain voltage level is reached. Thus, sustained oscillations are obtained at the resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{11.4}$$

Now you may like to attempt an SAQ.

SAQ 2 – **Tuned collector oscillator**

What will be the effect on voltage fed back at the base, if capacitor C_2 is not connected in the circuit shown in Fig. 11.5?

11.3.2 Hartley Oscillator

The Hartley oscillator is one of the simplest types of tuned oscillator circuits. In this circuit only one coil is used, which is tapped such that a portion L_1 of the coil is in the collector circuit, while L_2 is in the base circuit with the tapped point connected to the ground. The amplified energy in the collector section is fed back to the base by means of inductive coupling and amount of coupling will depend upon the number of turns in L_1 and L_2. Fig. 11.6 shows a Hartley oscillator circuit.

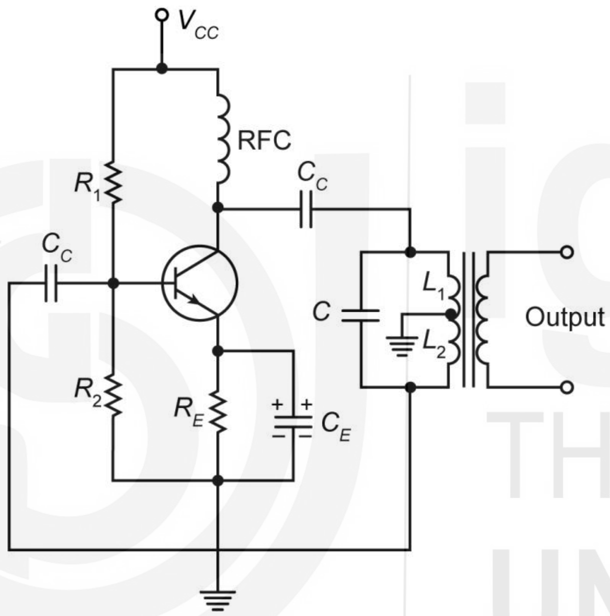


Fig. 11.6: **Hartley oscillator.**

An *RFC* (radio frequency choke) permits an easy flow of dc current. At the same time, it offers very high impedance to high frequency currents. In other words, an *RFC* ideally looks like a dc short and an ac open. Hence the high frequency signal at the collector does not reach the dc power supply and disturb the dc biasing of the circuit. The presence of the coupling capacitor C_c in the output circuit of the Hartley oscillator does not permit the dc currents to go to the tank circuit. The radio-frequency energy developed across the *RFC* is capacitively coupled to the tank circuit through the capacitor C_c.

In the tank circuit, the inductors L_1 and L_2 are in series; so effective inductance

$$L = L_1 + L_2 \qquad (11.5)$$

Hence, the resonance frequency can be expressed as

$$f = \frac{1}{2\pi\sqrt{(L_1 + L_2)C}} \qquad (11.6)$$

11.3.3 Colpitts Oscillator

The Colpitts oscillator shown in Fig. 11.7 is a widely used circuit in commercial signal generators above 1 MHz. The oscillator is similar to the Hartley oscillator given in Fig. 11.6 The only difference is that the Colpitts oscillator uses a split-tank capacitor instead of a split-tank inductor. The *RFC* has the same function as in the Hartley oscillator. The voltage developed across the capacitor C_2 provides the regenerative feedback required for the sustained oscillations to the base circuit.

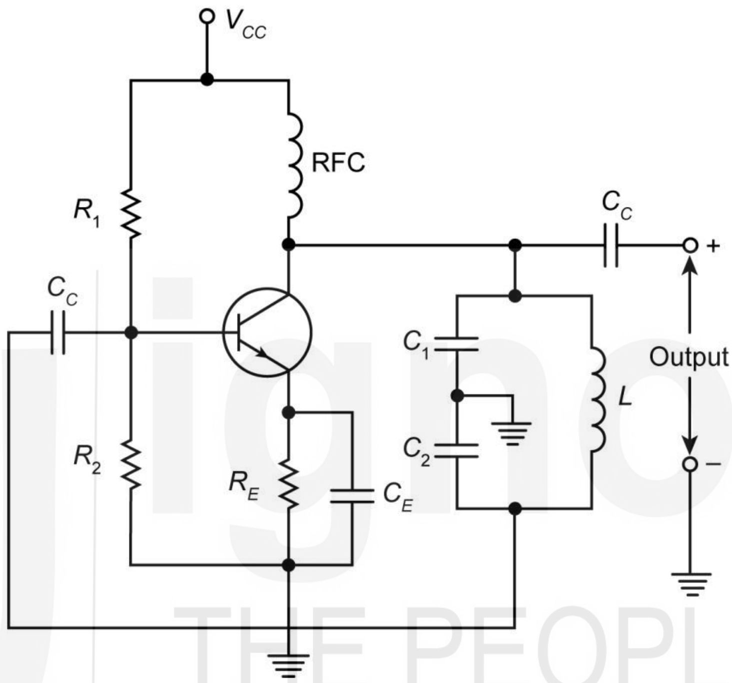


Fig. 11.7: **Colpitts oscillator using a transistor.**

The values of L, C_1 and C_2 determine the frequency of oscillation. The frequency of oscillation is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{11.7}$$

where

$$C = \frac{C_1 C_2}{C_1 + C_2} \tag{11.8}$$

since C_1 and C_2 are in series.

You may now like to attempt an SAQ.

SAQ 3 **– *LC* oscillators**

Considering the condition for starting the oscillations is $A\beta > 1$, what should be the condition on the value of gain A in terms of values of capacitors C_1 and C_2 in a Colpitts oscillator?

11.4 *RC* OSCILLATORS

Till now we have discussed only those oscillators which use an *LC*-tuned circuit. These tuned circuit oscillators are good for generating high frequencies. But for low frequencies (say, audio frequencies), the *LC* circuit becomes impracticable (due to extremely high values of *L* and *C*). In such cases, *RC* oscillators are more suitable. There are many types of *RC* oscillators, but the following two are the most important:

i) Phase-shift oscillator

ii) Wien bridge oscillator

Before discussing the particular *RC* oscillators let us understand the working principle of these oscillators.

Basic Principles of *RC* Oscillators

We know that a single stage of an *CE* amplifier not only amplifies the input signal but also shifts its phase by 180°. If we take a part of the output and directly feed it back to the input, a negative feedback takes place. The net output voltage then decreases. But for producing oscillations we must have positive feedback (of sufficient amount). Positive feedback occurs only when the feedback voltage is in phase with the original input signal. This condition can be achieved in two ways. We can take a part of the output of a single stage amplifier (giving a phase shift of 180°) and then pass it through a phase-shift network giving an additional phase shift of 180°. Thus a total phase shift of 180° + 180° = 360° (which is equivalent to a phase shift of 0°) occurs, as the signal passes through the amplifier and the phase-shift network. This is the principle of phase-shift oscillator.

Another way of getting a phase shift of 360° is to use two stages of amplifiers each giving a phase shift of 180°. A part of this output is fed back to the input through a feedback network without producing any further phase shift. This is the principle of Wien bridge oscillator.

11.4.1 Phase-Shift Oscillator

Fig. 11.8 shows a phase-shift oscillator. It consists of amplifier with three sections of *RC* sections as feedback network.

The phase of the signal at the input (*B*) gets reverse at output (*C*), when it is amplified by the amplifier. The output of the amplifier goes to a feedback network. The feedback network consists of three identical *RC* sections. Each *RC* section provides a phase of 60° Thus a total of 60° × 3 = 180° phase shift is provided by the feedback network. The output of this network is now in the same phase as the originally assumed input to the amplifier, as shown in the figure. If the condition $A\beta = 1$ is satisfied, oscillations will be maintained.

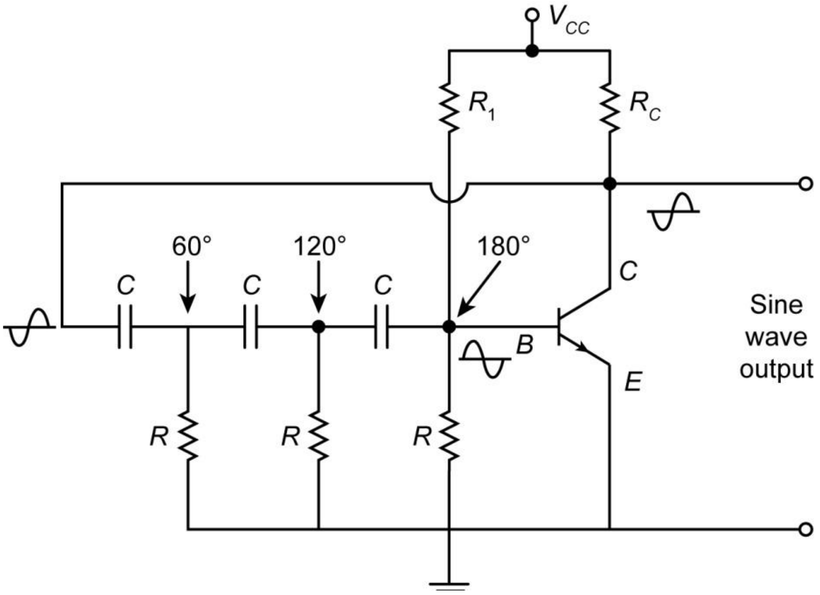


Fig. 11.8: **Phase-shift oscillator.**

It may be shown by a straightforward (but a little complicated) analysis that the frequency at which this *RC* network provides exactly 180° phase-shift is given by

$$f = \frac{1}{2\pi RC\sqrt{6}} \tag{11.9}$$

Hence, this must be the frequency of oscillation.

SAQ 4 **– Phase-shift oscillator**

A transistor phase-shift oscillator uses three identical *RC* sections in the feedback network. The values of the components are R = 100 kΩ and C = 0.01 μF. Calculate the frequency of oscillation.

11.4.2 Wien Bridge Oscillator

The Wien bridge oscillator is a standard circuit for generating low frequencies in the range of 10 Hz to about 1 MHz. It is used in most of the commercial audio generators. Basically, this oscillator consists of two stages of *RC*-coupled amplifier and a feedback network. The block diagram of Fig. 11.9 explains the principle of working of this oscillator.

Here, the blocks A_1 and A_2 represent two amplifier stages with each providing 180° phase shift. The output of the second stage goes to the feedback network. The voltage across the parallel combination $C_2 R_2$ is fed to the input of the first stage. The net phase shift through the two amplifiers is zero. Therefore, it is evident that for the oscillation to be maintained, the phase shift through the coupling network must be zero. It can be shown that this condition occurs at a frequency given by

$$f = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}} \tag{11.10}$$

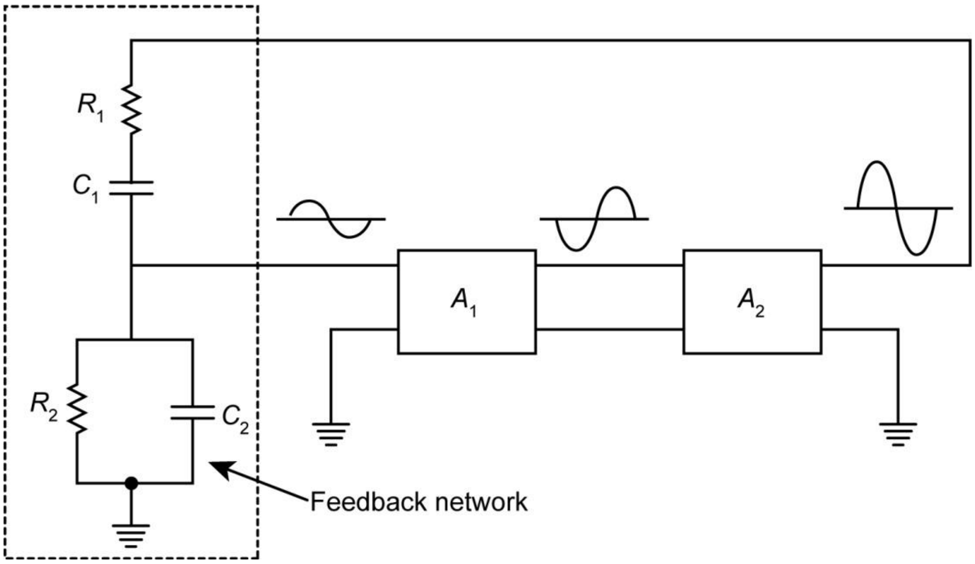
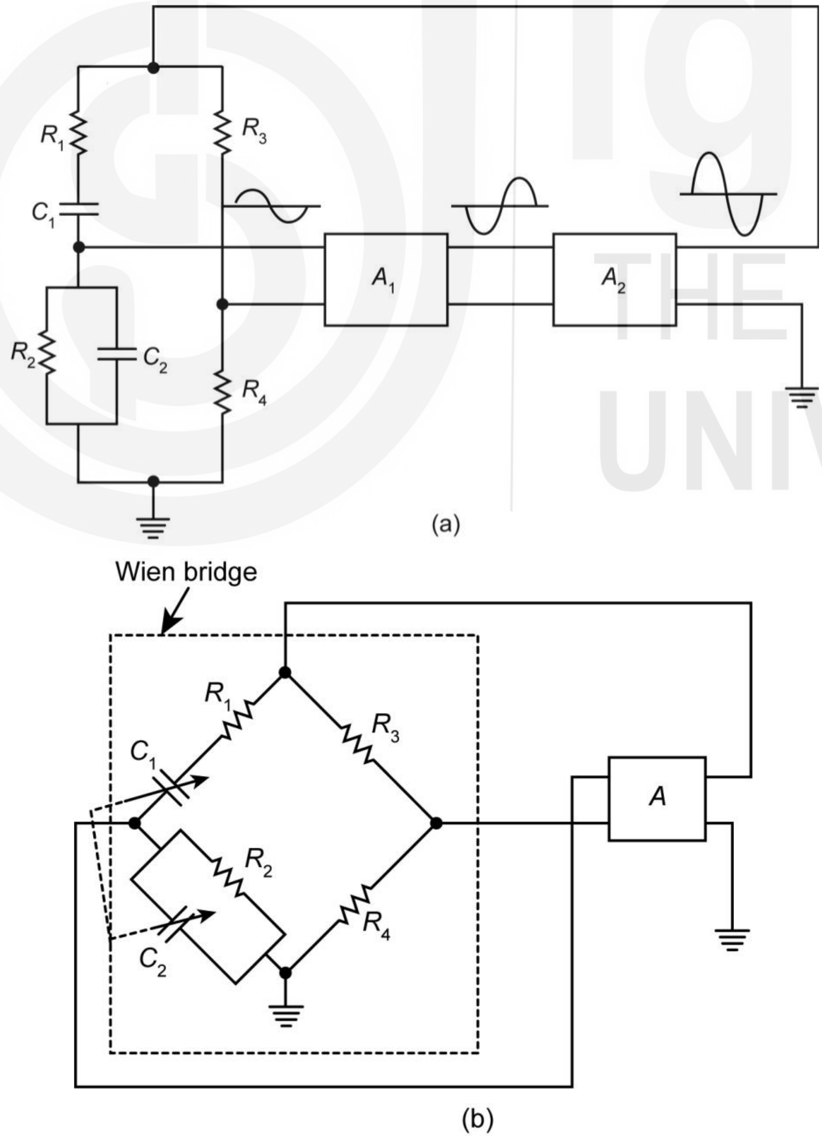


Fig. 11.9: **Block diagram of a basic Wien bridge oscillator.**

To have a gain we add some amount of negative feedback. The addition of negative feedback modifies the circuit in Fig. 11.9 to that shown in Fig. 11.10a.



