COURSE GUIDE

PHY 308
ELECTRONICS I

Course Team

Adebayo Adenrele Samuel (Course Writer)-
Independent Researcher
&
Dr. Ajibola Saheed O. NOUN
Dr. Ajibola S. O (Course Editing Team)-NOUN
Dr. Fayose FUTA, Mr. Adeola FUTA
Dr. Adeniran A. O (Course Reviewer)-UNIUYO

NATIONAL OPEN UNIVERSITY OF NIGERIA

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National Open University of Nigeria
Headquarters
University Village
Plot 91, Cadastral Zone,
Nnamdi Azikiwe Expressway
Jabi, Abuja

Lagos Office
14/16 Ahmadu Bello Way
Victoria Island, Lagos

e-mail: centralinfo@noun.edu.ng
URL: www.nouedu.net

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CONTENTS

INTRODUCTION

You would have become familiar with basic electronics concepts in the prerequisite to this course as you are encouraged to develop an enquiring attitude towards the electronics universe which abounds and with which you interact every single day.

It is the objectives of this course to build upon the lessons learnt in the prerequisite course, and formally to introduce to you the underlying principles of electronics, electronic components and circuits with the view to greater strengthening your understanding of the underlying concepts upon which developmental work and research in the electronics domain are based,

THE COURSE: PHY 308 Electronics I

This course comprises a total of eighteen Units distributed across four modules as follows:

Module 1 is composed of 5 Units
Module 2 is composed of 4 Units
Module 3 is composed of 5 Units
Module 4 is composed of 4 Units

In Module 1 which treats Amplifiers, Unit 1 will introduce to you the Classification of Amplifiers while unit 2 explains the Equivalent Circuits of Transistors. Unit 3 treats Hybrid Equivalent Model while Unit 4 deals with Operating Point. Finally in Module 1, Unit 5 dwells on the concepts and the practical application of bias stability

In Module 2 which treats Oscillators Unit 1 covers Negative Feedback while Unit 2 deals with Positive Feedback. Unit 3 explains the principles and the functioning of LC Oscillators while Unit 4 introduces RC Oscillators.
In Module 3 which treats Power supply Unit 1 will take you on a tour of Power Sources. Unit 2 treats in detail the subject of DC Power Units while unit 3 explains the Performance of Rectifiers. Units 4 and 5 respectively are dedicated to the subject of Filter Circuits, and the Regulation Of Output Voltage.
In Module 4 which treats Linear Integrated Circuits Unit 1 is devoted to the treatment of Operational Amplifiers commonly referred to as Op-Amps. Unit 2 reveals to you a few of the many applications of Operational Amplifiers while Unit 3 strives to explain the concepts behind amplification through the subject of Amplifiers – this is done in a simple and easily digestible manner. This course is concluded with Unit 4 of module 4 with the subject of Voltage Regulators.

COURSE AIMS AND OBJECTIVES

The aim of PHY 308 is to further intimate you with Amplifiers, Oscillators, Power supply and Linear Integrated Circuits - their parameters, characteristics and physical limitations. Further to acquaint you with the mathematical calculations and the practical approximations of the idealised theorems which lets you establish their practicable applications and indispensability in the real world.

You in turn shall be required to conscientiously and diligently work trough this course upon completion of which you should be able to:

- Define an Amplifier and understand the basic components of an Amplifier
- Know the basic classifications of an Amplifier.
- Understand the operations and the applications of the various classes of an Amplifier.
- Solve problems relating to the design of Amplifiers.
- Understand the operations of a Bipolar Junction Transistor (BJT).
- Analyze the BJT models and various configurations
- Familiarize with the hybrid parameters and equivalent circuits.
- Solve problems relating to transistor configurations
- Define the h-parameters
- Enumerate the various transistor hybrid equivalent models
- Deal with problems related to the hybrid equivalent models
- Identify the various operation points of a linear device (BJT) and the associated characteristics
- Know the four possible bias combinations of a BJT and their respective bias condition.
- Develop a level of familiarity with the BJT transistor that would permit a dc analysis of any system that might employ the BJT amplifier.
- Familiarize with the various bias circuits.
- Understand the concept of feedback and the types of feedbacks.
- Establish the implication of Negative feedback.
- Know the forms and advantages and disadvantage of negative feedback and its applications.
- Understand the concept of feedback.
- Establish the fact that positive feedback is a criterion for oscillation.
- Understand the Nyquist criterion.
- Understand the basic operations of an LC oscillator.
- Familiarize with the various types of oscillators that use the LC oscillatory circuit.
- Understand the basic operations of an RC oscillator.
- Familiarize with the various types of RC oscillators.
- Know the applications of RC network.
- Confirm that RC circuits are useful in the audio-frequency range
- Know what is meant by power supply.
- Know the major sources of power.
- Understand the environmental considerations of the sources of power.
- Know the various types of power supply.
- Distinguish between regulated power supply and unregulated power supply.
- Enumerate the 5 stages of a dc power supply unit.
- Understand and describe the rectifier circuits.
- Describe the output of each rectifier circuits

- Solve problems related to rectification of ac signal
- Understand the function of filter circuit in the dc supply unit.
- Know the various types of filter circuits.
- Solve related problems.
- Understand the function of Voltage regulators and the effect in a dc supply unit.
- Know the various types of voltage regulators.
- Know the application and forms of voltage regulators.
- Solve related problems
- Define and identify operational amplifiers.
- Understand the manipulations of the input of an operational amplifier to produce a desired output.
- Understand various connection modes of an operational amplifier
- Solve related problems
- Identify and familiarize with the various application of op-amp
- Solve related problems
- Know the various type of voltage regulator ICs and their respective functions.
- Know the connection modes with regard to the pins.
- Identify the voltage regulator IC series.

WORKING THROUGH THE COURSE

This course requires you to spend quality time to read. Whereas the content of this course is quite comprehensive, it is presented in clear language with lots of illustrations that you can easily relate to. The presentation style might appear rather qualitative and descriptive. This is deliberate and it is to ensure that your attention in the course content is sustained as a terser approach can easily "frighten" particularly when new concepts are being introduced.
You should take full advantage of the tutorial sessions because this is a veritable forum for you to "rub minds" with your peers – which provides you valuable feedback as you have the opportunity of comparing knowledge with your course mates.

COURSE MATERIAL

You will be provided course material prior to commencement of this course, which will comprise your Course Guide as well as your Study Units. You will receive a list of recommended textbooks which shall be an invaluable asset for your course material. These textbooks are however not compulsory.

STUDY UNITS

You will find listed below the study units which are contained in this course and you will observe that there are four modules. Each module comprises four Units each, except for module 4 which has two Units.

Module 1: Amplifiers

Unit 1 Classification of Amplifiers
Unit 2 Equivalent Circuits of Transistors
Unit 3 Hybrid Equivalent Model
Unit 4 Operating Point
Unit 5 Bias Stability

In Module 2: Oscillators

Unit 1 Negative Feedback
Unit 2 Positive Feedback
Unit 3 LC Oscillators
Unit 4 RC Oscillators.

Module 3 Power Supply

Unit 1 Power Sources
Unit 2 DC Power Units
Unit 3 Performance of Rectifiers
Unit 4 Filter Circuits

Module 4 Linear Integrated Circuits

Unit 1 Operational Amplifiers
Unit 2 Applications of Operational Amplifiers
Unit 3 Regulation of Output Voltage
Unit 4 Voltage Regulators
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TEXTBOOKS

There are more recent editions of some of the recommended textbooks and you are advised to consult the newer editions for your further reading.

A Textbook Of Electrical Technology 2010 By B.Ltheraja And A.K Theraja. Published by S.C Chand,

Electronic Devices and Circuit Theory 7th Edition 1999.

By Robert L. Boylestad, Published by Prentice-Hall Inc., Fundamentals Of Electric Circuits 4th Edition by Alexander And Sadiku Published By Mc Graw Hill

Semiconductor Device Fundamentals by Robert F. Pierret Published by Prentice Hill

Electrical Circuit Analysis by C. L. Wadhwa Published by New Age International

ASSESSMENT

Assessment of your performance is partly trough Tutor Marked Assessment which you can refer to as TMA, and partly through the End of Course Examinations.

TUTOR MARKED ASSIGNMENT

This is basically Continuous Assessment which accounts for 30% of your total score. During this course you will be given 4 Tutor Marked Assignments and you must answer three of them to qualify to sit for the end of year examinations. Tutor Marked Assignments are provided by your Course Facilitator and you must return the answered Tutor Marked Assignments back to your Course Facilitator within the stipulated period.

END OF COURSE EXAMINATION

You must sit for the End of Course Examination which accounts for 70% of your score upon completion of this course. You will be notified in advance of the date, time and the venue for the examinations which may, or may not coincide with National Open University of Nigeria semester examination.

SUMMARY

Each of the four modules of this course has been designed to stimulate your interest in Electronics through the subjects of Amplifiers, Oscillators, Power Supply and Linear Integrated Circuits which represent fundamental conceptual building blocks in the study and practical application of Electronics.

Module 1 **AMPLIFIERS**, tours you through the Classification of the various Amplifiers types and treats the equivalent models of transistors that serve as the building block. Operating point and stability are covered because of their practical significance in the real world where conceptual idealized devices reflect deviations from the ideal through thermal drift and non linear characteristics curves.

Module 2 **OSCILLATORS** is particularly relevant because of the high frequency of encounters with oscillators in everyday life. These oscillators generate oscillations which are either desirable or undesirable having for instance resulted from circuit instability. Negative feedback often is applied to suppress instability and control gain. LC oscillators are lossless oscillators and can either be series LC or parallel LC while RC oscillators are used to demonstrate that not all oscillators are realisable through lossless components alone.

Module 3 **POWER SUPPLY** finds significance in the fact that virtually all electronics circuitry depend on a power source – and these sources are either controlled voltage or controlled current sources. Direct Current Power Units are universally applied in everyday Electronics while in some cases; the DC supply is derived from Rectified AC voltage source. Filters are applicable to

DC Power sources derive from AC voltage while it is often desirable to regulate the output voltage of DC Power Sources.

Module 4 **LINEAR INTEGRATED CIRCUITS** represents the catalyst of contemporary electronics revolution through miniaturisation which has been largely responsible for the Communication revolution, the Information revolution and the Social revolution brought about by such technologies as the GSM, Computers and Satellite technologies.

Needless to emphasize that this course will change the way you see the world around you. My advise are - make sure that you have enough referential and study material available and at your disposal, and – devote sufficient time to your study.

I wish you the best of luck.

MAIN COURSE

CONTENTS

MODULE 1 AMPLIFIERS

UNIT 1 CLASSIFICATION OF AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

An amplifier receives a signal from some pickup transducer or other input source and provides a larger version of the signal to some output device or to another amplifier stage.

An input transducer signal is generally small (a few millivolts from a cassette or CD input, or a few microvolts from an antenna) and needs to be amplified sufficiently to operate an output device (speaker or other power-handling device). In small-signal amplifiers, the main factors are usually amplification linearity and magnitude of gain. Since signal voltage and current are small in a small-signal amplifier, the amount of power-handling capacity and power efficiency are of little concern. A voltage amplifier provides voltage amplification primarily to increase the voltage of the input signal. Large-signal or power amplifiers, on the other hand, primarily provide sufficient power to an output load to drive a speaker or other power device, typically a few watts to tens of watts. In "Electronics", signal amplifiers are widely used devices as they have the ability to amplify a relatively small input voltage signal, for example from a Sensor or microphone, into a much larger output signal to drive a Relay, lamp or loudspeaker for example. There are many forms of amplifiers, from Operational Amplifiers and Small Signal Amplifiers up to Large Signal and Power Amplifiers. Amplifiers can be thought of as a simple box or block containing the amplifying device, such as a Transistor, Field Effect Transistor or Op-amp, and which has two input terminals and two output terminals with the output signal being greater than that of the input signal, being "Amplified".

2.0 OBJECTIVES

Upon completion of this Module, you will be able to:

- Define an Amplifier and understand the basic components of an Amplifier
- Know the basic classifications of an Amplifier.
- Understand the operations and the applications of the various classes of an Amplifier.
- Solve problems relating to the design of Amplifiers.

3.0 MAIN CONTENT

3.1 WHAT IS AN AMPLIFIER

Generally, an amplifier or simply amp is any device that changes, usually increases, the amplitude of a signal.

An amplifier has three main properties, Input Resistance or (R_{in}), Output Resistance or (R_{out}) and of course Gain or(A). No matter how complicated an amplifier circuit is, a general amplifier model can be used to show the relationship of these three properties.

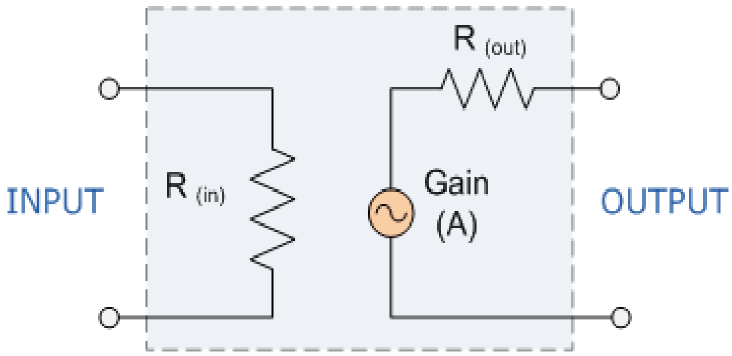

Figure 3.1: 'IDEAL' Amplifier Model

The relationship of the input to the output of an amplifier—usually expressed as a function of the input frequency—is called the transfer function of the amplifier, and the magnitude of the transfer function is termed the gain.

In popular use, the term usually describes an electronic amplifier, in which the input "signal" is usually a voltage or a current. In audio applications, amplifiers drive the loudspeakers used in PA systems to make the human voice louder or play recorded music.

3.1.1 Amplifier Gain

The gain of an amplifier is the ratio of output to input power or amplitude, and is usually measured in decibels. ($A(dB) = 10\log\frac{P_{out}}{P_{in}}$.)

Then the gain of an amplifier can be said to be the relationship that exists between the signals measured at the output with the signal measured at the input. There are three different kinds of Amplifier Gain(A), Voltage Gain (A_v), Current Gain (A_i) and Power Gain (A_p) and examples of these are given below.

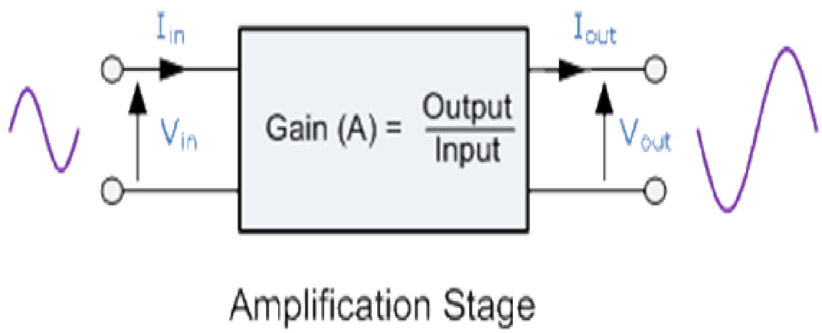

Figure 3.2: *Amplifier Gain of the Input Signal*

Voltage Amplifier Gain

Voltage gain Av= Output VoltageInput Voltage=VoutVin

Current Amplifier Gain

Current Gain Ai= Output CurrentInput Current= IoutIin

Power Amplifier Gain

Power Gain Ap= Av × Ai

Note that for the Power Gain you can also divide the power obtained at the output with the power obtained at the input. Also, the subscripts v, i and p denote the type of signal gain. To calculate the gain of the amplifier in Decibels or dB, we can use the following expressions.

- Voltage Gain in dB: $a_v = 20 \, log \, A_v$
- Current Gain in dB: $a_i = 20 \, log \, A_i$
- Power Gain in dB: $a_p = 10 \, log \, A_p$

Note that the DC power gain of an amplifier is equal to ten times the common log of the output to input ratio, whereas voltage and current gains are 20 times the common log of the ratio. Also, a positive value of dB represents a **Gain** and a negative value of dB represents a **Loss** within the amplifier. For example, an amplifier gain of $+3\,dB$ indicates that the output signal has "doubled", $(x2)$ while an amplifier gain of $-3\,dB$ indicates that the signal has "halved", $(x0.5)$ or in other words a loss.

Example

Determine the Voltage, Current and Power Gain of an amplifier that has an input signal of $1\ mA$ at $10\ mV$ and a corresponding output signal of $10\ mA$ at $1\ V$. Also, express all three gains in decibels, (dB).

Solution:

Av= Output VoltageInput Voltage= 10.01=100

Ai= Output CurrentInput Current= 101=10

$$A_p = A_v \times A_i = 100 \times 10 = 1{,}000$$

in Decibels (dB).

av = 20logAv= 20log100 = 40 dB

ai = 20logAi= 20log10 = 20 dB

ap = 10logAp= 10log1000 = 30 dB

Then the amplifier has a Voltage Gain of 100, a Current Gain of 10 and a Power Gain of $1{,}000$.

3.1.2 Amplifier Efficiency

Efficiency is a measure of how much of the power source is usefully applied to the amplifier's output. The efficiency of an amplifier refers to the ratio of output-signal power compared to the total input power. An amplifier has two input power sources: one from the signal, and one from the power supply. Since every device takes power to operate, an amplifier that operates for 360 degrees of the input signal uses more power than if operated for 180 degrees of the input signal. By using more power, an amplifier has less power available for the output signal; thus the efficiency of the amplifier is low. The perfect or ideal amplifier would give us an efficiency rating of 100% or at least the power IN is equal to the power OUT. However, this can never happen as some of its power is lost in the form of heat and also, the amplifier itself consumes power during the amplification process. Then the efficiency of an amplifier is given as:

Efficiencyη = power delivered to the load d.c. power taken from the supply=PoutPin

3.2 Classification of Amplifiers

Amplifiers may be classified according to the input (source) they are designed to amplify (such as a guitar amplifier, to perform with an electric guitar), the device they are intended to drive (such as a headphone amplifier), the frequency range of the signals (Audio, IF, RF, and VHF amplifiers, for example), whether they invert the signal (inverting amplifiers and non-inverting amplifiers), or the type of device used in the amplification (valve or tube amplifiers, FET amplifiers, etc.).

A related device that emphasizes conversion of signals of one type to another (for example, a light signal in photons to a DC signal in amperes) is a transducer, a transformer, or a sensor. However, none of these amplify power.

In the previous discussions, we assumed that for every portion of the input signal there was an output from the amplifier. This is not always the case with amplifiers. It may be desirable to have the transistor conducting for only a portion of the input signal. The portion of the input for which there is an output determines the class of operation of the amplifier. There are different classes of amplifier operations. They are class A, class AB, class B, class C and class D. However, by altering the position of the Base Bias voltage, it is possible to operate an amplifier in an amplification mode other than that for full waveform reproduction. By changing the amplifiers Base bias voltage different ranges or modes of operation can be obtained and these are classified according to their Class.

These different classes of operation range from a near linear output but with low efficiency to a non-linear output but with a high efficiency. There are typical maximum efficiencies for the various types or class of amplifier, with the most commonly used being:

- Class A - a maximum theoretical efficiency of less than 40%
- Class B - with a maximum theoretical efficiency of about 70%
- Class AB - which an efficiency rating between that of Class A and Class B

A brief description of amplifier classes is provided next.

Class A: The output signal varies for a full $360°$ of the cycle. Figure 3.3a shows that this requires the *Q*-point to be biased at a level so that at least half the signal swing of the output may vary up and down without going to a high enough voltage to be limited by the supply voltage level or too low to approach the lower supply level, or $0\ V$ in this description.

Class B: A class B circuit provides an output signal varying over one-half the input signal cycle, or for 180° of signal, as shown in Fig. 3.3b. The dc bias point for class B is therefore at 0 V, with the output then varying from this bias point for a half-cycle. Obviously, the output is not a faithful reproduction of the input if only one half-cycle is present. Two class B operations—one to provide output on the positive-output half-cycle and another to provide operation on the negative-output half-cycle—are necessary. The combined half-cycles then provide an output for a full $360°$ of operation. This type of connection is referred to as *push–pull operation*, which is discussed later in this chapter. Note that class B operation by itself creates a very distorted output signal since reproduction of the input takes place for only $180°$ of the output signal swing.

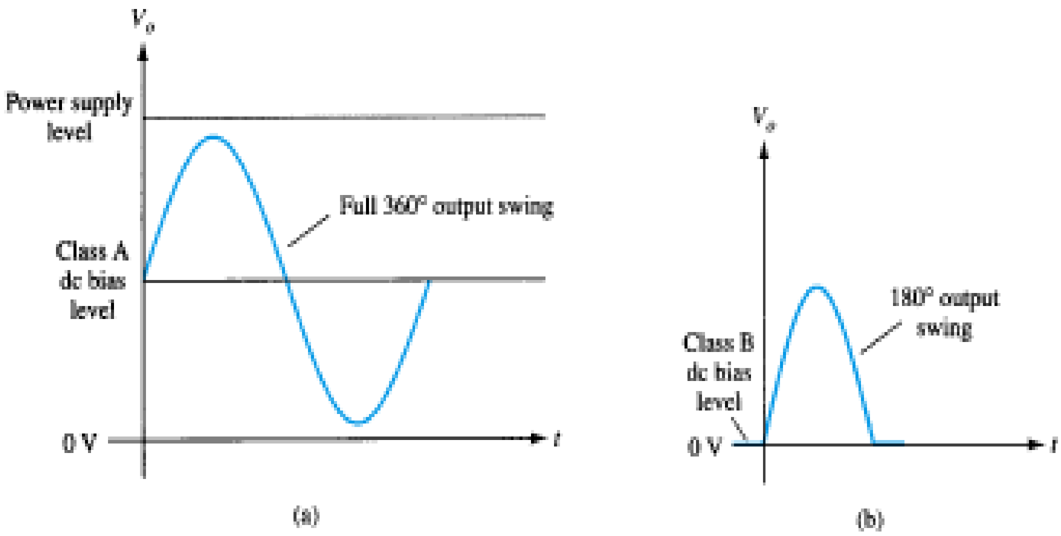

Figure 3.3:*Amplifier operating classes*

Class AB: An amplifier may be biased at a dc level above the zero-base-current level of class B and above one-half the supply voltage level of class A; this bias condition is class AB. Class AB operation still requires a push–pull connection to achieve a full output cycle, but the dc bias level is usually closer to the zero-base-current level for better power efficiency, as described shortly. For class AB operation, the output signal swing occurs between 180° and 360° and is neither class A nor class B operation.

Class C: The output of a class C amplifier is biased for operation at less than 180° of the cycle and will operate only with a tuned (resonant) circuit, which provides a full cycle of operation for the tuned or resonant frequency. This operating class is therefore used in special areas of tuned circuits, such as radio or communications.

Class D: This operating class is a form of amplifier operation using pulse (digital) signals, which are on for a short interval and off for a longer interval. Using digital techniques makes it possible to obtain a signal that varies over the full cycle (using sample-and-hold circuitry) to recreate the output from many pieces of input signal. The major advantage of class D operation is that the amplifier is "on" (using power) only for short intervals and the overall efficiency can practically be very high.

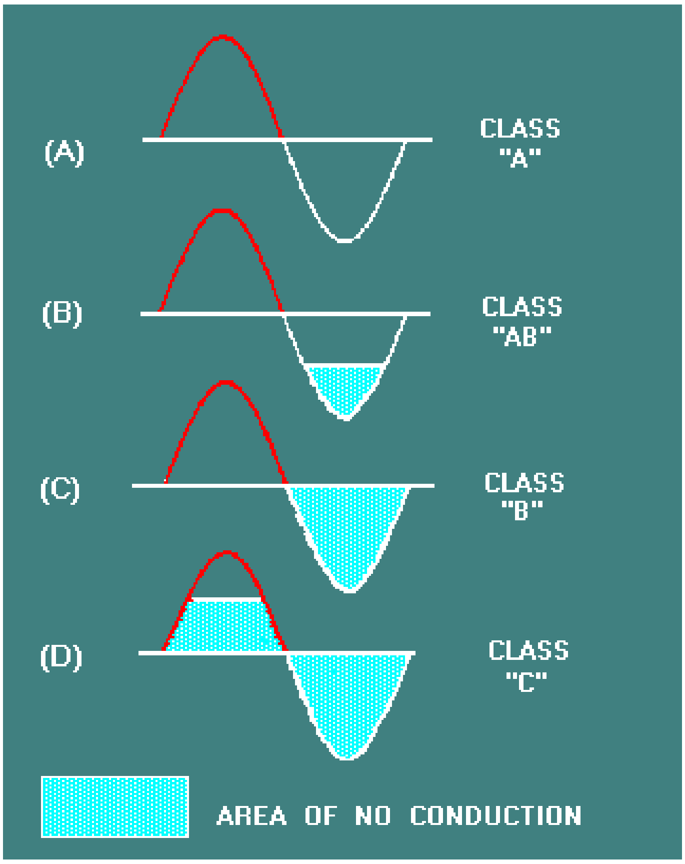

Figure 3.4: comparison of output signals for the different amplifier classes of operation.

3.2.1 Class a Amplifiers

Amplifying devices operating in Class A conduct over the whole of the input cycle such that the output signal is an exact scaled-up replica of the input with no clipping. A Class A amplifier (or operational amplifier) is distinguished by the output stage (and perhaps the driver) device(s) being biased into Class A; even Class AB and B amplifiers normally have early stages operating in Class A. Class A is the usual means of implementing small-signal amplifiers, so the term Class A design applied to equipment such as preamplifiers (for example, in recording studios) implies not so much their use of Class A, but that their sound is top quality - good enough to be matched with top quality Class A power amplifiers.

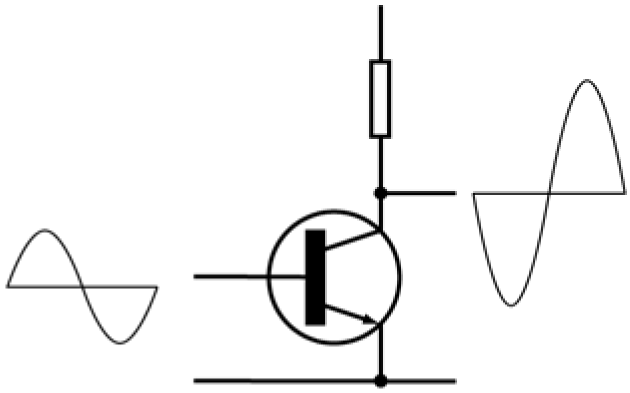

Figure 3.5: Class A amplifier

Class A Operation

Class A Amplifier operation is where the entire input signal waveform is faithfully reproduced at the amplifiers output as the transistor is perfectly biased within its active region, thereby never reaching either of its Cut-off or Saturation regions. This then results in the AC input signal being perfectly "centered" between the amplifiers upper and lower signal limits as shown below.

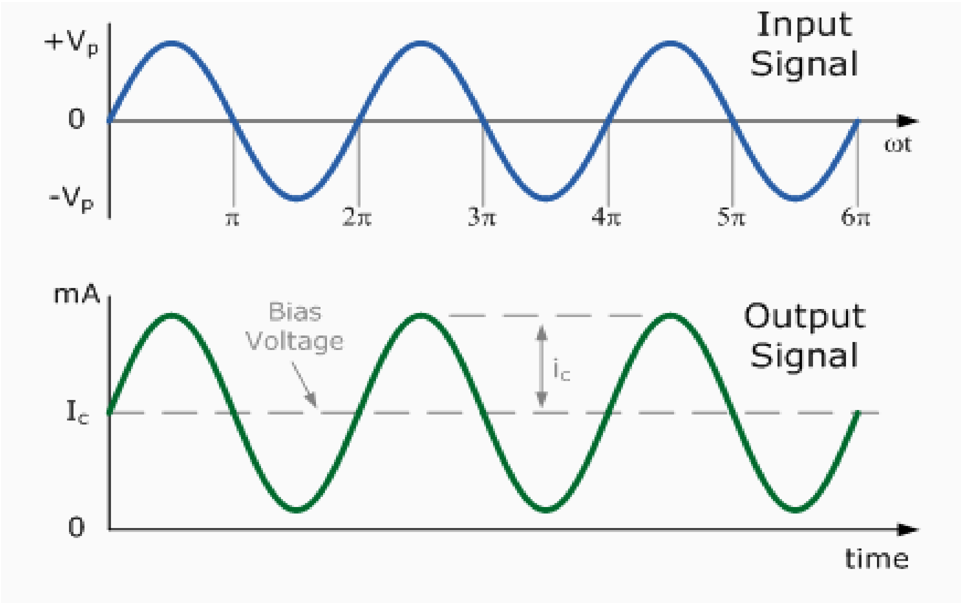

Fig 3.6 Class A Output Waveform

Here, the Class A amplifier uses the same transistor for both halves of the output waveform and due to its biasing arrangement always has current flowing through it, even if there is no input signal. In other words the output transistor never turns "OFF". This results in the class A type of operation being very inefficient as its conversion of the DC supply power to the AC signal power delivered to the load is usually very low. Generally, the output transistor of a Class A amplifier gets very hot even when there is no input signal present so some form of '*heat sinking*' is required. The DC current flowing through the output transistor (I_C) when there is no output signal will be equal to the current flowing through the load.

Advantages of Class a Amplifiers

Class A designs are simpler than other classes; for example Class AB and B designs require two devices (push-pull output) to handle both halves of the waveform, and circuitry to keep the quiescent bias optimal during temperature changes; Class A can use either single-ended or push-pull and bias is usually less critical.

The amplifying element is biased so the device is always conducting to some extent, normally implying the quiescent (small-signal) collector current (for transistors; drain current for FETs or anode/plate current for vacuum tubes) is close to the most linear portion (sometimes called the "sweet spot") of its characteristic curve (known as its transfer characteristic or trans conductance curve), giving the least audio distortion.

Because the device is never shut off completely there is no "turn on" time, little problem with charge storage, and generally better high frequency performance and feedback loop stability (and usually fewer high-order harmonics).

The point at which the device comes closest to being cut off (and so significant change in gain, hence non-linearity) is not close to zero signal, so the problem of crossover distortion associated with Class AB and B designs is avoided, even in Class A double-ended stages.

Disadvantage of Class A Amplifiers

They are very inefficient; a theoretical maximum of 50% is obtainable with inductive output coupling and only 25% with capacitive coupling, unless Square law output stages are used. In a power amplifier this not only wastes power and limits battery operation, it may place restrictions on the output devices that can be used (for example: ruling out some audio triodes if modern low-efficiency loudspeakers are to be used), and will increase costs. Inefficiency comes not just from the fact that the device is always conducting to some extent (that happens even with Class AB, yet its efficiency can be close to that of Class B); it is that the standing current is roughly half the maximum output current (although this can be less with Square law output stage), together with the problem that a large part of the power supply voltage is developed across the output device at low signal levels (as with Classes AB and B, but unlike output stages such as Class D). If high output powers are needed from a Class A circuit, the power waste (and the accompanying heat) will become significant. For every watt delivered to the load, the amplifier itself will, at best, dissipate another watt. For large powers this means very large and expensive power supplies and heat sinking.

Class A designs have largely been superseded by the more efficient designs for power amplifiers, though they remain popular with some hobbyists, mostly for their simplicity. Also, many audiophiles believe that Class A gives the best sound quality (for their absence of crossover distortion and reduced odd-harmonic and high-order harmonic distortion) which provides a small market for expensive high fidelity Class A amps.

3.2.1.1 Series-Fed Class a Amplifier

The simple fixed-bias circuit connection shown in figure 3.7 can be used to discuss the main features of a class A series-fed amplifier. This circuit is not the best to use as a large-signal amplifier because of its poor power efficiency. The beta of a power transistor is generally less than 100, the overall amplifier circuit using power transistor that are capable of handling large power or current while not providing much voltage gain.

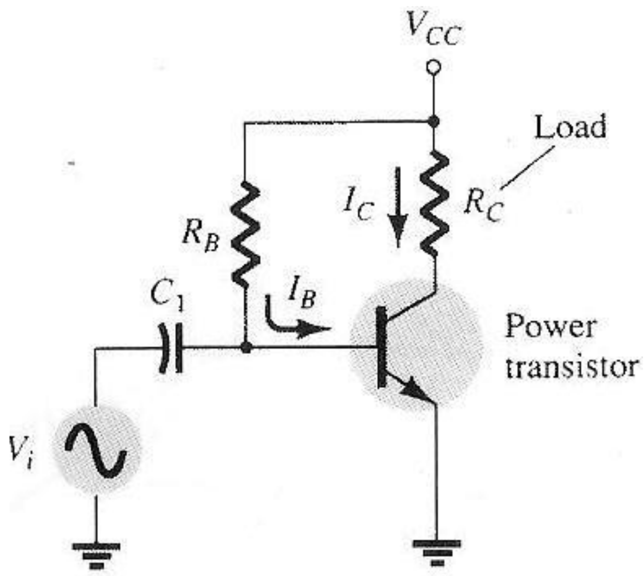

Figure 3.7 Series-fed class A large signal amplifier

DC Bias Operation

The dc bias set by V_{cc} and R_B fixes the dc base-bias current at

$$I_B = \frac{V_{CC} - 0.7V}{R_B}$$

With the collector current then being

$$I_C = \beta I_B V_{CC}$$

With the collector-emitter voltage then

$$V_{CE} = -I_C R_C$$

To appreciate the importance of the dc bias on the power amplifier, consider the collector characteristic shown in figure 3.8. An ac load is drawn using the values of V_{cc} and R_C. The intersection of the dc bias value of I_B with the dc load line then determines the operation point (Q-point) for the circuit. The quiescent-point values are those calculated using the above equations. If the dc bias collector current is set at one-half the possible signal swing (between 0 and V_{cc}/R_C), the largest collector current will be possible. Additionally, if the quiescent collector-emitter is set at one-half supply voltage, the largest voltage swing will be possible. With the Q-point set at this optimum bias point, the power considerations for the circuit of figure 3.7 are determined as described below.

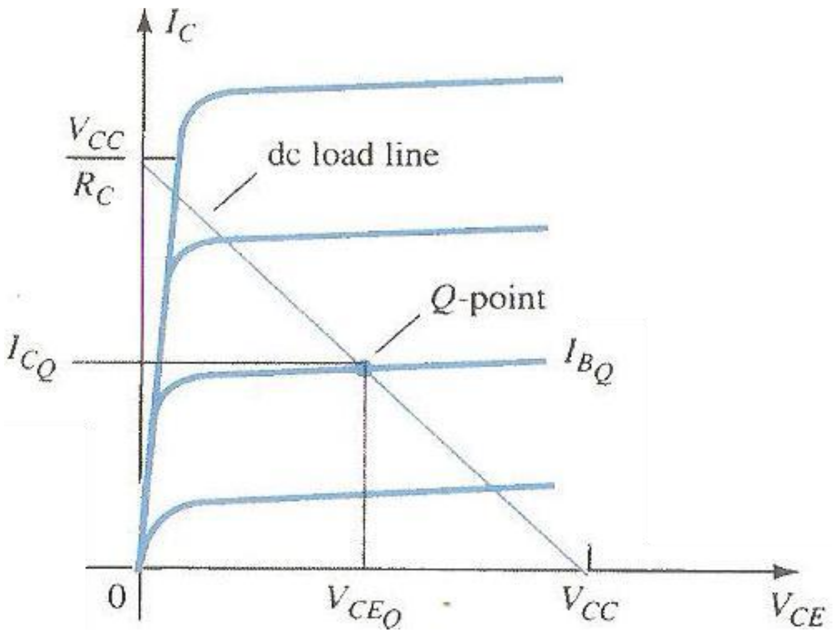

Figure 3.8 Transistor characteristics showing load line and Q-point.

AC Operation

When an output ac signal is applied to the amplifier of figuren3.7, the output will vary from its dc bias voltage and current, a small input signal, as shown in figure 3.9, will cause the best current to vary above and below the dc bias point, which will then cause the collector current (output) to vary from the dc bias point set as well as the collector-emitter voltage to vary around its dc bias value. As the input signal is made larger, the output will vary further around the established dc bias point until either the current or the voltage reaches a limiting condition. For the current this limiting condition is either at the low end or V_{CC}/R_C at the high end of its swing. For the collector-emitter voltage, the limit is either 0v or the supply voltage, V_{CC}

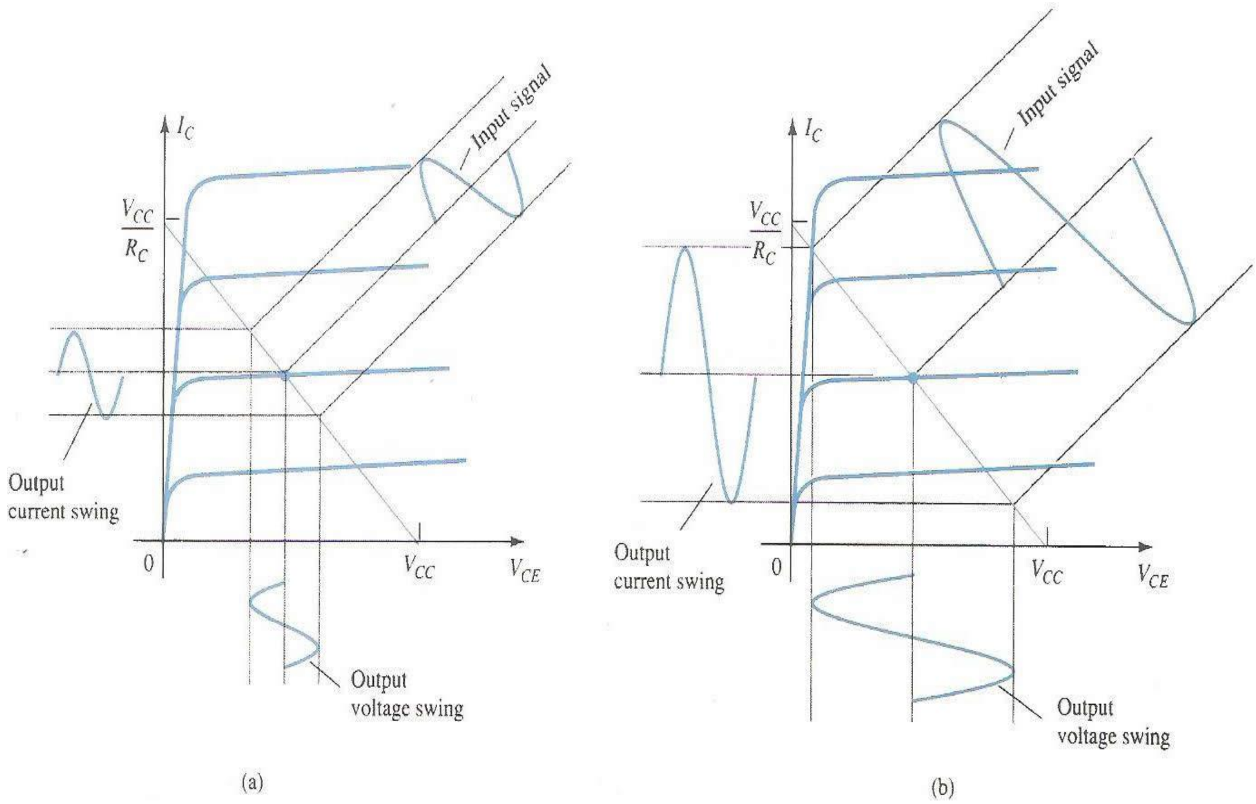

Figure 3.9 Amplifier input and output signal variation.

Power Considerations

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

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

Even with an ac signal applied, the average current drawn from the supply remains the same, so that the equation represents the input power supplied to the class A series-fed amplifier.

Output Power

The output voltage and current varying around the bias point provide ac power to the load. This as power is delivered to the load, R_C, in the circuit of figure 3.7. The ac signal,V_i, causes the base current to vary around the dc bias current and the collector current around its quiescent level, I_{QC}. As shown in fig 3.9, the ac input signal result in an ac current and ac voltage signals. The larger the input signal, the larger the output swing, up to the maximum set by the circuit. The ac power delivered to the load (R_C) can be expressed in a number of ways.

Using rms signals: The ac power delivered to the load (R_C) may be expressed using

$$P_o(ac) = V_{CE}(rms)I_C(rms)$$

$$P_o(ac) = I_C^2(rms)R_C$$

$$P_o(ac) = \frac{V_C^2(rms)}{R_C}$$

Using peak signals The ac power delivered to the load may be expressed using

$$P_o(ac) = \frac{V_{CE}(p)I_C(p)}{2}$$

$$P_o(ac) = \frac{I_C^2(p)}{2R_C}$$

$$P_o(ac) = \frac{V_{CE}^2(p)}{2R_C}$$

Using peak-to-peak signals: The ac power delivered to the load may be expressed using

$$P_o(ac) = \frac{V_{CE}(p\text{-}p)I_C(p\text{-}p)}{8}$$

$$P_o(ac) = \frac{I_C^2(p\text{-}p)}{8}R_C$$

$$P_o(ac) = \frac{V_{CE}^2(p\text{-}p)}{8}R_C$$

Efficiency

The efficiency of an amplifier represents the amount of ac power delivered (transferred) from the dc source. The efficiency of the amplifier is calculated using

$$\%\,\eta = \frac{P_o(ac)}{P_i(dc)} \times 100\%$$

3.2.1.2 The Transformer-Coupled Class a Amplifier

A form of class A amplifier having maximum efficiency of 50% uses a transformer to couple the output signal to the load as shown in Fig. 3.10. This is a simple circuit form to use in presenting a few basic concepts. The main reason for the poor efficiency of a direct-coupled class-A amplifier is the large amount of dc power that the resistive load in collector must dissipate. This problem can be solved by using a suitable transformer for coupling the load (say, a speaker) to the amplifier stage as shown in Fig. 3.10. Since the load is not directly connected to the collector terminal, the dc collector current does not pass through it. In an ideal transformer, primary winding resistance is zero. Hence, dc power loss in the load is zero. In practice, however, there is a small dc resistance of the primary winding which does absorb some power though much less than a direct-coupled load.

In short, what the transformer does is to substitute ac load in place of ohmic or dc load.

The secondary load R_L when referred to primary become

$$R_L' = R_L / K^2 = a^2 R_L$$

where $K = voltage\ transformation\ ratio = N_2 / N_1 = V_2 / V_1$

$a = turns\ ratio\ N_1/N_2 = 1/K$

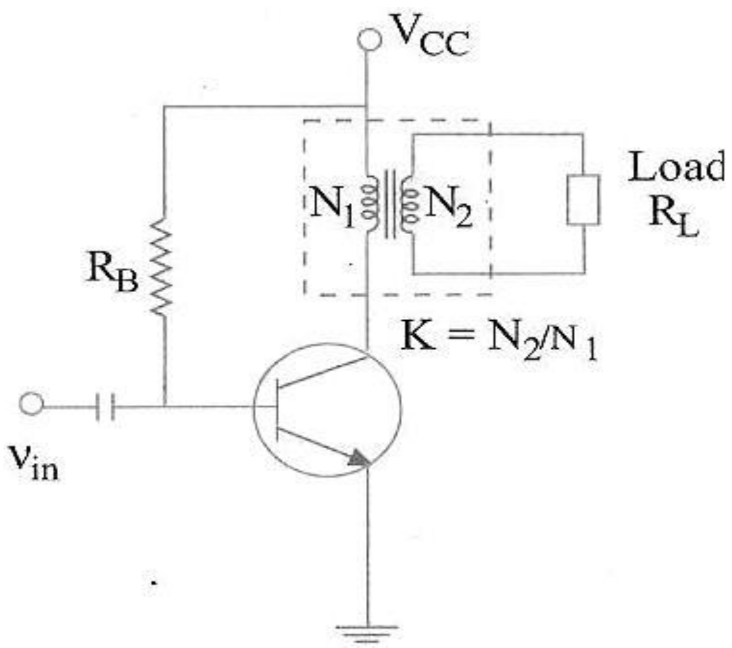

Fig 3.10

Since a is usually made much more than unity or K is much less than unity, R_L can be made to look much bigger than what it actually is.

In an ideal transformer, there is no primary drop, hence $V_{CC} = V_{CEQ}$. Now, all the power supplied by V_{CC} is delivered to the transistor. Hence, the overall and collector efficiencies become equal.

$$\eta_{overall} = \frac{P_{o(ac)}}{V_{CC} I_{CQ}} = \frac{P_{o(ac)}}{V_{CEQ} \cdot I_{CQ}}$$

3.2.2 Class B Amplifiers

Unlike the Class A amplifier above that uses a single transistor for its output stage, the **Class B Amplifier** uses two complimentary transistors (an NPN and a PNP) for each half of the output waveform. One transistor for the positive half of the waveform and another for the negative half of the waveform. This means that each transistor spends half of its time in the Active region and half its time in the Cut-off region. Class B operation has no DC bias voltage instead the transistor only conducts when the input signal is greater than the base-emitter voltage and for silicon devices is about $0.7\ V$. Therefore, at zero input there is zero output. This then results in only half the input signal being presented at the amplifiers output giving a greater efficiency as shown below.

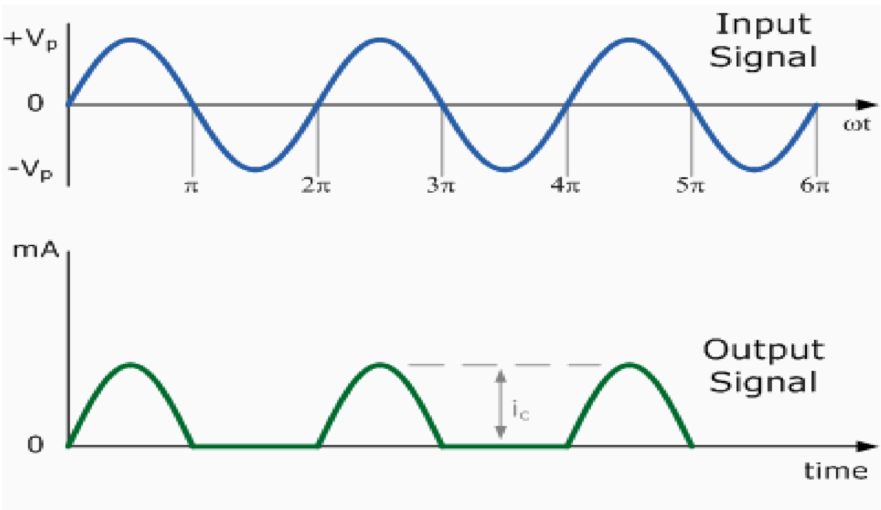

Fig3.11 Class B Output Waveform

As the output transistors for each half of the waveform, both positive and negative, requires a base-emitter voltage greater than the $0.7\ V$ required for the bipolar transistor to start conducting, the lower part of the output waveform which is below this $0.7\ V$ window will not be reproduced accurately resulting in a distorted area of the output waveform as one transistor turns "OFF" waiting for the other to turn back "ON". This type of distortion is called **Crossover Distortion** and is looked at later on in this section.

Class B Amplifier Operation

Class B operation is provided when the dc bias leaves the transistor biased just off, the transistor turning on when the ac signal is applied. This is essentially no bias, and the transistor conducts current for only one-half of the cycle. To obtain output full cycle of signal, it is necessary to use two transistors and have each conduct on opposite half-cycle, the combined operation providing a full cycle of output signal. Since one part of the circuit pushes the signal high during one half-cycle and the other part pulls the signal low during the other cycle, the circuit is referred to as a *push-pull circuit*. Fig 3.12 shows a diagram for push-pull operation. An ac input signal is applied to the push-pull circuit, with each half operating on alternate half-cycle, the load then receiving a signal for the full ac cycle. The power transistor used in the push-pull circuit are capable of delivering the desired power to the load, and the class B operation of these transistors provides greater efficiency than was possible using a single transistor in class A operation.

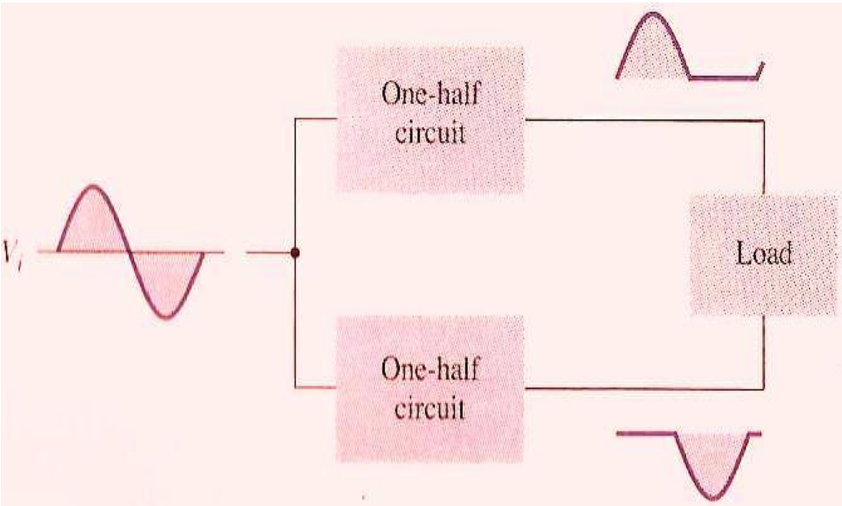

Fig 3.12 Block representation of push-pull operation.

Input (DC) Power

The power supplied to the load by an amplifier is drawn from the power supply (or power supplies; (see fig 3.13) that provides the input or dc power. The amount of this input power can be calculated using

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

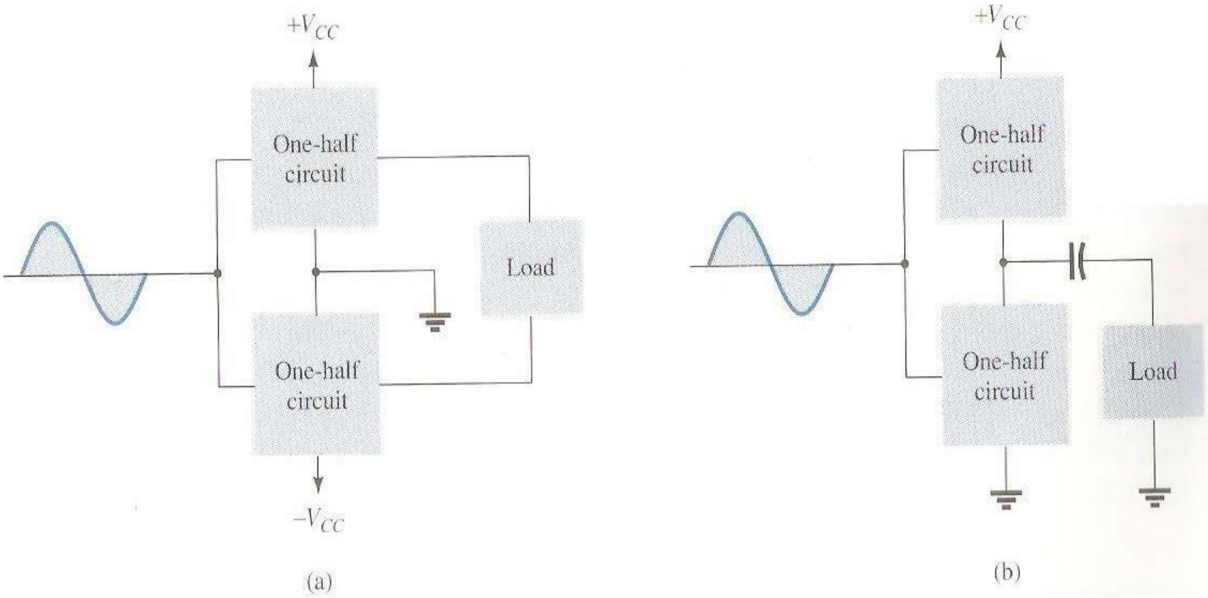

Fig 3.13 Connection of push-pull amplifier to load: (a) using two voltage supplies; (b) using one voltage supply.

where I_{dc} is the average or dc current drawn from the power supplies. In class B operation, the current drawn from a single power supply has the form of a full-wave rectified signal, while that drawn from two power supplies has the form of a half-wave rectified signal from each supply. In either case, the value of the average current drawn can be expressed as

$$I_{dc} = \frac{2}{\pi} I(p) \qquad \text{(ii)}$$

where $I(p)$ is the peak value of the output current waveform. Using Eq (ii) in the power input equation (Eq(i)) results in

$$P_i(dc) = V_{cc}\left(\frac{2}{\pi} I(p)\right) \qquad \text{(iii)}$$

Output (AC) Power

The power delivered to the load (usually referred to as a resistance, R_L) can be calculated using any one of a number of equations. If one is using an rms meter to measure the voltage across the load, the output power can be calculated as

$$P_o(ac) = \frac{V_L^2(rms)}{R_L}$$

$$P_o(ac) = \frac{V_L^2(p\text{-}p)}{8R_L} = \frac{V_L^2(p)}{2R_L}$$

If one is using an oscilloscope, the peak-to-peak, output voltage measured can be used

The larger the rms or peak output voltage, the larger the power delivered to the load.

Efficiency

The efficiency of the class B amplifier can be calculated using the basic equation:

$$\%\,\eta = \frac{P_o(ac)}{P_i(dc)} \times 100\%$$

Using Eq 16.19 and Eq 16.21 in the efficiency equation above results in

$$\%\,\eta = \frac{P_o(ac)}{P_i(ac)} \times 100\% = \frac{V_L^2(p)/2R_L}{V_{CC}[(2/\pi)I(p)]} \times 100\% = \frac{\pi}{4}\frac{V_L(p)}{V_{CC}} \text{(iv)}$$

(using $I_{(P)} = V_L(p)/R_L$). Equation (iv) shows that the larger the peak voltage, the higher the circuit efficiency, up to a maximum value when $V_L(p) = V_{CC}$, this maximum efficiency then being

$$maximum\ efficiency = \frac{\pi}{4} \times 100\% = 78.5\%$$

Power Dissipated by Output Transistors

The power dissipated (as heat) by the output power transistors is the difference between the input power delivered by the supplies and the output power delivered to the load.

$$P_{2Q} = P_i(dc) - P_o(ac)$$

whereP_{2Q} is the power dissipated by the two output power transistors. The dissipated power handled by each transistor is then

$$P_Q = \frac{P_{2Q}}{2}$$

3.2.2.1 Class B Amplifier Circuit

A number of circuit arrangements for obtaining class B operation are possible. We will consider the advantages and disadvantages of a number of the more popular circuits in this section. The input signals to the amplifier could be a single signal, the circuit then providing two different output stages, each operating for one-half the cycle. If the input is in the form of two opposite polarity signals, two similar stages could be used, each operating on the alternate cycle because of the input signal. One means of obtaining polarity or phase inversion is using a transformer, the transformer-coupled amplifier having being popular for a very long time. Opposite polarity inputs can easily be obtained using an op-amp having two opposite outputs or using a few op-amp stages to obtain two opposite polarity signals. An opposite polarity operation can also be achieved using a single input and complementary transistors (npn and pnp or $nMOS$and $pMOS$).

Figure 3.14 shows different ways to obtain phase-inverted signals from a single input signals. Fig 3.14a shows a center-tapped transformer to provide opposite phase signals. If the transformer is exactly center-tapped, the two signals are exactly opposite in phase and are of the same magnitude. The circuit of fig 3.14b uses a BJT stage with in-phase output from the emitter and opposite phase output from the collector. If the gain is made nearly 1 for each output, the same magnitude results. Probably most common would be using op-amp stages, one to provide an inverting gain of unity and the other a non-inverting gain of unity, to provide two outputs of the same magnitude but of opposite phase.

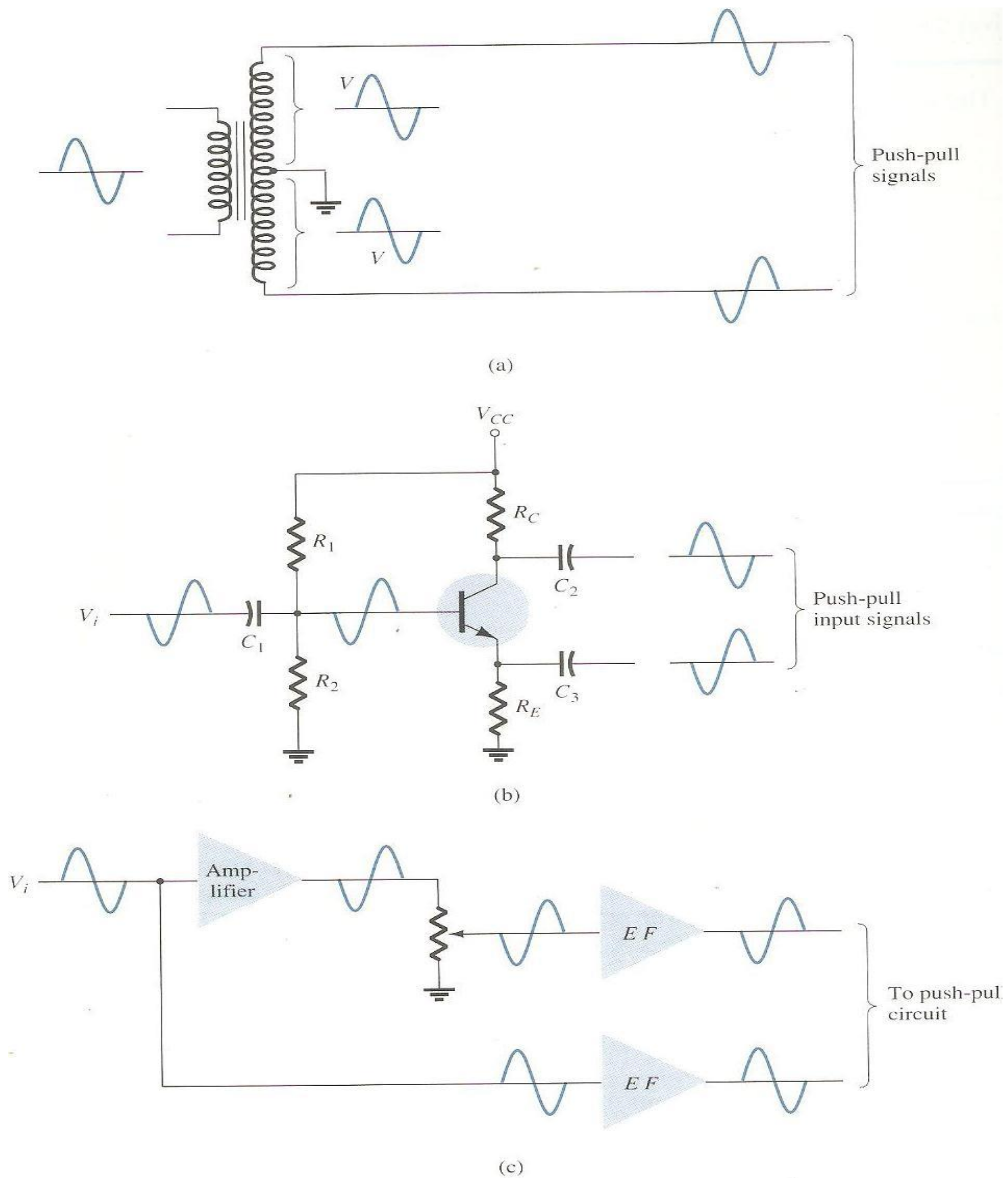

Fig 3.14 *Phase-splitter circuits*

3.2.3 Class AB Amplifiers

The **Class AB Amplifier** is a compromise between the Class A and the Class B configurations above. While Class AB operation still uses two complementary transistors in its output stage a very small biasing voltage is applied to the Base of the transistor to bias it close to the Cut-off region when no input signal is present. An input signal will cause the transistor to operate as normal in its Active region thereby eliminating any crossover distortion. A small Collector current will flow when there is no input signal but it is much less than that for the Class A amplifier configuration. This means then that the transistor will be "ON" for more than half a cycle of the waveform. This type of amplifier configuration improves both the efficiency and linearity of the amplifier circuit compared to Class A.

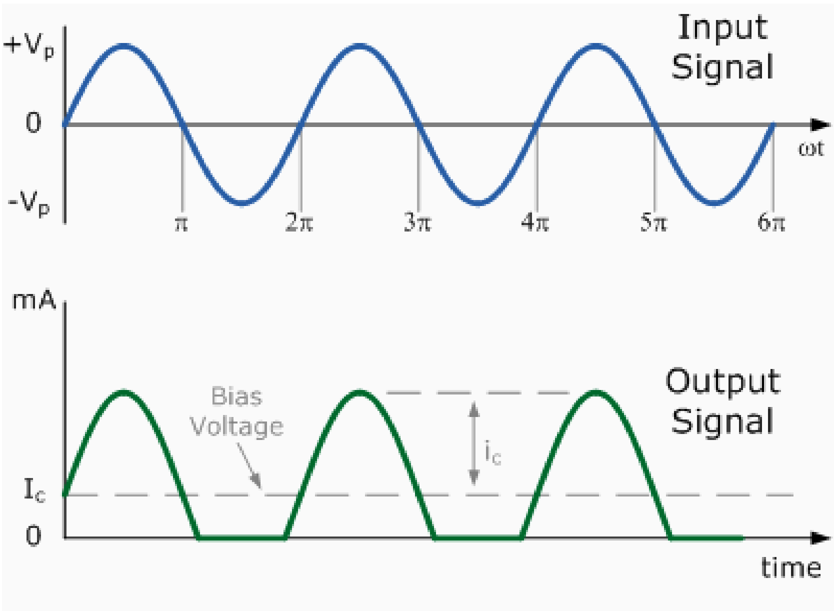

Fig3.15 Class AB Output Waveform

The class of operation for an amplifier is very important as it determines both the efficiency and the amount of power that the amplifier consumes and dissipates in the form of wasted heat, which may also require larger power transistors, more expensive heat sinks, cooling fans, or even an increase in the size of the power supply required to deliver the extra power required by the amplifier. Power converted into heat from transistors, resistors or any other component makes any electronic circuit inefficient and will result in premature failure of the device. So why use a Class A amplifier if its efficiency is less than 40% compared to a Class B amplifier that has a higher efficiency rating of nearly 70%. Basically, a Class A amplifier gives a more linear output meaning that it has, **Linearity** over a larger frequency response.

3.2.3.1 Transformer less Class AB Push-Pull Amplifier

We know that we need the base-emitter voltage to be greater than 0.7v for a silicon bipolar transistor to start conducting, so if we were to replace the two voltage divider biasing resistors connected to the base terminals of the transistors with two silicon **Diodes**, the biasing voltage applied to the transistors would now be equal to the forward voltage drop of the diode. These two diodes are generally called **Biasing Diodes** or **Compensating Diodes** and are chosen to match the characteristics of the matching transistors. The circuit below shows diode biasing.

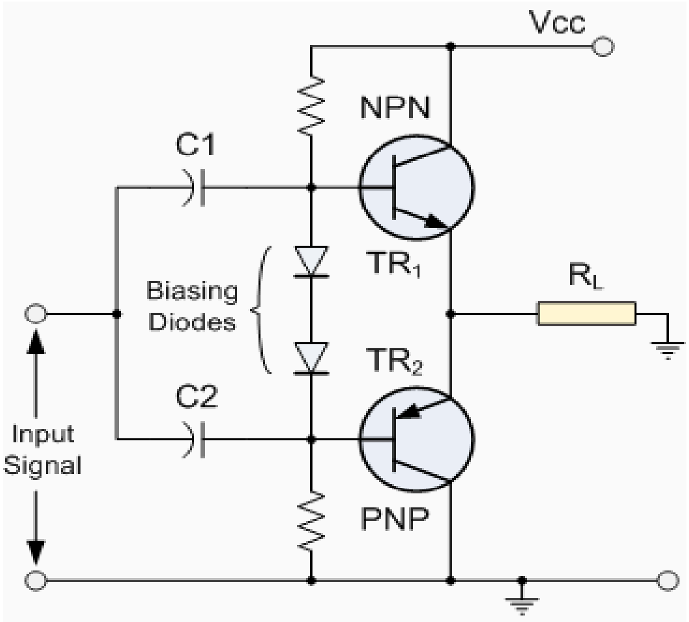

Fig3.16 Class AB Amplifier

The Class AB Amplifier circuit is a compromise between the Class A and the Class B configurations. This very small diode biasing voltage causes both transistors to slightly conduct even when no input signal is present. An input signal waveform will cause the transistors to operate as normal in their active region thereby eliminating any crossover distortion. A small collector current will flow when there is no input signal but it is much less than that for the Class A amplifier configuration. This means then that the transistor will be "ON" for more than half a cycle of the waveform but much less than a full cycle. The amount of diode biasing voltage present at the base terminal of the transistor can also be increased in multiples by adding additional diodes in series.

3.2.4 Crossover Distortion

We have seen that one of the main disadvantages of a Class A Amplifier is its low full power efficiency rating. But we also know that we can improve the amplifier and almost double its efficiency simply by changing the output stage of the amplifier to a Class B push-pull type configuration. However, this is great from an efficiency point of view, but most modern Class B amplifiers are transformer less or complementary types with two transistors in their output stage. This results in one main fundamental problem with push-pull amplifiers in that the two transistors do not combine together fully at the output both halves of the waveform due to their unique zero cut-off biasing arrangement. As this problem occurs when the signal changes or "crosses-over" from one transistor to the other at the zero voltage point it produces an amount of "distortion" to the output wave shape. This result in a condition that is commonly called **Crossover Distortion**.

Crossover Distortion produces a zero voltage "flat spot" or "dead band" on the output wave shape as it crosses over from one half of the waveform to the other. The reason for this is that the transition period when the transistors are switching over from one to the other, does not stop or start exactly at the zero crossover point thus causing a small delay between the first transistor turning "OFF" and the second transistor turning "ON". This delay results in both transistors being switched "OFF" at the same instant in time producing an output wave shape as shown below.