Here we are giving the positive and negative feedbacks to two separate inputs of an amplifier. You will learn about such amplifiers in Unit 13, where we discuss the operational amplifiers.

Fig. 11.10: **Wien bridge oscillator with negative feedback; b) same circuit redrawn to depict the "bridge" in the circuit.**

The same circuit is redrawn in Fig. 11.10b. The two amplifier blocks in Fig. 11.10a representing the two stages of the amplifier are replaced by a single block in Fig. 11.10b. You may now see why this circuit is called a bridge oscillator. In this circuit, the resistors R_3 and R_4 provide the desired negative feedback.

We can have a continuous variation of frequency in the oscillator by varying the two capacitors C_1 and C_2 simultaneously. These capacitors are variable air-gang capacitors. We can change the frequency range of the oscillator by switching into the circuit with different values of resistors R_1 and R_2.

SAQ 5 – **Wien bridge oscillator**

The *RC* network of a Wien bridge oscillator consists of resistors and capacitors of values $R_1 = R_2 = 220\,\text{k}\Omega$ and $C_1 = C_2 = 250\,\text{pF}$. Calculate the frequency of oscillations.

11.5 SUMMARY

Concept	Description
Positive feedback	■ If the feedback signal is in phase with the applied signal and aids it, positive or regenerative feedback takes place.
Gain with positive feedback	■ Gain increases with positive feedback, which may lead to oscillations. The gain is given by $A_f = \frac{A}{1 - A\beta}$
Oscillator	■ An oscillator acts as energy converter which changes direct current energy into alternating current energy.
Components of oscillator circuit	■ Essential parts of an oscillator are (i) the frequency determining network (ii) source of dc energy and (iii) a feedback circuit to provide positive feedback.
LC ***oscillators***	■ Hartley oscillator uses a tapped coil in the feedback circuit. ■ Colpitt's oscillator uses a tapped capacitance network in the feedback circuit. It has better frequency stability than Hartley oscillator.
RC ***oscillators***	■ Phase-shift oscillator has three *RC* sections to provide 180° phase shift in feedback voltage. ■ A Wien bridge oscillator is an *RC* oscillator whose frequency of oscillation can be varied over a wide range.

11.6 TERMINAL QUESTIONS

1. What is meant by loop gain?
2. A Wien bridge oscillators uses 10 kΩ resistors and 4.70 nF capacitors in its bridge circuit. What is the frequency of oscillation?

3. In Hartley oscillator the input and output inductors are 0.1 mH each and capacitor is 0.1 nF. Calculate the frequency of this oscillator.

11.7 SOLUTIONS AND ANSWERS

Self-Assessment Questions

1. $\beta = 5\% = 0.05$

   By Barkhausen criteria,

   $$A\beta = 1 \text{ for sustained oscillations}$$

   $$\therefore \quad A = \frac{1}{\beta} = \frac{1}{0.05} = 20.$$

2. If capacitor C_2 is not connected across resistor R_2, the complete feedback voltage induced in the secondary of the transformer would not go the input of the transistor because some of this voltage will drop across R_2.

3. To start the oscillations, initial condition is $A\beta > 1$. Hence

   $$A > \frac{1}{\beta}$$

   In the circuit of Colpitts oscillator (Fig. 11.7), the output voltage appears across C_1, whereas the feedback voltage across C_2. Since, same current is flowing through these capacitors in the tank circuit made up of C_1 and C_2, we can write

   $$\beta = \frac{v_f}{v_{out}} = \frac{i\,X_{C_2}}{i\,X_{C_1}} = \frac{X_{C_2}}{X_{C_1}}$$

   $$= \frac{1/(2\pi f C_2)}{1/(2\pi f C_1)} = \frac{C_1}{C_2}$$

   In order to start the oscillations, we need

   $$A > \frac{C_2}{C_1}$$

4. The frequency of oscillation of a phase-shift oscillator is given as

   $$f = \frac{1}{2\pi RC\sqrt{6}}$$

   Here, $R = 100\,\text{k}\Omega = 10^5$; $C = 0.01\,\mu\text{F} = 10^{-8}\,\text{F}$.

   Therefore,

   $$f = \frac{1}{2 \times 3.141 \times 10^5 \times 10^{-8} \times 2.452} = 64.97\,\text{Hz}$$

5. For a Wien bridge oscillator, the frequency of oscillation is given as

   $$f_0 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} = \frac{1}{2\pi RC}$$

   where $R_1 = R_2 = R$ and $C_1 = C_2 = C$.

Here, $R = 220\,\text{k}\Omega = 2.2\times10^5\,\Omega$, $C = 250\,\text{pF} = 2.5\times10^{-10}\,\text{F}$.

Therefore,

$$f_0 = \frac{1}{2\times3.141\times2.2\times10^5\times2.5\times10^{-10}}$$

$$= 2893.7\,\text{Hz}$$

$$= 2.89\,\text{kHz}.$$

Terminal Questions

1. The product $A\beta$ is known as loop gain. The input signal is multiplied by A times in passing through the amplifier and β times in the feedback network before it arrives at the input. Hence the name loop gain.

2. $$f = \frac{1}{2\pi RC};\quad R = 10\,\text{k}\Omega = 10\times10^3\,\Omega$$

   $C = 4.7\,\text{nF} = 4700\,\text{pF}.$

   $$f = \frac{1}{2\times3.142\times10\times10^3\times4700\times10^{-12}}$$

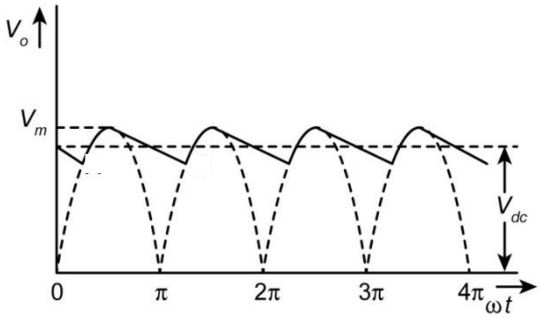
   $$= 3386\,\text{Hz}$$

3. For Hartley oscillator

   $$f = \frac{1}{2\pi\sqrt{(L_1+L_2)C}}$$

   $$= \frac{1}{2\pi\sqrt{(0.1+0.1)\times10^{-3}\times0.1\times10^{-9}}}$$

   $$= \frac{1}{2\pi\sqrt{0.2\times0.1\times10^{-12}}} = \frac{10^7}{2\pi\sqrt{2}} = 1.125\,\text{MHz}.$$



Power supplies provide dc voltage to the system. While obtaining dc from ac, rectifiers are used alongwith filters. The figure shows output obtained from full wave rectifier and capacitance filter as discussed in this unit.

UNIT 12

REGULATED POWER SUPPLY

Structure

STUDY GUIDE

The power required to drive the circuits discussed so far in this course is obtained from a circuit called power supply. It provides a dc voltage of desired value. It requires conversion of ac mains voltage received from the electric supply company into dc voltage using the circuits called rectifier followed by a filter. Efficiency of rectification can be calculated using simple mathematics. You will require basic knowledge of calculus for this. The filtered voltage is then given to a circuit that regulates the output voltage to a set value. These regulators commonly use zener diode as a constant voltage reference device. You should revise the zener characteristics you studied in Unit 3 of Block 1 of this course to understand its use as a voltage reference.

You should work out the SAQs and TQs given in this unit on your own before turning to the solutions given at the end.

"Power is a neutral energy source, like tofu. It's what you do with it gives it flavour."

Elizabeth Gilbert

12.1 INTRODUCTION

Many electronic devices, such as pocket calculators and small radios operate on batteries that provide steady (dc) voltage and currents. Usually, we use dry cells, but sometimes a battery eliminator is used in place of dry cells. The battery eliminator converts the ac mains voltage into dc voltage and thus eliminates the need for dry cells. So far, in all the previous units, where you learnt about various circuits like amplifiers, oscillators, digital circuits it was assumed that voltage and currents required to operate them were available. For the operation of most of the devices in electronic equipment, a dc voltage is needed. Most common dc source used by us is the charger used for our mobiles or laptops.

In our country, the electrical energy available in homes, laboratories and industries is in the form of alternating voltage of 220 V (rms) at a frequency of 50 Hz. But that cannot be used as received. Hence almost all electronic equipment include a circuit that converts the ac voltage of mains supply into dc voltage. This part of the equipment is called power supply.

Every power supply can be thought of as comprising (a) a dc power unit consisting of a transformer followed by a diode circuit called rectifier, which creates a dc voltage from the ac mains; (b) some circuitry consisting of filter to remove any ac component present in the output of the rectifier; and (c) a voltage regulator circuit, which gives a precisely controlled dc voltage. A block diagram of such a power supply is shown in Fig. 12.1

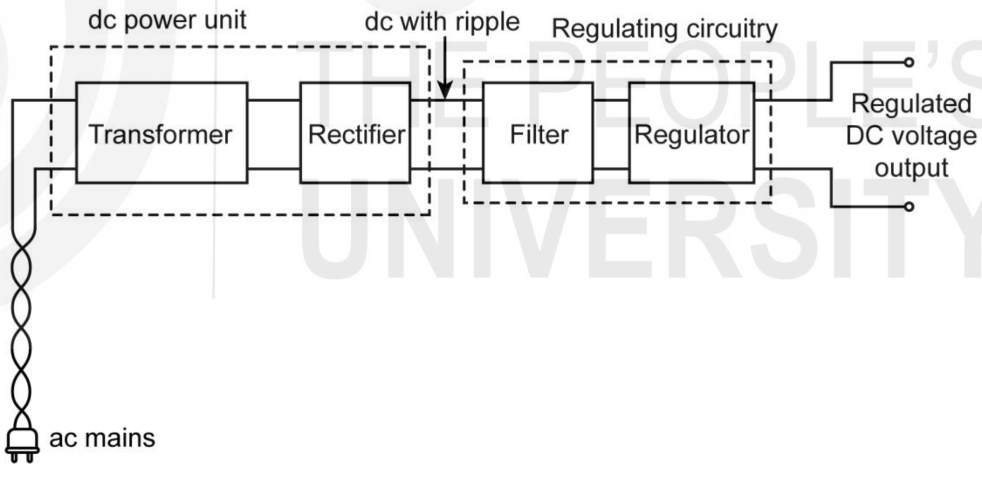


Fig. 12.1: **The block diagram of power supply. It consists of a dc power unit, which converts the ac supply to a dc voltage plus some ripple; followed by circuitry which reduces the ripple and regulates the output voltage.**

The output from a dc power unit on its own is usually unsatisfactory for two reasons:

i) It usually carries a small amount of **ac ripple** superimposed on the dc voltage. If it is used to supply power to an audio amplifier, it would give rise to some audible ‘hum’ from the loudspeaker.

ii) The internal resistance of the dc power unit is usually higher than desirable. Because of this, the voltage output can be significantly affected by variations in the current drawn from the unit. The change in output voltage per unit change of output current is called the **regulation** of the dc source.

The regulating circuitry added to the dc power unit in a regulated power supply reduces the ripple and improves the regulation.

In Sec. 12.2 you will learn about the dc power unit where we describe the transformer and the rectifier circuits using diodes. The main two types of rectifiers are half wave rectifier and full wave rectifier. Along with circuits and working, you will also learn about their important characteristics like output dc voltage and peak inverse voltage (PIV). The rectification efficiency and the amount of ac component in the rectified voltage are very important factors and influence the choice of rectifier in our circuit. You will learn about the performance of the half and full wave rectifiers in Sec. 12.3.

The output voltage of rectifiers always possesses some ac component (ripple) in it. This ripple can be removed by the filter circuits comprising either inductor or capacitor or both. In Sec. 12.4 some important filter circuits are described. The output of the filter needs to be regulated to obtained a constant desired value of output voltage. You will study about the regulator circuits in Sec. 12.5.

Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ explain the following terms: half-wave rectification, full-wave rectification, bridge rectifier, ripple, load regulation, line regulation;
- ❖ draw the circuit diagram and explain the working of half-wave rectifier, centre-tapped full-wave rectifier and bridge rectifier;
- ❖ derive the expressions for output dc voltage, average or dc current, rms current, ripple factor and rectifier efficiency in case of half-wave and full-wave rectifiers;
- ❖ explain with the help of suitable waveforms the working of filters using shunt-capacitor, series inductor and *LC* filters; and
- ❖ design the shunt and series pass voltage regulator circuits.

12.2 DC POWER UNIT

DC power units consist of transformer and rectifier circuit.

12.2.1 The Transformer

The first component in any power supply circuit is a transformer. It serves two purposes. Firstly, it allows us to step the voltage up or down. This way we can get the desired level of dc voltage. For example, the charger used with mobiles phone gives a dc voltage of about 5V. We can use a *step down* transformer to get such a low ac voltage at the input of the rectifier. On the other hand, the cathode-ray tube used in an oscilloscope needs a very high dc voltage – of the order of a few kV. Here, we may use a *step up* transformer.

The second advantage of the transformer is the isolation it provides from the power line. It reduces the risk of electrical shock.

The output voltage from the transformer is determined by the number of turns in the primary and secondary windings of the transformer.