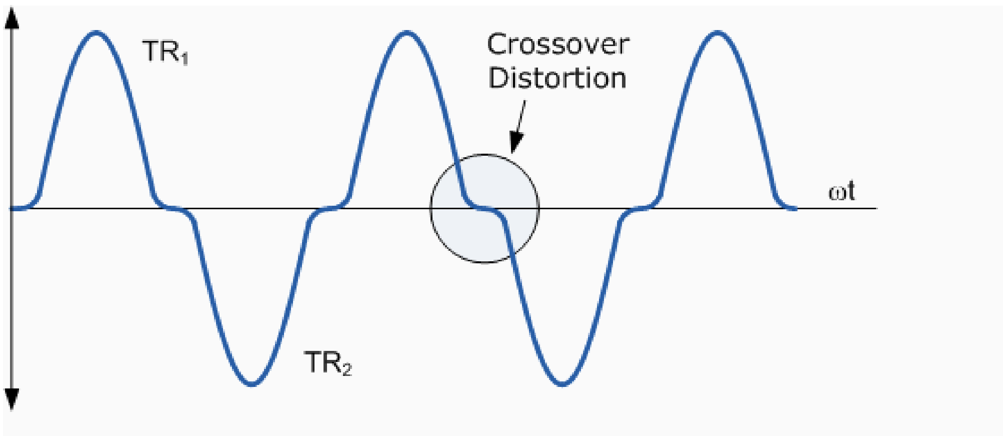

Fig3.17 Crossover Distortion Waveform

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

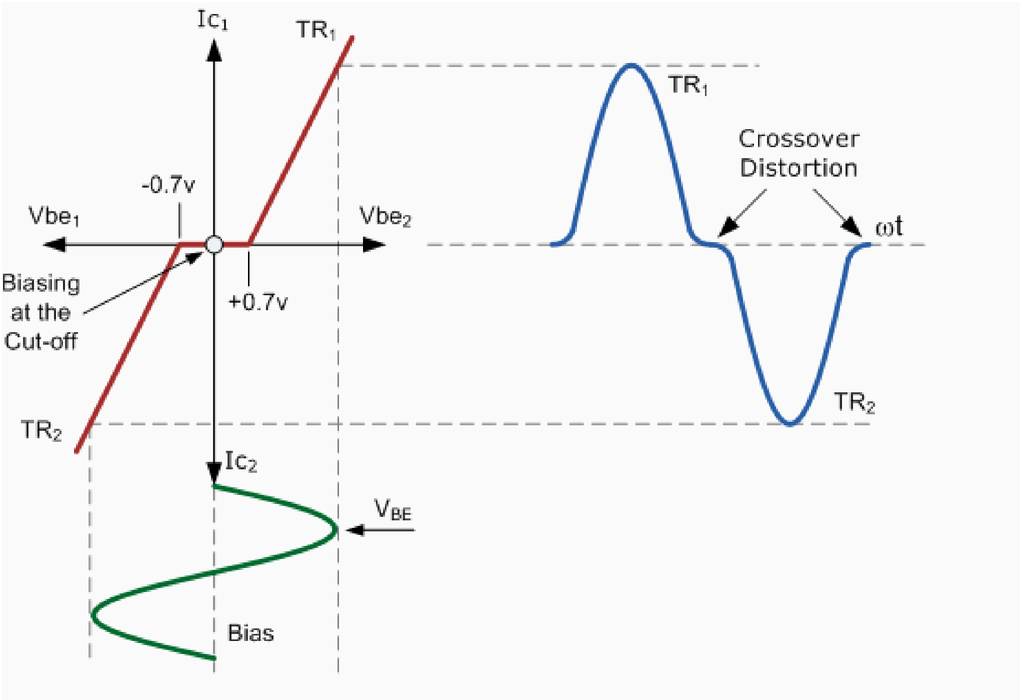

Fig 3.18 Non-Linear Transfer Characteristics

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

Pre-biasing the Output

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

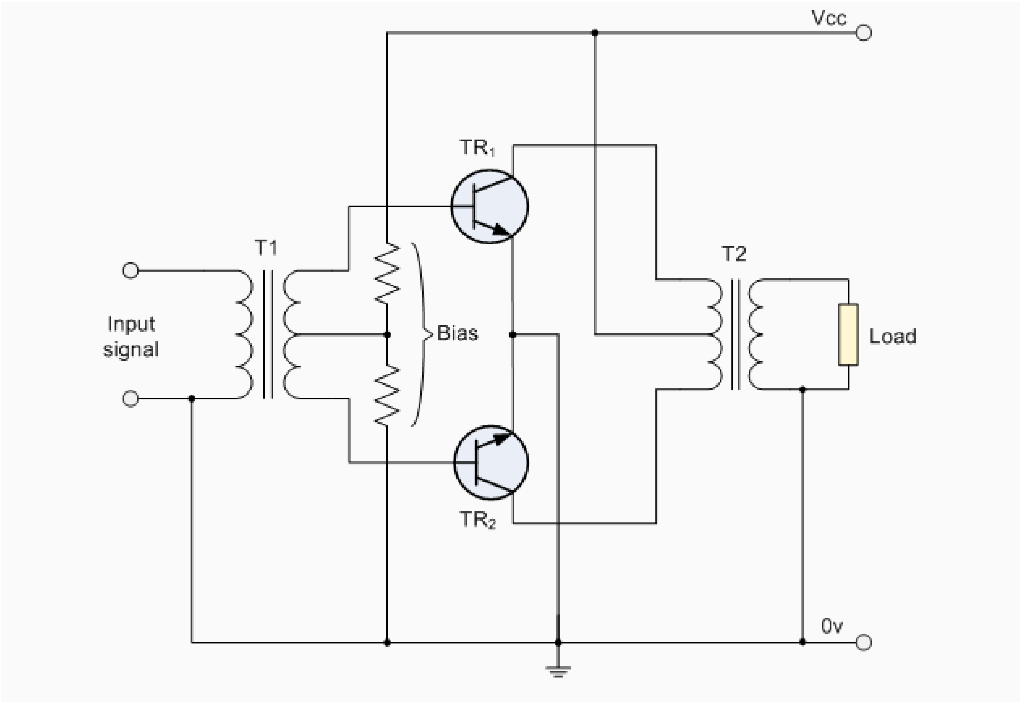

Fig3.19 Push-pull Amplifier with Pre-biasing

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

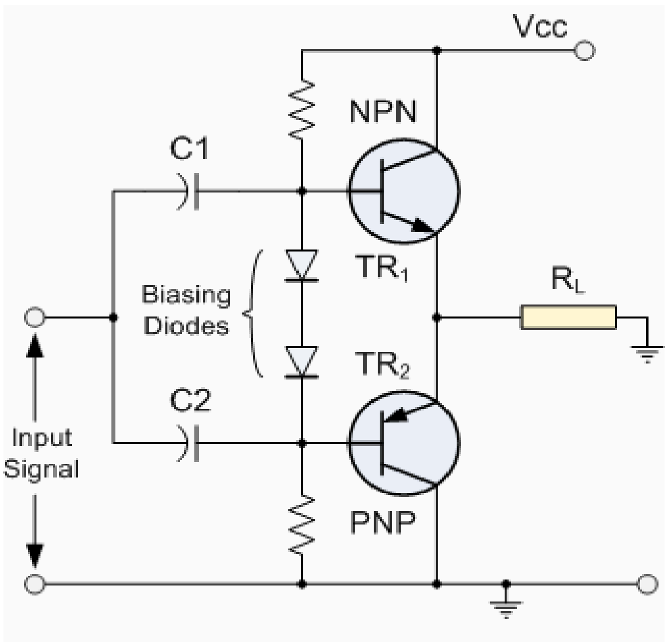

Fig3.20 Pre-biasing with Diodes

This pre-biasing voltage either for a transformer or transformer less amplifier circuit, has the effect of moving the amplifiers Q-point past the original cut-off point thus allowing each transistor to operate within its active region for slightly more than half or 180^o of each half cycle. In other words $180^0 +$ Bias. This then produces an amplifier circuit commonly called a **Class AB Amplifier** and its biasing arrangement is given below.

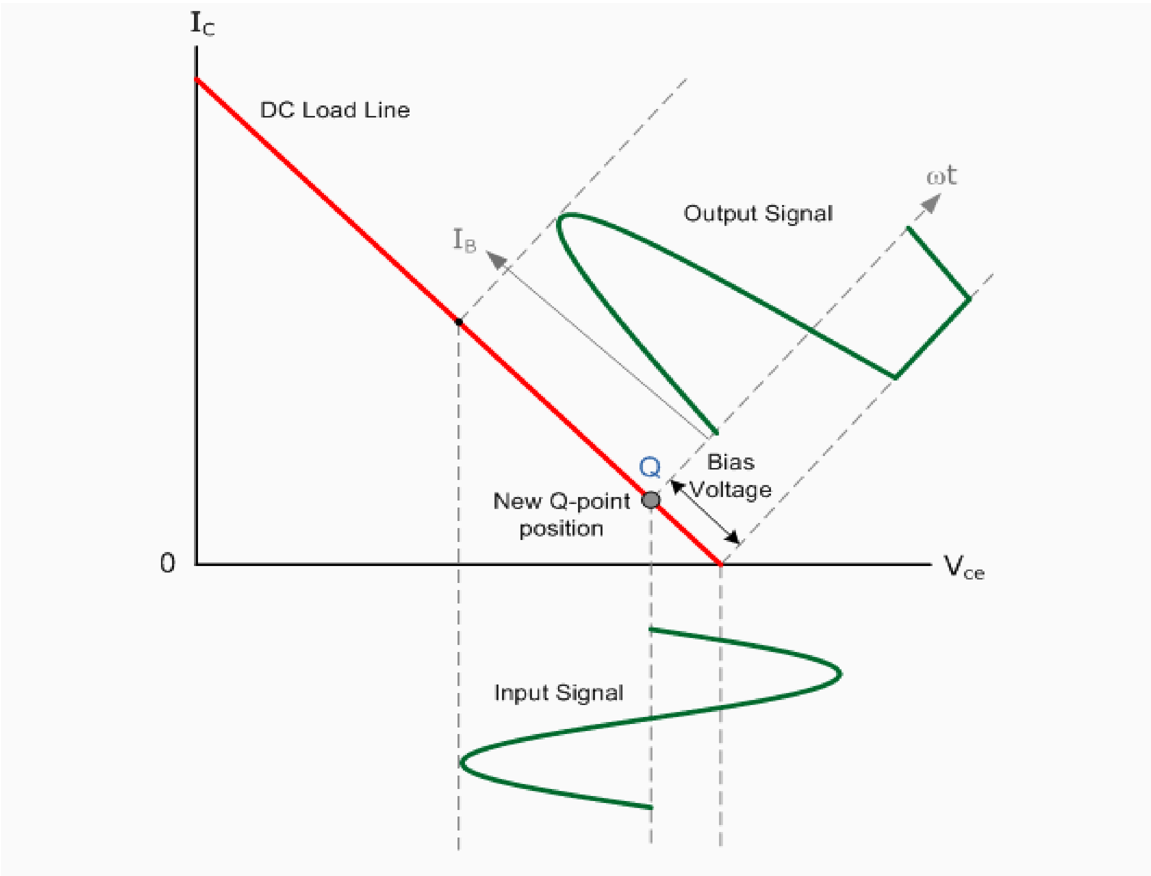

Fig 3.21Class AB Output Characteristics

Distortion Summary

Then to summarize, Crossover Distortion occurs in Class B amplifiers because the amplifier is biased at its cut-off point. This then results in BOTH transistors being switched "OFF" at the same instant in time. By applying a small base bias voltage either by using a resistive potential divider circuit or diode biasing this crossover distortion can be greatly reduced or even eliminated completely. The application of a biasing voltage produces another type or class of amplifier circuit commonly called a Class AB Amplifier. Then the difference between a pure Class B amplifier and an improved Class AB amplifier is in the biasing level applied to the output transistors. Therefore, we can say that Class AB amplifier is a Class B amplifier with Bias and we can summarize as:

- Class A Amplifiers have no Crossover Distortion as they are biased in the center of the load line.
- Class B Amplifiers have large amounts of Crossover Distortion due to biasing at the cut-off point.

Class AB Amplifiers may have some Crossover Distortion if the biasing level is too low.

Class C And Class D Amplifiers

Although class A, class B and class AB amplifiers are the most used as power amplifiers, class D amplifiers are popular because of their very high efficiency. Class C amplifiers, while not used as audio amplifiers; do find use in tuned circuits as used in communications.

3.2.5 Class C Amplifier

A class C amplifier, as that shown in figure 3.22, is biased to operate for less than 180^0 of the input signal cycle. The tuned circuit in the output, however, will provide a full cycle of output signal for the fundamental or resonant frequency of the tuned circuit (L and C tank circuit) of the output. This type of operation is therefore limited to use at one fixed frequency, as occurs in a communications circuit, for example. Operation of a class C circuit is not intended primarily for large-signal or power amplifiers.

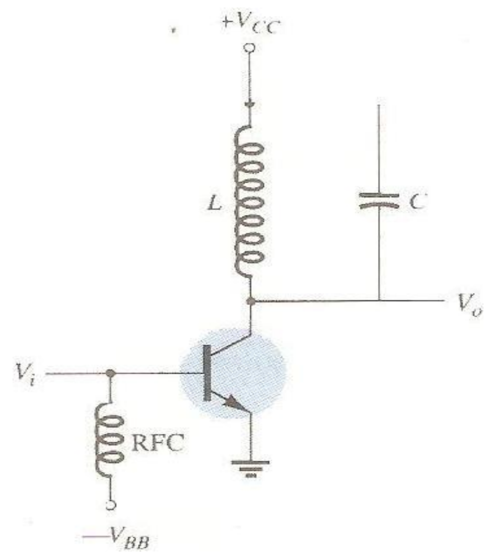

Fig 3.22 Class C amplifier circuit.

3.2.6 Class D Amplifier

A class D amplifier is designed to operate with digital or pulse-type signals. An efficiency of over 90% is achieved using this type of circuit, making it quite desirable in power amplifiers. It is necessary , however, to convert any input signal to a pulse-type waveform before using it to drive a large power load and convert the signal back to a sinusoidal-type signal to recover the original signal. While the letter D is used to describe the next type of bias operation after class C, the D could also be considered to stand for “Digital”, since that is the nature of the signal provided to the class D amplifier.

Fig 3.23 shows a block diagram of the unit needed to amplify the class D signal and then convert back to the sinusoidal-type signal using a low-pass filter.

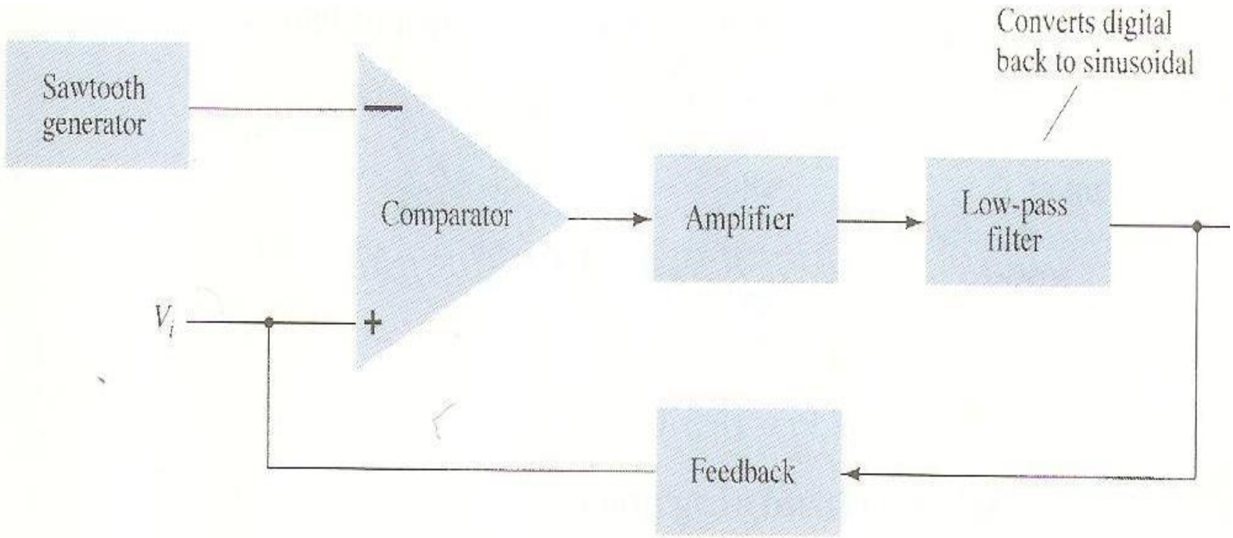

Fig 3.23 Block diagram of class D amplifier.

Since the amplifier’s transistor devices used to provide the output are basically either off or on, they provide current only when they are turned on, with little power loss due to their low on-voltage. Since most of the power applied to the amplifier is transferred to the load, the efficiency of the circuit is typically very high. Power MOSFET devices have been quite popular as the driver devices for the class D amplifier.

3.3 Test

Question 1 *calculate the input power, output power, and the efficiency of the amplifier circuit in figure 2.24 for an input voltage that results in a base current of 10mA peak.*

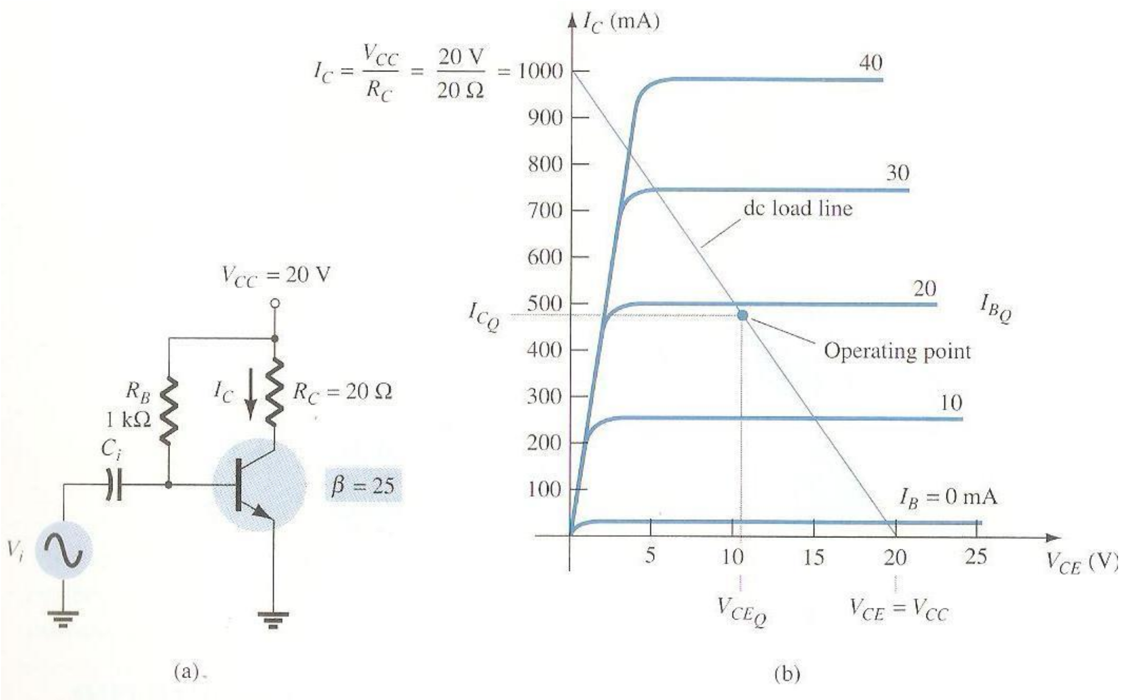

Figure 3.24

Solution

Using Eq 16.1 through 16.3, the Q-point can be determined to be

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

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

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

The bias point is marked on the transistor collector characteristic of fig 16,5b. The ac variation of the output signal can be obtained graphically using the dc load line drawn on fig 16,5b by connecting $V_{CE} = V_{CC} = 20\ V$ with$I_C = V_{CC}/R_C = 1000\ mA = 1\ A$, as shown. When the output ac base current increases from its dc bias level, the collector current rises by

$$I_C(p) = \beta I_B(p) = 25(10\ mA\ peak) = 250\ mA\ peak$$

Therefore;

$$P_o(ac) = \frac{I_C^2(p)}{2} R_C = \frac{(250 \times 10^{-3}\ A)^2}{2}(20\ \Omega) = \mathbf{0.625\ W}$$

And;

$$P_i(dc) = V_{CC} I_{CQ} = (20\ V)(0.48\ A) = \mathbf{9.6\ W}$$

Hence;

$$\% \eta = \frac{P_o(ac)}{P_i(ac)} \times 100\% = \frac{0.625\ W}{9.6\ W} \times 100\% = \mathbf{6.5\%}$$

Question 2 *For a Class B amplifier providing a* $20\ V$ *peak signal to a* $16\ \Omega$ *(speaker) and a power supply of* $V_{CC} = 30\ V$, *determine the input power, output power and circuit efficiency.*

Solution

A 20- V peak signal across a 16Ω load provides a peak load current of

$$I_L(p) = \frac{V_L(p)}{R_L} = \frac{20\ V}{16\ \Omega} = 1.25\ A$$

The dc value of the current drawn from the power supply is then

$$I_{dc} = \frac{2}{\pi} I_L(p) = \frac{2}{\pi}(1.25\ A) = 0.796\ A$$

And the input delivered by the supply voltage is

$$P_i(dc) = V_{CC} I_{dc} = (30\ V)(0.796\ A) = \mathbf{23.9\ W}$$

The output power delivered to the load is

$$P_o(ac) = \frac{V_L^2(p)}{2R_L} = \frac{(20\ V)^2}{2(16\ \Omega)} = \mathbf{12.5\ W}$$

For a resulting efficiency of

$$\% \eta = \frac{P_o(ac)}{P_i(dc)} \times 100\% = \frac{12.5\ W}{23.9\ W} \times 100\% = \mathbf{52.3\ \%}$$

Question 3

(a) *The optimum load resistance for a certain transistor is 200 Ω. What is the turns ratio* (N_1/N_2) *of a transformer required to couple an 8-Ω loud-speaker to the transistor?*

(b) *In a transformer-coupled class-A amplifier* $V_{CE(max)} = 27\ V$ *and* $V_{CE(min)} = 3V$.

Compute its overall efficiency.

Solution

(a) $R_L' = a^2 R_L \therefore 200 = a^2 \times 8 \quad or \quad a = 5$

Hence, it should be a5: 1 step-down transformer.

(b) $\eta_{overall} = 50\left(\frac{27-3}{27+3}\right)^2 = 32\%$

4.0 CONCLUSION

In this unit, you have been introduced to the basic operations of Amplifier and its major classes which include: Class A, Class B, Class AB, Class C and Class D. Also, the different design circuits were treated with enough details covered.

5.0 SUMMARY

Small Signal Amplifiers

- Small Signal Amplifiers are also known as **Voltage Amplifiers**.
- Voltage Amplifiers have 3 main properties, **Input Resistance**, **Output Resistance** and **Gain**.
- The Gain of a small signal amplifier is the amount by which the amplifier "Amplifies" the input signal.
- Gain is a ratio of input divided by output, therefore it has no units but is given the symbol (A) with the most common types being, **Voltage Gain (Av), Current Gain (Ai)** and **Power Gain (Ap)**
- The power Gain of the amplifier can also be expressed in **Decibels** or simply **dB**.
- In order to amplify all of the input signal distortion free in a Class A type amplifier, DC Base Biasing is required.
- DC Bias sets the Q-point of the amplifier half way along the load line.
- This DC Base biasing means that the amplifier consumes power even if there is no input signal present.
- The transistor amplifier is non-linear and an incorrect bias setting will produce large amounts of distortion to the output waveform.
- Too large an input signal will produce large amounts of distortion due to clipping, which is also a form of amplitude distortion.
- Incorrect positioning of the Q-point on the load line will produce either **Saturation Clipping** or **Cut-off Clipping**.

- The **Common Emitter Amplifier** configuration is the most common form of all the general purpose voltage amplifier circuits.

Large Signal Amplifiers

- Large Signal Amplifiers are also known as **Power Amplifiers**.
- Power Amplifiers can be sub-divided into different Classes, for example **Class A Amplifiers**, where the output device conducts for all of the input cycle, **Class B Amplifiers,** where the output device conducts for only 50% of the input cycle and **Class AB Amplifiers**, where the output device conducts for more than 50% but less than 100% of the input cycle.
- An ideal Power Amplifier would deliver 100% of the available DC power to the load.
- Class A amplifiers are the most common form of power amplifier but only have an efficiency rating of less than 40%.
- Class B amplifiers are more efficient than Class A amplifiers at around 70% but produce high amounts of distortion.
- Class B amplifiers consume very little power when there is no input signal present.
- By using the "Push-pull" output stage configuration, distortion can be greatly reduced.
- However, simple push-pull Class B Power amplifiers can produce high levels of **Crossover Distortion** due to their cut-off point biasing.
- Pre-biasing resistors or diodes will help eliminate this crossover distortion.

Class B Power Amplifiers can be made using Transformers or Complementary Transistors in its output stage.

6.0 TUTOR MARKED ASSIGNMENTS

1(a) Calculate the input power for the circuit of fig 3.25 the input signal results in a base current of 5 mA rms.

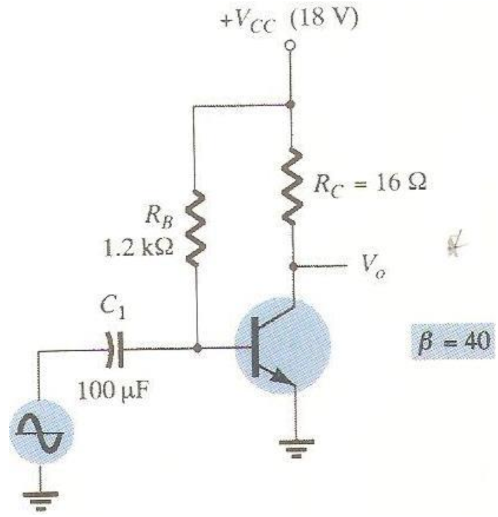

Fig 3.25

(b) What maximum output power can be delivered by the circuit of fig 3.25 if R_B is changed to 1.5 kΩ

2. What turns ratio transformers needed to couple to an 8-Ω load so that it appears as an 8-kΩ effective load.

3. For a class B amplifier providing a 22-V peak signal to an 8-Ω load and a power supply of V_{CC}= 25 V, determine

(a) Input power

(b) Output power

(c) Circuit efficiency

4. Draw the circuit diagram of a class A transformer-coupled amplifier using an npn transistor.

5. An amplifier has an input signal of 16 V peak-to-peak and an input impedance of 320 K. It gives an output voltage of 8 V peak-to-peak across a load resistor of 4 W. Calculate the dB power gain of the amplifier.

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UNIT 2 EQUIVALENT CIRCUITS OF TRANSISTORS

CONTENTS

1.0 INTRODUCTION

The first solid-state device discussed was the two-element semiconductor diode. The next device on our list is even more unique. It not only has one more element than the diode but it can amplify as well. Semiconductor devices that have-three or more elements are called TRANSISTORS. The term transistor was derived from the words TRANSfer and resISTOR. This term was adopted because it best describes the operation of the transistor - the transfer of an input signal current from a low-resistance circuit to a high- resistance circuit. Basically, the transistor is a solid-state device that amplifies by controlling the flow of current carriers through its semiconductor materials. There are many different types of transistors, but their basic theory of operation is all the same. As a matter of fact, the theory we will be using to explain the operation of a transistor is the same theory used earlier with the PN-junction diode except that now two such junctions are required to form the three elements of a transistor.

Diodes are made up from two pieces of semiconductor material, either Silicon or Germanium to form a simple PN-junction. If we now join together two individual diodes end to end giving two PN-junctions connected together in series, we now have a three layer, two junctions, three terminal device forming the basis of a Bipolar Junction Transistor, or BJT for short. This type of transistor is generally known as a Bipolar Transistor, because its basic construction consists of two PN-junctions with each terminal or connection being given a name to identify it and these are known as the Emitter, Base and Collector respectively.

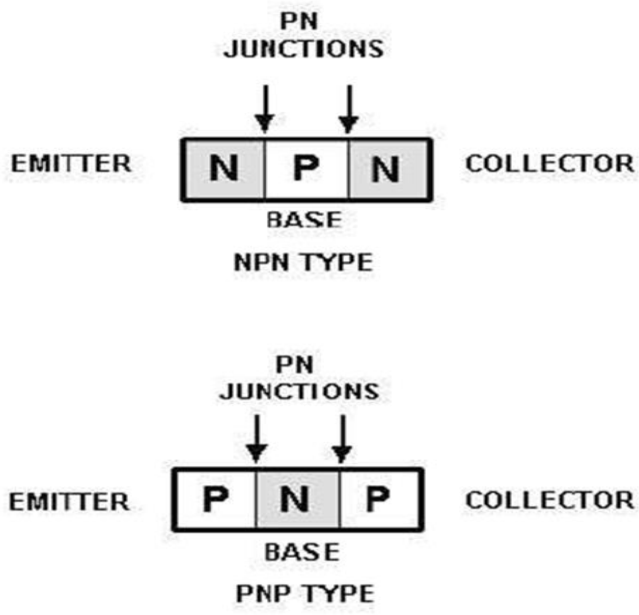


Fig 1.1

2.0 OBJECTIVES

After going through this unit, you should be able to:

- Understand the operations of a Bipolar Junction Transistor (BJT).
- Analyze the BJT models and various configurations
- Familiarize with the hybrid parameters and equivalent circuits.
- Solve problems relating to transistor configurations

3.0 MAIN CONTENT

3.1 Bipolar Junction Transistor (BJT)

The three elements of the two-junction transistor are:

(1) The EMITTER, which gives off, or emits," current carriers (electrons or holes);

(2) The BASE, which controls the flow of current carriers; and

(3) The COLLECTOR, which collects the current carriers.

Transistors are classified as either NPN or PNP according to the arrangement of their N and P materials. Their basic construction and chemical treatment is implied by their names, "NPN" or "PNP." That is, an NPN transistor is formed by introducing a thin region of P-type material between two regions of N-type material. On the other hand, a PNP transistor is formed by introducing a thin region of N-type material between two regions of P-type material. Transistors constructed in this manner have two PN junctions, one PN junction is between the emitter and the base; the other PN junction is between the collector and the base. The two junctions share one section of semiconductor material so that the transistor actually consists of three elements. Since the majority and minority current carriers are different for N and P materials, it stands to reason that the internal operation of the NPN and PNP transistors will also be different. The theory of operation of the NPN and PNP transistors will be discussed separately in the next few paragraphs.

To prepare you for the forthcoming information, the two basic types of transistors along with their circuit symbols are shown in figure 3.1. It should be noted that the two symbols are different. The horizontal line represents the base, the angular line with the arrow on it represents the emitter, and the other angular line represents the collector. The direction of the arrow on the emitter distinguishes the NPN from the PNP transistor. If the arrow points in, (Points iN) the transistor is a PNP.

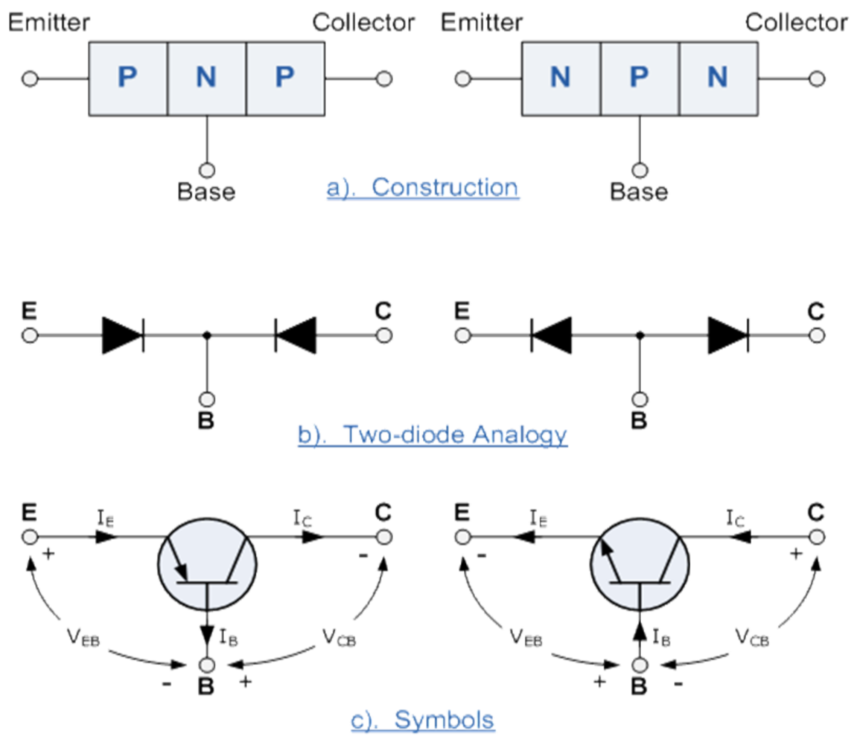


Figure 3.1: The construction and circuit symbols for both the NPN and PNP bipolar transistor are shown above with the arrow in the circuit symbol always showing the direction of conventional current flow between the base terminal and its emitter terminal, with the direction of the arrow pointing from the positive P-type region to the negative N-type region, exactly the same as for the standard diode symbol

3.2 THE TRANSISTOR MODELS

There are basically three possible ways to connect a Bipolar Transistor within an electronic circuit with each method of connection responding differently to its input signal as the static characteristics of the transistor vary with each circuit arrangement.

1. Common Base Configuration - has Voltage Gain but no Current Gain.
2. Common Emitter Configuration - has both Current and Voltage Gain.
3. Common Collector Configuration - has Current Gain but no Voltage Gain.

3.2.1 The Common Base Configuration.

As its name suggests, in the Common Base or Grounded Base configuration, the BASE connection is common to both the input signal AND the output signal with the input signal being applied between the base and the emitter terminals. The corresponding output signal is taken from between the base and the collector terminals as shown with the base terminal grounded or connected to a fixed reference voltage point. The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a Current Gain for this type of circuit of less than "1", or in other words it "Attenuates" the signal.

3.2.1.1 The Common Base Amplifier Circuit

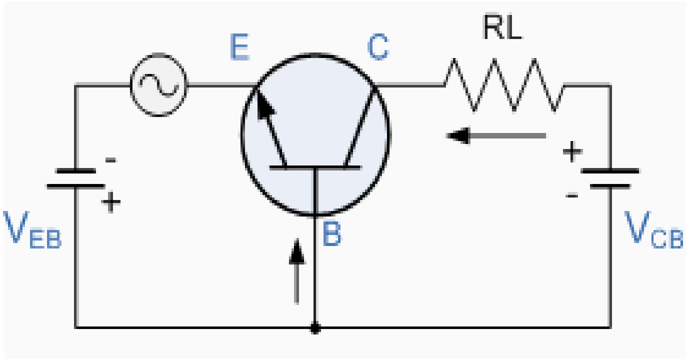


Fig 3.2the Common Base Amplifier Circuit

This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages V_{in} and V_{out} are In-Phase. This type of arrangement is not very common due to its unusually high voltage gain characteristics. Its Output characteristics represent that of a forward biased diode while the Input characteristics represent that of an illuminated photo-diode. Also this type of configuration has a high ratio of Output to Input resistance or more importantly "Load" resistance (RL) to "Input" resistance (Rin) giving it a value of "Resistance Gain". Then the Voltage Gain for a common base can therefore be given as:

AV= IC × RLIe × Rin= α × RLRin

The Common Base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or RF radio amplifiers due to its very good high frequency response.

3.2.2 The Common Emitter Configuration.

In the **Common Emitter** or Grounded Emitter configuration, the input signal is applied between the base, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of connection. The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward-biased junction, while the output impedance is HIGH as it is taken from a reverse-biased junction.

3.2.2.1 The Common Emitter Amplifier Circuit

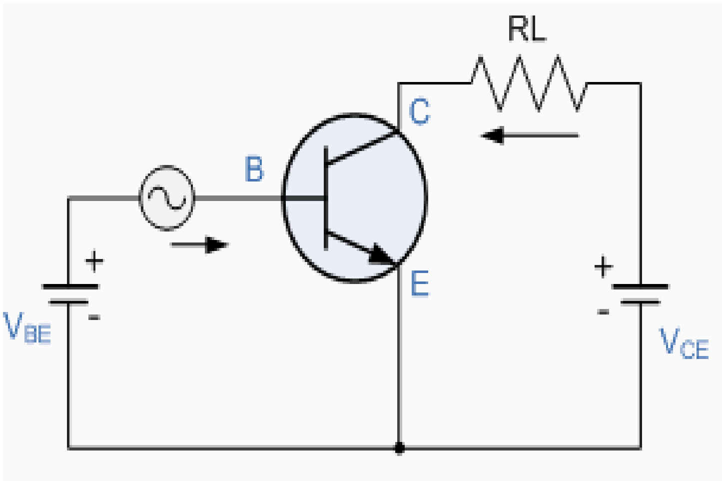


Fig 3.3the Common Emitter Amplifier Circuit

In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib. Also, as the load resistance (RL) is connected in series with the collector, the Current gain of the Common Emitter Transistor Amplifier is quite large as it is the ratio of Ic/Ib and is given the symbol of Beta, (β). Since the relationship between these three currents is determined by the transistor itself, any small change in the base current will result in a large change in the collector current. Then, small changes in base current will thus control the current in the Emitter/Collector circuit.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the amplifier can be given as:

E and β= ICIB

α= ββ+1 β= α1- α

Where: "I_c" is the current flowing into the collector terminal "I_B" is the current flowing into the base terminal and "I_E" is the current flowing out of the emitter terminal.

Then to summarize, this type of bipolar transistor configuration has a greater input impedance, Current and Power gain than that of the common Base configuration but its Voltage gain is much lower. The common emitter is an inverting amplifier circuit resulting in the output signal being 180^o out of phase with the input voltage signal.

3.2.3 The Common Collector Configuration.

In the Common Collector or Grounded Collector configuration, the collector is now common and the input signal is connected to the Base, while the output is taken from the Emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit. The Emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms, and it has relatively low output impedance.

3.2.3.1 The Common Collector Amplifier Circuit

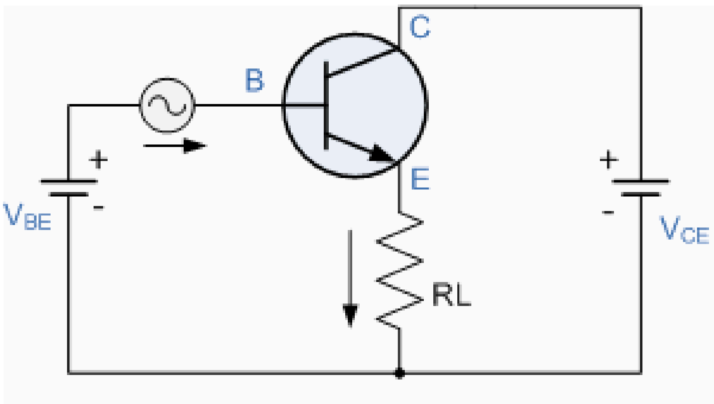


Fig 3.4The Common Collector Amplifier Circuit

The Common Emitter configuration has a current gain equal to the β value of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current. As the emitter current is the combination of the collector AND base currents combined the load resistance in this type of amplifier configuration also have both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

IE= IC+ IB

Ai = IEIB= IC- IBIB

Ai = ICIB+1

Ai= β+1

This type of bipolar transistor configuration is a non-inverting amplifier circuit in that the signal voltages of V_{in} and V_{out} are "In-Phase". It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector amplifier configuration receives both the base and collector currents giving a large current gain (as with the Common Emitter configuration) therefore, providing good current amplification with very little voltage gain.

3.2.4 Bipolar Junction Transistor Summary.

The behavior of the bipolar transistor in each one of the above circuit configurations is very different and produces different circuit characteristics with regards to Input impedance, Output impedance and Gain and this is summarized in the table below.

Transistor Characteristics

The static characteristics for **Bipolar Transistor** amplifiers can be divided into the following main groups.

Input Characteristics:-	Common Base -	$I_E \div V_{EB}$
	Common Emitter -	$I_B \div V_{BE}$
Output Characteristics:-	Common Base -	$I_C \div V_C$
	Common Emitter -	$I_C \div V_C$
Transfer Characteristics:-	Common Base -	$I_E \div I_C$
	Common Emitter -	$I_B \div I_C$

Table 3.1

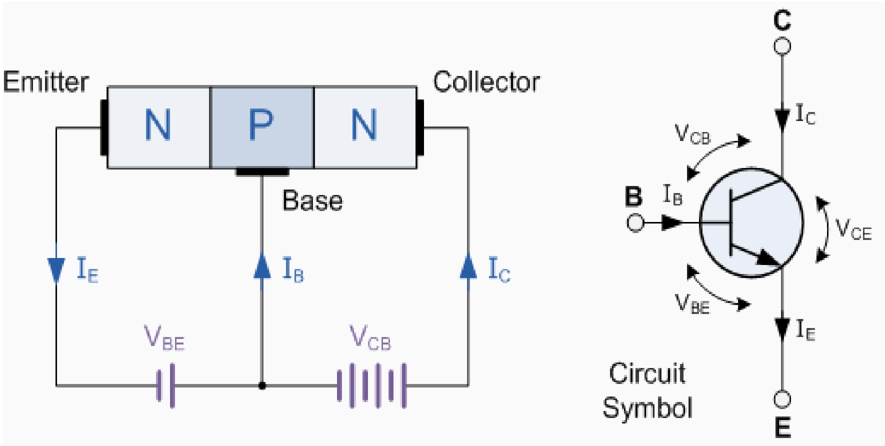
with the characteristics of the different transistor configurations given in the following table:

Characteristic	Common Base	Common Emitter	Common Collector
Input impedance	Low	Medium	High
Output impedance	Very High	High	Low
Phase Angle	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

Table 3.2

3.3 The NPN Transistor

In the previous discussion we saw that the standard Bipolar Transistor or BJT, comes in two basic forms. An NPN (Negative-Positive-Negative) type and a PNP (Positive-Negative-Positive) type, with the most commonly used transistor type being the **NPN Transistor**. We also learnt that the transistor junctions can be biased in one of three different ways - **Common Base**, **Common Emitter** and **Common Collector**. In this tutorial we will look more closely at the "Common Emitter" configuration using NPN Transistors and an example of its current flow characteristics is given below.



Note: Conventional current flow.

Fig 3.5an NPN Transistor Configuration

We know that the transistor is a "CURRENT" operated device and that a large current (I_C) flows freely through the device between the collector and the emitter terminals. However, this only happens when a small biasing current (I_B) is flowing into the base terminal of the transistor thus allowing the base to act as a sort of current control input. The ratio of these two currents (I_C/I_B) is called the **DC Current Gain** of the device and is given the symbol of hfe or nowadays Beta, (β). Beta has no units as it is a ratio. Also, the current gain from the emitter to the collector terminal, I_C/I_E, is called Alpha, (α), and is a function of the transistor itself. As the emitter current I_E is the product of a very small base current to a very large collector current the value of this parameter α is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 *to* 0.999.

α and β Relationships

DC Current Gain= Output CurrentInput Current= ICIB

β= ICIB α= ICIE

IE= IC+ IB

VCE= VCB+ VBE

By combining the two parameters α *and* β we can produce two mathematical expressions that give the relationship between the different currents flowing in the transistor.

α= ββ+1 β= α1- α

The values of Beta vary from about 20 for high current power transistors to well over 1000 for high frequency low power type bipolar transistors. The equation for Beta can also be re-arranged to make I_C as the subject, and with zero base current $(I_B = 0)$ the resultant collector current Ic will also be zero, $(\beta \ x \ 0)$. Also when the base current is high the corresponding collector current will also be high resulting in the base current controlling the collector current. One of the most important properties of the Bipolar Junction Transistor is that a small base current can control a much larger collector current. Consider the following example.

Example An NPN Transistor has a DC current gain, (Beta) value of 200. Calculate the base current I_B required to switch a resistive load of $4 \ mA$.

Solution

IB= ICβ= 4 × 10-3200=20 µA

where, $\beta = 200, I_C = 4mA \ and \ I_B = 20\mu A.$

One other point to remember about NPN Transistors. The collector voltage, (V_C) must be greater than the emitter voltage, (V_E) to allow current to flow through the device between the collector-emitter junction. Also, there is a voltage drop between the base and the emitter terminal of about 0.7v for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode. Then the base voltage, (V_{BE}) of an NPN Transistor must be greater than this 0.7 V otherwise the transistor will not conduct with the base current given as.

IB= VB- VERB

Where: I_B is the base current, V_B is the base bias voltage, V_{BE} is the base-emitter volt drop (0.7v) and R_B is the base input resistor.

Example

An NPN Transistor has a DC base bias voltage, V_B of 10v and an input base resistor, R_B of 100kΩ. What will be the value of the base current into the transistor?

IB= VB-VBERB= 100-0.1100 kΩ=93 μA

Therefore, $I_B = 93\ \mu A$.

3.3.1 The Common Emitter Configuration.

As well as being used as a switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor, NPN Transistors can also be used to produce a circuit which will also amplify any small AC signal applied to its Base terminal. If a suitable DC "biasing" voltage is firstly applied to the transistors Base terminal thus allowing it to always operate within its linear active region, an inverting amplifier circuit called a Common Emitter Amplifier is produced.

One such *Common Emitter Amplifier* configuration is called a Class A Amplifier. A Class A Amplifier operation is one where the transistors Base terminal is biased in such a way that the transistor is always operating halfway between its cut-off and saturation points, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of the AC input signal superimposed upon the DC Biasing voltage. Without this "Bias Voltage" only the positive half of the input waveform would be amplified. This type of amplifier has many applications but is commonly used in audio circuits such as pre-amplifier and power amplifier stages.

With reference to the common emitter configuration shown below, a family of curves known commonly as the Output Characteristics Curves relates the output collector current, (I_C) to the collector voltage, (V_{CE}) when different values of base current, (I_B) are applied to the transistor for transistors with the same β value. A DC "Load Line" can also be drawn onto the output characteristics curves to show all the possible operating points when different values of base current are applied. It is necessary to set the initial value of V_{CE} correctly to allow the output voltage to vary both up and down when amplifying AC input signals and this is called setting the operating point or Quiescent Point, Q-point for short and this is shown below.

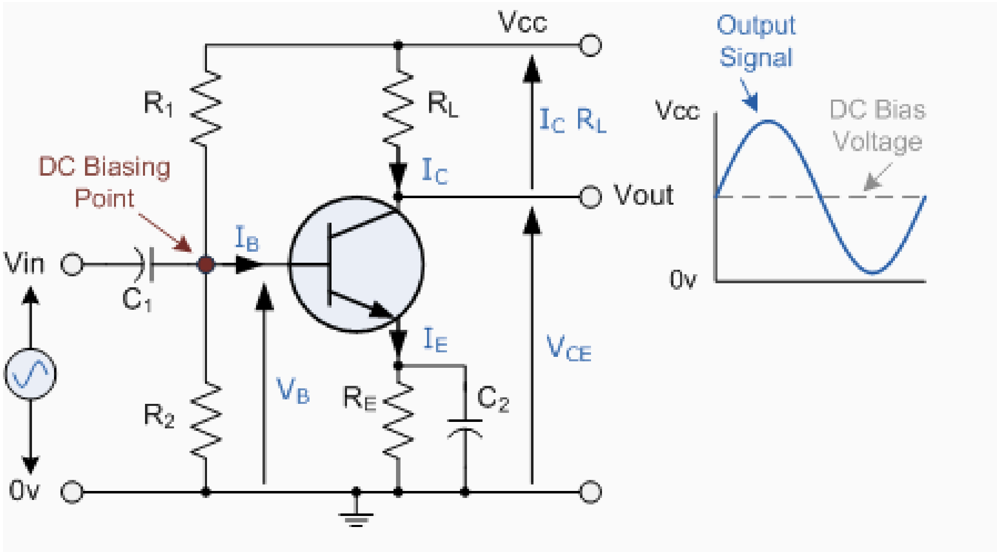


Fig 3.6the Common Emitter Amplifier Circuit

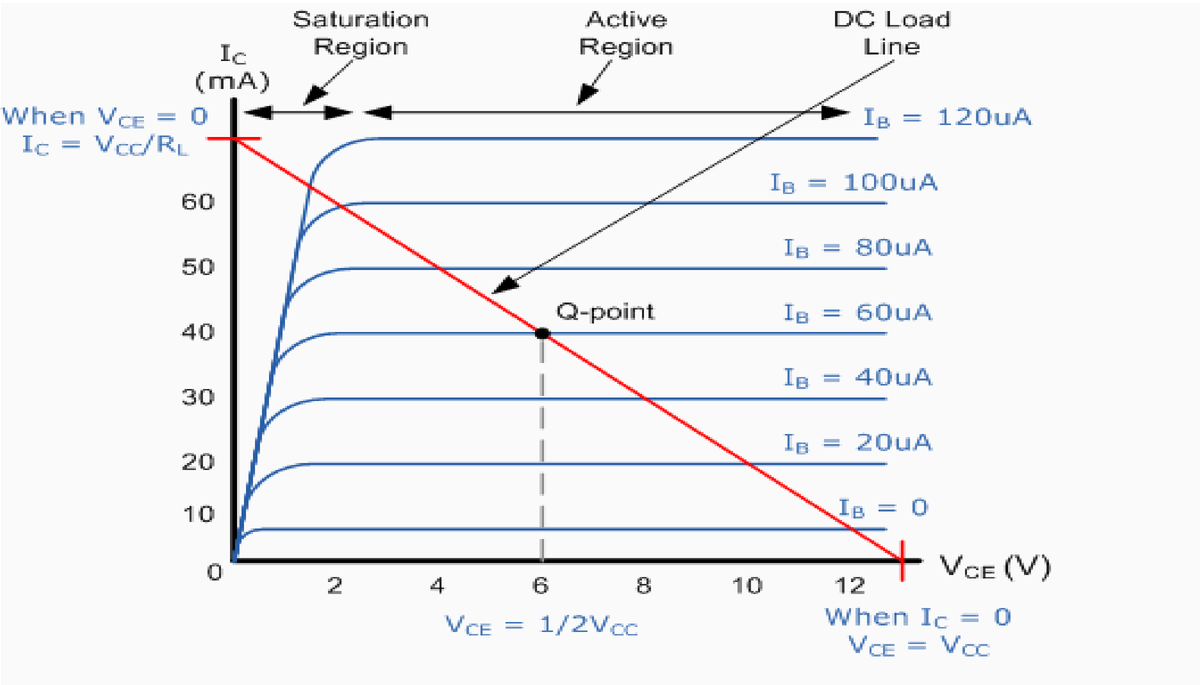


Fig 3.7Output Characteristics Curves for a Typical Bipolar Transistor

The most important factor to notice is the effect of V_{CE} upon the collector current I_{CE} when V_{CE} is greater than about 1.0 volts. You can see that I_C is largely unaffected by changes in V_{CE} above this value and instead it is almost entirely controlled by the base current, I_B. When this happens we can say then that the output circuit represents that of a "Constant Current Source". It can also be seen from the common emitter circuit above that the emitter current I_E is the sum of the collector current, I_C and the base current, I_B, added together so we can also say that " $I_E = I_C + I_B$ " for the common emitter configuration.

By using the output characteristics curves in our example above and also Ohm´s Law, the current flowing through the load resistor, (R_L), is equal to the collector current, I_C

entering the transistor which in-turn corresponds to the supply voltage, (V_{CC}) minus the voltage drop between the collector and the emitter terminals, (V_{CE}) and is given as:

Collector Current, IC= VCC- VCERL

Also, a **Load Line** can be drawn directly onto the graph of curves above from the point of "Saturation" when $V_{CE} = 0$ to the point of "Cut-off" when $I_C = 0$ giving us the "Operating" or **Q-point** of the transistor. These two points are calculated as:

when VCE=0, IC= VCC- 0 RL, IC= VCCRL

when IC=0, 0= VCC- VCERL, VCC= VCE

Then, the collector or output characteristics curves for Common Emitter NPN Transistors can be used to predict the Collector current, *Ic*, when given V_{CE} and the Base current, I_B. A Load Line can also be constructed onto the curves to determine a suitable Operating or Q-point which can be set by adjustment of the base current.

3.4 The PNP Transistor

The **PNP Transistor** is the exact opposite to the **NPN Transistor** device we looked at in the previous discussion. Basically, in this type of transistor construction the two diodes are reversed with respect to the NPN type, with the arrow, which also defines the Emitter terminal this time pointing inwards in the transistor symbol. Also, all the polarities are reversed which means that *PNP Transistors* "sink" current as opposed to the NPN transistor which "sources" current. Then, PNP Transistors use a small output base current and a negative base voltage to control a much larger emitter-collector current. The construction of a PNP transistor consists of two P-type semiconductor materials either side of the N-type material as shown below.

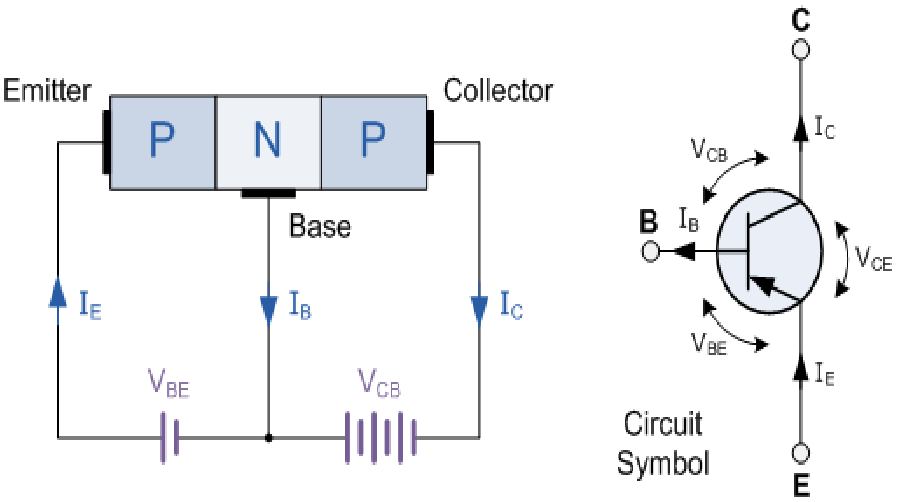


FIG 3.8A PNP Transistor Configuration

The PNP Transistor has very similar characteristics to their NPN bipolar cousins, except that the polarities (or biasing) of the current and voltage directions are reversed for any one of the possible three configurations looked at in the first tutorial, Common Base, Common Emitter and Common Collector. Generally, PNP Transistors require a negative (-ve) voltage at their Collector terminal with the flow of current through the emitter-collector terminals being **Holes** as opposed to **Electrons** for the NPN types. Because the movement of holes across the depletion layer tends to be slower than for electrons, PNP transistors are generally more slower than their equivalent NPN counterparts when operating.

To cause the Base current to flow in a PNP transistor the Base needs to be more negative than the Emitter (current must leave the base) by approx 0.7 volts for a silicon device or 0.3 volts for a germanium device with the formulas used to calculate the Base resistor, Base current or Collector current are the same as those used for an equivalent NPN transistor and is given as.

IE= IC + IB

IC = βIBIB= ICβ

Generally, the PNP transistor can replace NPN transistors in electronic circuits; the only difference is the polarities of the voltages, and the directions of the current flow. PNP Transistors can also be used as switching devices and an example of a PNP transistor switch is shown below.

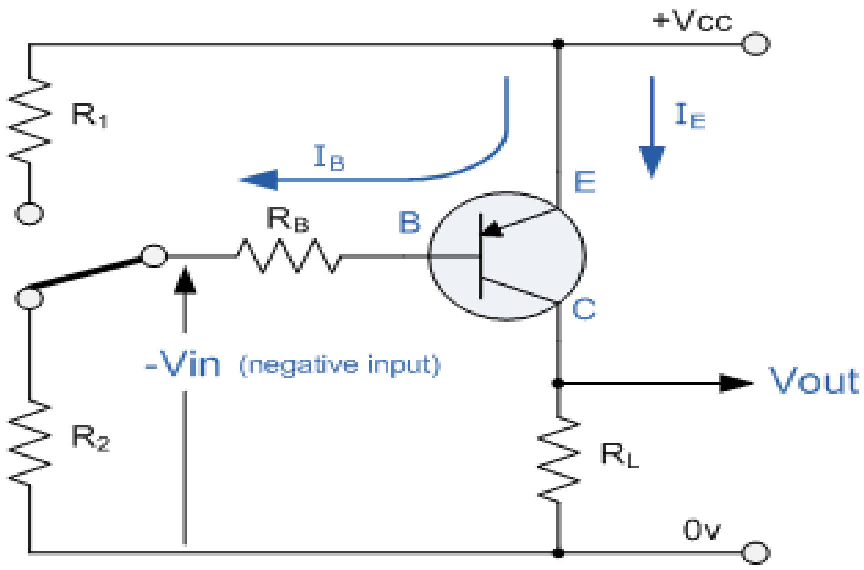


Fig 3.9A PNP Transistor Circuit

The **Output Characteristics Curves** for a PNP transistor look very similar to those for an equivalent NPN transistor except that they are rotated by 180^{o} to take account of the reverse polarity voltages and currents, (the currents flowing out of the Base and Collector in a PNP transistor are negative).

3.5 Transistor Matching

You may think what is the point of having a PNP Transistor, when there are plenty of NPN Transistors available?. Well, having two different types of transistors PNP & NPN, can be an advantage when designing amplifier circuits such as Class B Amplifiers that use "Complementary" or "Matched Pair" transistors or for reversible **H-Bridge** motor control circuits. A pair of corresponding NPN and PNP transistors with near identical characteristics to each other are called **Complementary Transistors** for example, a TIP3055 (NPN), TIP2955 (PNP) are good examples of complementary or matched pair silicon power transistors. They have a DC current gain, Beta, (I_C / I_B) matched to within 10% and high Collector current of about 15A making them suitable for general motor control or robotic applications.

Identifying the PNP Transistor

We saw earlier in this unit, that transistors are basically made up of two Diodes connected together back-to-back. We can use this analogy to determine whether a transistor is of the type PNP or NPN by testing its Resistance between the three different leads, Emitter, Base and Collector. By testing each pair of transistor leads in both directions will result in six tests in total with the expected resistance values in Ohm's given below.

- 1. Emitter-Base Terminals - The Emitter to Base should act like a normal diode and conduct one way only.
- 2. Collector-Base Terminals - The Collector-Base junction should act like a normal diode and conduct one way only.
- 3. Emitter-Collector Terminals - The Emitter-Collector should not conduct in either direction.

Between Transistor Terminals		PNP	NPN
Collector	Emitter	R_{HIGH}	R_{HIGH}
Collector	Base	R_{LOW}	R_{HIGH}
Emitter	Collector	R_{HIGH}	R_{HIGH}
Emitter	Base	R_{LOW}	R_{HIGH}
Base	Collector	R_{HIGH}	R_{LOW}
Base	Emitter	R_{HIGH}	R_{LOW}

Table 3.3 Transistor Resistance Values for the PNP transistor and NPN transistor types

3.6 The Transistor as a Switch

When used as an AC signal amplifier, the transistors Base biasing voltage is applied so that it operates within its "**Active**" region and the linear part of the output characteristics curves are used. However, both the NPN & PNP type bipolar transistors can be made to operate as an "ON/OFF" type solid state switch for controlling high power devices such as motors, solenoids or lamps. If the circuit uses the **Transistor as a Switch**, then the biasing is arranged to operate in the output characteristics curves seen previously in the areas known as the "**Saturation**" and "**Cut-off**" regions as shown below.

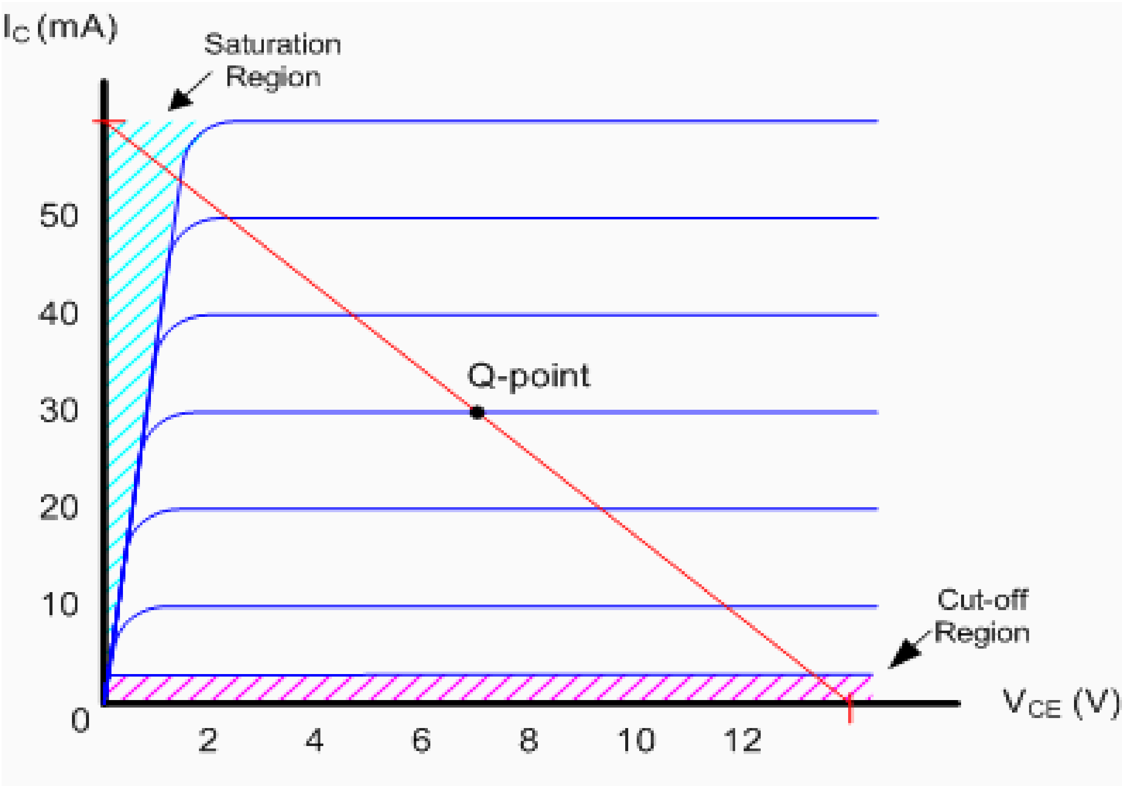


Fig 3.10Transistor Curves

The pink shaded area at the bottom represents the "Cut-off" region. Here the operating conditions of the transistor are zero input base current (I_B), zero output collector current (I_C) and maximum collector voltage (V_{CE}) which results in a large depletion layer and no current flows through the device. The transistor is switched "Fully-OFF". The lighter blue area to the left represents the "Saturation" region. Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current flow and minimum collector emitter voltage which results in the depletion layer being as small as possible and maximum current flows through the device. The transistor is switched "Fully-ON". Then we can summarize this as:

- 1. Cut-off Region - Both junctions are Reverse-biased, Base current is zero or very small resulting in zero Collector current flowing, the device is switched fully "OFF".
- 2. Saturation Region - Both junctions are Forward-biased, Base current is high enough to give a Collector-Emitter voltage of 0v resulting in maximum Collector current flowing, the device is switched fully "ON".

An example of an NPN Transistor as a switch being used to operate a relay is given below. With inductive loads such as relays or solenoids a flywheel diode is placed across the load to dissipate the back EMF generated by the inductive load when the transistor switches "OFF" and so protect the transistor from damage. If the load is of a very high current or voltage nature, such as motors, heaters etc, then the load current can be controlled via a suitable relay as shown.

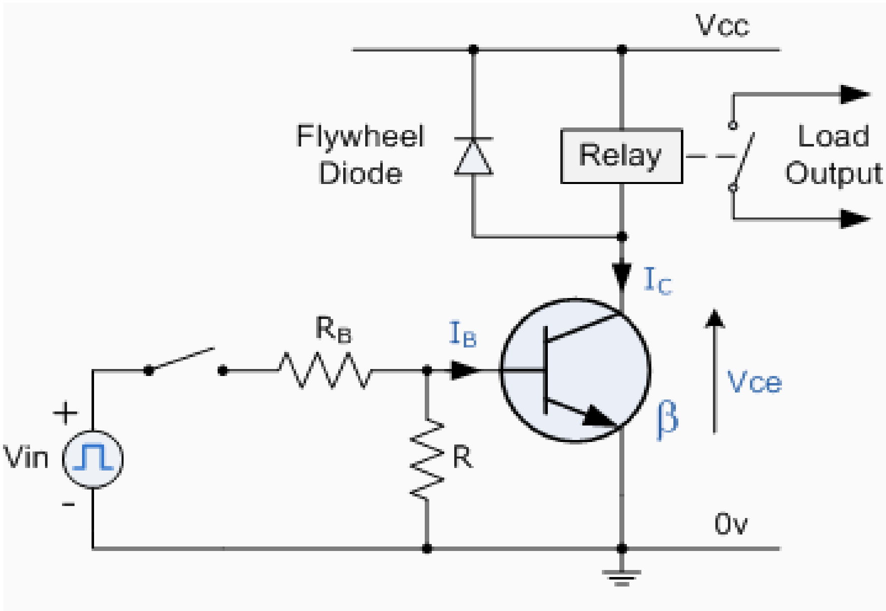


FIG 3.11 Transistor Switching Circuit

The circuit resembles that of the Common Emitter circuit we looked at in the previous discussion. The difference this time is that to operate the transistor as a switch the transistor needs to be turned either fully "OFF" (Cut-off) or fully "ON" (Saturated). An ideal transistor switch would have an infinite resistance when turned "OFF" resulting in zero current flow and zero resistance when turned "ON", resulting in maximum current flow. In practice when turned "OFF", small leakage currents flow through the transistor and when fully "ON" the device has a low resistance value causing a small saturation voltage (V_{CE}) across it. In both the Cut-off and Saturation regions the power dissipated by the transistor is at its minimum.

To make the Base current flow, the Base input terminal must be made more positive than the Emitter by increasing it above the 0.7 volts needed for a silicon device. By varying the Base-Emitter voltage V_{BE}, the Base current is altered and which in turn controls the amount of Collector current flowing through the transistor as previously discussed. When maximum Collector current flows the transistor is said to be saturated. The value of the Base resistor determines how much input voltage is required and corresponding Base current to switch the transistor fully "ON".

Example

A transistor has the following values: $\beta = 200$, $I_C = 4mA$ and $I_B = 20uA$, find the value of the Base resistor (R_B) required to switch the load "ON" when the input terminal voltage exceeds 2.5v.

RB= Vin- VBEIB2.5 V-0.7 V20 × 10-6= 90 kΩ

Example

Again using the same values, find the minimum Base current required to turn the transistor fully "ON" (Saturated) for a load that requires 200mA of current.

IB= ICβ= 200 mA200=1 mA

Transistor switches are used for a wide variety of applications such as interfacing large current or high voltage devices like motors, relays or lamps to low voltage digital logic IC's or gates like AND Gates or OR Gates. Here, the output from a digital logic gate is only +5v but the device to be controlled may require a 12 or even 24 volts supply. Or the load such as a DC Motor may need to have its speed controlled using a series of pulses (Pulse Width Modulation) and transistor switches will allow us to do this faster and more easily than with conventional mechanical switches.

3.7 The Important Parameters:

Let us now concentrate on those parameters of a two-port system that are of paramount importance from an analysis and design viewpoint. For the two-port (two pairs of terminals) system of fig3.12, the input side (the side to which the signal is normally applied) is to the left and the output side (where the load is connected) is to the right. In fact, for most electrical and electronics systems, the general flow is usually from the left to the right. For both set of terminals, the impedance between each pair of terminals under normal operating conditions is quite important.

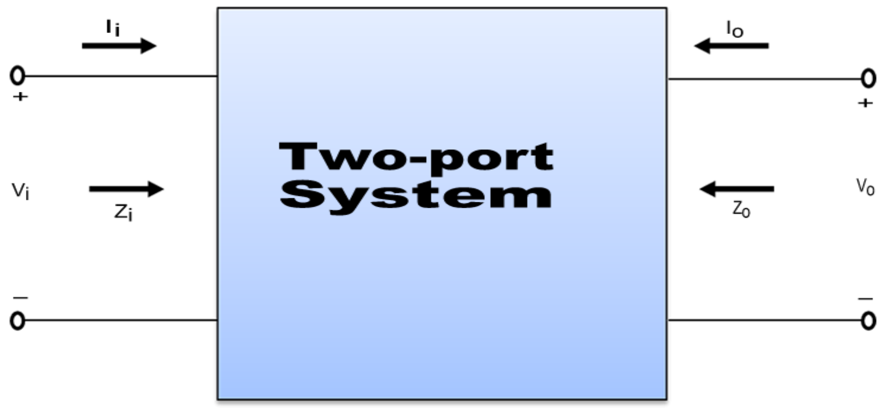


Fig 3.12 Two-port system

3.7.1 Input Impedance, Z_i

For the input side, the input impedance Z_i is defined by Ohm's law as the following:

$$Z_i = \frac{V_i}{I_i} \qquad \text{(v)}$$

If the input signal V_i is changed, the current I_i can be computed using the same level of input impedance. In other words:

For small-signal analysis, once the input impedance has been determined the same numerical value can be used for changing levels of applied signal.

In fact, we will find out that the input impedance of a transistor can be approximately determined by the dc biasing conditions – conditions that do not change simply because the magnitude of the applied ac signal has changed.

It is particularly noteworthy that for frequencies in the low to mid-range (typically $\leq = 100kHz$):

The input impedance of a BJT transistor amplifier is purely resistive in nature and, depending on the manner in which the transistor is employed, can vary from a few ohms to megohms.

In addition,

An ohmmeter cannot be used to measure the small-signal ac impedance since the ohmmeter operates in the dc mode.