If n_1 is the number of turns in the primary winding and n_2 is the number of turns in the secondary winding, then the ratio $n_1 : n_2$ is called the **turns ratio** of the transformer. If the input voltage at primary is v_{in} and the output voltage at the secondary is v_{out} , then

$$\frac{v_{in}}{v_{out}} = \frac{n_1}{n_2} \quad (12.1)$$

Hence

$$v_{out} = \frac{n_2}{n_1} v_{in} \quad (12.1a)$$

So you can easily understand that when we wish to step down the voltage, we have $n_1 > n_2$.

The transformer in a dc power unit uses either a single secondary winding or a centre-tapped one, depending on the design of the rectifier circuit, you will be learning in the next sections. Before moving further, you may solve the following SAQ which will serve as revision of your previous knowledge.

SAQ 1 – **Transformer voltage**

a) Recall from your earlier knowledge that 220 V of mains supply means that rms (root mean square) voltage is 220 V. What is the maximum voltage (also called peak voltage amplitude)?

b) You know that to obtain lower voltages, a step down transformer is needed. If the turns ratio of such a transformer is 15:1 and if the input mains rms voltage is 220 V, what will be the rms and maximum voltage across the secondary?

12.2.2 Half-Wave Rectification

The simplest type of a rectifier circuit is the half-wave rectifier. Fig. 12.2 shows the circuit of half-wave rectifier where the diode forms a series circuit with the secondary of the transformer and the load resistor R_L .

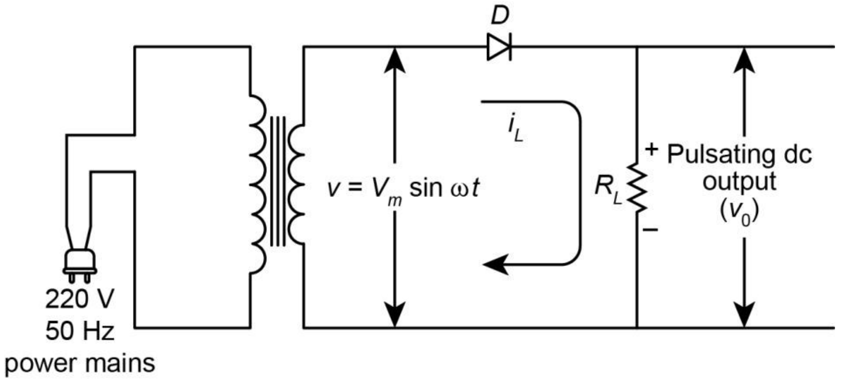


Fig. 12.2: **A half-wave rectifier circuit consisting of a transformer, a diode and a load resistor.**

Let us see how this circuit rectifies ac into dc.

The primary of the transformer is connected to the power mains. An ac voltage is induced across the secondary of the transformer. The voltage may be less than, or equal to, or greater than the primary voltage depending upon the turns ratio of the transformer. We can represent the voltage across the secondary (input voltage to rectifier) by the equation.

$$v = V_m \sin \omega t \qquad (12.2)$$

where ω (= $2\pi f$) is the angular frequency of the input ac voltage.

Fig. 12.3a shows how input voltage varies with time. It has alternate positive and negative half-cycles. Voltage V_m is the peak value of this alternating voltage.

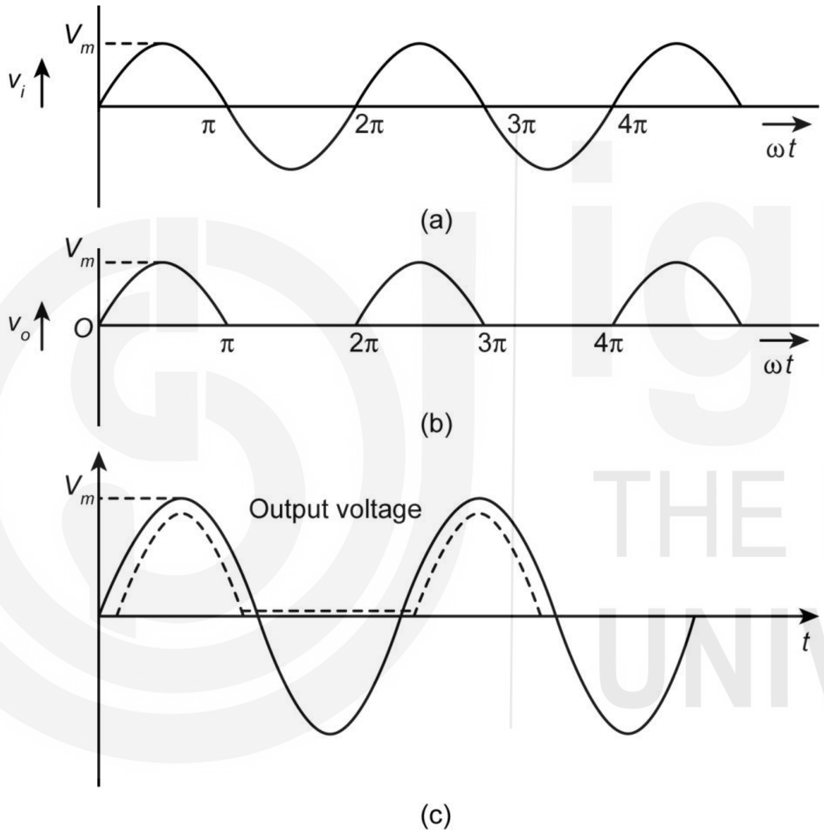


Fig. 12.3: **Half-wave rectifier: a) input voltage waveform; b) output voltage waveform; c) the transformer output voltage (input voltage) waveform (continuous line) together with the rectified voltage (output voltage) waveform across the load (shown dashed) in practical circuit.**

During the positive half-cycle of the input voltage, the polarity of the voltage across the secondary is as shown in Fig. 12.4a. This polarity makes the diode forward biased. The diode conducts, and current i_L flows through the load resistor R_L . This current makes the terminal *A* positive with respect to terminal *B*. Since a forward-biased diode offers a very low resistance, the voltage drop across it is also very small (about 0.3 V for Ge diode and about 0.7 V for Si diode). Therefore, the voltage appearing across the load terminals *AB* is practically the same as the input voltage *v* at every instant. But ideally speaking the situation is slightly different. By solving SAQ 2 you can find it out by yourself.

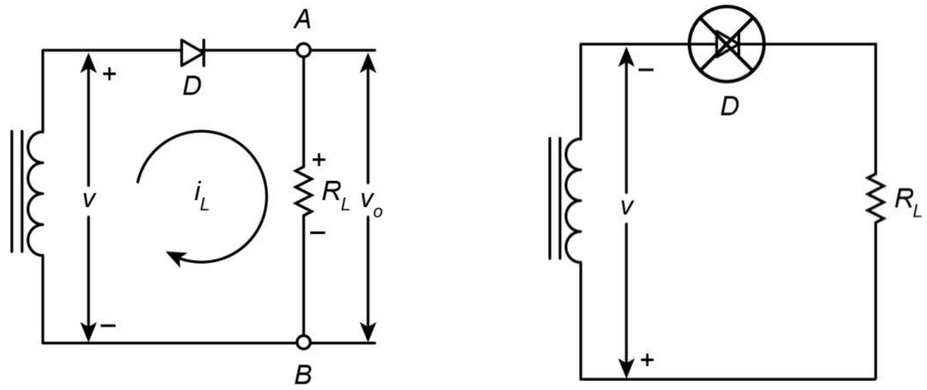


Fig. 12.4: **Half-wave rectifier circuit: a) during positive half-cycle; b) during negative half-cycle.**

During the negative half-cycle of the input voltage, the polarity gets reversed as shown in Fig. 12.4b. The diode is now reverse biased and hence non-conducting. Practically no current flows through the circuit. Therefore, almost no voltage is developed across the load resistance. All the input voltage appears across the diode itself. The output voltages in the two half cycles are shown in Fig. 12.3b.

To sum up, when the input voltage is going through its positive half-cycle, the voltage of the output is almost the same as the input voltage. During the negative half-cycle, no voltage is available across the load. The complete waveform of the output voltage v_o across the load is shown in Fig. 12.3b. This voltage, though not a perfect dc, is at least unidirectional.

SAQ 2 – **Voltage drop across forward biased diode**

Fig. 12.3c shows the transformer output (input voltage to half wave rectifier) waveform as a continuous line and the voltage across the load resistor (output voltage) as a dashed line. Why is the output voltage less than the input voltage in the positive half cycle?

Peak Inverse Voltage

Let us again focus our attention on the diode in Fig. 12.4b. During the negative half-cycle of the input, the diode is reverse biased. The whole of the input voltage appears across the diode (as there is no voltage across the load resistance). When the input reaches its peak value V_m in the negative half-cycle, the voltage across the diode is also maximum. This maximum voltage is known as the **peak inverse voltage** (PIV). It represents the maximum voltage the diode must withstand during the negative half-cycle of the input. Thus, for a half-wave rectifier,

$$PIV = V_m \tag{12.3}$$

Output dc Voltage

The average value of a sine wave (such as that in Fig. 12.3a) over one complete cycle is zero. If a dc ammeter (moving coil type) is connected in an ac circuit, it will read zero. (The dc meter reads average value of current in a circuit.) Now, if the dc ammeter is connected in the half-wave rectifier circuit (Fig. 12.2), it will show some reading. This indicates that there is some dc current flowing through the load R_L. We can find out the value of this current for a half-wave rectifier circuit.

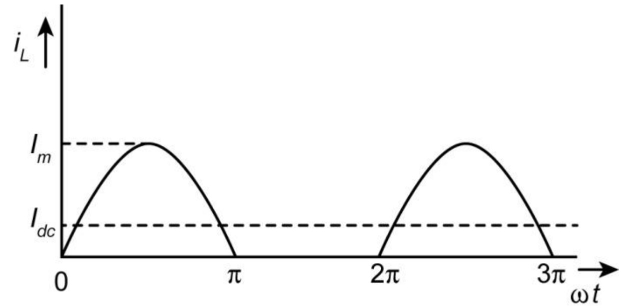


Fig. 12.5: **Waveform of the current flowing through load R_L in a half-wave rectifier.**

In Fig. 12.3b, we had plotted the waveform of the voltage across the load resistor R_L. If we divide each ordinate of this curve by the value of resistance R_L, we get the current waveform. This is shown in Fig. 12.5. Note that the two waveforms (for current and for voltage) are similar. Mathematically, we can describe the current waveform as follows:

$$i_L = I_m \sin \omega t; \text{ for } 0 < \omega t < \pi \tag{12.4a}$$

and

$$i_L = 0; \text{ for } \pi < \omega t < 2\pi \tag{12.4b}$$

Here, I_m is the peak value of the current i_L. It is obviously related to the peak value of voltage V_m as

$$I_m = \frac{V_m}{R_L}, \tag{12.5}$$

since the diode resistance in the conducting state is assumed to be zero. To find the dc or average value of current, we add or integrate the instantaneous values of the current over one complete cycle, i.e. from 0 to 2π (curve repeats itself after the first cycle). Using Eq. (12.4a) and (12.4b) we find the dc current as follows:

$$I_{dc} = \frac{1}{2\pi} \int_0^{2\pi} i_L \, d(\omega t) \tag{12.6}$$

$$= \frac{1}{2\pi} \left[\int_0^{\pi} i_m \sin \omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0 \, d(\omega t) \right]$$

$$= \frac{1}{2\pi} \left[I_m (-\cos \omega t)\Big|_0^{\pi} + 0 \right]$$

$$= \frac{1}{2\pi} [I_m (-\cos \pi - (-\cos 0))]$$

$$= \frac{1}{2\pi} [I_m (1+1)] = \frac{I_m}{\pi}$$

$$\therefore \quad I_{dc} = \frac{I_m}{\pi} \tag{12.7}$$

The dc voltage developed across the load R_L is

$$V_{dc} = I_{dc} \times R_L = \frac{I_m}{\pi} \times R_L = \frac{V_m}{\pi} \tag{12.8}$$

Remember that while writing Eq. (12.5), we have assumed that

i) the diode resistance in forward bias is zero, and
ii) the secondary winding of transformer has zero resistance.

The second assumption is often very near to the truth. The winding resistance is almost zero. But, the forward diode resistance r_d is sometimes not so small. If it is comparable to the load resistance R_L , we must take it into consideration. Eq. (12.5) for peak current then gets modified to

$$I_m = \frac{V_m}{(R_L + r_d)} \tag{12.9}$$

The dc voltage across the load resistor R_L , can now be written with the help of Eq. (12.8) as

$$V_{dc} = \frac{V_m R_L}{\pi(R_L + r_d)} = \frac{V_m}{\pi(1 + r_d / R_L)}$$

$$= \frac{V_m}{\pi} \text{ (if } r_d << R_L) \tag{12.10}$$

***EXAMPLE 12.1*: DC VOLTAGE AND PIV RATING OF DIODE**

The turns ratio of a transformer used in a half-wave rectifier (shown in Fig. 12.2) is 12:1. The primary is connected to the power mains: 220 V, 50 Hz. Assuming the diode resistance in forward bias to be zero, calculate the dc voltage across the load. What is the PIV of the diode?

SOLUTION ■ The maximum (peak value) primary voltage is

$$V_p = \sqrt{2}\, V_{rms} = \sqrt{2} \times 220 = 311 \text{ V}.$$

Therefore, the maximum secondary voltage is

$$V_m = \frac{1}{12} \times 311 = 25.9 \text{ V}$$

The dc load voltage is

$$V_{dc} = \frac{V_m}{\pi} = \frac{25.9}{\pi} = 8.24 \text{ V}$$

The peak inverse voltage is

$$\text{PIV} = V_m = 25.9 \text{ V}$$

12.2.3 Full-Wave Rectification

In a half-wave rectifier we utilize only one half-cycle of the input wave. In a full-wave rectifier we utilize both the half cycles. Alternate half cycles are inverted to give a unidirectional load current. For full-wave rectification we can use two types of circuit. One is called centre-tap rectifier that uses two diodes. The other is called bridge rectifier and it uses four diodes.

Centre-Tap Rectifier

The circuit of a centre-tap rectifier is shown in Fig. 12.6a. It uses two diodes *D*1 and *D*2. During the positive half-cycles of secondary voltage, diode *D*1 is forward biased and *D*2 is reverse biased. The current flows through the diode *D*1, load resistor R_L, and the upper half of the secondary winding, as shown in Fig. 12.6b. During negative half-cycles diode *D*2 becomes forward biased and *D*1 reverse biased. Now *D*2 conducts and *D*1 becomes open. The current flows through diode *D*2, load resistor R_L, and the lower half of the winding, as shown in Fig. 12.6c. Note that the load current in both Figs. 12.6b and c flows in the same direction. The waveform of the current i_L, and hence of the load voltage v_o, is shown in Fig. 12.6d.

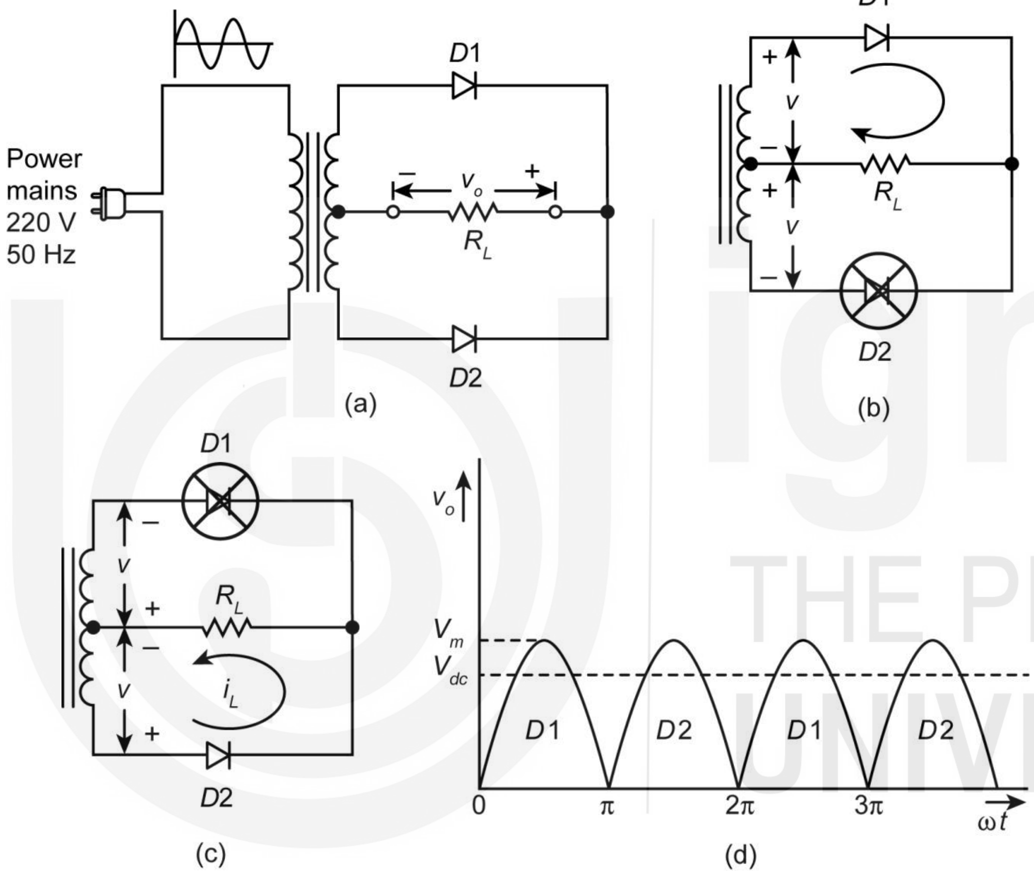


Fig. 12.6: **Centre-tap full-wave rectifier: a) circuit; b) operating during positive half cycle; c) operating during negative half cycle; d) voltage across the load resistor.**

Peak Inverse Voltage

Fig. 12.7 shows the centre-tap rectifier circuit at the instant the secondary voltage reaches its positive maximum value.

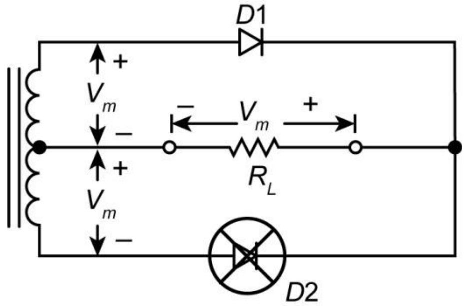


Fig. 12.7: **The PIV across the non-conducting diode *D*2 in a centre-tap rectifier is $2V_m$.**

The voltage V_m is the maximum (peak) voltage across half of the secondary winding. At this instant, the diode $D1$ is conducting and it offers almost zero resistance. The whole of the voltage V_m across the upper half winding appears across the load resistor R_L . Therefore, the reverse voltage that appears across the non-conducting diode is the summation of the voltage across the lower half winding and the voltage across the load resistor R_L . From the figure this voltage is $V_m + V_m = 2V_m$. Thus,

$$\text{PIV} = 2V_m \tag{12.11}$$

Bridge Rectifier

A more widely used full-wave rectifier circuit is the bridge rectifier, shown in Fig. 12.8a. It uses four diodes instead of two, but avoids the need for a centre-tapped transformer. During the positive half-cycle of the secondary voltage, diodes $D2$ and $D4$ are conducting and diodes $D1$ and $D3$ are non-conducting. Therefore, current flows through the secondary winding, diode $D2$, load resistor R_L and diode $D4$, as shown in Fig. 12.8b. During negative half-cycles of the secondary voltage, diodes $D1$ and $D3$ conduct, and diodes $D2$ and $D4$ do not conduct. The current flows through the secondary winding, diode $D3$, load resistor R_L and the diode $D1$ as shown in Fig. 12.8c. In both the cases, the current flows through the load resistor in the same direction. Therefore, a fluctuating, unidirectional voltage is developed across the load. The load voltage waveform is shown in Fig. 12.8d.

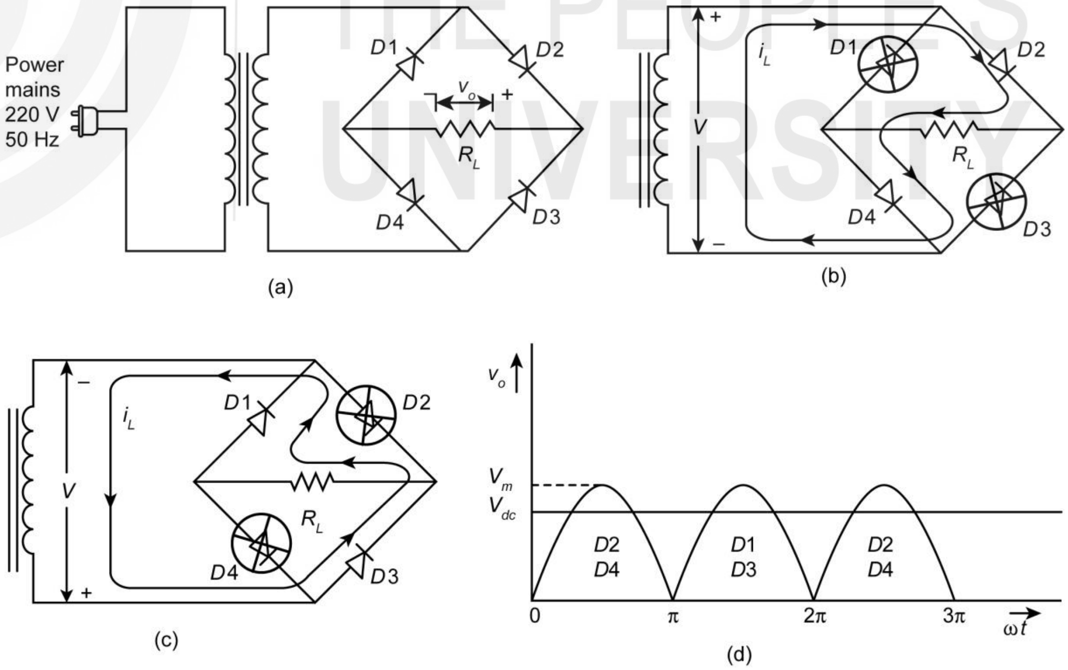


Fig. 12.8: **Bridge rectifier.**

Peak Inverse Voltage

Let us now find the peak inverse voltage that appears across a non-conducting diode in a bridge rectifier. Fig. 12.9 shows the bridge rectifier circuit at the instant the secondary voltage reaches its positive peak value, V_m. The diodes $D2$ and $D4$ are conducting whereas diodes $D1$ and $D3$ are reverse biased and are non-conducting. The conducting diodes $D2$ and $D4$ have almost zero resistance (and hence zero voltage drops across them). Point B is at the same potential as the point A. Similarly, point D is at the same potential as the point C. The entire voltage V_m across the secondary winding appears across the load resistor R_L. The reverse voltage across the non-conducting diode $D1$ (or $D3$) is also V_m. Thus,

$$\text{PIV} = V_m \tag{12.12}$$

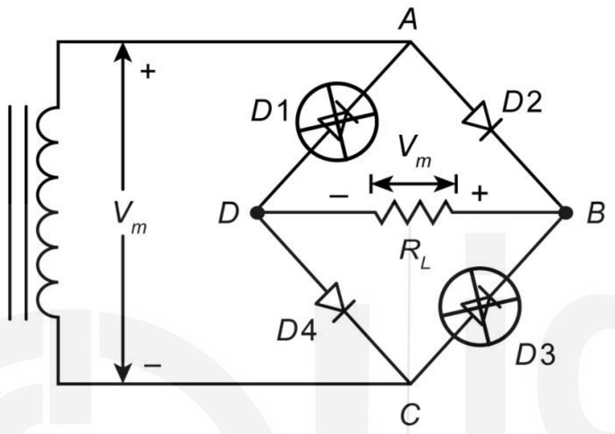


Fig. 12.9: **The PIV across the non-conducting diode *D*1 or *D*3** is V_m.

Output dc Voltage in Full-Wave Rectifiers

The voltage waveform in Fig. 12.8d is exactly the same as that in Fig. 12.6d. In both the rectifier circuits the load voltage is the same. However, there is one difference. In the bridge rectifier, V_m is the maximum voltage across the secondary winding. But in the centre-tap rectifier, V_m represents the maximum voltage across half the secondary winding.

Now, let us compare the full-wave rectifier voltage waveform (of Fig. 12.6d or Fig. 12.8d) with the half-wave rectifier voltage waveform (of Fig. 12.3b). In a half-wave rectifier, only positive half-cycles are utilized for the dc output. But a full-wave rectifier utilizes both the half-cycles. Therefore, the dc or average voltage available in a full-wave rectifier will be double the dc voltage available in a half-wave rectifier. If the resistance of a forward biased diode is assumed to be zero, the dc voltage of a full-wave rectifier (refer Eq. 12.10) is

$$V_{dc} = \frac{2V_m}{\pi} \tag{12.13}$$

We can mathematically derive Eq. 12.13, on the same lines as we derived Eq. (12.8) in the previous sub-section. Try to derive it by solving the following SAQ.

SAQ 3 – **DC output from a full-wave rectifier**

The output voltage of a full-wave rectifier (see Fig. 12.8b) is described as

$$V_o = V_m \sin \omega t \qquad 0 < \omega t < \pi$$

$$V_o = -V_m \sin \omega t \qquad \pi < \omega t < 2\pi$$

A minus sign appears in the second equation because during the second half-cycle the wave is still sinusoidal, but inverted. The average or the dc value of voltage is

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_o \, d(\omega t)$$

Prove that

$$V_{dc} = \frac{2V_m}{\pi}$$

So, now you know that a dc power unit can be of any one of the three forms: it can contain a half-wave rectifier or a centre-tap full-wave rectifier or a bridge rectifier circuit.

Let us now compare the performances of half and full-wave rectifiers.

12.3 RECTIFIER PERFORMANCE

If we connect a load resistor R_L directly across the secondary of the transformer, the current flowing through it will be purely ac (sinusoidal having zero average value). This current is as shown in Fig. 12.10a.

In some applications, we require a dc current to flow through the load. The dc current is unidirectional and, ideally, has no fluctuations with time. The ideal dc current is shown in Fig. 12.10b. To see how effectively a rectifier converts ac into dc, we compare its output current waveshape with the ideal dc current.

If the load takes current from a half-wave rectifier, the current waveform will be as in Fig. 12.10c. It is unidirectional, but fluctuates greatly with time. The waveform of the load current, when the load is connected to a full-wave rectifier, is shown in Fig. 12.10d. This too is unidirectional and fluctuates with time. A unidirectional, fluctuating waveform may be considered as consisting of a number of components. It has an average or dc value over which a number of ac (sinusoidal) components of different frequencies are superimposed. These undesired ac components are called **ripples**. The lowest ripple frequency in case of a half-wave rectifier is the same as the power-mains frequency. But, for full-wave rectifier it is not so. As can be seen from Figs. 12.10d and a, the period of the output wave of a full-wave rectifier is half the period of the input wave. The variation in current (or voltage)

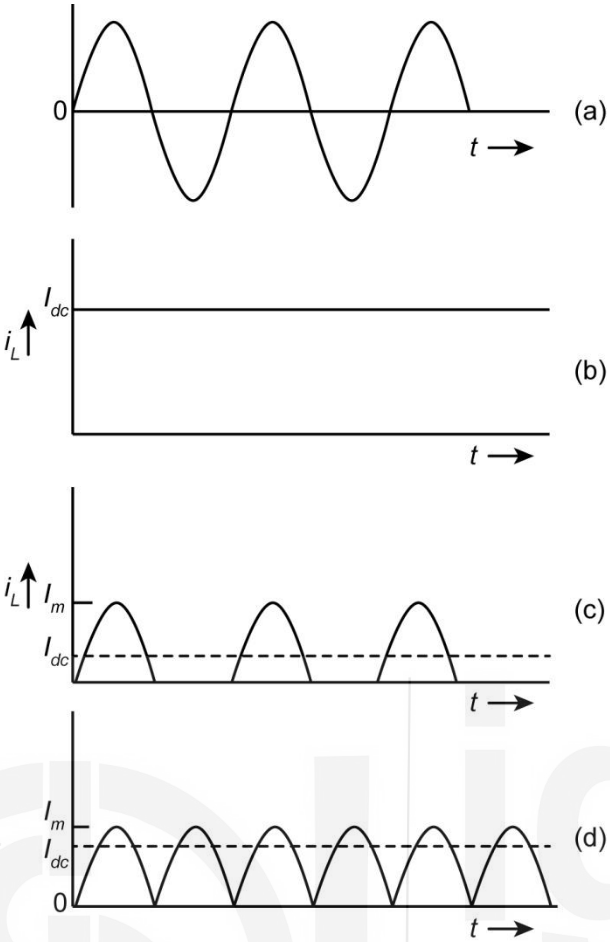


Fig. 12.10: **Comparison of half-wave and full-wave rectifiers with an ideal ac-to-dc converter.**

repeats itself after each angle π of the input wave. Therefore, the lowest frequency of the ripple in the output of a full-wave rectifier is twice the input frequency. That is, the ripple frequency

$$f_r = f_i = 50\,\text{Hz} \quad \text{(half-wave rectifier)}$$

and

$$f_r = 2f_i = 100\,\text{Hz} \quad \text{(full-wave rectifier)}$$

Ripple Factor

In order to have an assessment of the ac component in the output of a rectifier circuit, we use a parameter called **Ripple factor**. It is defined as

$$\text{Ripple factor } (\gamma) = \frac{\text{rms value of ac component of load voltage}}{\text{dc component of load voltage}} \quad (12.14)$$