Equation (v) is particularly useful in that it provides a method for measuring the input resistance in the ac domain. For instance, in fig 3.13 a sensing resistor has been added to the input side to permit a determination of I_i using Ohm's law. An oscilloscope or sensitive digital multimeter (DDM) can be used to measure the voltage V_s and V_i. Both voltages can be the peak-peak, peak, or rms values, as long as both level use the same standard. The input impedance is then determined in the following manner:

$$I_i = \frac{V_s - V_I}{R_{sense}}$$

$$Z_i = \frac{V_i}{I_i}$$

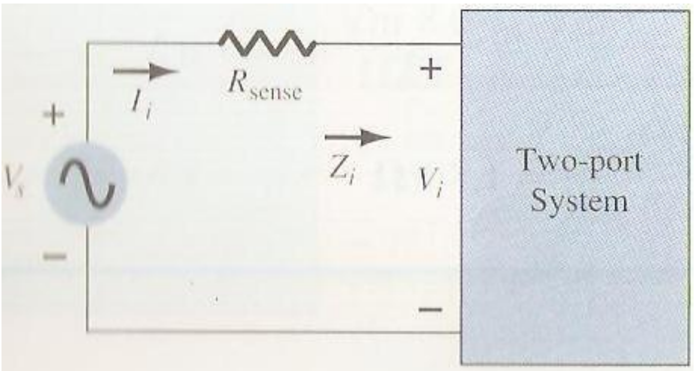


Fig 3.13 Determining Z_i.

The importance of the input impedance of a system can be demonstrated by the network of fig 3.14. The signal source has an internal resistance of 600 Ω, and the system (possibly a transistor amplifier) has an input resistance of 1.2 kΩ. If the source were ideal ($R_s = 0\Omega$), the full 10 mV would be applied to the system, but with a source impedance, the input voltage must be determined using the divider rule as follows:

$$V_i = \frac{Z_i V_s}{Z_i - R_{source}} = \frac{(1.2\ k\Omega)(10\ \text{mV})}{1.2\ k\Omega + 0.67\ mV} = 6.67\ mV$$

Thus, only 66.7% of the full-input signal is available at the input. If Z_i were only 600 Ω, then $V_i = \frac{1}{2}(10\ mV) = 5\ mV\ or\ 50\%$ of the available signal. Of course $Z_i = 8.2k\Omega$, V_i will be 93.2% of the applied signal. The level of input impedance, therefore, can have a significant impact on the level of signal that reaches the system (or amplifier).

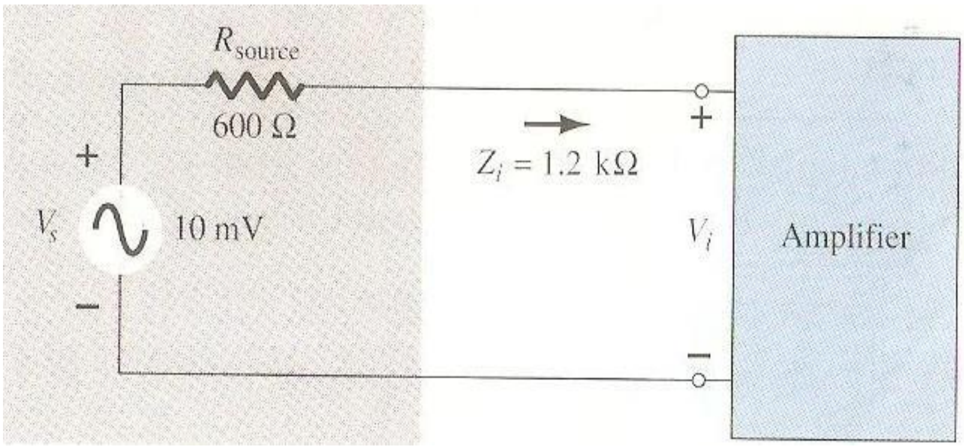


Fig 3.14 Demonstrating the impact of Z_i on an amplifier's response.

3.7.2 Output Impedance, Z_o

The output impedance is naturally defined as the output set of terminals, but the manner in which its defined is quite different from the of the input impedance. That is:

The output impedance is determined at the output terminals looking back into the system with the applied signal set to zero.

In figure 3.15, for example, the applied signal has been set to zero volts. To determine Z_o, a signal, V_s, is applied to the output terminals and the level of V_o is measured with an oscilloscope or sensitive DMM. the output impedance is then determined in the following manner:

$$I_o = \frac{V - V_o}{R_{sense}}$$

And

$$Z_o = \frac{V_o}{I_o}$$

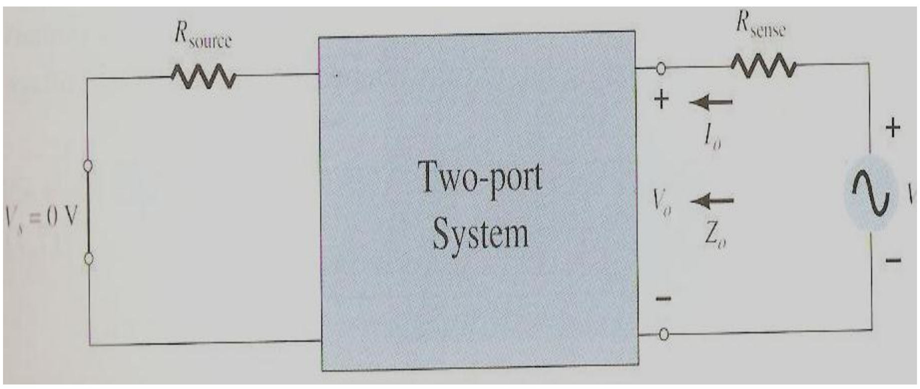


Fig 3.15 DeterminingZ_o

In particular, for frequencies in the low to mid-range (typically ≤ 100 kHz):

The output impedance of a BJT transistor amplifier is resistive in nature and, depending on the configuration and the placement of the resistive elements, Z_o, can vary from a few ohms to a level that can exceed 2 MΩ.

In addition:

An ohmmeter cannot be used to measure the small-signal ac output impedance since the ohmmeter operates in the dc mode.

3.7.3 Voltage Gain, A_v

One of the most important characteristics of an amplifier is the small signal ac voltage gain as determined by

$A_v = \frac{V_o}{V_i}$(vi)

For the system of fig 3.16, a load has not been connected to the output terminals and the level of gain determined by Eq. (vi), is referred to as the no-load voltage gain. That is,

$$A_{v_{NL}} = \frac{V_o}{V_i} \Big|_{with\ R_L = \infty\ \Omega (open\ circuit)}$$

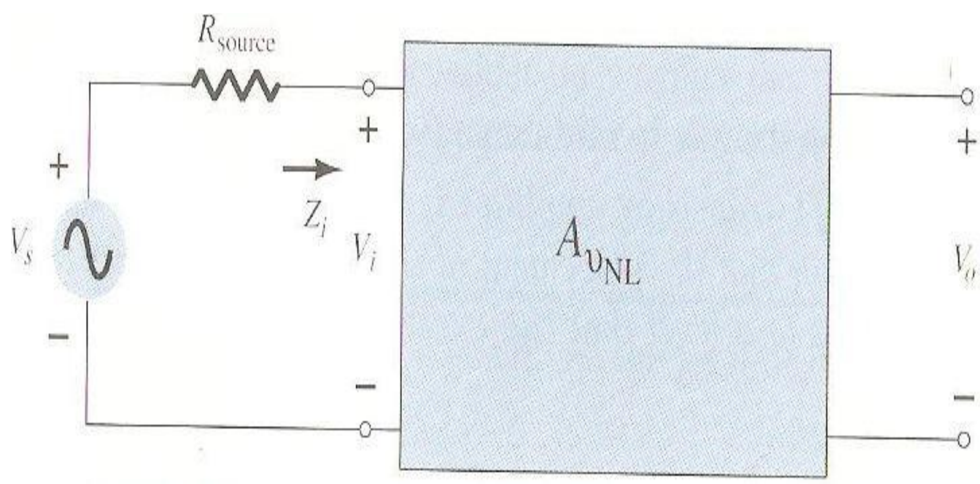


Fig 3.16 Determining the no-load voltage gain.

3.7.4 Current Gain, A_i

The last numerical characteristic to be is the current gain defined by

$$A_i = \frac{I_o}{I_i}$$

Although typically the recipients of less attention than the voltage gain, it is, however, an important quantity that can have significant impact on the overall effectiveness of a design. In general:

For BJT amplifiers, the current gain typically ranges from a level just less than 1 to a level that mat exceed 100.

For the loaded situation of fig 3.17,

$$I_i = \frac{V_i}{Z_i} \qquad and \qquad I_l = -\frac{V_o}{R_L}$$

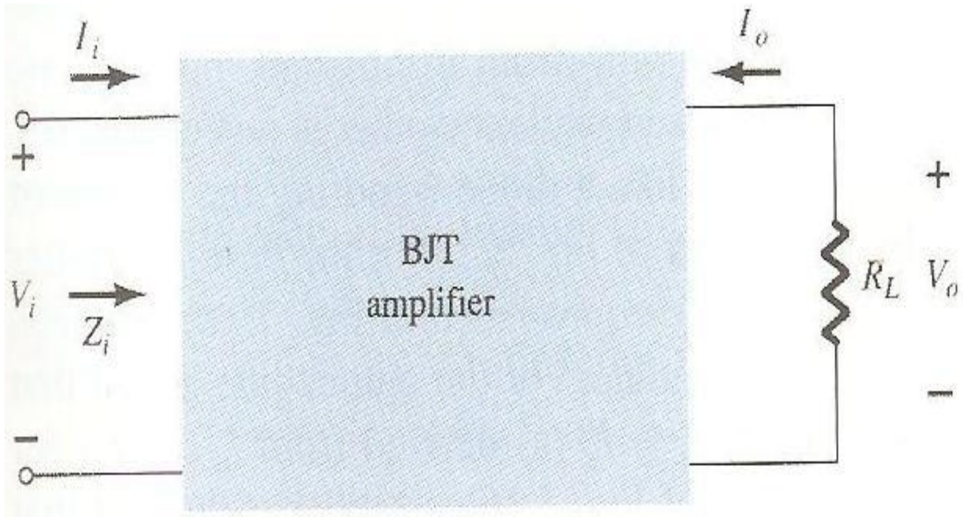


Fig 3.17 Determining the loaded current gain.

with

$$A_i = \frac{I_o}{I_i} = -\frac{V_o/R_L}{V_i/Z_i} = -\frac{V_o Z_i}{V_i R_L}$$

And

$$A_i = -A_o \frac{Z_i}{R_L} \text{(vii)}$$

Eq.(vii) allows the determination of the current gain from the voltage gain and the impedance levels.

3.8 Phase Relationship

The phase relationship between input and output sinusoidal signal is important for a variety of practical reasons. Fortunately, however:

For the typical transistor amplifier at frequencies that permit ignoring the effects of the reactive elements, the input and output signals are either180^o out of phase or in phase.

3.9 THE r_e TRANSISTOR MODEL

The r_e model employs a diode and controlled current source to duplicate the behavior of a transistor in the region of interest. Recall that a current-controlled current source is one where the parameters of the current source are controlled by a current elsewhere in the network. In fact, in general:

BJT transistor amplifiers are referred to as current-current controlled devices.

Common Base Configuration

In fig 3.18a, a common-base *pnp* transistor has been inserted within the two-port structure employed in our previous discussion. In fig 3.18b, the r_e model for the transistor has been placed between the same four terminals. As noted earlier, the model is chosen in such a way as to approximate the behavior of the device that it is replacing in the operating region of interest. In other words, the result obtained with the model in place should be relative close to those obtained with the actual transistor. Also recall that one junction of an operating transistor is forward-biased while the other is reversed-biased. The forward-biased junction will behave much like a diode. For the base-to-emitter junction of the transistor of fig 3.18a, the diode equivalent of fig 3.18b between the same two terminals seems to be quite appropriate. Recall that:

$$I_C \cong I_e \text{ as derived from } I_C = I_e \text{ for the range of values of } V_{CE} .$$

The current source of Fig 7.16b establishes the fact that $I_C = \alpha I_e$, with the controlling current I_e appearing in the input side of the equivalent circuit as described by fig 3.18a. We have therefore established an equivalent at the input and output terminals with the current-controlled source, providing a link between the two.

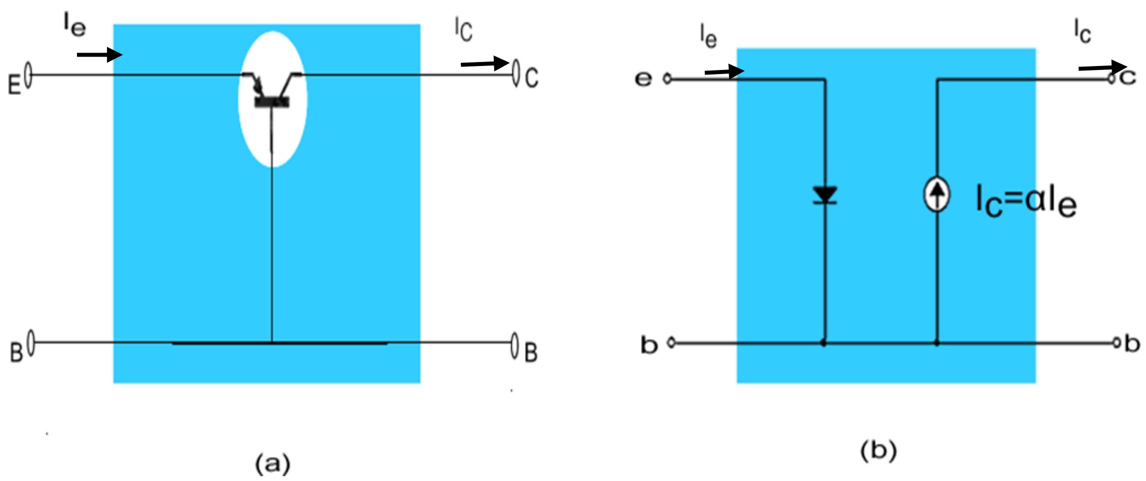


Fig 3.18 (a) Common-base BJT transistor; (b) r_e model for the configuration

The resistance of a diode can be determined by $r_{ac} = 26\ mV/I_D$, where I_D is the current through the diode at the Q-point. This same equation can be used to find the ac resistance of the diode of fig 3.18b if we simply substitute the emitter current as follows:

$$r_e = \frac{26\ mV}{I_E}$$

The subscript $e\ of\ r_e$ was chosen to emphasize that it is the dc level =l of emitter current that determines the ac level of the resistance of the diode of fig 3.18b. Substituting the resulting value of r_e in fig 3.18b will result in the very useful model of fig 3.19.

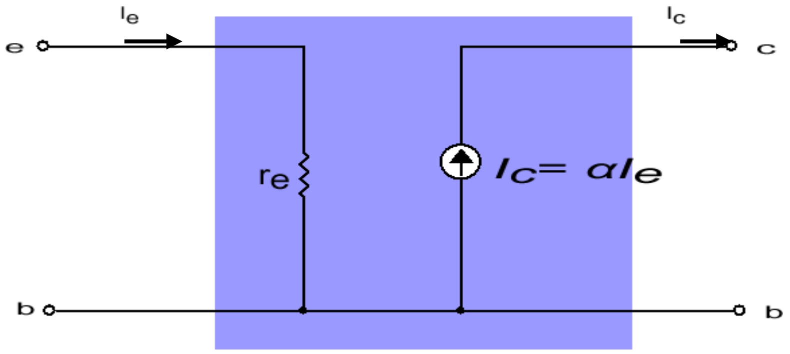


Fig 3.19 Common-base equivalent circuit

Due to the isolation that exists between input and output circuit of fig 3.19, it should be fairly obvious that the input impedance Z_i for the common-base configuration of a transistor is simply r_e. That is:

$$[Z_i = r_e]_{CB}$$

For common-base configuration, typical values of Z_i range from a few ohms to a maximum of about 50 Ω.

For the output impedance, if we set the signal to zero, then $I_e = 0\ A$, and $I_C = \alpha I_e = \alpha\ (0\ A)$, resulting in the open-circuit equivalent of the output terminals. The result is that for the model of fig 3.19

$$[Z_0 = \infty\ \Omega](\text{viii})$$

In actuality,

For the common-base configuration, typical values of Z_o are in the megohms range.

The output resistance of the common-base configuration is determined by the slope of the characteristic lines of the output characteristics as shown in fig 3.20. Assuming the lines to be perfectly horizontal would result in the conclusion of eq.(vii). If care were taking to measure Z_o graphically or experimentally, levels typically in the range 1 - to 2- MΩ would be obtained.

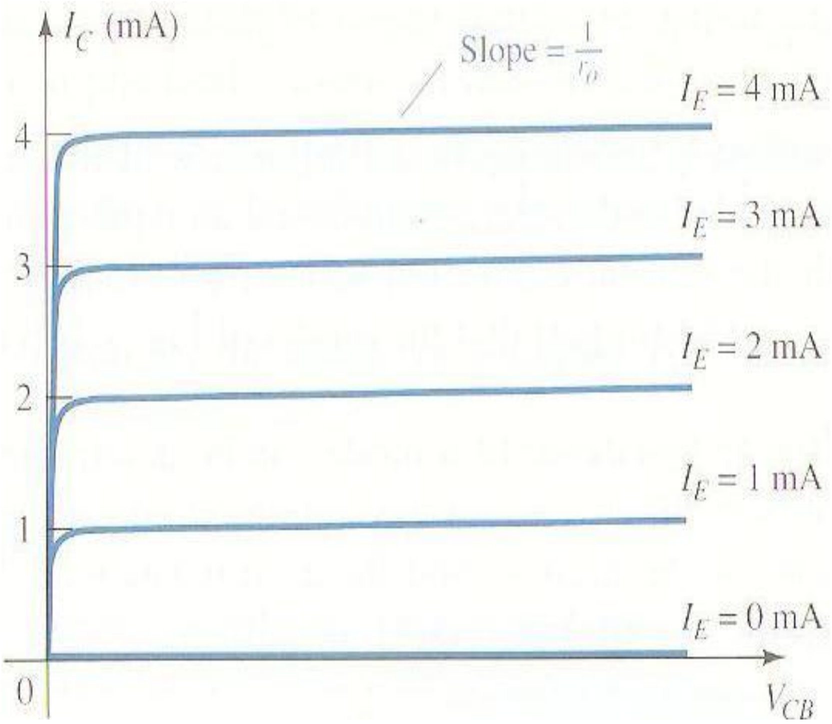


Fig 3.20 DefiningZ_o

In general, for the common-base configuration the input impedance is relatively small and the output impedance quite high.

The voltage gain will now be determined for the network of fig 3.21

$I_o = -I_o R_L = -(-I_C)R_L = \alpha I_e R_L$

And $V_i = I_e Z_i = I_e r_e$

So that $A_v = \frac{V_o}{V_i} = \frac{\alpha I_e R_L}{I_e r_e}$

And $\left[A_v = \frac{\alpha R_L}{r_e} \cong \frac{R_L}{r_e}\right]_{CB}$

For the current gain,

$A_i = \frac{I_o}{I_i} = \frac{-I_C}{I_e} = -\frac{\alpha I_e}{I_e}$

And $[A_i - \alpha \cong -1]_{CB}$

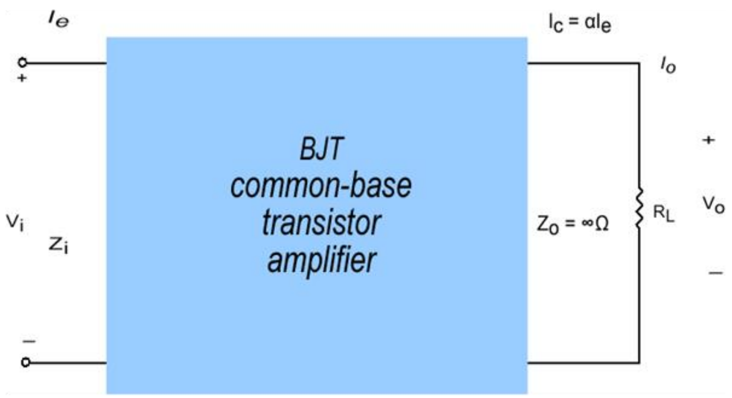


Fig 3.21 Defining $A_V = V_o/V_i$ for the common-base configuration

The fact that the polarity of the voltage V_o as determined by the current I_C is the same as defined by Fig 7.19 (i.e., the negative side is at ground potential) reveals that V_o and V_i are in phase for the common-base configuration. For npn transistor in the common-base configuration, the equivalence would appear as shown in fig 7.20.

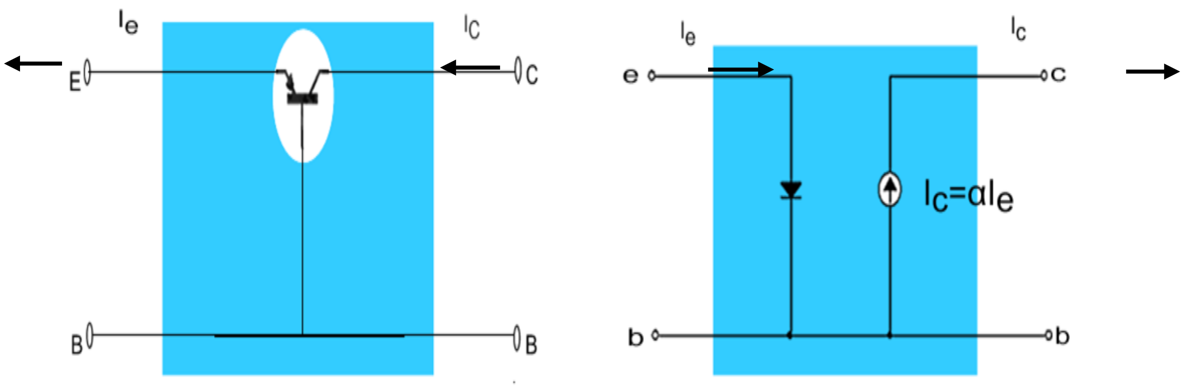


Fig 3.22 Approximate model for a common-base npn transistor configuration

3.10 Test

Question 1

For a common-base configuration of figure 3.19 with I_E = 4mA, and $\alpha = 0.98$, and an ac signal of 2mV applied between the base and emitter terminals:

(a) Determine the input impedance.

(b) Calculate the voltage gain if the load of 0.56 kΩ is connected to the output terminals.

(c) Find the output impedance and current gain.

Solution

(a) $r_e = \frac{26\ mV}{I_E} = \frac{26\ mV}{4\ mA} = 6.5\ \Omega$

(b) $I_i = I_e = \frac{V_i}{Z_i} = \frac{2\ mV}{6.5\ \Omega} = 307.69\ \mu A$

$V_o = I_C R_L = \alpha I_e R_L = (0.98)(307.69\ \mu A)(0.56\ k\Omega)$

$= 168.86\ mV$

and $\quad A_v = \frac{V_o}{V_i} = \frac{168.86\ mV}{2\ mV} = 84.43$

Or $\quad A_v = \frac{\alpha R_L}{r_e} = \frac{(0.98)(0.56\ k\Omega)}{6.5\ k\Omega} = 84.43$

(c) $\quad Z_o \cong \infty\ \Omega$

$$A_i = \frac{I_o}{I_i} = -\alpha = -0.98$$

Question 2 Following current readings are obtained in a transistor connected in CB configuration: $I_E = 2\ mA\ and\ I_B = 20\ mA$. Compute the values of $\alpha\ and\ I_C$.

Solution

$I_C = I_E - I_B = 2 \times 10^{-3} - 20 \times 10^{-3} = 1.98\ mA$

$\alpha = \frac{I_C}{I_E} = 1.98/2 = 0.99$

Question 3 A transistor operating in CB configuration has
$I_C = 2.98\ mA, I_E = 3.00\ mA$

$and\ I_{CO} = 0.01\ mA$. What current will flow in the collector circuit of this transistor when connected in CE configuration with a base current of 30 μA.

Solution

For CE configuration, $I_C = \beta I_B + (1 + \beta)\ I_{CO}$

Let us find the value of β from data given for CB configuration. For such a circuit

$I_C = \alpha I_E + I_{CO}$

$2.98 = \alpha \times 3 + 0.01$

$\alpha = 0.99$

$\beta = \alpha/(1 - \alpha) = 0.99/(1 - 0.09) = 99.$

$\therefore For\ CE\ circuit, I_C = 99 \times 0.03 + (1 + 99) \times 0.01 = \mathbf{3.97\ mA}.$

4.0 CONCLUSION

This unit has introduced you to the basic theories and equations of Bipolar Junction Transistors (BJT) and also, to the various transistor models, configurations, and the equivalent circuit of transistors with its parameters.

5.0 SUMMARY

The advent of Bipolar Junction Transistor has already made tremendous contributions to the technological revolution that is still continuing in the twenty first century. All of the complex electronic devices and systems developed or in use today, are outgrowths of early developments in semiconductor transistors.

The four basic guideposts about all transistor circuits are:

1. Conventional current flows along the arrow whereas electrons flow against it;
2. E/B junction is always forward-biased;
3. C/B junction is always reverse-biased;
4. $I_E = I_B + I_C.$

6.0 TUTOR-MARKED ASSIGNMENT

(1) A transistor operating in CB configuration has $I_C = 2.98\ mA, I_E = 3.00\ mA\ and\ I_{CO} = 0.01\ mA$. What current will flow in the collector circuit of this transistor when connected in CE configuration with a base current of 30 μA?

(2) Discuss the operation of a PNP transistor. The reverse saturation current in a PNP germanium transistor type OC 71 is 8 μA. If the transistor common base current gain is 0.979, calculate the collector and emitter current for 40 μA base current. What is the collector current when base current is zero?

(3) For the common-base configuration of fig 3.19, an ac signal of 10mV is applied, resulting in an emitter current of 0.5mA. If $\alpha = 0.980$, determine:

(a) Z_i.

(b) $V_o\ if\ R_L = 1.2\ k\Omega$.

(c) $A_v = V_o/V_i$.

(d) Z_o $with$ $r_0 = \infty\Omega$.

(e) $A_i = I_o/I_i$.

(f) I_b

7.0 REFERENCES/FURTHER READING

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UNIT 3 THE HYBRID EQUIVALENT MODEL

CONTENTS

1.0 INTRODUCTION

Every linear circuit has a set of parameters associated with it, which fully describe its behavior. When small ac signals are involved, a transistor behaves like a linear device because its output ac signal varies directly as the input signal. Hence for small ac signals, each transistor has its own characteristic set of *h*-parameters or constants.

The *h*-parameters depend on a number of factors such as:

1. Transistor type.
2. Configuration.
3. Operating point.
4. Temperature.
5. Frequency.

These *h*-parameters can be found experimentally or graphically.

2.0 OBJECTIVES

After going through this unit, you should be able to:

- Define the h-parameters
- Enumerate the various transistor hybrid equivalent models
- Deal with problems related to the hybrid equivalent models

3.0 MAIN CONTENT

3.1 What are h-parameters?

These are four constants which describe the behavior of a two-port linear network. A linear network is one in which resistance; inductance and capacitance remain fixed when voltage across them is changed.

Consider an unknown linear network contained in a black box as shown in fig 59.42. As a matter of convention current flowing into the box are taken positive whereas those flowing out of it are considered negative.

Fig 59.42 (3.1)

Similarly, voltages are positive from the upper to the lower terminals and negative from the other way round.

The electrical behavior of such a circuit can be described with the help of a four hybrid parameters or constants designated as h_{11}, h_{12}, h_{21}, h_{22}. In this type of double-number subscript, it is implied that the first variable is always divided by the other. The quantity 1 refers to the quantity on the input side and 2 to the quantity on the output side. The letter '*h'* has come from the word hybrid which means mixture of distinctly different items. These constants are hybrid because they have different units.

3.2 THE HYBRID EQUIVQLENT MODEL

It was pointed out earlier in the previous unit that the r_e model for a transistor is sensitive to the dc level of operation of the amplifier. The result is an input resistance that will vary with the dc operating point, for the hybrid equivalent model to be described here, the parameters are defined at an operating point that may or may not reflect the actual operating condition of the amplifier. This is due to the fact specification sheet cannot provide parameters for an equivalent circuit at every possible operating point. They must choose operating conditions that they believe reflect general characteristics of the device. The hybrid parameters as shown in fig 7.28 are drawn from the specification sheet for 2N4400 transistor. The values are provided at a dc collector current of 1 mA and a collector-to-emitter voltage of 10 V. in addition, a range of values is provided for each parameter for guidance in the initial design or analysis of a system. One obvious advantage of the specification sheet listing is the immediate knowledge of typical level for the parameters of the device as compared to other transistors.

	Min.	Max.

Input impedance 2N4400 ($I_C = 1\ mA\ dc, V_{CE} = 10\ V\ dc, f = 1kHz$)	h_{ie}	0.5	7.5	kΩ
Voltage feedback ratio $I_C = 1\ mA\ dc, V_{CE} = 10\ V\ dc, f = 1\ kHz$)	h_{re}	0.1	8.0	$\times 10^{-4}$
Small signal current gain 2N4400 $I_C = 1\ mA\ dc, V_{CE} = 10\ V\ dc, f = 1\ kHz$)	h_{fe}	20	250	—
Output admittance $I_C = 1\ mA\ dc, V_{CE} = 10\ V\ dc, f = 1\ kHz$)	h_{oe}	1.0	30	1 µS

Table 3.1 Hybrid parameter for the 2N4400 transistor

The quantities h_{ie}, h_{re}, h_{fe}, and h_{oe} of the table above are called the hybrid parameters and are the components of a small-signal equivalent circuit to be described shortly. For years, the hybrid model with all its parameters was the chosen model for the educational and industrial communities. Presently, however, the r_e model is applied more frequently, but often with the h_{oe} parameter of the hybrid equivalent model to provide some measure for the output impedance. Since specification sheet do provide the hybrid parameters and the hybrid model continues to receive a good measure of attention, it is quite important the hybrid model be covered in some details in this unit. Once developed, the similarities between r_e and hybrid models will be quite apparent. In fact, once the components of one are defined for a particular operating point, the parameters of other model are immediately available.

Our description of the hybrid equivalent model will begin with the general two-port system of fig 3.2. The following set of eq. 7.23 is only one of a number of ways in which the four variables of fig 3.2 can be related. It is the most frequently employed in transistor circuit analysis, however, and therefore is discussed in details.

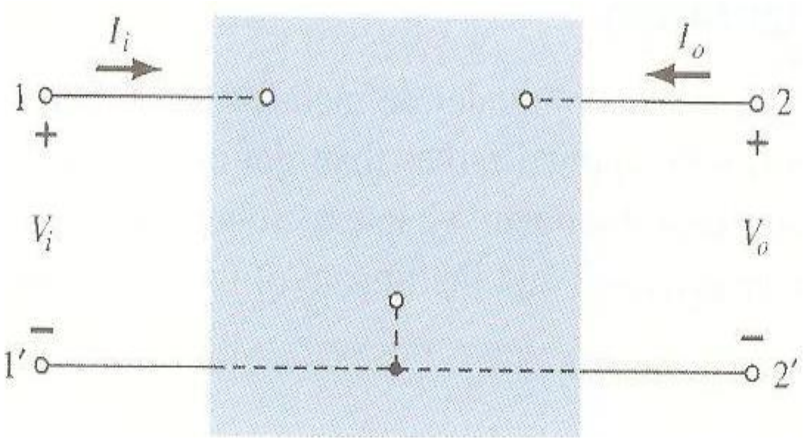

Fig 3.2 Two-port system

$$V_i = h_{11} I_i + h_{12} V_o \qquad 7.23a$$

$$I_o = h_{21} I_i + h_{22} V_o \qquad 7.32b$$

The parameters relating the four variables are called the *h-parameters* from the word "hybrid."

If we arbitrarily set $V_o = 0$ (short circuit the output terminals) and solve for h_{11} in eq. 7.23a, the following will result:

$$h_{11} = \left.\frac{V_i}{I_i}\right|_{V_o = 0} \text{ ohms} \qquad 7.24$$

The ratio indicates that the parameter h_{11} is an impedance parameter with the units of ohms. Since it is the ratio of the input voltage to the input current with the output terminals shorted, it is called the *short-circuit input-impedance parameter*. The subscript 11 of h_{11} defines the fact that the parameter is determined by the ratio of quantities measured at the input terminals.

If I_i is set equal to zero by opening the input leads, the following will result for h_{12}:

$$h_{12} = \left.\frac{V_i}{V_o}\right|_{I_o = 0} \text{ unit less} \qquad 7.25$$

The parameter h_{12}, therefore, is the ratio of the input voltage to the output voltage with the input current set to zero. It has no units since it is a ratio of voltage levels and is called *open-circuit reverse transfer voltage ratio parameter*. The subscript 12 of h_{12} reveal that the parameter is a transfer quantity determined by a ratio of input to output measurements. The first integer of the subscript defines measured quantity to appear in the numerator; the second integer defines the source of the quantity to appear in the denominator. The term reverse is included because the ratio is an input voltage over an output voltage rather than the reverse ratio typically of interest.

If in eq 7.23b, V_o is equal to zero by again shorting the output terminals, the following will result for h_{21}:

$$h_{21} = \left.\frac{I_o}{I_i}\right|_{V_o = 0} \text{ unit less} \qquad 7.26$$

Note that we now have the ratio of an output to an output quantity. The term forward will now be used rather than reverse as indicated for h_{12}. The parameter h_{21} is the ratio of the output current to the input current with the output terminals shorted. It is called the *short circuit forward transfer current ratio parameter*: and it is unit less.