Now, the rms voltage across the load comprises both, a dc component and an ac component. We can express it as

$$v_{Lrms}^2 = (V_{Ldc})^2 + (v_{Lacrms})^2 \quad (12.15)$$

$$\therefore \quad (v_{Lacrms})^2 = (v_{Lrms})^2 - (V_{Ldc})^2$$

$$\gamma = \text{Ripple factor} = \frac{(v_{Lacrms})}{(V_{Ldc})} = \sqrt{\frac{(v_{Lrms})^2 - (V_{Ldc})^2}{(V_{Ldc})^2}}$$

$$\gamma = \sqrt{\left(\frac{v_{Lrms}}{V_{Ldc}}\right)^2 - 1} = \sqrt{\left(\frac{i_{Lrms}}{I_{Ldc}}\right)^2 - 1} \quad (12.16)$$

Form Factor (F): It is defined as the ratio of rms value of load voltage to the dc component.

$$\text{Form factor (F)} = \frac{v_{Lrms}}{V_{Ldc}} = \frac{i_{Lrms}}{I_{Ldc}} \quad (12.17a)$$

Clearly, γ (Ripple factor) = $\sqrt{F^2 - 1}$. (12.17b)

Rectification Efficiency (η):

It tells us what percentage of total input ac power is converted into useful dc output power. Thus, rectification efficiency is defined as

$$\eta = \frac{\text{dc power delivered to load}}{\text{ac input power from transformer secondary}}$$

or

$$\eta = \frac{P_{dc}}{P_{ac}} \quad (12.18)$$

Wattmeter or power meter is the instrument to measure the ac power. You can calculate dc power by multiplying dc current and dc voltage at the output of the circuit at any instant of time.

Here, P_{ac} is the power that would be indicated by a wattmeter connected in the rectifying circuit with its voltage terminals placed across the secondary winding and P_{dc} is the dc output power.

We shall now analyse half-wave and full-wave rectifiers to find their ripple factor and rectification efficiency.

12.3.1 Performance of Half-Wave Rectifier

The half-wave rectified current wave is plotted in Fig. 12.11 and is described mathematically as

$$i_L = I_m \sin\omega t \qquad \text{for } 0 < \omega t < \pi \quad (12.19a)$$

and

$$i_L = 0 \qquad \text{for } \pi < \omega t < 2\pi \quad (12.19b)$$

For determining the ripple factor or rectification efficiency, we first find the rms value of the current.

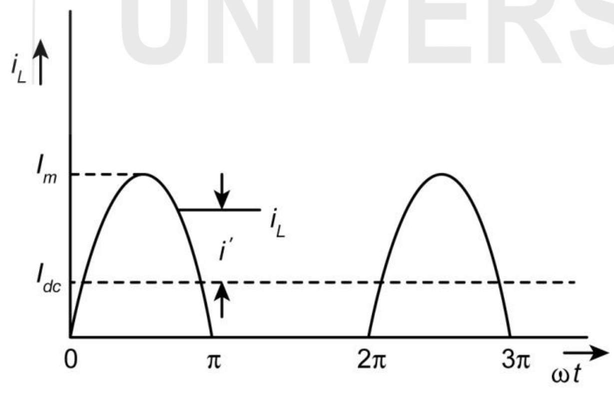


Fig. 12.11: **Half-wave rectified current waveform. (The instantaneous ac component of current is the difference between instantaneous total current and dc current, i.e., $i' = i_L - I_{dc}$).**

RMS Value of Current

The rms or effective value of the current flowing through the load is given as

$$i_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 (\omega t)} \quad (12.20)$$

where current i_L is described by Eqs. (12.19a) and (12.19b). Therefore,

$$i_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} I_m^2 \sin^2 \omega t\, d(\omega t) + \int_{\pi}^{2\pi} 0\, d(\omega t)\right]}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{(1-\cos 2\omega t)}{2} d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{2\pi \times 2}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_0^{\pi}}$$

$$\therefore \quad i_{rms} = \frac{I_m}{2} \tag{12.21}$$

Form Factor

Using the values of I_{dc} from Eq. (12.7) and i_{rms} from Eq. (12.21), the form factor is given by

$$F = \frac{i_{Lrms}}{i_{Ldc}} = \frac{I_m / 2}{I_m / \pi} = \frac{\pi}{2} = 1.57 \tag{12.22}$$

Ripple Factor

From Eq. (12.17b), the ripple factor is given as

$$\gamma = \sqrt{F^2 - 1} = \sqrt{(1.57)^2 - 1} = 1.21 \tag{12.23}$$

Here, we see that the ripple current (or voltage) exceeds the dc current (or voltage). This shows that the half-wave rectifier is a poor converter of ac into dc.

Rectification Efficiency

For a half-wave rectifier, the dc power delivered to the load is

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$$

and the total input ac power is

$$P_{ac} = i_{rms}^2 (r_d + R_L) = \left(\frac{I_m}{2}\right)^2 (r_d + R_L)$$

Therefore, the rectification efficiency is

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(I_m / \pi)^2 R_L}{(I_m / 2)^2 (r_d + R_L)} \times 100\%$$

$$= \frac{40.5}{1 + (r_d / R_L)}\% \tag{12.24}$$

If $r_d < R_L, \eta \rightarrow 40.5\%$. It means that under the best conditions (i.e. no diode loss), only 40.5% of the ac input power is converted into dc power. The rest remains as ac power in the load.

12.3.2 Performance of Full-Wave Rectifier

Fig. 12.12 shows a full-wave rectified current waveform. You will notice that its period is π. The wave repeats itself after each π. Therefore, while computing the average or rms values, we should take the integration between the limits 0 to π, instead of 0 to 2π. The waveshape between 0 to π is described as

$$i_L = I_m \sin \omega t \tag{12.25}$$

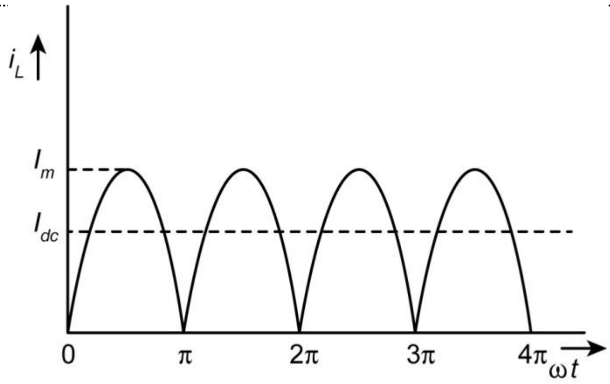


Fig. 12.12: **Full-wave rectified current waveform.**

RMS Value of Current

Effective or rms value of current is given as

$$i_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_L^2 d(t)} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d(\omega t)}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d(\omega t)} = \sqrt{\frac{I_m^2}{\pi}\left|\frac{\omega t}{2} - \frac{\sin 2\omega t}{4}\right|_0^{\pi}}$$

$$= \sqrt{\frac{I_m^2}{\pi} \times \frac{\pi}{2}}$$

or

$$i_{rms} = \frac{I_m}{\sqrt{2}} \quad (12.26)$$

Note that this is the same as the rms value of the full sinusoidal ac wave.

The dc or average value of the current is

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i_L \, d(\omega t) = \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t \, d(\omega t)$$

$$= \frac{2I_m}{\pi} \quad (12.27)$$

This current is obviously double the dc current of a half-wave rectifier.

Form Factor

$$F = \frac{i_{Lrms}}{i_{dc}} = \frac{I_m / \sqrt{2}}{2I_m / \pi} = \frac{\pi}{2\sqrt{2}} = 1.11 \quad (12.28)$$

Ripple Factor

From Eq. (12.17b)

$$\gamma = \sqrt{F^2 - 1} = \sqrt{(1.11)^2 - 1} = 0.48 \quad (12.29)$$

Rectification Efficiency

For a full-wave rectifier, the dc power delivered to the load is

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

and the total input ac power is

$$P_{ac} = i_{rms}^2 (r_d + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_d + R_L)$$

Therefore, the rectification efficiency is

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2I_m / \pi)^2 R_L}{(I_m / \sqrt{2})^2 (r_d + R_L)} \times 100\%$$

For $r_d << R_L$

$$\eta = \frac{8}{\pi^2} \times 100 = 81.1\% \qquad (12.30)$$

This shows that the rectification efficiency of a full wave rectifier is twice that of a half-wave rectifier under identical conditions. The maximum possible efficiency can be 81.1% (when $r_d << R_L$).

EXAMPLE 12.2: RIPPLE FACTOR AND RECTIFICATION EFFICIENCY

In a centre-tap full-wave rectifier, the load resistance $R_L = 1\text{k}\Omega$. Each diode has a forward-bias dynamic resistance r_d of 10 Ω. The voltage across half the secondary winding is (220 sin 314 t). Find a) the peak value of current, b) the dc or average value of current, c) the rms value of current, d) the ripple factor, and e) the rectification efficiency.

SOLUTION ■ The voltage across half the secondary winding is given as

$$v = 220 \sin 314 t$$

a) The peak value of voltage is

$$V_m = 220 \text{ V}$$

Therefore, peak value of current is

$$I_m = \frac{V_m}{r_d + R_L} = \frac{220}{10 + 1000} = 0.2178 \text{ A}$$

$$= 217.8 \text{ mA}$$

b) The dc or average value of current for full wave rectifier is

$$I_{dc} = \frac{2I_m}{\pi} = \frac{2 \times 217.8}{\pi} = 138.7 \text{ mA}$$

c) The rms value of current for full wave rectifier is

$$I_{rms} = \frac{I_m}{\sqrt{2}} = 154 \text{ mA}$$

d) The ripple factor is given by Eq. (12.16)

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{154}{138.7}\right)^2 - 1} = 0.482$$

e) The rectification efficiency is given

$$\eta = \frac{P_{dc}}{P_{ac}}$$

But, $P_{dc} = I_{dc}^2 R_L = (0.1387)^2 \times 1000 = 19.23 \text{ W}$

$$P_{ac} = I_{rms}^2 (r_d + R_L)$$

$$= (0.154)^2 (10 + 1000)$$

$$= 23.96 \text{ W}$$

$$\therefore \quad \eta = \frac{P_{dc}}{P_{ac}} = \frac{19.23}{23.96} = 0.8026 \times 100\% = 80.26\%$$

A full-wave rectifier is preferred to a half-wave rectifier, because its rectification efficiency is double and its ripple factor is low. Table 12.1 gives the comparison between different rectifiers discussed so far. Unless otherwise indicated, all rectifiers we will use in our further discussion are full-wave rectifiers (either centre-tap or bridge).

Table 12.1: Comparison between different rectifiers

	Half-wave	**Full-wave**	
		Centre-tap	**Bridge**
Number of diodes	1	2	4
Transformer necessary	Single secondary winding	Centre tapped secondary winding	Single secondary winding
Peak secondary voltage	V_m	V_m	V_m
Peak inverse voltage	V_m	$2V_m$	V_m
Peak load current, I_m	$V_m/(r_d + R_L)$	$V_m/(2r_d + R_L)$	$V_m/(r_d + R_L)$
RMS current, i_{rms}	$I_m/2$	$I_m/\sqrt{2}$	$I_m/\sqrt{2}$
DC current, I_{dc}	I_m/π	$2I_m/\pi$	$2I_m/\pi$
Forms factor	1.57	1.1	1.1
Ripple factor, r	1.21	0.48	0.48
Rectification efficiency (max)	40.5%	81.1%	81.1%
Lowest ripple frequency, f_r	f_i	$2f_i$	$2f_i$

Most electronic equipment require smooth dc operating voltages. The output of a rectifier cannot be applied directly to such equipment because of the ripple. Consequently, the ripple must be eliminated. Circuits for accomplishing this are called filter circuits. Let us now discuss about the filter circuits.

12.4 FILTER CIRCUITS

The aim of rectification is to provide a steady dc voltage, similar to the voltage from a battery. We have seen that a full-wave rectifier provides a better dc than a half-wave rectifier. But, even a full-wave rectifier does not provide ripple-free dc voltage. Actually, the rectifiers provide what we may call "a pulsating dc". We can filter or smooth out the ac variations from the rectified voltage. For this we use a filter or smoothing circuit (see Fig. 12.1). In this section, we shall discuss different types of filter circuits.

12.4.1 Capacitance Filter

The ripple output of a rectifier represents energy being supplied to the load in pulses. The ripple fluctuations can be reduced considerably if some of the output is stored while the rectifier is delivering a pulse and then released to the load between output pulses. This is the basic operating principle of the capacitance filter.

Such a filter consists of a large value capacitor *C* in shunt (parallel) with the load resistor R_L , as shown in Fig. 12.13a. The capacitor offers a low-resistance path to the ac components of current. To dc (with zero frequency), this is an open circuit. All the dc current passes through the load. But due to capacitor, most of the ac component part flows to the ground and only a small part of the ac component passes through the load producing a small ripple voltage.

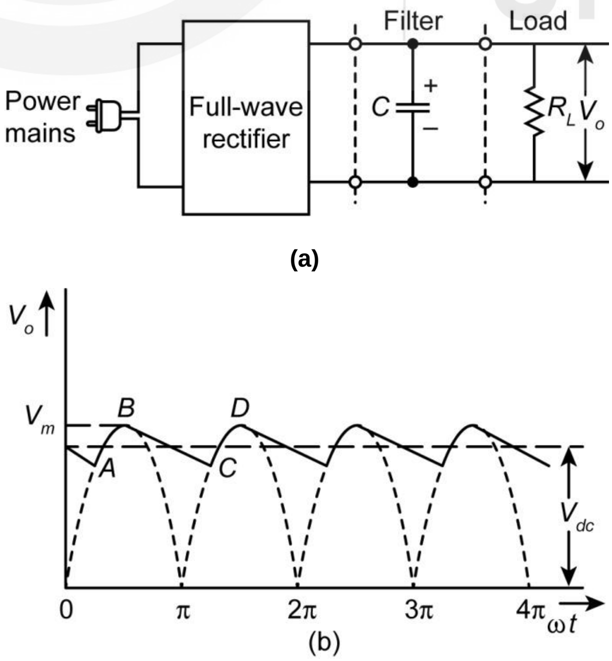


Fig. 12.13: **a) Circuit of full-wave rectifier with shunt capacitor filter; b) filtering action by capacitor charging-discharging.**

The waveforms of filter output are shown in Fig. 12.13b. When the rectifier output voltage is increasing, the capacitor charges to the peak voltage V_m. Just past the positive peak (point *B*), the rectifier output voltage starts to fall (see the dotted curve in Fig. 12.13b). But at point *B*, the capacitor has + V_m volts across it. Since the source voltage becomes slightly less than V_m the capacitor will try to send current back through the diode (of the rectifier). This reverse-biases the diode, i.e. it becomes open-circuited. Thus, the capacitor changes the conditions under which the diodes (of the rectifier) conduct.

The diode (open-circuit) disconnects or separates the source from the load. The capacitor starts to discharge through the load. This prevents the load voltage from falling to zero. The capacitor continues to discharge until the source voltage (the dotted curve) becomes more than the capacitor voltage (at point *C*). The diode again starts conducting, and the capacitor is again charged to peak value V_m . During the time the capacitor is charging (from point *C* to point *D*) the rectifier supplies the charging current i_c through the capacitor branch as well as the load current i_L . When the capacitor discharges (from point *B* to point *C*), the rectifier does not supply any current, the capacitor sends current i_L through the load. In this way, the current is maintained through the load all the time.

The rate at which the capacitor discharges between points *B* and *C* (in Fig. 12.13b) depends upon the time constant CR_L . The longer this time constant is, the steadier is the output voltage. If the load current is fairly small (i.e., R_L is sufficiently large) the capacitor does not discharge very much, and the average load voltage V_{dc} is slightly less than the peak value V_m .

Any increase in the load current (i.e. decrease in the value of R_L) makes the time constant of the discharge path smaller. The capacitor then discharges more rapidly, and the load voltage does not remain constant. The ripple increases with increase in load current. Also, the dc output voltage, V_{dc} decreases.

12.4.2 Inductance Filter

An inductor is another device that can store and release electrical energy. It does this by extracting energy from a flowing current and storing it in the form of magnetic field when the current is increasing. Then it releases the energy to keep the current flowing when the current begins to decrease. This ability of an inductor to store and release energy can be used to help prevent the abrupt changes in the output of a rectifier. This property is used in the inductance filter of Fig. 12.14a. Whenever the current through an inductor tends to change, a “back emf” is induced in the inductor. This induced back emf prevents the current from changing its value. Any sudden change in the current that might have occurred in the circuit without an inductor is smoothed out by the presence of the inductor. Its effect on the output waveform is shown in Fig. 12.14b.

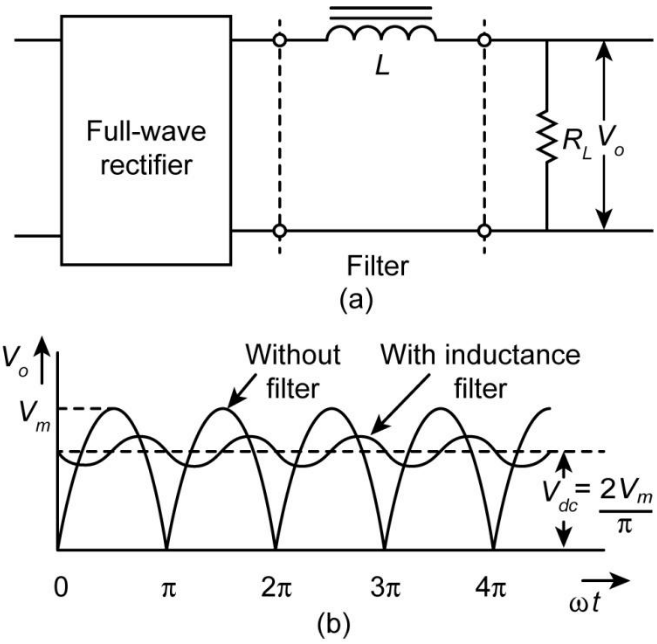


Fig. 12.14: **a) Full-wave rectifier with inductance filter; b) the filtering action.**

The inductance filter prevents the current, and, therefore, the output voltage from ever reaching the peak value that would be obtained if the inductor were not in the circuit.

Therefore, a rectifier that has an inductance filter will not produce as high an output voltage as the one that has a capacitance filter. However, a large load current can be drawn from the inductance filter without changing the output voltage.

The operation of a series inductor filter depends upon the current flowing through it. Therefore this filter (and also the choke (inductor) input *LC* filter discussed in the next sub-section) can only be used together with a full-wave rectifier (since it requires current to flow at all times). Furthermore, the higher the current flowing through it, the better is its filtering action. Therefore, an increase in load current results in reduced ripple.

12.4.3 *LC* Filter

We have seen that an inductance filter has a feature of decreasing the ripples when the load current is increased. Reverse is the case with a capacitor filter. In this case, as the load current is increased, the ripples also increase. An *LC* filter combines the features of both the inductor filter and shunt capacitor filter. Therefore, the ripples remain fairly the same even when the load current changes. There are two types of *LC* filter: capacitor input filter and choke (inductor) input filter. Let us describe each one of them.

Capacitor input filter

This type of *LC* filter is shown in Fig. 12.15. This is called a capacitor input filter because capacitor (C_1) is the first filtering element directly after the rectifier. It is also called the "pi" filter because its schematic arrangement of C's and *L* resembles the Greek letter π.

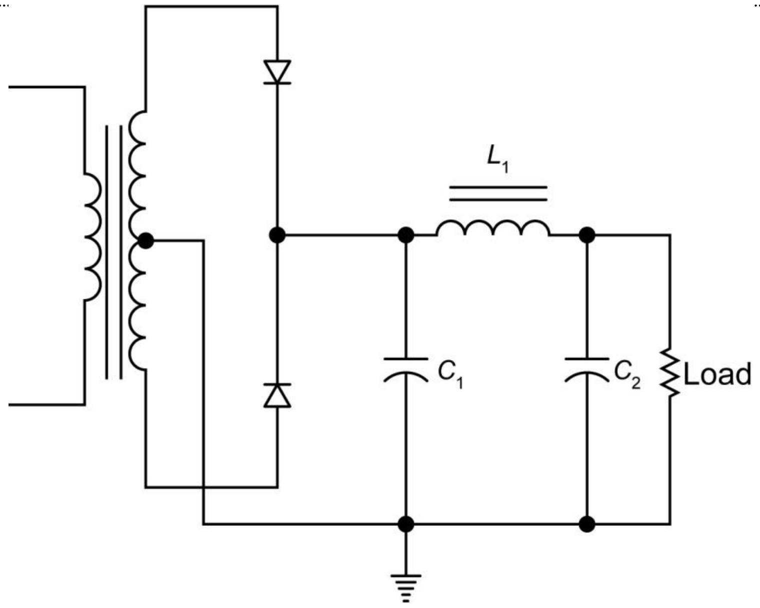


Fig. 12.15: **Capacitor input filter.**

In this type of filter, capacitor C_1 performs the same function as the simple capacitance filter described earlier. It charges to the peak voltage of the rectified output pulses and then discharges through the load, when the rectifier output falls. Capacitor C_2 provides similar filtering action but to a lesser degree. Inductor L_1 adds to the overall filtering action by opposing changes in both, the output current filtered by C_2 and the current drawn by the load.

The output of such a filter contains only small amount of ripple. However, the voltage regulation of such a filter is relatively poor. This is because of the decrease in the voltage across C_1 as it discharges between rectified pulses.

Choke (inductor) input filter

When an inductor is used as primary filtering element in an *LC* filter, the network is called a choke input filter. The term choke is used because of the inductor's ability to stop, or choke, the passage of ripple voltage to the load. Fig. 12.16 shows a simple choke input filter.

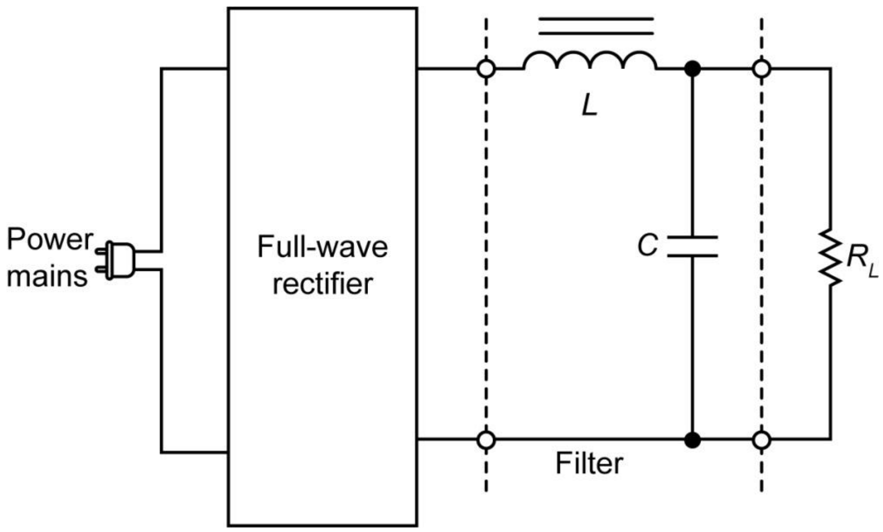


Fig. 12.16: **Choke input filter.**

Due to the arrangement of components, this filter is also known as “L” shaped filter.

The inductor opposes current changes while the capacitor charges and discharges in standard filter-capacitor fashion. Since the inductor reduces the peak rectifier current and this in turn reduces the maximum voltage to which the capacitor charges, the output voltage of the choke input filter is lower than that of the capacitor input filter. This output voltage, though, is affected less by changes in the load current.

12.5 REGULATION OF OUTPUT VOLTAGE

So far we have discussed the rectifier and filter system. The filters are used to reduce the ripple and help in regulation of voltage. A very important characteristics of any power supply is the degree to which its output voltage remains constant despite changes in the amount of current drawn from the supply by the load. This characteristic is called the **regulation** of the supply. A supply whose output voltage changes little over a wide variation in load current is said to have good regulation. If output voltage falls sharply as the load current increases such power supply circuit has poor regulation. To obtain good regulation, additional circuits are added so that the output voltage remain constant. These additional circuits are called **voltage regular circuits.**

12.5.1 Voltage Regulator Parameters

Basically, the output voltage tends to vary because of two things:
(a) fluctuating line (input ac) voltage, and (b) fluctuating load current. Every time the line voltage goes up, the output voltage will go up. But when the load current goes up, the output voltage will go down. This is because the output voltage is actually what is left after the voltage drops across the internal components in the circuit are taken away from the input voltage. As the load current increases, the internal drop increases and less is left for the output. Thus, we define two terms: (i) source regulation, and (ii) load regulation.

Source regulation

It is also called source effect or *line regulation*. It is the change in regulated load (output) voltage for the specified range of line voltage and is defined as:

$$\%\,\text{Source Regulation} = \frac{SR}{V_{nom}} \times 100\% \qquad (12.31)$$

where

SR = change in load voltage for full line voltage change

V_{nom} = nominal load voltage

For instance, if the change in load voltage is 5 mV and the nominal load voltage is 10V then

$$\%\,\text{Source Regulation} = \frac{5\text{ mV}}{10\text{ V}} \times 100\% = 0.05\%$$

Load regulation

It is also called load effect. It is defined as the change in regulated output voltage when the load current changes from minimum to maximum.

$$LR = V_{NL} - V_{FL} \tag{12.32}$$

where

LR = load regulation

V_{NL} = load voltage with no load current

V_{FL} = load voltage with full load current

Load regulation is often expressed as a percent by dividing the change in load voltage by the no load voltage

$$\%\text{Load Regulation} = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100\% \tag{12.33}$$

Before proceeding further, you may like to solve an SAQ.

SAQ 4 – **Load regulation**

If no load voltage is 10V and the full load voltage is 9.9V, then what is the percent load regulation?

12.5.2 Principle of Voltage Regulation

There are different types of voltage regulator. One is the **linear regulator** which is operating throughout the cycle of ac, and so there is no ripple problem. But its efficiency is less.

The other kind of regulator is called a **switching regulator**, where we use a device to charge and discharge and supply this shunt dc voltage to the load. But since we are going to switch on and off the charging of that storage device, we are going to get a ripple which will be riding on the output dc. In this unit we will be restricting our discussion to the linear voltage regulators only.

The principle of linear regulator is quite simple as shown in Fig. 12.17. The rectified and filtered input (unregulated) (V_{UR}) is given it to the linear regulator circuit, and we get a regulated output (V_{OR}) which is smaller than the input that we have given.

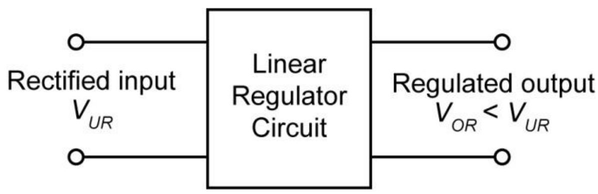


Fig. 12.17: **Principle of linear regulation**

In the regulator circuit we compare the input unregulated voltage with a fixed reference voltage and that fixed reference voltage determines the output regulated voltage. The excess voltage, that is the difference between the input and the output voltage is dissipated within the circuit as an ohmic loss i.e. in the form of heat. It is not a very efficient circuit because we are losing on a power here; but we get excellent regulation in this method.

The linear regulators are of two types:

i) shunt voltage regulator; and

ii) series voltage regulator or series pass regulator.