The last parameter, h_{22}, can be found by again opening the input leads to set $I_I = 0$ and solving for h_{22} in eq 7.23b:

$$h_{22} = \frac{I_o}{V_o}\bigg|_{I_i=0} \quad \text{Siemens} \qquad 7.27$$

Since it is the ratio of the output current to the output voltage, it is the output conductance parameter and is measured in Siemens (S). *It is therefore called the open-circuit output admittance parameter.*

Summary of *h*-parameters

$$h_{11} = \frac{V_i}{I_i}\bigg|_{V_o=0} \quad \text{ohms} \quad \text{- input impedance}$$

$$h_{12} = \frac{V_i}{V_o}\bigg|_{I_o=0} \quad \text{unit less} \quad \text{- forward current gain}$$

$$h_{21} = \frac{I_o}{I_i}\bigg|_{V_o=0} \quad \text{unit less} \quad \text{-reverse voltage gain}$$

$$h_{22} = \frac{I_o}{V_o}\bigg|_{I_i=0} \quad \text{Siemens} \quad \text{-output admittance}$$

3.2.1 Hybrid Input Equivalent Circuit

Since each term of eq 7,23a has a unit volt, let us apply Kirchhoff's voltage law in reverse to find a circuit that fits the equation. Performing this operation will result on fig 3.3

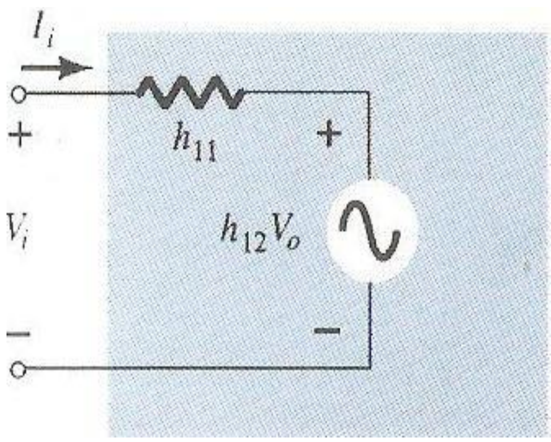

Fig 3.3*Hybrid Input Equivalent Circuit*

Since the parameter h_{11} has the unit ohm, it is represented by resistor in fig 3.3. The quantity h_{12} is dimensionless and therefore simply appears as a multiplying factor of the feedback term in the input circuit.

3.2.2 Hybrid Input Equivalent Circuit

Since each term of eq 7.23b has a unit of current, let us now apply Kirchhoff's current law in reverse to obtain the circuit of fig 3.4.

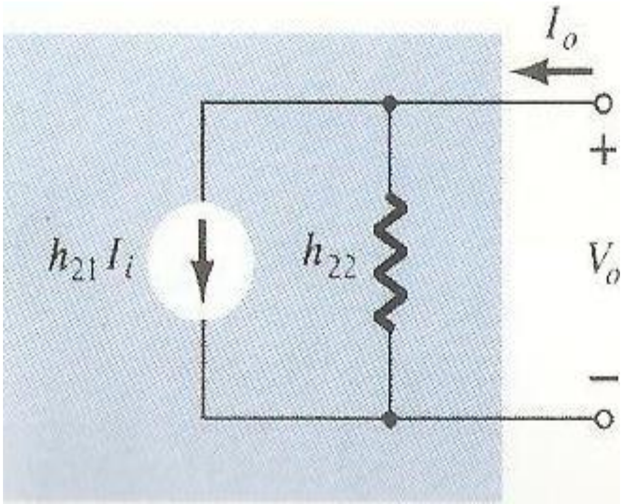

Fig 3.4 Hybrid output equivalent circuit

Since h_{22} is has the unit of admittance, which for transistor model is conductance, it is represented by the resistor symbol. Keep in mind, however, that the resistance in ohms of this resistor is equal to the reciprocal of conductance$(1/h_{22})$.

3.2.3 Complete Hybrid Equivalent Circuit

The complete "ac" equivalent circuit for the basic three-terminal linear device is indicated in fig 7.32 with a new set of subscripts for the h-parameters.

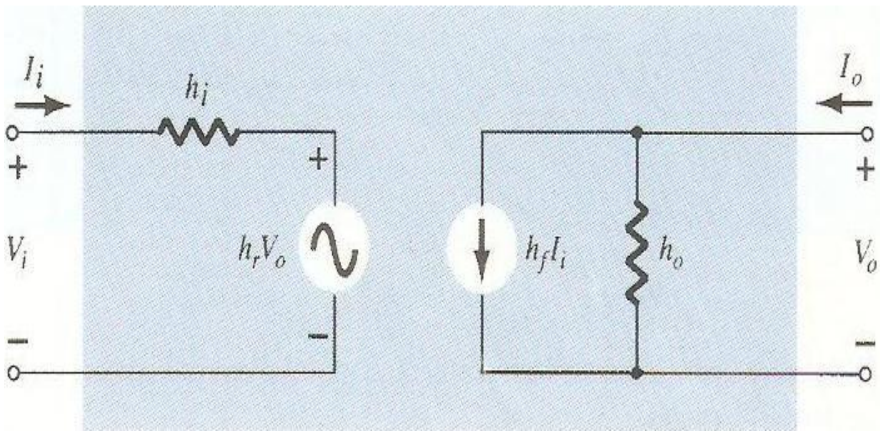

Fig 3.5 Complete hybrid equivalent circuit

The notation is of more practical nature since it relates the *h*-parameters to the resulting ratio obtained earlier.

Using the h-parameter for a three terminal device (transistor circuits), their numerical subscript are replaced by the first letters for defining them:

$$h_{11} = h_i = \text{input impedance}$$

$$h_{12} = h_f = \text{forward current gain}$$

$$h_{21} = h_r = \text{reverse voltage gain}$$

$$h_{22} = h_o = \text{output impedance}$$

A second subscript is added to the above parameters to indicate the particular configuration. For example, for common-emitter connection, the four parameters are written as :

h_{ie} h_{fe} h_{re} and h_{oe}

Similarly, for common-base and common-collector connections, these are written as h_{ib}, h_{fb}, h_{rb}, h_{ob}, and h_{ic}, h_{fc}, h_{rc}, h_{oc} respectively.

When small signals are involved, a transistor behaves like a linear device because its output ac signals varies directly as the input signal. Hence for small ac signals, each transistor has its own characteristics set of h-parameters or constants.

The h-parameter depends on a number of factors such as:

1. Transistor type
2. Configuration
3. Operating point
4. Temperature
5. frequency

These parameters can be found experimentally or graphically. The parameters h_i and h_r are determined from the input characteristics of the common-emitter transistors wheras h_f and h_o are found from the output characteristics.

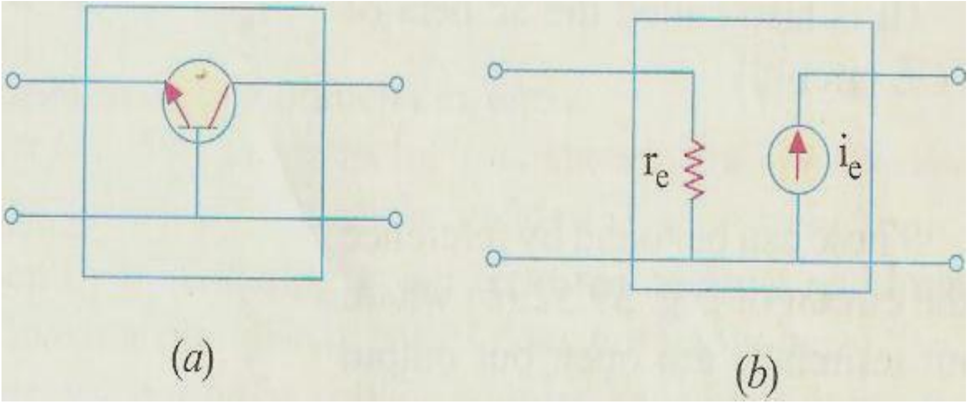

Fig 3.6

Fig 59.48a shows a common-base transistor connected in a black box. Fig 59.48b gives its equivalent circuit. It should be noted that no external biasing resistor or any signal source is connected to the transistor.

The forward h-parameters can be found from the circuit of fig 59.49a where a short has been put across the output. The input impedance is simply r_e.

$$\therefore \quad h_{ib} = r_e \qquad 7.31$$

The output current equals the input current i.e. since it flows out of the box, it is taken as negative. The forward current gain is:

$$h_{fb} = \frac{-i_e}{i_e} = -\alpha \cong -1 \qquad 7.32$$

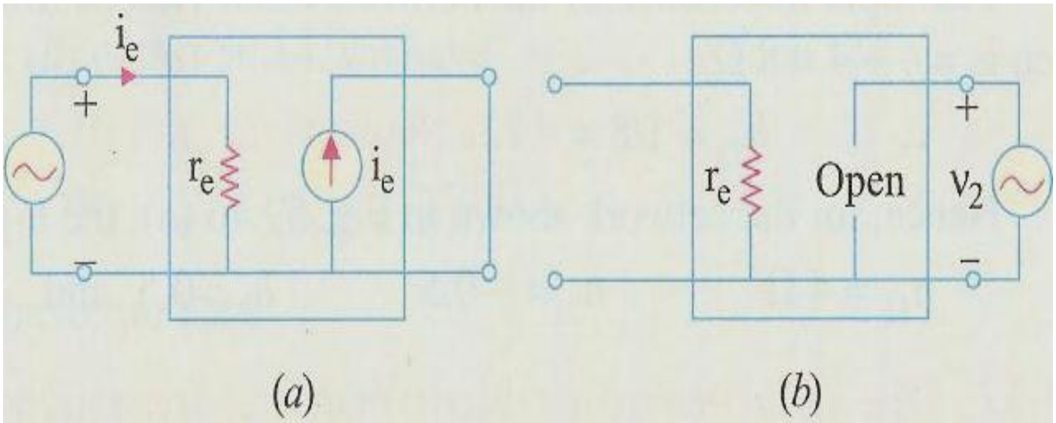

Fig 3.7

Also, the reverse parameters can be found from the circuit diagram of fig 59.49b. When input terminals are open, there can be no ac emitter current. It means that ac current source (inside the box) has a value of zero and so appears as an ‘open’. Because of this open, no voltage can appear across input terminals, however, large V_2 may be. Hence $V_1 = 0$.

$$\therefore \quad h_{rb} = \frac{v_1}{v_2} = \frac{0}{v_2} = 0$$

This procedure can also be repeated for the common-emitter configuration which will lead to:

$$h_{ie} = \beta r_e \qquad 7.33$$

$$h_{fe} = \beta \qquad 7.34$$

$$h_{re} = 0$$

$$h_{oe} = 0$$

3.3 TEST

1. Given I_E= 2.5 mA, h_{fe} = 140, h_{oc} = 20 μS (µmho) and h_{ob} = 0.5 μS, determine:

   (a) The common-emitter hybrid equivalent circuit.
   (b) The common-base r_e model.

Solution

(a) $$r_e = \frac{26\ mV}{I_E} = \frac{26\ mV}{2.5\ mA} = 10.4\ \Omega$$

$$h_{ie} = \beta r_e = (140)(10.4\ \Omega) = 1.456\ k\Omega$$

$$r_o = \frac{1}{h_{oe}} = \frac{1}{20\ \mu S} = 50\ k\Omega$$

Note fig 3.8

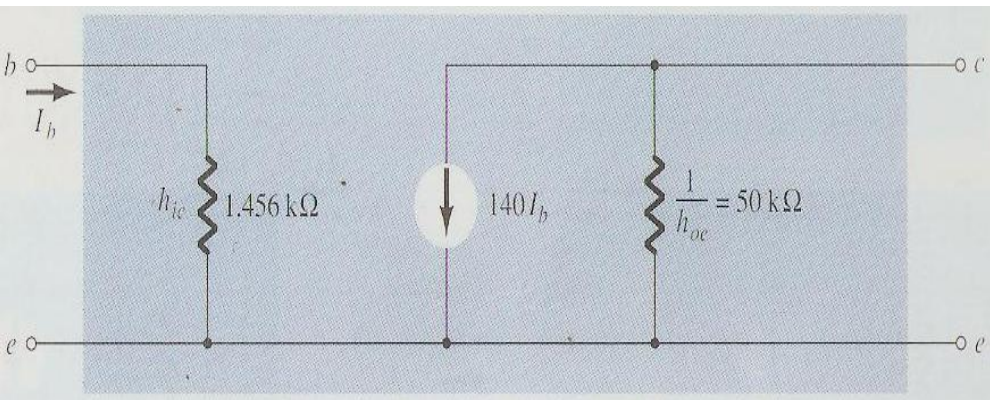

Fig 3.8

(b) $r_e = 10.4\ k\Omega$

$$\alpha \cong 1, \qquad r_o = \frac{1}{h_{ob}} = \frac{1}{0.5\ \mu S} = 2\ M\Omega$$

Note fig 3.9

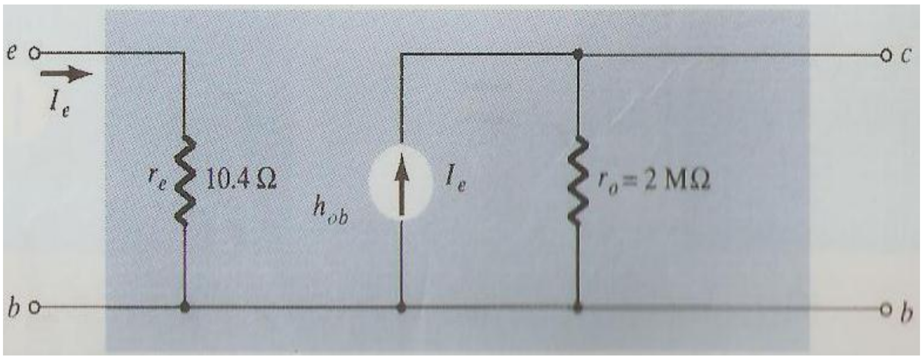

Fig 3.9

4.0 CONCLUSION

In this unit, you have been introduced to concept of the hybrid parameters and the importance of these parameters in the analysis of small signal fed to various transistor models. Also, the derivations and calculation relating to these *h*-parameters were treated.

5.0 SUMMARY

The hybrid model with all its parameters was the chosen model for the educational and industrial communities for many years. Presently, however, the r_e model is applied more frequently, but often with the h_{oe} parameter of the hybrid equivalent model to provide some measure for the output impedance. Since specification sheet do provide the hybrid parameters and the hybrid model continues to receive a good measure of attention, thus still retains its importance.

6.0 TUTOR-MARKED ASSIGNMENT

(1) Calculate the gain of a common-emitter transistor amplifier whose hybrid parameter are:

$h_{ie} = 1100\ ohms, h_{re} = 2.5 \times 10^{-4}, h_{fe} = 50, h_{oe} = 25\mu S, R_L = 5k.$

(2) A junction transistor has the following *h*-parameters $h_{ie} = 2000\ ohms, h_{re} = 15 \times 10^{-4}, h_{fe} = 49, h_{oe} = 50\ \mu S,$ determine the current gain, voltage gain, input resistance and output resistance of the CE amplifier if the load resistance is 10K and the source resistance is 600 ohm.

(3) Given $h_{ie} = 2.4\ k\Omega,\ h_{fe} = 100, h_{re} = 4 \times 10^{-4}\ and\ h_{oe} = 25\ \mu S$, skech the:

(a) common-emitter hybrid equivalent model

(b) common-emitter r_e equivalent model

(c) common-base hybrid equivalent mode

(d) common-baser r_e equivalent model

(4) (a) Describe the difference between the r_e and hybrid equivalent models for a BJT transistor.

(b) for each models, list the conditions under which it should be applied.

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UNIT 4 OPERATING POINT

CONTENTS

1.0 INTRODUCTION

The term biasing is an all-inclusive term for the application of dc voltages to establish a fixed level of current and voltage. For transistor amplifiers the resulting dc current and voltage establish an operating point on the characteristics that define the region that will be employed for amplification of the applied signal. Since the operating point is a fixed point on the on the characteristics, it is also called the quiescent point (Q-point). By definition, quiescent means, quite, still, inactive.

2.0 OBJECTIVES

By the end of this unit, you should be able to:

- Identify the various operation points of a linear device (BJT) and the associated characteristics
- Know the four possible bias combinations of a BJT and their respective bias condition.

3.0 MAIN CONTENT

Operating Point

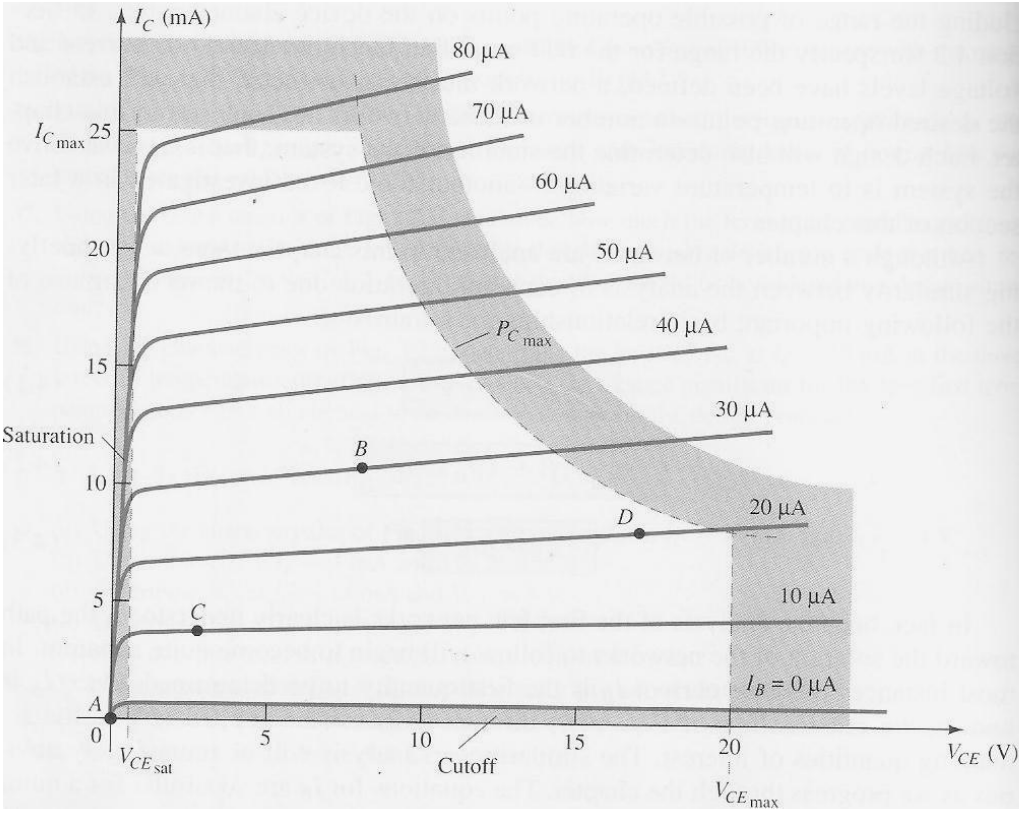

Fig 3.1

Fig 3.1 shows a general output device characteristic with four operating points indicated. The biasing circuit can be designed to set the device operation at any of these points or others within the active region. The maximum ratings are indicated on the characteristics of fig 3.1 by the horizontal line for the maximum collector current $I_{C_{max}}$ and the vertical line at the maximum collector-to-emitter voltage $V_{CE_{max}}$. The maximum power constraint is defined by the $P_{C_{max}}$ curve in the same figure. At the lower end of the scales are the cutoff region, defined by $I_B \leq 0\mu A$, and the saturation region, defined by $V_{CE} \leq V_{CE_{sat}}$.

The BJT device could be biased to operate outside its maximum limits, but the result of such operation would be either a considerable shortening of the lifetime of the device or destruction of the device. Confining ourselves to the active region, one can select many different operating areas or points. The chosen Q-point often depends on the intended use of the circuit. Still, we can consider some difference among the various points shown in fig 3.1 to present some basic ideas about the operating point and thereby, the bias circuit,

If no bias were used, the device would initially be completely off, resulting in a Q-point at A – namely, zero current through the device (and zero voltage across it).

Since it is necessary to bias a device so that it can respond to the entire range of an input signal, point A would not be suitable. For point B, if a signal is applied to the circuit, the device will vary in current and voltage from operating point, allowing the device to react to (and possibly amplify) both the positive and negative excursions of the input signal. If the input signal is properly chosen, the voltage and current of the device will vary but not enough to drive into cutoff or saturation. Point C will allow some positive and negative variation of the output signal, but the peak-to-peak would be limited by the proximity of$V_{CE} = 0\ V / I_C = 0\ mA$. Operating at point C also raise some concern about the non-linearities introduced by the fact that the space between I_B curves is rapidly changing in this region. In general, it is preferable to operate where the gain of the device is fairly constant (or linear) to ensure that the amplification of the entire swing of input is the same. Point B is a region of more linear spacing and therefore more linear operation, as shown in fig 3.1. Point D sets the device operating near the maximum voltage and power level. The output voltage swing in the positive direction is thus limited if the maximum voltage is not exceeded. Point B therefore seems the best operating point in terms of linear gain and largest possible voltage and current swing. This is usually the desired condition for small-signal amplifier but not the case necessary for power amplifiers.

One other very important biasing factor must be considered. Having selected and biased the BJT at a desired operating point, the effect of temperature must also be taken into account. Temperature causes the device parameters such as transistor current gain (β_{ac}) and the transistor leakage current (I_{CEO}) to change. Higher temperatures result in increased leakage current in the device, thereby changing the operating condition set by the biasing network. The result is that the network design must also provide a degree of temperature stability so that temperature changes result in minimum changes in the operating point. This maintenance of the operating point can be specified by a stability factor, S, which indicates the degree of change in the operating point due to temperature variation. A highly stable circuit is desirable, and stability of a few basic bias circuits will be compared.

For BJT to be biased in its linear or active operating region the following must be true;

1. The base-emitter junction must be forward-biased (p-region voltage more positive), with a resulting forward-bias voltage of about 0.6 to 0.7 V.

2. The base-collector junction must be reversed-biased (n-region more positive), with the reverse-bias voltage being any value within the maximum limit of the device

A BJT has two junctions i.e. base-emitter and base-collector junctions either of which could be forward-biased or reverse-biased. With two junctions, there are four possible combinations of bias condition.

(i) both junctions reverse-biased,

(ii) both junctions forward-biased,

(iii) BE junction forward-biased, BC junction reverse-biased.

(iv) BE junction reverse-biased, BC junction forward-biased.

Since condition (iv) is generally not used, we will consider the remaining three conditions below.

(a) Cut-off

This condition corresponds to reverse-bias for both base-emitter and base collector junctions. In fact, both diodes act like open circuits under these conditions as shown in Fig. 3.2, which is true for an ideal transistor. The reverse leakage current has been neglected. As seen, the three transistor terminals are uncoupled from each other. In cut-off, $V_{CE} = V_{CC}$.

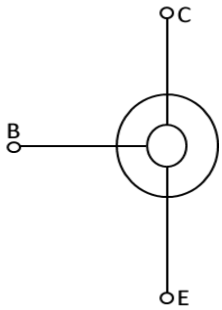

Fig. 3.2

(b) Saturation

This condition corresponds to forward-bias for both base-emitter and base-collector junctions. The transistor becomes saturated i.e. there is perfect short-circuit for both base-emitter and base-collector diodes. The ideal case is shown in Fig. 57.42, where the three transistor terminals have been connected together thereby acquiring equal potentials. In this case, VCE = 0.

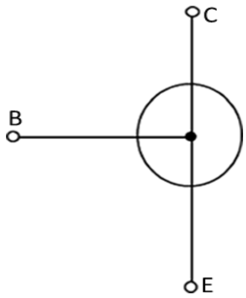

Fig.3.3

(c) Active Region

This condition corresponds to forward-bias for base-emitter junction and reverse bias for base-collector junction. In this, $VCE > 0$.

Operation in the cutoff, saturation, and linear regions of the BJT characteristic are summarized as follows:

1. *Linear-region operation:*
   Base-emitter junction forward biased
   Base-collector junction reversed biased

2. *Cutoff-region operation:*
   Base-emitter junction reverse biased

3. *Saturation-region operation:*
   Base-emitter junction forward biased
   Base-collector junction forward biased

4.0 CONCLUSION

In this unit, you have been introduced to the different operation points (Q-point) and the characteristics of these Q-points with the bias conditions.

5.0 SUMMARY

The operating point defines the characteristics of the region that will be employed for amplification of transistor amplifier's applied signal. Since the operating point is a fixed point on the on the characteristics, it is also called the quiescent point (Q-point).

6.0 TUTOR-MARKED ASSIGNMENT

7.0 REFERENCES/FURTHER READINGS

A textbook of electrical technology, B.L Theraja and A.K Theraja, New Delhi, S.C Chand, 2010

Electronic Devices and Circuit Theory, Robert L. Boylestad, New Jersey, Prentice-Hall Inc., 7th ed. 1999

UINT 5 BIAS STABILITY

CONTENTS

1.0 INTRODUCTION

The analysis or design of a transistor amplifier requires knowledge of both the dc and ac response of the system. Too often it is assumed that the transistor is a magical device that can raise the level of the applied ac input without the assistance of an external energy source. In actuality, the improved output ac power level is the result of a transfer of energy from the applied dc supplies. The analysis or design of any electronic amplifier therefore has two components: the dc portion and the ac portion. However, one must keep in mind that during the design or synthesis stage the choice of parameters for the required dc levels will affect the ac response, and vice-versa.

The dc level of operation of a transistor is controlled by a number of factors, including the range of possible operating point on the device characteristics.

The term biasing is an all-inclusive term for the application of dc voltages to establish a fixed level of current and voltage.

2.0 OBJECTIVES

By the end of this unit, you should be able to:

- Develop a level of familiarity with the BJT transistor that would permit a dc analysis of any system that might employ the BJT amplifier.
- Familiarize with the various bias circuits.

3.0 MAIN CONTENT

3.1 Fixed-Bias Circuit

The fixed-bias circuit of fig 3.1 provides a relatively straightforward and simple introduction to transistor dc bias analysis. Even though the network employs an *npn* transistor, the equations and calculations apply equally well to a *pnp* transistor configuration merely by changing all current direction and voltage polarities. The current direction of fig 3.1 is actually current directions, and the voltages are defined by the standard double-subscript notation. For the dc analysis the network can be isolated from the indicated ac level by replacing the capacitor with an open circuit equivalent. In addition, the dc supply V_{cc} can be separated into two supplies (for analysis purpose only) as shown in fig 3.2 to permit a separation of input and output circuits. It also reduces the linkage between the two to the base current I_B. the separation is certainly valid, as we note in fig 3.2 that V_{CC} is connected directly to R_B and R_C just as in fig 3.1.

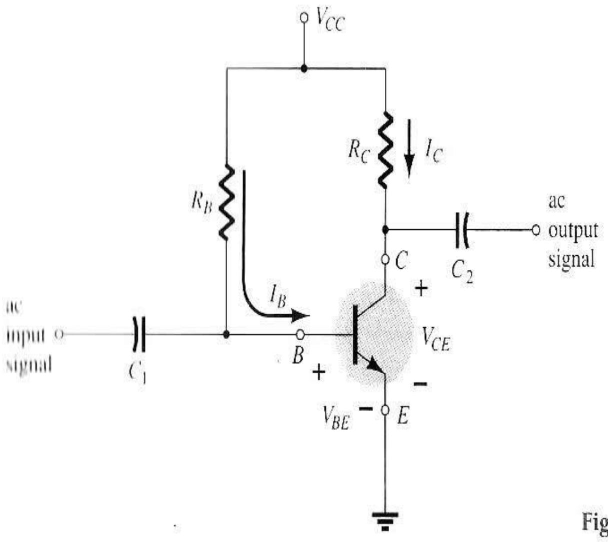

Figure 3.1 Fixed-bias circuit.

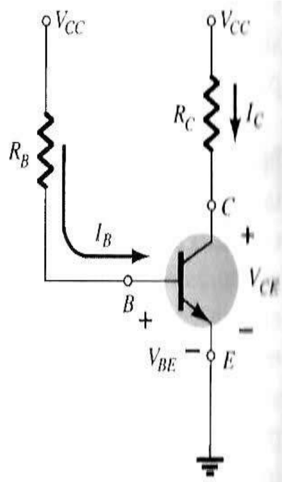

Figure 3.2 dc equivalent of Fig. 3.1

Forward Bias Base Emitter

Consider first the base-emitter circuit loop of fig 3.3. Writing Kirchhoff's voltage equation in the clockwise direction for the loop, we obtain

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

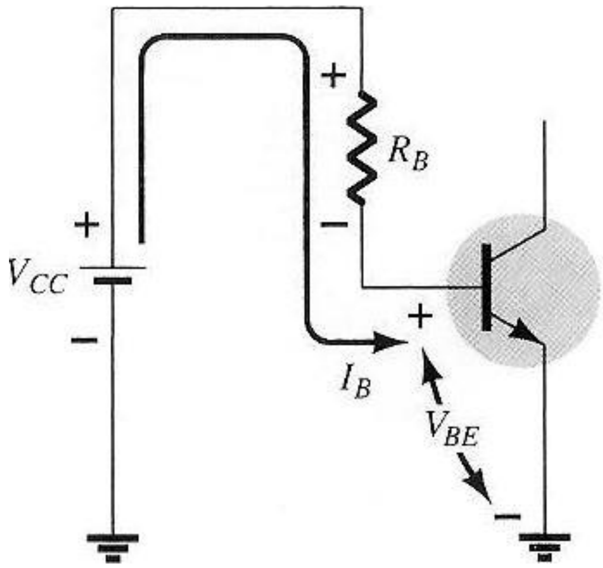

Fig 3.3 Base-emitter loop.

Note the polarity of the voltage drop across R_B as established by the indicated direction of I_B. Solving the equation for the current I_B will result in the following

IB= VCC- VBERB

This equation is certainly not a difficult one to remember if one simply keeps in mind that the base current is the current through R_B divided the resistance R_B. The voltage across R_B is the applied voltage V_{CC} at one end less the drop across the base-emitter junction (V_{BE}).

In addition, since the supply voltage V_{CC} and the base-emitter voltage V_{BE} are constant, the selection of base resistor, R_B, sets the level of base current for the operating point.

Collector-Emitter Loop

The collector-emitter section of the network appears in fig 3.4 with the indicated direction of current I_C and the resulting polarity across R_C. The magnitude of the collector current is related directly to I_B through

IC= βIB

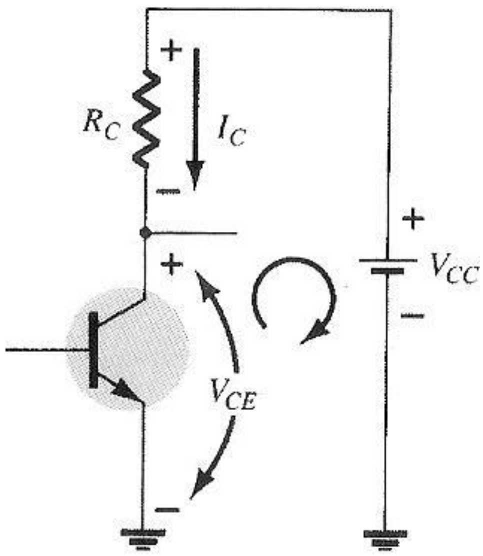

Fig 3.4 Collector-emitter loop.

It is interesting to note that since the base current is controlled by the level of R_B and I_C is related to I_B by a constant β, the magnitude of I_C is not a function of the resistance R_C. Change R_C to any level and it will not affect the level of I_B or I_C as long as we remain in the active region of the device. However, as we shall see, the level of R_C will determine the magnitude of V_{CE}, which is an important parameter.

Applying Kirchhoff's voltage law in clockwise direction around the indicated closed loop of fig 3.4 will result in the following:

VCE+ ICRC-VCC=0

And

VCE= VCC- ICR_C

which states in words that the voltage across the collector-emitter region of a transistor in a fixed-bias configuration is the supply voltage less the drop across R_C.

As a brief review of single- and double-subscript notation note that

VCE= VC- VE

Where V_{CE} is the voltage from collector to emitter and V_C and V_E are the voltages from collector and emitter to ground respectively. But in this case, since $V_E = 0\ V$, we have

VCE= VC

In addition, since

VBE= VB- VE

and $V_E = 0\ V$, then

VBE= VB

Example Determine the following for the fixed-bias configuration of fig 3.5

(a) IBQ and ICQ
(b) VCEQ
(c) VB and VC
(d) VBC

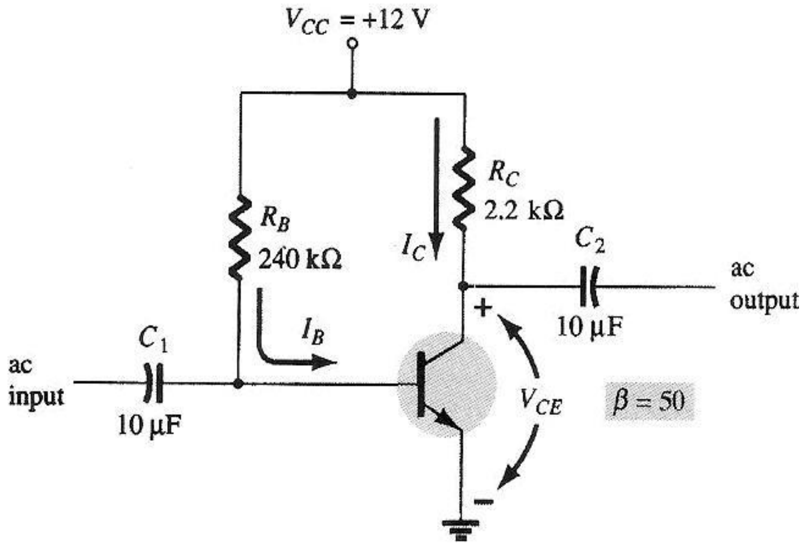

Fig 3.5 dc fixed bias circuit

Solution

(a) IBQ= VCC- VBERB= $\frac{12\ V - 0.7\ V}{240\ k\Omega} = \mathbf{47.08\ \mu A}$

ICQ= βIBQ= $(50)(47.08\ \mu A) = \mathbf{2.3\ mA}$

(b) VCEQ=VCC- ICR_C
=12 V-(2.35 mA)(2.2 kΩ)
=6.83 V

(c) VB= VBE=0.7 V
VC= VCE=6.83 V

(d) Using double-subscript notation yields
VBC= VB-VC =0.7 V$-6.83\ V$
= -6.13 V

With the negative sign revealing that the junction is reversed-biased, as it should be for linear amplification.

3.2 Emitter-Stabilized Bias Circuit

The dc bias network of fig 3.6 contains an emitter resistor to improve the stability level over that of the fixed-bias configuration. The analysis will be performed by first examining the base-emitter loop and then using the result to investigate the collector-emitter loop.

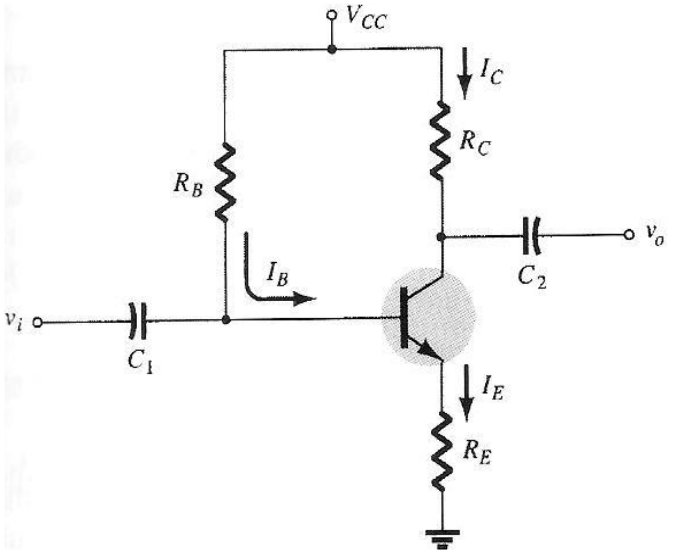

Fig 3.6 BJT bias circuit with emitter resistor.

Base-Emitter Loop

The base-emitter loop of network of fig 3.6 can be redrawn as shown in fig 3.7. Writing Kirchhoff's voltage law around the indicated loop in the clockwise direction will result in the following equations:

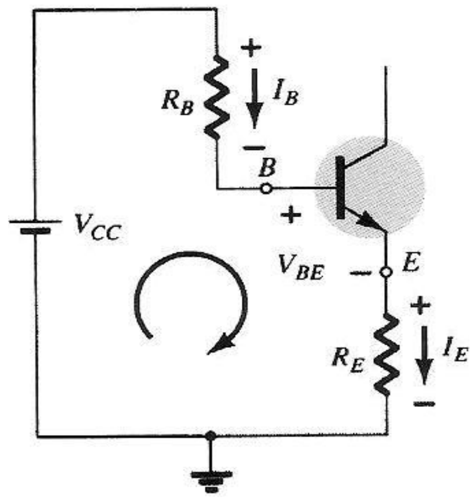

Fig 3.7Base-emitter loop.

+VCC- IBRB- VBE-IERE= 0
4.15

Recall that IE=(β +1)IB 4.16

Substituting for I_E in Eq 4.15 will result in

VCC- IBRB- VBE-β+1IBRE=0

Expanding and multiplying through by (-1) we have

IBRB+β+1RE- VCC+ VBE=0

And solving for I_B gives

IB= VCC- VBERB+(β+1)RE

Note that the only difference between this equation for I_B and that for the fixed-bias configuration is the term$(\beta + 1)R_E$.

Collector-Emitter Loop

The collector-emitter loop is redrawn in fig 3.8. Writing Kirchhoff's voltage law for the indicated loop in the clockwise direction will result in

$+ I_E R_E + V_{CE} + I_C R_C - V_{CC} = 0$

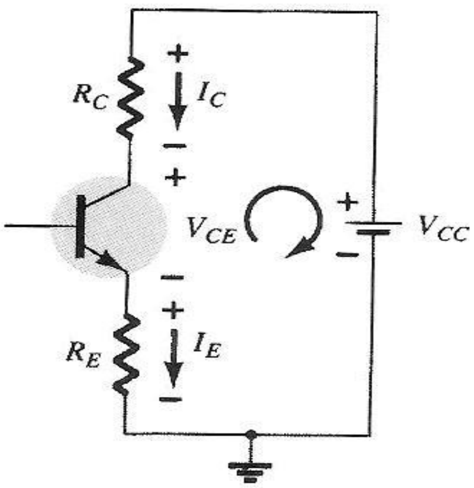

Figure 3.8 Collector–emitter loop.

Substituting $I_E \cong I_C$ and regrouping terms gives

$V_{CE} - V_{CC} + I_C(R_C + R_E) = 0$

and

$V_{CE} = V_{CC} - I_C(R_C + R_E)$ 4.19

The single subscript voltage V_E is the voltage from emitter to ground and is determined by

$V_E = I_E R_E$4.20

While the voltage from collector to ground can be determined from

$V_{CE} = V_C - V_E$

and

$$V_C = V_{CE} + V_E \qquad 4.21$$

or

$$V_C = V_{CC} - I_C R_C \qquad 4.22$$

The voltage at the base with respect to ground can be determined from

$$V_B = V_{CC} - I_B R_B \qquad 4.23$$

$$V_B = V_{BE} + V_E \qquad 4.24$$

3.3 Voltage Divider Bias

In the previous bias configurations the bias current I_{C_Q} and voltage V_{CE_Q} were a function of the current Gain (β) of the transistor. However, since β is temperature sensitive, especially for silicon transistors, and the actual value of beta is usually not well defined, it will be desirable to develop a bias circuit that is less dependent, or in fact, independent of the transistor beta. The voltage-divider bias configuration of fig 3.9 is such a network. If analyzed on an exact basis the sensitivity to changes in beta is quite small. If the circuit parameters are properly chosen, the resulting level of I_{C_Q} and V_{CE_Q} can be almost totally independent of beta. Recall, from previous discussion that a Q-point is defined by fixed level of I_{c_Q} and V_{CE_Q} as shown in fig 3.10. The level I_{B_Q} will change with the change in beta, but the operating point on the characteristic defined by I_{C_Q} and V_{CE_Q} can remain fixed if the proper circuit parameters are employed.

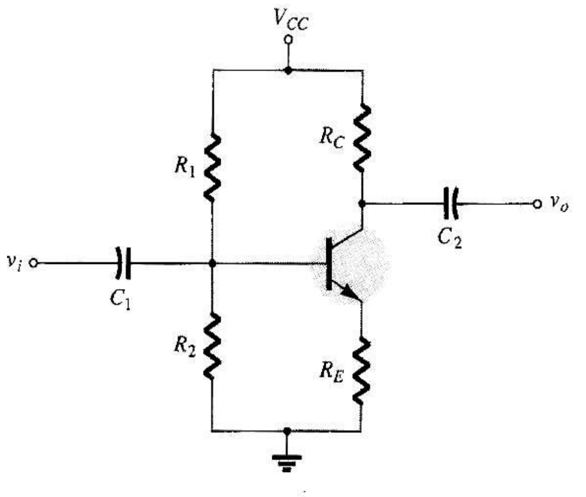

Figure 3.9 Voltage-divider bias configuration.

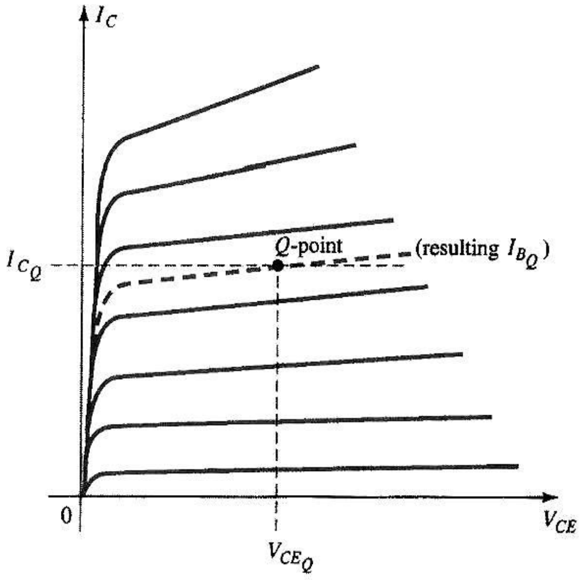

Figure 3.10 Defining the Q-point for the voltage-divider bias configuration.

As noted above, there are two methods that can be applied to analyze the voltage–divider configuration. The reason for the choice of names for this configuration will become obvious in the analysis to follow. The first to be demonstrated is the exact method that can be applied to any voltage–divider configuration. The second is refers to as approximate method and can be applied only if specific conditions are satisfied. The approximate approach permits a more direct analysis with a savings in time and energy. It is also particularly helpful in the designed made to be described later.

3.3.1 Exact Analysis

The input side of the network of fig 3.9 can be redrawn as shown in fig 3.11for the dc analysis. The Thevenin equivalent network for the network to the left of the base terminal can be found in the following manner:

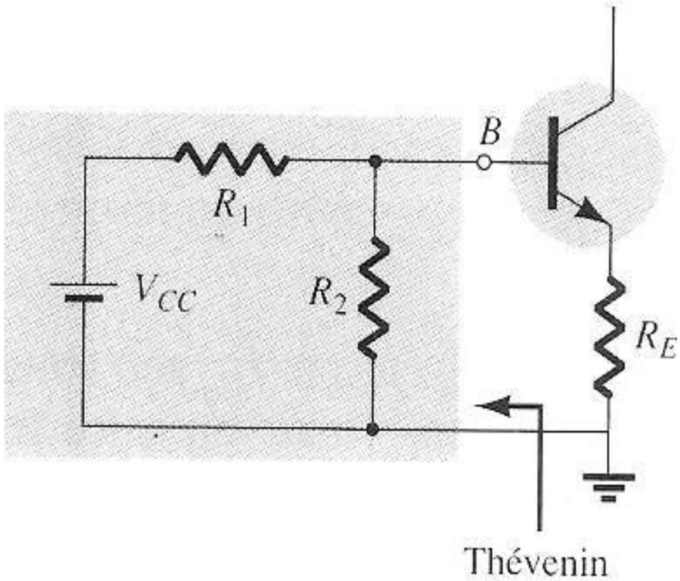

Fig 3.11 Redrawing the input side of the network of Fig.3.9

R_{Th}: The voltage source is replaced by a short-circuit equivalent as shown in fig 3.12.

$$R_{Th} = R_1 \| R_2 \qquad 4.28$$

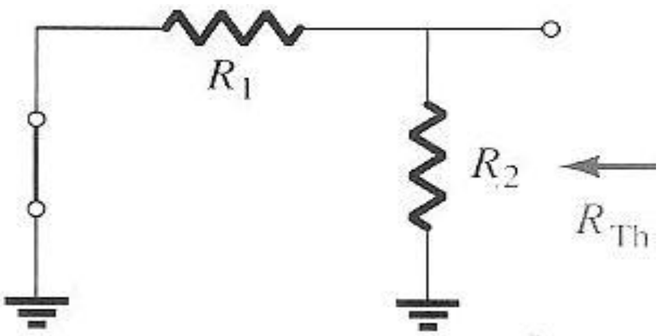

Fig 3.12

E_{Th}: The voltage source V_{CC} is returned to the network and the open-circuit Thevenin voltage of fig 3.13 determined as follows:

Applying the voltage-divider rule:

$$E_{Th} = V_{R_2} = \frac{R_2 V_{CC}}{R_1 + R_2} \qquad 4.29$$

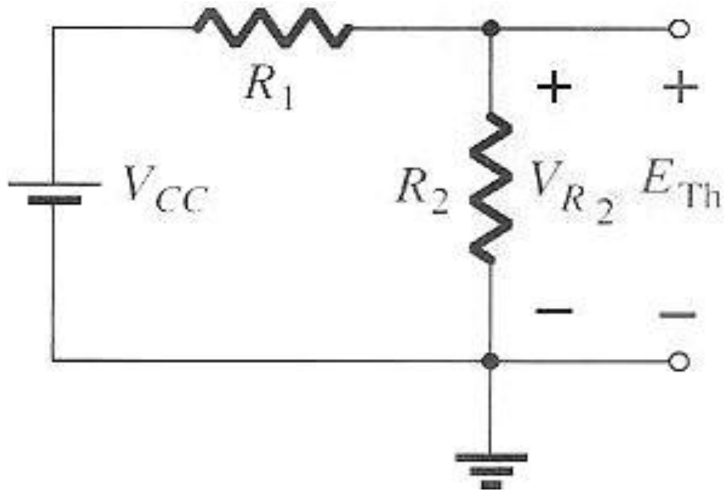

Fig 3.13

The Thevenin network is redrawn as shown in fig 3.14, and I_{BQ} can be determined by first applying Kirchhoff's voltage law in the clockwise direction for the loop indicated:

$E_{Th} - I_B R_{Th} - V_{BE} - I_E R_E = 0$

Substituting $I_E = (\beta + 1)I_B$ and solving for I_B yields

$$I_B = \frac{E_{Th} - V_{BE}}{R_{Th} + (\beta+1)R_E} \quad 4.30$$

Although Eq 4.30 initially appears different from those earlier, note that the numerator is again a difference of two voltage levels and the denominator is the base resistance plus the emitter resistor reflected by $(\beta + 1)$--- certainly very similar to Eq 4.17.

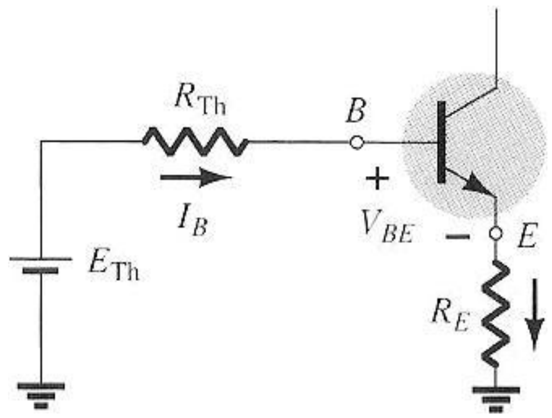

Fig 3.14

Once I_B is known, the remaining quantities of the network can be found in the same manner as developed for the emitter-bias configuration. That is,

$$V_{CE} = V_{CC} - I_C(R_C + R_E) \qquad 4.31$$

Which is exactly the same as Eq 4.19. The remaining equations for V_E, V_C *and* V_B are also the same as obtained for the emitter-bias configuration.

3.3.2 Approximate Analysis

The input section of the voltage-divider configuration can be represented by the network of fig 3.15 the resistance R_i is the equivalent resistance between base and ground for the transistor with an emitter resistor R_E. Recall that $R_i = (\beta + 1)R_E$. If R_i is much larger than the resistance R_2, the current I_B will be much smaller than I_2 (current always seek the path of the least resistance) and I_2 will be approximately equal to I_1. If we accept the approximation that I_B is essentially zero amperes compared to I_1 *or* I_2, then $I_1 = I_2$ and R_1 and R_2 can be considered series elements. The voltage across R_2, which is actually the base voltage, can be determined using the voltage-divider rule (hence the name for the configuration). That is:

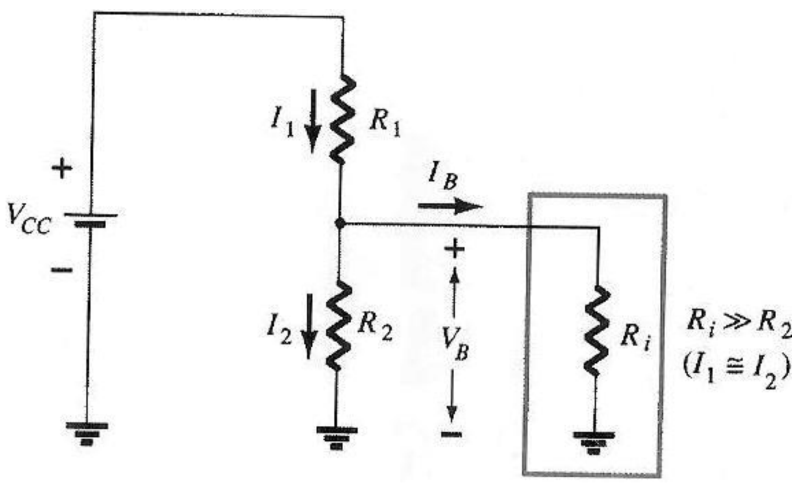

Fig 3.15 Partial-bias circuit for calculating the approximate voltage V_B

$$V_B = \frac{R_2 V_{CC}}{R_1 + R_2} \qquad 4.32$$

Since $R_1 = (\beta + 1)R_E \cong \beta R_E$ the condition that will define whether the approximate approach can be applied will be the following:

$$\beta R_E \geq 10R_2 \qquad 4.33$$

In other words, if β times the value of R_E is at least 10 times the value of R_2, the approximate approach can be applied with a high degree of accuracy.

Once V_B is determined, the level of V_E can be calculated from

$$V_E = V_B - V_{BE} \quad 4.34$$

And the emitter current can be determined from

$$I_E = \frac{V_E}{R_E} \quad 4.35$$

And

$$I_{C_Q} \cong I_E \quad 4.36$$

The collector-to-emitter voltage is determined by

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

But since $I_E \cong I_C$,

$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E) \quad 4.37$$

Note in the sequence of calculations from Eq 4.33 through Eq 4.37 that β does not appear and I_B was not calculated. The Q-point (as determined by I_{C_Q} and V_{CE_Q}) is therefore independent of the value of β.

3.4 TEST

Question 1

For the emitter bias network of Fig 3.16, determine:

(a) I_B.
(b) I_c.
(c) V_{CE}.
(d) V_C.
(e) V_E.
(f) V_B.
(g) V_{BC}.

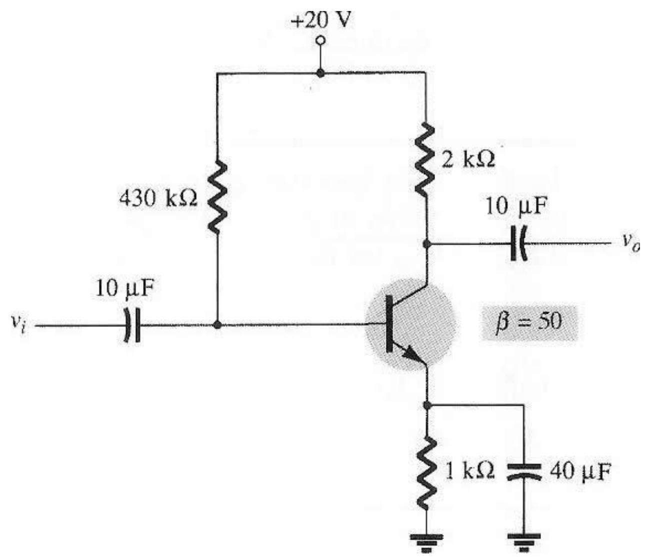

Fig 3.16

Solution

(a) $$I_B = \frac{V_{CC} - V_{BE}}{R_B + (\beta+1)R_E} = \frac{20\ V - 0.7\ V}{430\ k\Omega + (51)(1\ k\Omega)}$$

$$= \frac{19.3\ V}{481\ k\Omega} = \mathbf{40.1\ \mu A}$$

(b) $$I_C = \beta I_B$$

$$= (50)(40.1\ \mu A)$$

$$= \mathbf{2.01\ mA}$$

(c) $$V_{CE} = V_{CC} - I_C(R_C + R_E)$$

$$= 20\ V - (2.01\ mA)(2\ k\Omega + 1\ k\Omega)$$

$$= 20\ V - 6.03\ V = \mathbf{13.97\ V}$$

(d) $$V_C = V_{CC} - I_C R_C$$

$$= 20\ V - (2.01\ mA)(2\ k\Omega)$$

$$= 20\ V - 4.02\ V = \mathbf{15.98\ V}$$

(e) $$V_E = V_C - V_{CE}$$

$$= 15.98\ V - 13.97\ V = \mathbf{2.01\ V}$$

Or $V_E = I_E R_E \cong I_C R_E$

$= (2.01\ mA)(1\ k\Omega)$

$= \mathbf{2.01\ V}$

(f) $V_B = V_{BE} + V_E$

$= 0.7\ V + 2.01\ V$

$= \mathbf{2.17\ V}$

(g) $V_{BC} = V_B - V_C$

$= 2.71\ V - 15.98\ V$

$= \mathbf{-13.27\ V}$ (reversed-biased as required)

Question 2

Determine the dc bias voltage V_{CE} and the current I_C for the voltage-divider configuration of Fig 3.17.

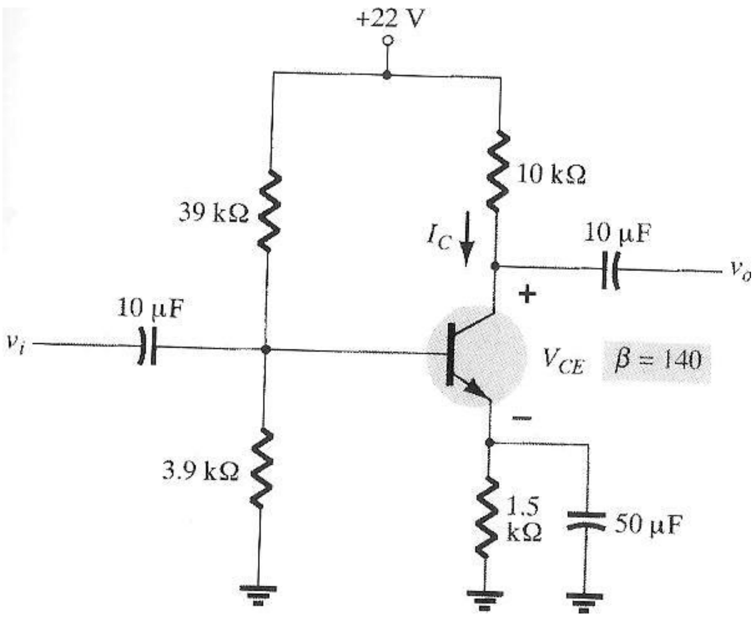

Fig 3.17

Solution

$R_{Th} = R_1 \| R_2$

$$= \frac{(39\ k\Omega)(3.9\ k\Omega)}{39\ k\Omega + \ 3.9\ k\Omega} = 3.55\ k\Omega$$

$$E_{Th} = \frac{R_2 V_{CC}}{R_1 + \ R_2}$$

$$= \frac{(39\ k\Omega)(22\ V)}{39\ k\Omega + \ 3.9\ k\Omega} = 2\ V$$

$$I_B = \frac{E_{Th} - \ V_{BE}}{R_{Th} + (\beta + 1)R_E}$$

$$= \frac{2\ V - 0.7\ V}{3.55\ k\Omega - (141)(1.5\ k\Omega)} = \frac{1.3}{3.55\ k\Omega + 211.5\ k\Omega}$$

$= 6.05\ \mu A$

$I_C = \ \beta I_B = (140)(\ 6.05\ \mu A)$

$= \mathbf{0.85\ mA}$

$V_{CE} = \ V_{CC} \ - \ I_C(R_C + \ R_E)$

$= 22\ V - (0.85\ mA)(10\ k\Omega + 1.5\ k\Omega)$

$= 22\ V - 9.78\ V$

$= \mathbf{12.22\ V}$

Question 3

Repeat the analysis of Fig 3.17 using the approximate technique, and compare the solutions for I_{C_Q} and V_{C_Q}.

Solution

Testing:

$\beta R_E \ \geq 10R_2$

$(140)(1.5\ k\Omega) \ \geq 10(3.9\ k\Omega)$

$210\ k\Omega \ \geq 39\ k\Omega \ \ (satisfied)$

$$V_B = \frac{R_2 V_{CC}}{R_1 + R_2}$$

$$= \frac{(3.9\ k\Omega)(22\ V)}{39\ k\Omega + 3.9\ k\Omega}$$

$$= 2\ V$$

$$V_E = V_B - V_{BE}$$

$$= 2\ V - 0.7\ V$$

$$= 1.3\ V$$

$$I_{C_Q} \cong I_E = \frac{V_E}{R_E}$$

$$\frac{1.3\ V}{1.5\ k\Omega} = \mathbf{0.867\ mA}$$

Compared to $0.85\ mA$ with the exact analysis. Finally,

$$V_{CE_Q} = V_{CC} - I_C(R_C + R_E)$$

$$= 22\ V - (0.867\ mA)(10\ k\Omega + 1.5\ k\Omega)$$

$$= 22\ V - 9.97\ V$$

$$= \mathbf{12.03\ V}$$

Versus 12.22 V obtained in the exact analysis.

4.0 CONCLUSION

In this unit, you have been introduced to the various conditions of bias and the different bias circuits.

5.0 SUMMARY

The term biasing is an all-inclusive term for the application of dc voltages in the analysis or design of a transistor amplifier to establish a fixed level of current and voltage. The analysis or design of any electronic amplifier therefore has two components: the dc portion and the ac portion and the choice of parameters for the required dc levels will affect the ac response, and vice-versa.

6.0 TUTOR-MARKED TUTORIAL

1. For the fixed-bias configuration of Fig 3.18, determine:

(a) I_{B_Q}.
(b) I_{c_Q}.
(c) V_{CE_Q}.
(d) V_C.
(e) V_B.
(f) V_E.

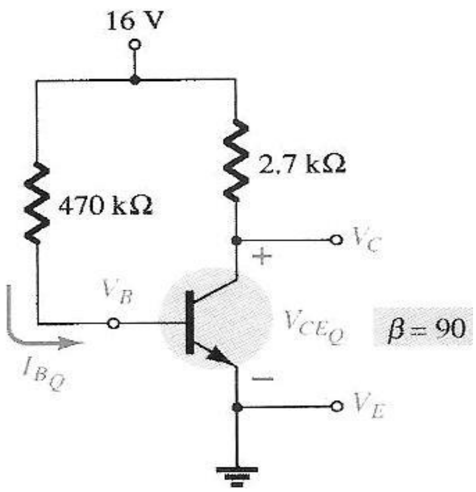

Fig 3.18

2. Given the information appearing in fig 3.19, determine:

(a) I_C.
(b) V_{CC}.
(c) β.
(d) R_B.

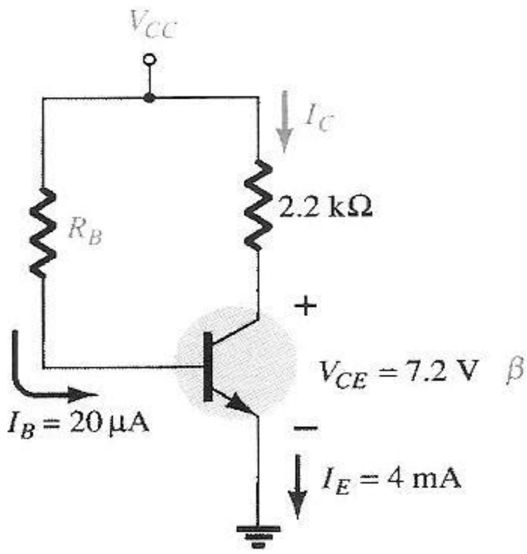

Fig 3.19

3. For the emitter-stabilized bias circuit of Fig 3.20, determine:

(a) I_{B_Q}.

(b) I_{c_Q}.

(c) V_{CE_Q}.

(d) V_C.

(e) V_B.

(f) V_E.

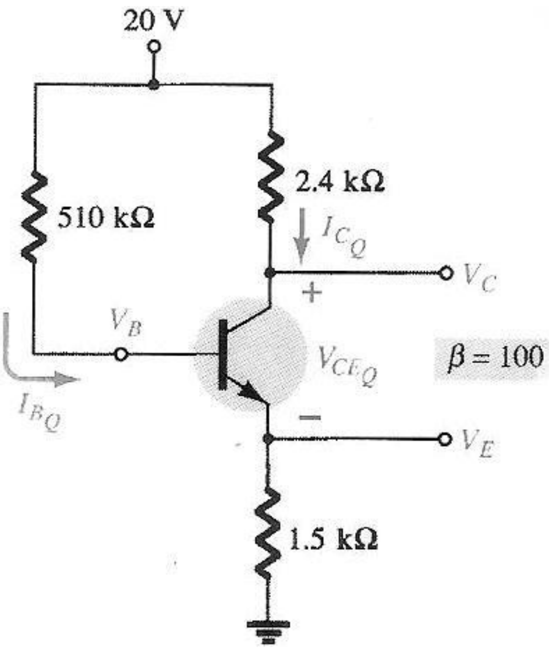

Fig 3.20

4. Given the information provided in Fig 3.21, determine:

(a) R_C.
(b) R_E.
(c) R_B.
(d) V_{CE}.
(e) V_B.

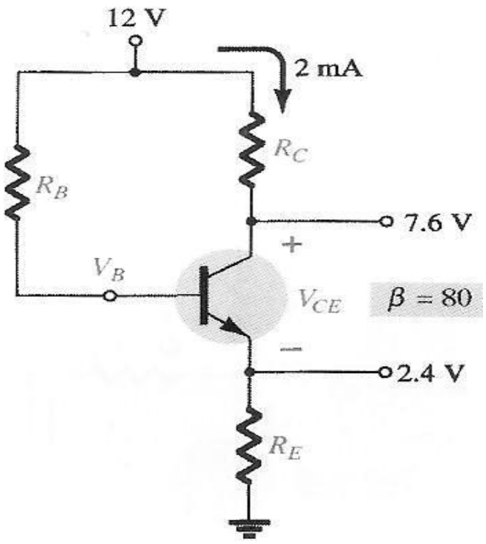

Fig 3.21

5. For the emitter-stabilized bias circuit of Fig 3.22, determine:

(a) I_{B_Q}.
(b) I_{c_Q}.
(c) V_{CE_Q}.
(d) V_C.
(e) V_B.
(f) V_E.

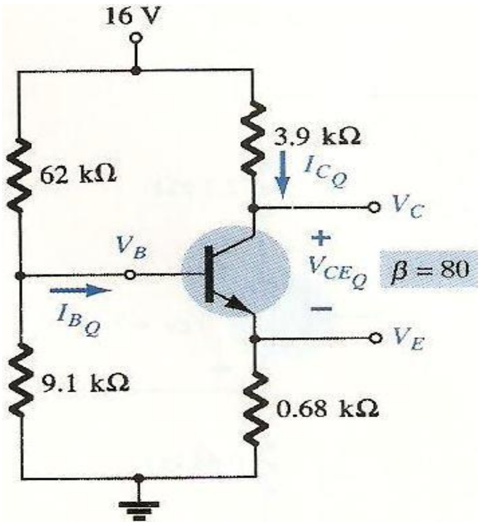

Fig 3.22

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MODULE 2 OSCILLATORS

UNIT 1 NEGATIVE FEEDBACK

CONTENTS

1.0 INTRODUCTION

Oscillators are circuits that produce periodic waveforms. In oscillators, the only input requirement is of DC power supply which is required for operation of the active device.

An oscillator can be thought of as an amplifier that provides itself (through feedback) with an input signal.

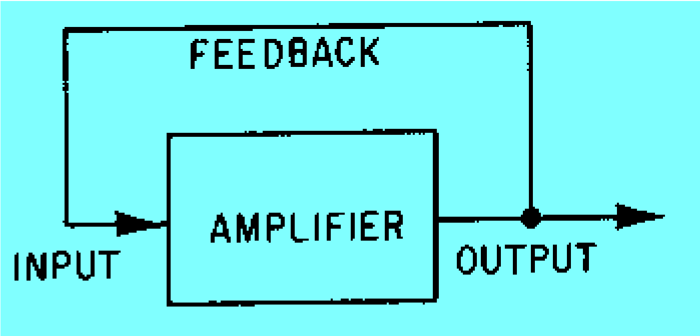


Figure 1.1 - Basic oscillator block diagram.

Feedback is the process of transferring energy from a high-level point in a system to a low-level point in a system. This means transferring energy from the output of an amplifier back to its input. If the output feedback signal opposes the input signal, the signal is DEGENERATIVE or NEGATIVE FEEDBACK. However, if the feedback aids the input signal, the feedback is REGENERATIVE or POSITIVE FEEDBACK. Regenerative or positive feedback is one of the requirements to sustain oscillations in an oscillator. This feedback can be applied in any of several ways to produce a practical oscillator circuit.

Depending on the relative polarity of the signal being fed back into a circuit, one may have negative or positive feedback. Negative feedback results in decreased voltage gain, for which a number of circuit features are improved as summarized below. Positive feedback drives a circuit into oscillation as in various types of oscillator circuits.

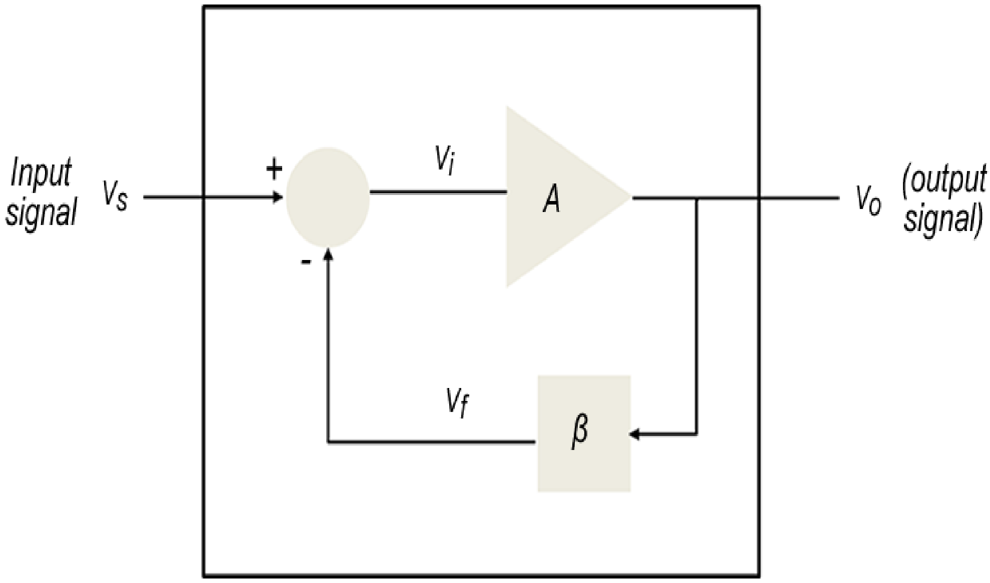


Figure 1.2- Simple block diagram of a feedback amplifier

A typical feedback connection is shown in Figure 2.3. The input signal, V_s, is applied to a mixer network, where it is combined with a feedback signal, A'. The difference of these signals, V_o, is connected to the feedback network (β), which provides a reduced portion of the output as feedback signal to the input mixer network.