In the shunt voltage regulator, we connect the load in parallel with the reference voltage. The reference voltage is derived through a special device which ensures constant voltage across it. Since the load is directly parallel to the reference voltage, it will always have a fixed voltage (equal to the reference voltage) across it.

In series voltage regulator or series pass regulator, we connect the load in series with a variable element that drops the excess voltage between the input and the output across it.

Now for these regulator circuits, we need the reference voltage device which will give a rock steady reference voltage irrespective of any conditions like change the input voltage, change the current flowing through the load, or change in ambient conditions like temperature, humidity etc. One of the best candidate used for generating a reference voltage is a zener diode. You have learnt about in Unit 2 of this course. A zener diode is a *p-n* junction diode with very high doping and so the depletion region between the *p* and *n* junctions is very thin. When we apply a forward bias to this diode, it just operates like a normal rectifier diode and has same forward bias characteristics. But in case of the reverse bias, when we give certain voltage across the depletion layer, due to its small thickness, it allows a lot of charge generation in the form of avalanche and zener breakdown. Then a current gets sustained in the device and the voltage across the device remains constant. It is called breakdown voltage or the *zener voltage*. In this particular case, the breakdown is not a permanent deformity and does not damage the device. Whenever we reduce the reverse voltage it comes back to its normal operation.

Before discussing the types of regulators you may solve one SAQ.

SAQ 5 – **Zener reference voltage**

Why can normal *p-n* junction diode not be used as reference voltage source?

12.5.3 Shunt Voltage Regulator

Use of zener diode in a shunt voltage regulator is shown in Fig. 12.18. Here, we connect the zener diode cathode to the positive terminal and anode to the ground potential. In this way, we operate it in the reverse bias mode with a resistance *R* connected between the supply and the diode. Due to reverse bias condition, the voltage across the zener diode remains constant. Since the load is attached in parallel to the zener diode, it always has the same voltage (the zener voltage) across it. In this way, we have a constant voltage delivered to the load.

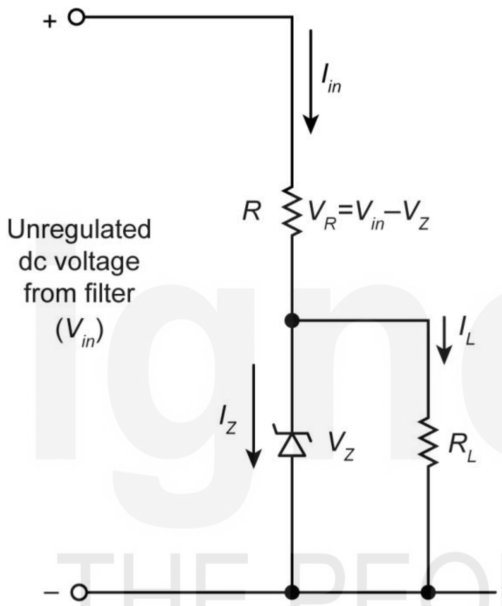


Fig. 12.18: **Shunt voltage regulator using zener diode.**

Now the zener is going to draw V_Z voltage across it. But the input is the rectified, filtered unregulated voltage V_{in}. The balance of $(V_{in} - V_Z)$ voltage gets dropped across *R*. So *R* is the dissipative element in shunt voltage regulator. For the zener to get operational; minimum zener current should always pass through it and that is denoted by I_Z.

The load current $I_L = V_Z / R_L$. Hence the resistance value of the load determines I_L. Here the input current I_{in} drawn from filter output gets divided in two parts: one goes to the zener, and other to the load. Minimum I_Z is determined from the specification of the zener diode, but the load current is determined by the value of load resistance. For lower values of R_L, I_L is larger. Now, in order to keep the zener working, we need minimum I_Z flowing through it irrespective of I_L value. So when we design a regulator, we should have provision to draw the input current

$$I_{in} = I_Z + I_{L(\max)}$$

Let us understand the design of shunt regulator with an example.

Example 12.3: DESIGN OF SHUNT REGULATOR FOR VARIABLE LOAD

Design a shunt regulator using zener diode to provide 5V dc voltage for a variable load of 100 Ω to 500 Ω. The minimum zener current for its proper operation is 5 mA. The unregulated input voltage = 6 V.

SOLUTION ■ Refer to Fig. 12.18. For obtaining 5 V across the load, we choose the zener with breakdown voltage = 5 V. When the load resistance is maximum, current though the load

$$I_{L_{\min}} = \frac{5\text{ V}}{500\ \Omega} = 10\text{ mA}$$

When the load resistance is minimum, maximum load current flows in the load,

$$I_{L_{\max}} = \frac{5\text{ V}}{100\ \Omega} = 50\text{ m}\Omega$$

The input current sourced from the filter output is the sum of zener current and maximum load current

$$\therefore \quad I_{in} = I_Z + I_{L_{\max}}$$

$$= 5\text{ mA} + 50\text{ mA} = 55\text{ mA}$$

This current always flows from the filter output. It gets divided among load and zener diode. For lowest load current (10 mA),

zener current = 55 – 10 = 45 mA

Hence the power rating of zener

$= 5\text{ V} \times 45\text{ mA}$

$= 225\text{ mW}$

Since the input voltage = 6 V and, zener voltage = 5 V.

Hence 1 V is dropped across *R*. Current flowing through $R = I_{in} = 55\text{ mA}$ \

$$\therefore \quad R = \frac{1\text{ V}}{55\text{ mA}} = 18.2\ \Omega$$

And the power rating of *R* is

$$\therefore \quad I_{in}^2 \times R = (55\text{ mA})^2 \times (18.2\Omega) = 0.055\text{ W}$$

So the circuit of voltage regulator will have zener diode with 5 V and 250 mW rating. The resistance is 18.2 Ω with 55 mW rating.

From this example you can see that 55 mA current is always going to flow through 18.2 Ω resistor. Hence it is a dissipative kind of configuration;

because whether we require just 10 mA current or 50 mA current through the load, *R* is always going to draw 55 mA.

So far we considered about the load regulation where we get regulated voltage even when load is changing. But now, the rectified input that we are getting is also unregulated. So its value may also vary. We considered in our example a fixed voltage drop of 1 V (= 6V – 5V) across the dissipative element *R*. But this drop will change, if input voltage varies. This will effectively change the current flowing through resistor *R*, as you will find out from the next SAQ.

SAQ 6 **– Regulation again input voltage regulation**

Consider the regulator discussed in Example 12.1. Find out the range of current flowing through the resistor *R* when the input voltage V_{in} varies between 6 V and 8 V; if $R = 18.2\ \Omega$.

From this SAQ you will realize that the current in *R* depends on the voltage drop across it. So this I_{in} is going to change with V_{in} but I_L will remain constant for given load. Now, the extra variation in the current will have to be borne by current through zener.

Hence the power rating of the zener has to be calculated not just on the basis of load variation, but also based on the expected changes in the input supply.

The shunt regulator is not very energy efficient, since the excess voltage will result into excess power dissipation in *R*. Now, we will discuss another relatively efficient configuration of linear regulator called the series pass voltage regulator.

12.5.4 Series Pass Voltage Regulator

Refer to Fig. 12.19 which shows a schematic of series pass voltage regulator.

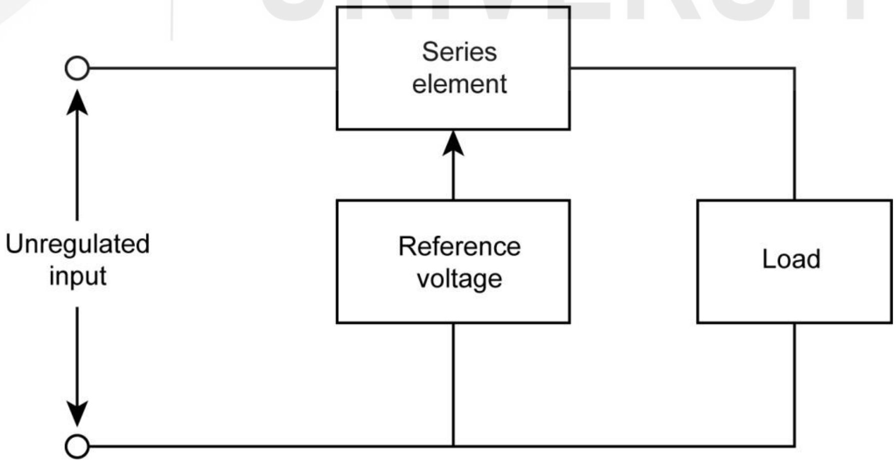


Fig. 12.19: **Schematic of series pass voltage regulator.**

In this regulator a variable element (like transistor) is placed in series with the load. The reference voltage is given to the series element which controls the current passing through the element.

In order to supply regulated voltage at the output, we control the voltage drop across the series pass element by changing its resistance. That is, the difference between V_{in} and V_{out} is dropped by the series pass element which, in turn, will be determined by the current passing through it. For this purpose, the series pass element should be controllable electronically depending on the reference voltage. Hence, we need to have an active device as our series pass element.

The first choice is a transistor, because we can always control the voltage across the transistor which depends on the current flowing through it as well as the base current supplied to it. Here, we use emitter follower (common collector) configuration of an *n-p-n* transistor as the series pass element as shown in Fig. 12.20.

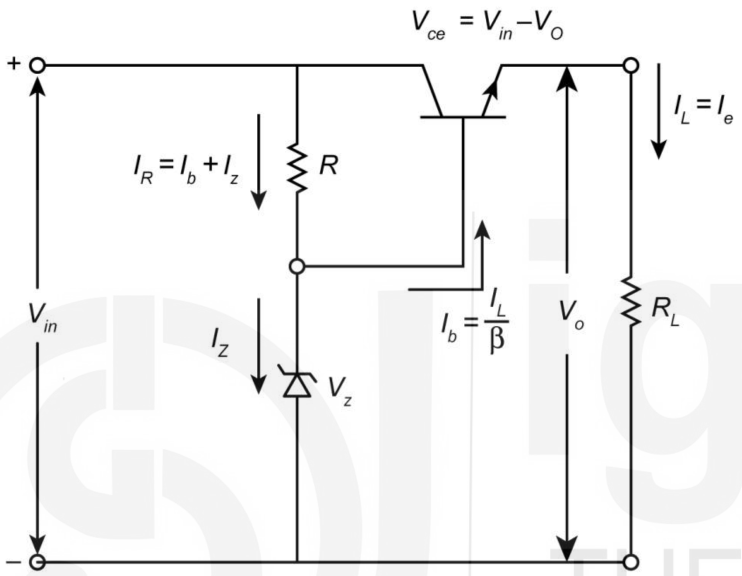


Fig. 12.20: **Transistor as series pass element.**

We apply the reference voltage to the base of the transistor in the form of a reverse biased zener diode. The transistor is biased to conduct in its active region. Thus, the base emitter voltage (V_{be}) of the transistor will be constant (of the order of 0.6 V, if we use a silicon transistor). So the voltage appearing at the output of this series regulator is $V_o = V_z - V_{be}$, i.e. V_o is less than the reference voltage by 0.6 V.

In this case, the load current is nothing but the emitter current flowing through the transistor and the voltage drop across the transistor, that is the collector-emitter voltage $V_{ce} = V_{in} - V_o$.

Now, the current given to the base of this transistor is going to be determined by the load current, because the load current is nothing but the emitter current. Hence we can estimate

$$I_b = \frac{I_L}{\beta},$$

where β is the current gain of the transistor. Hence, the zener current is now restricted only to the minimum current that is required for zener to operate (I_z) plus the base current required for the transistor to operate.

Hence this is an efficient circuit, than the shunt regulator because the requirement of current is quite less as far as the base current is concerned, and so there are less losses in the resistor. An added advantage is that with the series pass element regulator we can also have a possibility of feedback configuration. Before studying the advantages of feedback configuration, let us discuss an example on designing of a series pass regulator.

EXAMPLE 12.4: DESIGN OF SERIES PASS REGULATOR

Design a series pass regulator to obtain 10 V dc output with maximum load current of 100 mA. Consider the nominal input voltage to be 15 V.

SOLUTION ■ Refer to Fig. 12.20. Let us consider that we are using a silicon *n-p-n* transistor with β = 50. We need output voltage = 10 V. For silicon transistor, $V_{BE} = 0.6$ V.

Hence $V_z = V_o + V_{BE} = 10\text{ V} + 0.6\text{ V} = 10.6\text{ V}$.

Maximum output current $I_L = I_E = 100\text{ mA}$.

For $\beta = 50$, $I_B = \frac{100}{50} = 2\text{ mA}$.

$$V_{CE} = V_{in} - V_{out} = 15 - 10 = 5\text{ V}$$

Current through the resistor R

$$I_R = I_Z + I_{BE}$$

If we consider, $I_Z = 5\text{ mA}$.

$$I_R = 5 + 2 = 7\text{ mA}$$

Voltage across R,

$$V_R = V_{in} - V_Z = 15\text{ V} - 10.6\text{ V} = 4.4\text{ V}$$

$$\therefore \quad R = \frac{4.4\text{ V}}{7\text{ mA}} = 628\ \Omega$$

In this case, since very small currents are flowing through R and zener diode, their power ratings will be quite low; as you will calculate in the following SAQ.

SAQ 7 – Regulator components

Calculate the power ratings of the zener diode and resistor R used in Example 12.4.

Now let us discuss how series pass regulator with feedback can be used as a variable voltage supply.

12.5.5 Variable Voltage Supply using Potential Divider

So far we discussed the power supply with fixed output voltage, determined by the reference voltage. But, we can have a feedback, sampled from the output voltage and feed it back to a comparator which compares the sampled voltage with the reference voltage and generates an error signal to control the series element. In such case, the portion of output voltage sampled decides the value of output voltage.

You will learn about the operational amplifier in Unit 13.

Typically for a comparator, we use operational amplifier because it has high gain and so with small difference between two input voltages it generates adequate output signal to control the series pass element. The feedback circuit can be a potential divider consisting of two resistors R_1 and R_2 as shown in Fig. 12.21.

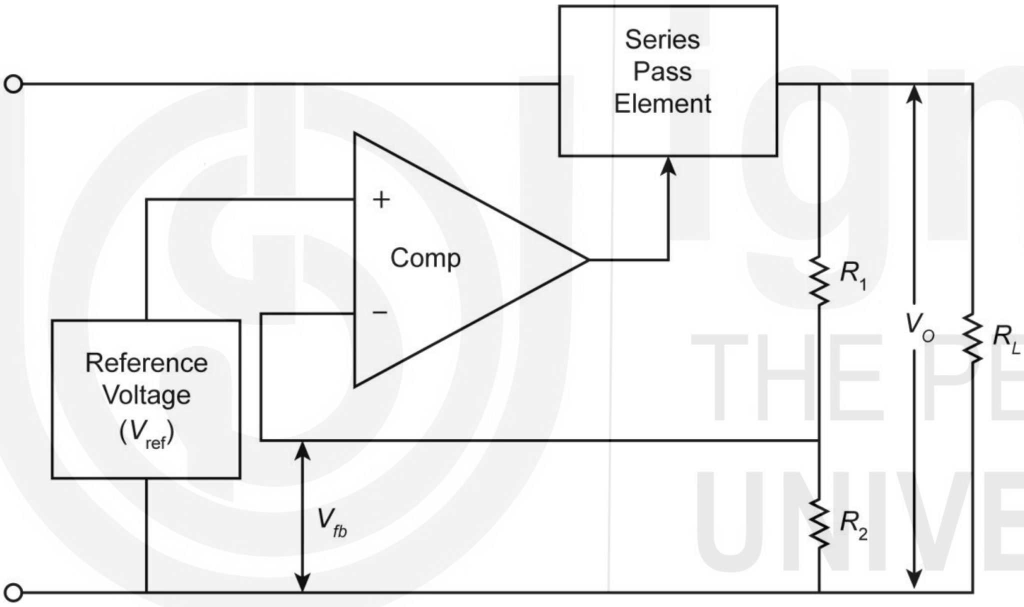


Fig. 12.21: **Voltage supply with potential divider.**

This configuration of the regulator circuit allows us to have higher output voltage than the zener voltage rating. Here, we are using the sampling circuit in the form of a potential divider R_1 and R_2 and the voltage across R_2 is fed back to the negative terminal of the comparator.

$$\text{The feedback voltage} = V_{fb} = \frac{R_2}{R_1 + R_2} V_o \tag{12.33}$$

The second input of the comparator is connected to the zener diode. Hence, the feedback voltage is compared to the reference voltage and the error signal is generated to control the series pass element to provide output voltage V_o. So we are able to generate the output voltage which is greater than the reference voltage given by the relation:

$$V_o = \frac{R_1 + R_2}{R_2} \times V_{ref} \tag{12.34}$$

Now, if we replace the resistor R_2 by a variable resistor, by changing its value, we can obtain variable output voltage from a fixed reference voltage.

You will appreciate the working of potential divider regulator by solving the following SAQ.

SAQ 8 – **Potential divider regulator**

Design a potential divider circuit to obtain 10 V output voltage using a reference voltage of 5 V.

Now, we summarise the points discussed in this unit.

12.6 SUMMARY

Concept	Description
DC power unit	■ The ac mains voltage is first reduced by means of a transformer and then rectified by using half wave or full wave rectifier.
Half-wave rectifier	■ A half-wave rectifier consists of a diode and a load resistor. It delivers an output during only half of the input voltage cycle.
Full-wave rectifier	■ Full-wave rectifier delivers an output during both halves of the input voltage cycle. • Full-wave rectifier with centre tapped transformer circuit consists of two diodes having a common load. • Bridge rectifier consists of four diodes and a common load.
Filters	■ Fluctuation of the dc output from a rectifier above and below its average value is called *ripple*, which can be removed by filter circuit. • Inductance filter consists of an inductor connector in series with the load. • Capacitance filter is connected in shunt with the load. • Combination of *L* and *C* improves filtering action.
Shunt regulator	■ A reference voltage derived usually from a reverse biased zener diode is applied to the load in parallel.
Series pass regulator	■ As series pass element in the form of a transistor is used for dissipating the difference voltage between input and output. The load current is delivered by the emitter current in *CC* configuration. Very small (base) current is required to control the series pass element.
Potential divider regulator	■ Variable voltage can be obtained using single reference voltage with the help of a feedback network.

12.7 TERMINAL QUESTIONS

1. If the peak voltage across a transformer secondary is 100 V, what is the dc voltage value of a) a half-wave rectifier, and b) full-wave rectifier?

2. Which has greater ripple frequency: a half-wave rectifier whose input is 500 Hz or a full-wave rectifier whose input is 300 Hz?

3. The turns ratio of the transformer used in a bridge rectifier is $n_1 : n_2 = 12 : 1.$ The primary is connected to 220 V, 50 Hz power mains. Assuming that the diode voltage drop to be zero, find the dc voltage across the load. What is the PIV of each diode? If the same dc voltage is obtained by using a centre tap rectifier, what is the PIV?

4. In a full-wave rectifier without filter, the load resistance is of 4000 Ω. Each diode has a resistance of 800 Ω, voltage applied to each diode is (240 sin 100 πt). Calculate

   a) peak, average and rms values of current,
   b) dc power output and total power input
   c) rectifier efficiency
   d) form factor
   e) ripple factor

5. Nominal supply voltage of a regulator is 10 V and over the entire variable range of input, the output changes from 9.97 V to 10.02 V. Calculate percentage source regulation.

6. Design a potential divider voltage regulator circuit to give 5 V to 10 V dc with maximum load current of 100 mA using an unregulated dc input of 15 V and a zener diode with $V_Z = 5$ V.

12.8 SOLUTIONS AND ANSWERS

Self-Assessment Questions

1. a) The rms value of a sinusoidal waveform is the amplitude divided by $\sqrt{2}$, so in this case the peak amplitude, or maximum voltage, is $220 \times \sqrt{2} = 311$ V.

   b) rms voltage across secondary = $220 \times \dfrac{1}{15} = 14.7$ V.

   Maximum voltage across secondary = $\dfrac{311}{15} = 20.7$ V.

2. The difference between the output voltage and input voltage is caused by the presence of a silicon (or Germanium) diode. When the transformer output voltage is positive the diode conducts, so the voltage applied to the load resistance is the ac voltage minus the voltage dropped across the diode. When the transformer output voltage is negative no current flows so there is zero voltage drop across the load, as shown in Fig. 12.3c.

3. $$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_o\, d(\omega t)$$

$$= \frac{1}{2\pi}\int_0^{\pi} (V_m \sin\omega t)\, d(\omega t) + \int_{\pi}^{2\pi} (-V_m \sin\omega t)\, d(\omega t)$$

$$= \frac{1}{2\pi}\left[-V_m \cos\omega t\big|_0^{\pi} + V_m \cos\omega t\big|_{\pi}^{2\pi}\right]$$

$$= \frac{V_m}{2\pi}[-\cos\pi + \cos 0 + \cos 2\pi - \cos\pi]$$

$$= \frac{2V_m}{\pi}.$$

4. $$\%LR = \frac{10\text{ V} - 9.9\text{ V}}{10\text{ V}} \times 100\% = 1\%.$$

5. In case of normal *p-n* junction diode the reverse bias breakdown voltage is very large, and beyond this voltage the diode gets damaged. Hence it cannot act as a constant reference voltage device in reverse bias condition.

6. Voltage across R,

   $$V_R = V_{in} - V_Z$$

   We have taken $V_Z = 5$ V.

   Hence for

   $$V_{in} = 6\text{ V}, \quad V_R = 6 - 5 = 1\text{ V}; \; I_{in} = \frac{1\text{ V}}{18.2\,\Omega} = 55\text{ mA}$$

   and for

   $$V_{in} = 8\text{ V}, \quad V_R = 8 - 5 = 3\text{ V}; \; I_{in} = \frac{3\text{ V}}{182\,\Omega} = 165\text{ mA}$$

   Hence the current in the range of 55 mA to 165 mA may flow in the resistance R for variation in the input voltage.

7. Voltage across zener diode = 10.6 V

   and current through zener = 5 mA

   Hence the power rating of zener diode = 53 mW.

   Power rating of the resistor R

   $$= 4.4\text{ V} \times 7\text{ mA} = 31\text{mW}.$$

   These power ratings are quite low as compared to the components used in the shunt regulator.

8. We want $V_o = 10$ V and $V_{ref} = 5$ V.

   Now

   $$V_o = \frac{R_1 + R_2}{R_2} V_{ref}$$

   $$\therefore \quad 10\text{ V} = \frac{R_1 + R_2}{R_2} 5\text{ V}$$

   Hence,

   $$\therefore \quad R_1 + R_2 = \frac{10}{5} R_2 = 2R_2$$

   $$\therefore \quad R_1 = R_2$$

   If $R_1 = 10\,\text{k}\Omega$, then $R_2 = 10\,\text{k}\Omega$.

Terminal Questions

1. a) $\frac{100}{\pi}$ V

   b) $\frac{200}{\pi}$ V

2. Full-wave rectifier.

   For half-wave rectifier, ripple frequency is 500 Hz.

   For full-wave rectifier, ripple frequency is 300 × 2 = 600 Hz.

3. The maximum primary voltage is

$$V_p = \sqrt{2}\,V_{rms} = \sqrt{2} \times 220 = 311\,\text{V}$$

   Therefore, the maximum secondary voltage is

$$V_m = \frac{n_2}{n_1} V_p = \frac{1}{12} \times 311 = 25.9\ \text{V}$$

   The dc voltage across the load is

$$V_{dc} = \frac{2V_m}{\pi} = \frac{2 \times 25.9}{\pi} = 16.49\ \text{V}$$

   The PIV (for bridge rectifier) is

$$\text{PIV} = V_m = 25.9\ \text{V}$$

   For the centre-tap rectifier, the PIV is

$$\text{PIV} = 2V_m = 2 \times 25.9 = 51.8\ \text{V}$$

4. a) Peak value of current, $I_m = \dfrac{V_m}{r_d + R_L}$

$$\therefore \quad I_m = \frac{240}{800 + 4000} = 50 \times 10^{-3}\,\text{A} = 50\,\text{mA}$$

   Average value of current, $I_{dc} = \dfrac{2I_m}{\pi} = \dfrac{50 \times 2}{\pi} = 31.83\,\text{mA}$

   The rms value of current output, $I_{rms} = \dfrac{I_m}{\sqrt{2}} = \dfrac{50}{1.41} = 35.36\,\text{mA}$

   b) The dc power output

$$P_{dc} = I_{dc}^2 \times R_L$$
$$= (31.83)^2 \times 10^{-6} \times 4000$$
$$= 4.05\,\text{W}$$

   Total power input

$$P_{in} = (I_{rms})^2 \times (r_d + R_L)$$
$$= (35.36 \times 10^{-3})^2 \times (800 + 4000)$$
$$= 6.0\,\text{W}$$

   c) Rectifier efficiency

$$\eta = \frac{P_{dc}}{P_{in}} = \frac{4.05\ \text{W}}{6.001\text{W}} \times 100\% = 67.5\%$$

d) Form factor,

$$\frac{I_{rms}}{I_{dc}} = \frac{35.36\,\text{mA}}{31.84\,\text{mA}} = 1.11$$

e) Ripple factor $= \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$

$$= \sqrt{(1.11^2) - 1} = 0.48$$

5. $$\%\,\text{Source Regulation} = \frac{V_{\max} - V_{\min}}{V_{nom}} \times 100$$

$$= \frac{10.02 - 9.97}{10} \times 100$$

$$= \frac{0.05}{10} \times 100 = 0.5\%$$

6 $$V_{ref} = V_Z = 5\text{ V}$$

Range of $\frac{R_1 + R_2}{R_1}\left(\text{i.e.}\,\frac{V_o}{V_{ref}}\right)$ is 1 to 2. So potential divider R_1, R_2 can be designed by using a potentiometer of 100 kΩ as shown in Fig. 12.22.

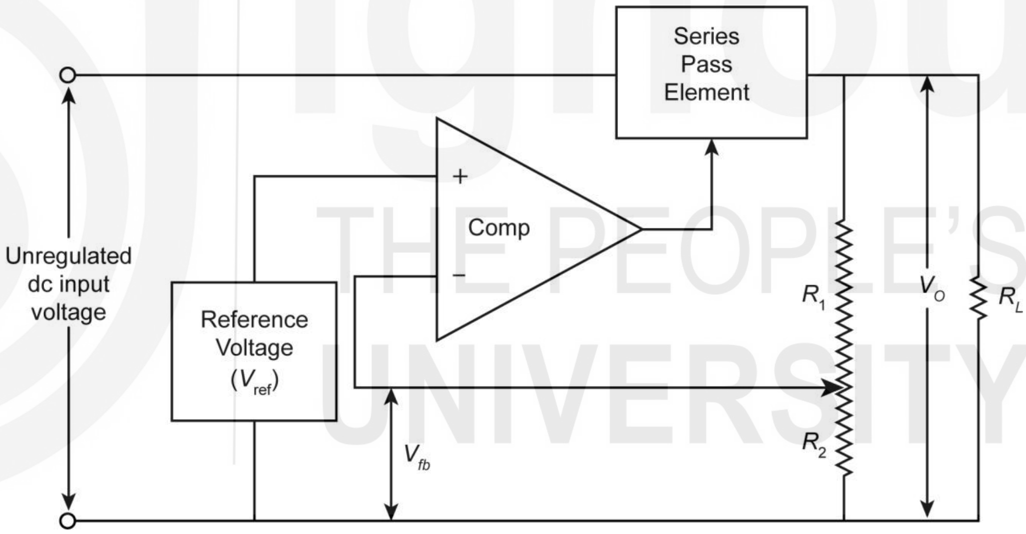


Fig. 12.22: **Variable dc supply**

Transistor emitter current ~ 100 mA for maximum load condition. With assumed current gain of 50, base current ≈ 2 mA. By changing the position of pointer on the potentiometer, ratio of R_1 and R_2 can be changed to obtain desired output voltage.

For $V_0 = 5\text{ V}$, the pointer is at the top of the potentiometer, so that, $R_1 = 0,$ and

$$V_0 = \frac{R_1 + R_2}{R_2} V_{ref} = \frac{0 + R_2}{R_2} \times 5\text{ V} = 5\text{ V}$$

For $V_0 = 10\text{ V}$, the pointer is kept in the middle of the potentiometer, so that $R_1 = R_2$ and

$$V_0 = \frac{R_1 + R_2}{R_2} V_{ref} = 2V_{ref} = 10\text{ V}$$