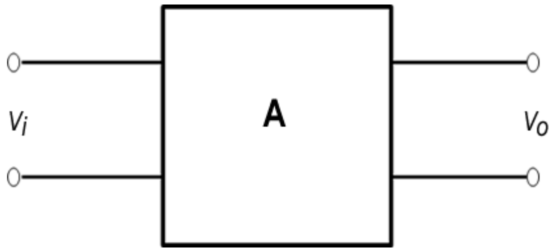


Figure 1.3

For an ordinary amplifier i.e. one without feedback, the voltage gain is given by the ratio of the output voltage V_o and input voltage V_i. As shown in the block diagram of Fig. 2.4, the input voltage V_i is amplified by a factor of A to the value Vo of the output voltage.

$$\therefore\ A = \frac{V_o}{V_i}$$

This gain A is often called *open-loop* gain.

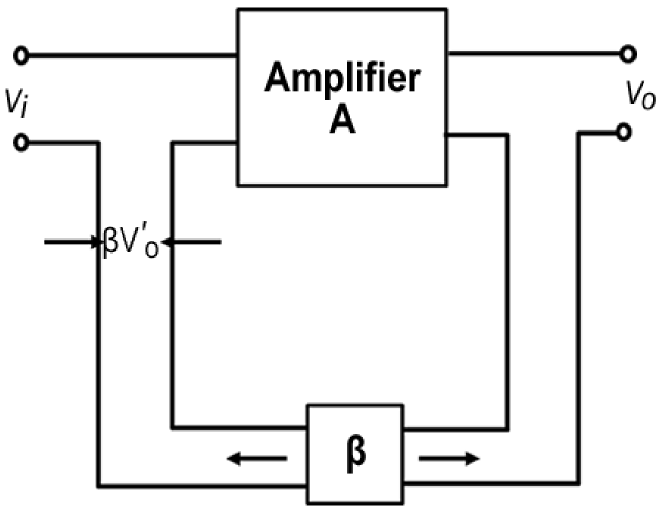


Fig. 1.4 *Feedback Loop*

Suppose a feedback loop is added to the amplifier (Fig. 2.5). If V_o' is the output voltage with feedback, then a fraction β (it is not the same as the β of a transistor) of this voltage is applied to the input voltage which, therefore, becomes $(V_i \pm \beta V_o')$ depending on whether the feedback voltage is in phase or anti-phase with it. Assuming positive feedback, the input voltage will become $(V_i \pm \beta V_o')$ When amplified A times, it becomes $A(V_i \pm \beta V_o')$

$$\therefore \quad A\,(V_i \pm \beta V_o') = V_o'$$

$$or \quad V_o'(1 - \beta A) = AV_i$$

The amplifier gain A' with feedback is given by

$$A' = \frac{V_o'}{V_i} = \frac{A}{1 - \beta A}$$

$$\therefore \quad A' = \frac{A}{1-\beta A} \text{— Positive feedback}$$

$$= \frac{A}{1-(\beta A)} = \frac{A}{1+\beta A} \qquad \text{— Negative feedback}$$

The term 'βA' is called *feedback factor* whereas β is known as *feedback ratio*. The expression $(1 \pm \beta A)$ is called loop gain. The amplifier gain A' with feedback is also referred to *as closed-loop gain* because it is the gain obtained after the feedback loop is closed. The sacrifice factor is defined as $S = A/A'$.

2.0 OBJECTIVES

By the end of this unit, you should be able to:

- Understand the concept of feedback and the types of feedbacks.
- Establish the implication of Negative feedback.
- Know the forms and advantages and disadvantage of negative feedback and its applications.

3.0 MAIN CONTENT

3.1 Negative Feedback

If the feedback signal is of opposite polarity to the input signal, as shown in Fig 1.2, negative feedback results.

The amplifier gain with negative feedback is given by, $A' = \frac{A}{1+\beta A}$

Obviously, $A' < A$ because $|1 + \beta A| > 1$.

Suppose, $A = 90$ and $\beta = 1/10 = 0.1$

Then, gain without feedback is 90 and with negative feedback is

$$A' = \frac{A}{1 + \beta A} = \frac{90}{1 + 0.1 \times 90} = 9$$

As seen, negative feedback reduces the amplifier gain. That is why it is called *degenerative feedback*. A lot of voltage gain is sacrificed due to negative feedback. When $|\beta A| \gg 1$, then

$$A' = \frac{A}{\beta A} \cong \frac{1}{\beta}$$

It means that A´ depends only on β. But it is very stable because it is not affected by changes in temperature, device parameters, supply voltage and from the aging of circuit components etc. Since resistors can be selected very precisely with almost zero temperature-coefficient of resistance, it is possible to achieve highly precise and stable gain with negative feedback.

3.2 Advantages of Negative Feedback

While negative feedback results in reduced overall voltage gain, a number of improvements are obtained, among them being:

- High input impedance.
- Better stabilized voltage gain.
- Improved frequency response.
- Lower output impedance.
- Reduced noise.
- More linear operation.
- Less harmonic distortion.
- Less phase distortion.
- Less amplitude distortion.

Example

In the series-parallel (SP) feedback amplifier of Fig. 3.1, calculate:

(a) Open-loop gain of the amplifier,

(b) Gain of the feedback network,

(c) Closed-loop gain of the amplifier,

(d) Sacrifice factor, S.

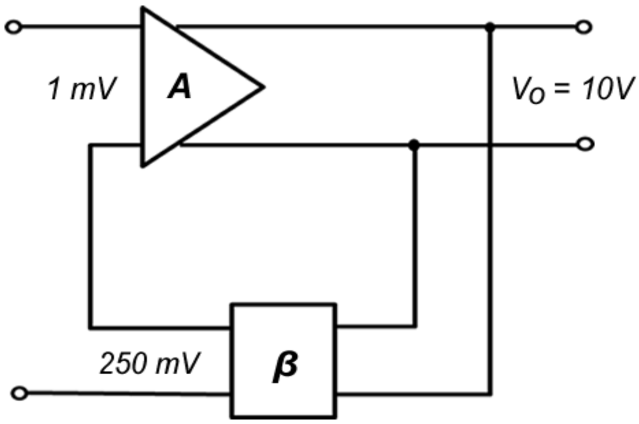


Figure 3.1

Solution

(a) Since 1 mV goes into the amplifier and 10 V comes out

$$A = \frac{10\ V}{1\ mV} = \mathbf{10{,}000}$$

(b) The feedback network is being driven by the output voltage of 10 V.

∴ Gain of the feedback network

$$\frac{output}{input} = \frac{250\ mV}{10\ V}\mathbf{0.025}$$

(c) So far as the feedback amplifier is concerned, input is $(250\ +\ 1)\ =\ 251\ mV$ and final output is $10\ V$.Hence, gain with feedback is

$$A' \ =\ 10\ V/251\ mA\ =\ \mathbf{40}$$

(d) The sacrifice factor is given by

$$S = \frac{A}{A'} = \frac{10000}{40} = \mathbf{250}$$

By sacrificing so much voltage gain, we have improved many other amplifier quantities.

3.3 Gain Stability

In addition to the β factor setting a precise gain value, we are also interested in how stable the feedback amplifier is compared to an amplifier is compared to an amplifier without feedback.

The gain of an amplifier with negative feedback is given by $A' = \frac{A}{1+\beta A}$

Taking logs of both sides, we have $\log_e A' = \log_e A - \log_e(1 + \beta A)$

Differentiating both sides, we get

$$\frac{dA'}{A'} = \frac{dA}{A} - \frac{\beta . dA}{1 + \beta A} = dA\left(\frac{1}{A} - \frac{\beta}{1 + \beta A}\right) = \frac{1}{1 + \beta A}\frac{dA}{A} = \frac{(dA/A)}{1 + \beta A}$$

If $\beta A \gg 1$, then the above expression becomes

$$\frac{dA'}{A'} = \frac{1}{\beta A} . \frac{dA}{A}$$

3.4 Decreased Distortion

Let the harmonic distortion voltage generated within the amplifier change from *D* to *D´* whennegative feedback is applied to the amplifier.

Suppose $D' = x\,D$ ... ***(i)***

The fraction of the output distortion voltage which is feedback to the input is

$\beta D' = \beta\, x\, D$

After amplification, it become $\beta\, x\, DA$and is anti-phase with original distortion voltage *D*.

Hence, the new distortion voltage *D´* which appears in the output is

$$D' = D - \beta\, x\, DA \ldots\ldots \textbf{\textit{(ii)}}$$

From (i) and (ii), we get

$$xD = D - \beta xDA \qquad or \qquad x = \frac{1}{1 + \beta A}$$

Substituting this value of x in Eq. (i) above, we have $D' = \frac{D}{1+\beta\, A}$

It is obvious from the above equation that $D' < D$. In fact, negative feedback reduces the amplifier distortion by the amount of loop gain i.e. by a factor of (1+βA).

However, it should be noted that improvement in distortion is possible only when the distortions produced by the amplifier itself, not when it is already present in the input signal.

3.5 Feedback over Several Stages

Multistage amplifiers are used to achieve greater voltage or current amplification or both. In such a case, we have a choice of applying negative feedback to improve amplifier performance.

Either we apply some feedback across each stage or we can put it in one loop across the whole amplifier.

A multistage amplifier is shown in Fig.3.2. In Fig. 3.2 (a) each stage of the n-stage amplifier has a feedback applied to it. Let A and β_1 be the open-loop gain and feedback ratio respectively of each stage and A_1 the overall gain of the amplifier. Fig. 1.6 (b) shows the arrangement where n amplifiers have been cascaded in order to get a total gain of An. Let the overall feedback factor be $\beta_2$and the overall gainA_2. The values of the two gains are given as

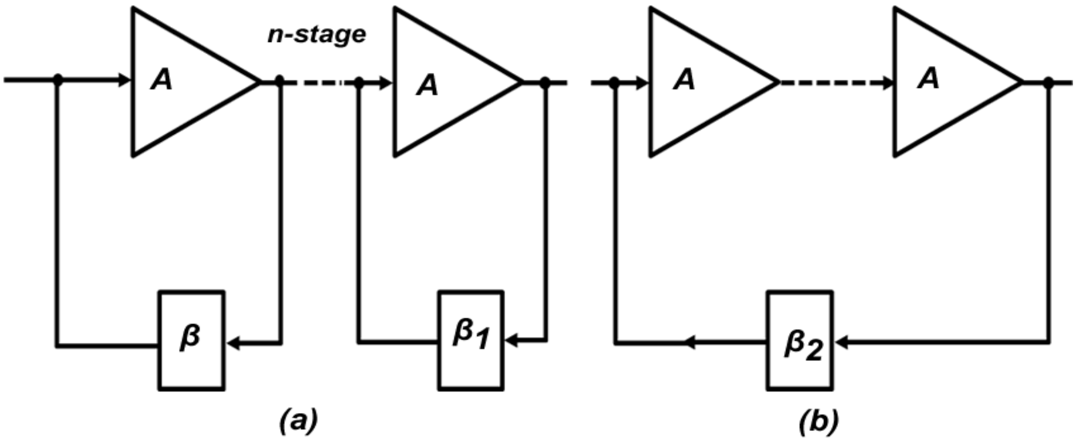


Fig. 3.2- Feedback over several stages

$$A_1 = \left(\frac{A}{1 + A\beta_1}\right)^n \quad and \quad A_1 = \frac{A^n}{1 + A^n\beta_2}$$

Differentiating the above two expressions, we get

$$\frac{dA_1}{A_1} = \frac{n}{1 + A\beta_1} \cdot \frac{dA}{A} \quad and \quad \frac{dA_2}{A_2} = \frac{n}{1 + A^n\beta_2} \cdot \frac{dA}{A}$$

For the two circuits to have the same overall gain, $A_1 = A_2$. Hence, from Eqn. (i) above, we get

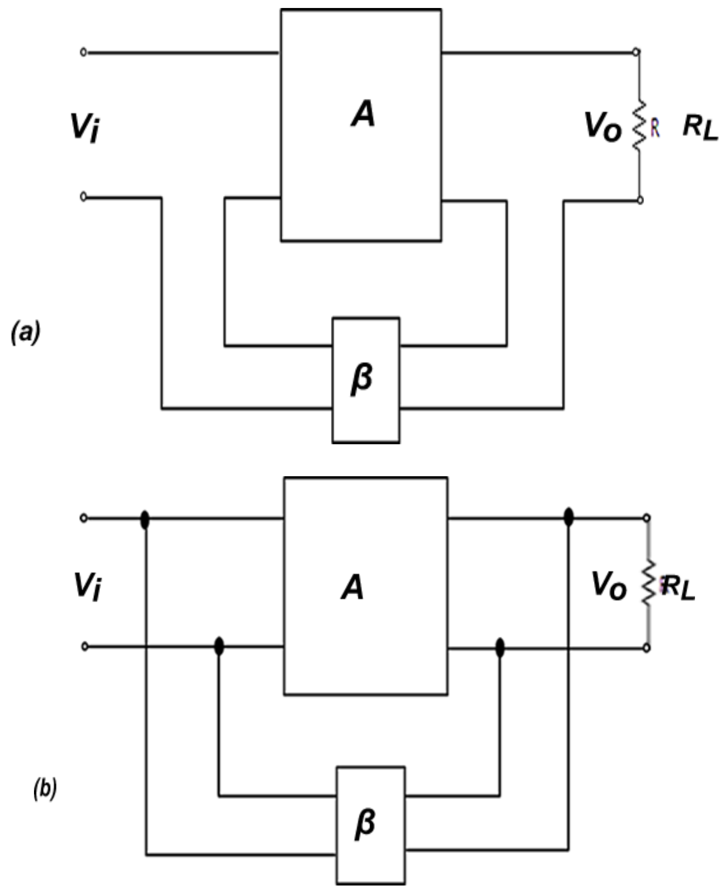
$$(1 - 1\beta)^n = 1 + A^n\beta_2$$

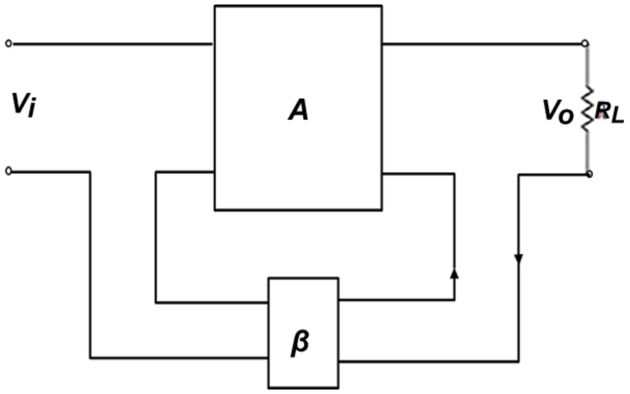
$$\therefore \quad \frac{dA_2/A_2}{dA_1/A_1} = \frac{1}{(1+A\beta)^{n-1}}$$

If $n = 1$, then the denominator in the above equation becomes unity so that fractional gain variations are the same as expected. However, for $n > 1$ and with $(1 + A\beta_1)$ being a normally large quantity, the expression dA_2/A_2 will be less than dA_1/A_1. It means that the overall feedback would appear to be beneficial as far as stabilizing of the gain is concerned.

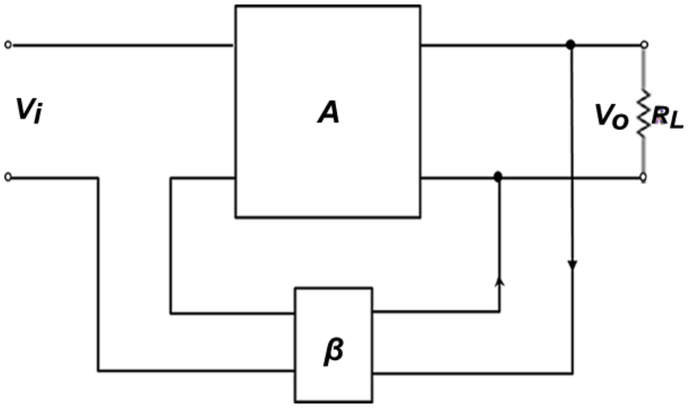
3.6 Forms of Negative Feedback

The four basic arrangements for using negative feedback are shown in the block diagram of Fig. 3.3.As seen; both voltage and current can be feedback to the input either in series or in parallel. The output voltage provides input in Fig. 3.3 (*a*) and (*b*). However, the input to the feedback network is derived from the output current in Fig. 3.3 (*c*) and (*d*).





(c)



(d)

Fig 3.3 –Forms of Negative Feedback

(a) Voltage-series Feedback

It is shown in Fig. 3.3 (a). It is also called shunt-derived series-fed feedback. The amplifier and feedback circuit are connected series-parallel. Here, a fraction of the output voltage is applied in series with the input voltage via the feedback. As seen, the input to the feedback network is in parallel with the output of the amplifier. Therefore, so far as V_o is concerned, output resistance of the amplifier is reduced by the shunting effect of the input to the feedback network. It can be proved that:

$$R_o' = \frac{R_o}{1 + \beta A}$$

Similarly, V_i sees two circuit elements in series:

(i) The input resistance of the amplifier and

(ii) Output resistance of the feedback network.

Hence, input resistance of the amplifier as a whole is increased due to feedback. It can be proved that

$$R_i' = R_i(1 + \beta A)$$

In fact, series feedback always increases the input impedance by a factor of $(1 + \beta A)$.

(*b*) Voltage-shunt Feedback

It is shown in Fig. 3.3(*b*). It is also known as ***shunt-derived shunt-fed feedback*** *i.e.* it is parallel-parallel (*PP*) prototype. Here, a small portion of the output voltage is coupled back to the input voltage parallel (shunt).

Since the feedback network shunts both the output and input of the amplifier, it decreases both its output and input impedances by a factor of $1/(1 + \beta A)$
A shunt feedback always decreases input impedance.

(c) Current-series Feedback

It is shown in Fig. 3.3(c). It is also known as series-derived series-fed feedback. As seen, it is a series-series (SS) circuit. Here, a part of the output current is made to feedback a proportional voltage in series with the input. Since it is a series pick-up and a series feedback, both the input and output impedances of the amplifier are increased due to feedback.

(d) Current-shunt Feedback

It is shown in Fig. 3.3(d). It is also referred to as series-derived shunt-fed feedback. It is a parallel-series (PS) prototype. Here, the feedback network picks up a part of the output current and develops a feedback voltage in parallel (shunt) with the input voltage. As seen, feedback network shunts the input but is in series with the output. Hence, output resistance of the amplifier is increased whereas its input resistance is decreased by a factor of loop gain.

The effects of negative feedback on amplifier characteristics are summarized below:

Characteristics	*Type of Feedback*			
	Voltage series	Voltage shunt	Current series	Current shunt
Voltage gain	Decreases	Decreases	Decreases	decreases
Bandwidth	Increases	Increases	Increases	increases
Harmonic Distortion	Decreases	Decreases	Decreases	decreases

Noise	Decreases	Decreases	Decreases	decreases
Input Resistance	Increases	Decreases	Increases	decreases
Output Resistance	Decreases	Decreases	Increases	increases

3.7 Shunt-derived Series-fed Voltage Feedback

The basic principle of such a voltage-controlled feedback is illustrated by the block diagram of Fig. 3.4. Here, the feedback voltage is derived from the voltage divider circuit formed of R_1 and R_2.

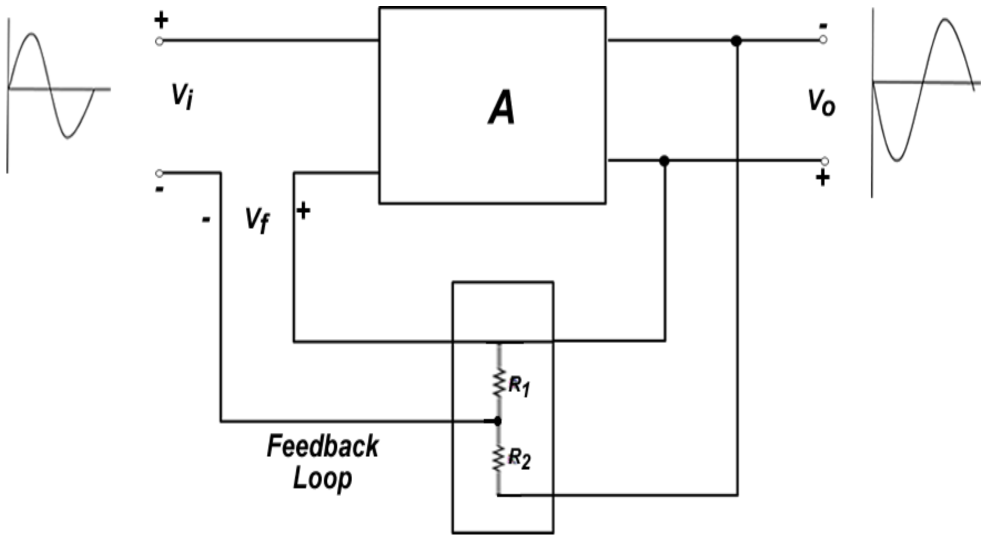


Figure 3.4 - Shunt-derived Series-fed Voltage Feedback

As seen, the voltage drop across R1 forms the feedback voltage V_f.

$$\therefore \quad V_f = V_o \frac{R_1}{R_1 + R_2} = \beta V_o$$

3.8 Current-series Feedback Amplifier

Fig. 3.6 shows a series-derived series-fed feedback amplifier circuit. Since the emitter resistor is un bypassed, it effectively provides current-series feedback. When I_E passes through R_E, the feedback voltage drop $V_f = I_E R_E$ is developed which is applied in phase opposition to the input voltage V_i. This negative feedback reduces the output voltage V_o. This feedback can, however, be eliminated by either removing or bypassing the emitter resistor. It can be proved that:

$$\beta = \frac{R_E}{R_C} \quad ; \quad A' = \frac{R_C}{r_e + R_E} \quad ; \quad A = \frac{R_C}{r_e}$$

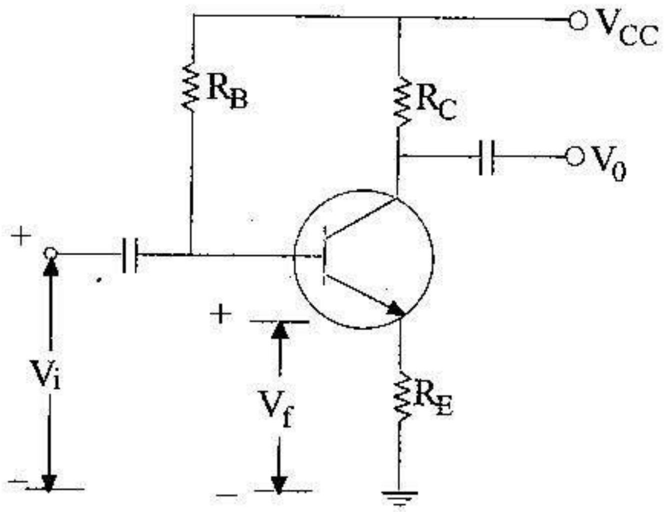


Fig. 3.6

3.9 Voltage-shunt Negative Feedback Amplifier

The circuit of such an amplifier is shown in Fig. 3.7.

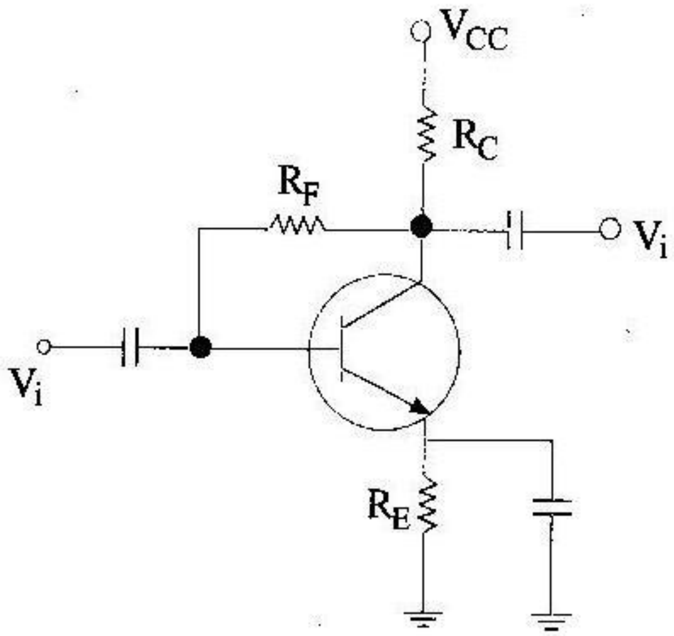


Fig3.7

As seen, a portion of the output voltage is coupled through R_E in parallel with the input signal at the base. This feedback stabilizes the overall gain while decreasing both the input and output resistances. It can be proved that $\beta = R_c/R_F$.

3.10 Current-shunt Negative Feedback Amplifier

The two-stage amplifier employing such a feedback is shown in Fig. 3.8. The feedback circuit (consisting of C_F *and* R_F) samples the output current and develops a feedback voltage in parallel with the input voltage. The un bypassed emitter resistor of Q_2 provides current sensing.

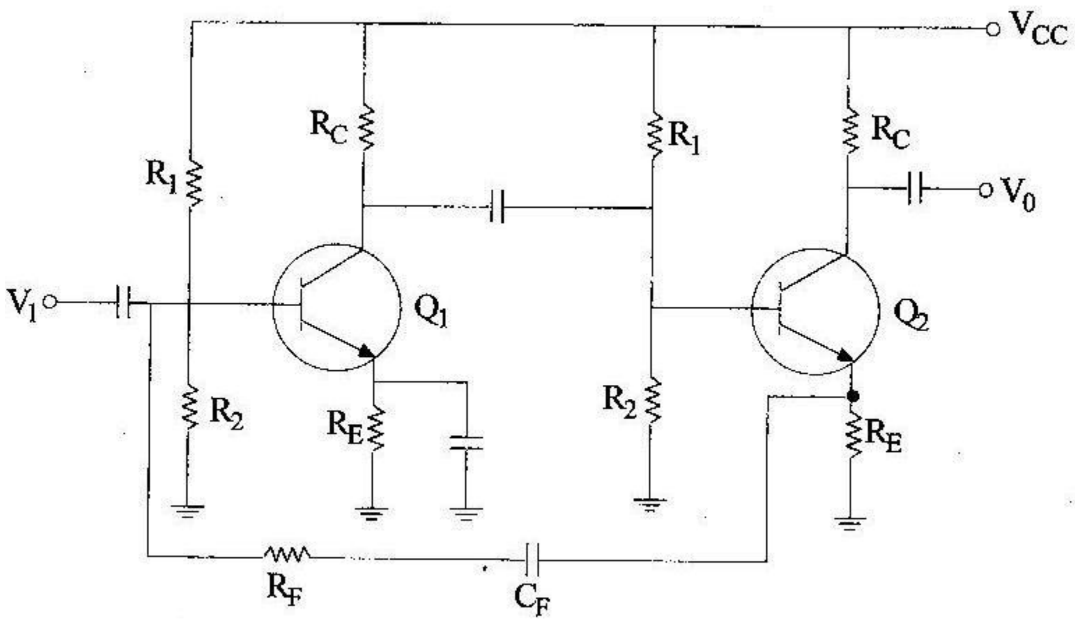


Fig. 3.8

The polarity of the feedback voltage is such that it provides the negative feedback.

3.11 Non-inverting Op-amp With Negative Feedback

The closed-loop non-inverting op-amp circuit using negative feedback is shown in Fig. 3.9. The input signal is applied to the non-inverting input terminal. The output is applied back to the input terminal through the feedback network formed by R_i *and* R_f.

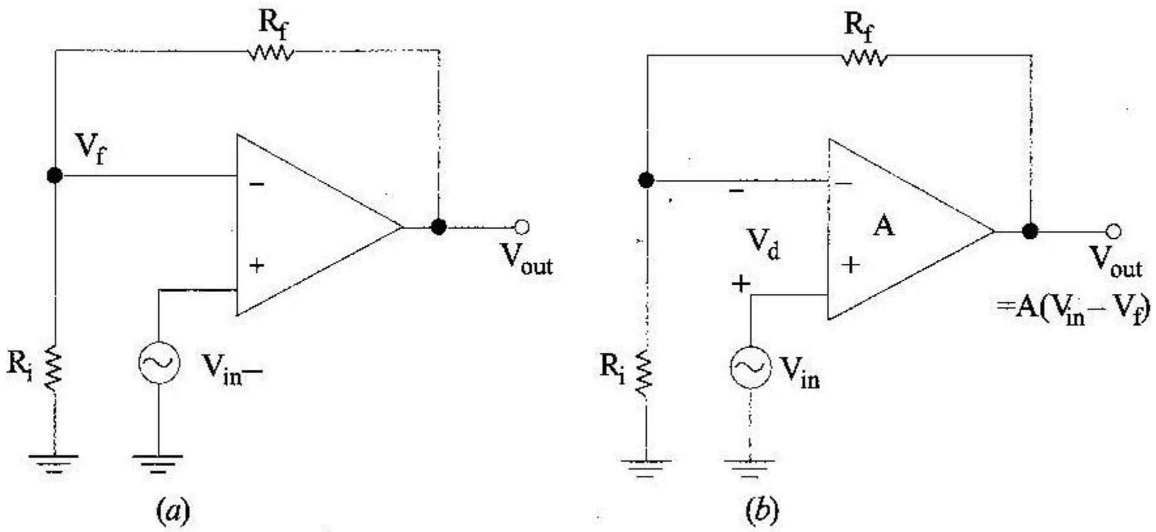


Fig3.9

The op-amp acts as both the difference circuit and the open-loop forward gain. The differential input to the op-amp is $(V_{in} - V_f)$. This differential voltage is amplified A times and an output voltage is produced which is given by:

$V_{out} = A_{v1} = A(V_{in} - V_f)$; where A is the open-loop gain of the op-amp

Since, $(R_i + R_f)$ acts as voltage divider across V_{out},

$$\therefore \quad V_f = V_{out}\frac{R_i}{R_i + R_f}$$

Now, $\beta = R_i/(R_1 + R_f)$, hence $V_f = \beta V_{out}$

Substituting this value in the above equation, we get

$$V_{out} = A\,(V_{in} - \beta V_{out})\text{ or } V_{out}\,(1 + \beta A) = AV_{in}$$

Hence, voltage gain A´ with negative feedback is

$$A' = \frac{V_{out}}{V_{ij}} = \frac{A}{1 + \beta A} = \frac{A}{1 + AR_i(R_i + R_f)}$$

If A is so large that 1 can be neglected as compared to βA, the above equation becomes

$$A' = \frac{A}{\beta A} = \frac{1}{\beta} = \frac{R_i + R_f}{R_i}$$

It is seen that closed-loop gain of a non-inverting op-amp is essentially independent of the open-loop gain.

3.12 TEST

1. *An amplifier has an open-loop gain of 400 and a feedback of 0.1. If open-loopgain changes by 20% due to temperature, find the percentage change in closed-loop gain.*

Solution

Here, $A = 400, \beta = 0.1,\ dA/A = 20\% = 0.2$

Now, $\frac{dA'}{A'} = \frac{1}{\beta A} \cdot \frac{dA}{A} = \frac{1}{0.1 \times 400} \times 20\% = 0.5\%$

It is seen that while the amplifier gain changes by 20%, the feedback gain changes by only

0.5% *i.e.* an improvement of 20/0.5 = 40 times

2. *An amplifier with* 10% *negative feedback has an open-loop gain of* 50. *If open-loop gain increases by* 10%, *what is the percentage change in the closed-loop gain?*

Solution

Let A_1' *and* A_2^1 be the closed-loop gains in the two cases andA_1 *and* A_2 the open-loop gains respectively.

(i) $A_1' = \frac{A_1}{1+\beta A_1} = \frac{50}{1+0.1\times 50} = 8.33$

(ii) When open-loop gain changes by 10%, then $A_2 = 50 + 0.1 \times 50 = 55$

$$\therefore \quad A_2' = \frac{A_2}{1 + \beta A_2} = \frac{55}{1 + 0.1 + 55} = 8.46$$

∴ Percentage change in closed-loop gain is

$$= \frac{A_2' - A_1'}{A_1'} \times 100 = \frac{8.46 - 8.33}{8.33} \times 100 = 1.56\%$$

3. In the two-stage R_C coupled amplifier (Fig. 62.14) using emitter feedback, find the overall gain. Neglect V_{BE} and take $\beta_1 = \beta_2 = 100$.

Solution

In this amplifier circuit, voltage gain has been stabilized to some extent with the help of 500Ω unbypassed emitter resistance. This $500\ \Omega$ resistance swamps out r_e.

$$A_{v.2} = \frac{r_{L.2}}{r_e + r_E} \cong \frac{r_{L.2}}{r_E} = \frac{10K \parallel 10K}{500\Omega} = 10$$

Now, $\beta r_E = 100 \times 500 = 50\ K$

$r_{i-2} = 80K \parallel 40K \parallel 50K$

$r_{L.1} = R_{C.1} \parallel r_{i.2}$

$= 10K \parallel 80K \parallel 40K \parallel 50K = 6.3\ K$

$$\therefore \quad A_{v.1} = \frac{r_{L1}}{r_E} = \frac{6.3 \times 10^3}{500} = 12.6$$

$A = 10 \times 12.6 = 126$

4.0 CONCLUSION

This unit has introduced you to the concept of feedback in an amplifier circuit with emphasis on the negative feedback. Also, you were introduced to the implication, advantages and various forms of negative feedback.

5.0 SUMMARY

If the feedback signal is of opposite polarity to the input signal, negative feedback results. Although negative feedback results in reduced overall voltage gain, a number of improvements are obtained, among them being:

- High input impedance.
- Better stabilized voltage gain.
- Improved frequency response.
- Lower output impedance.
- Reduced noise.
- More linear operation.
- Less harmonic distortion.
- Less phase distortion.
- Less amplitude distortion

6.0 TUTOR MARKED ASSIGNMENT

(1) Calculate A, r_{in}(stage) and $I_{o(stage)}$ of the cascaded amplifier shown in $h_{fe} = 100, h_{ie} = 2\ K$ and $h_{oe} = 0$.

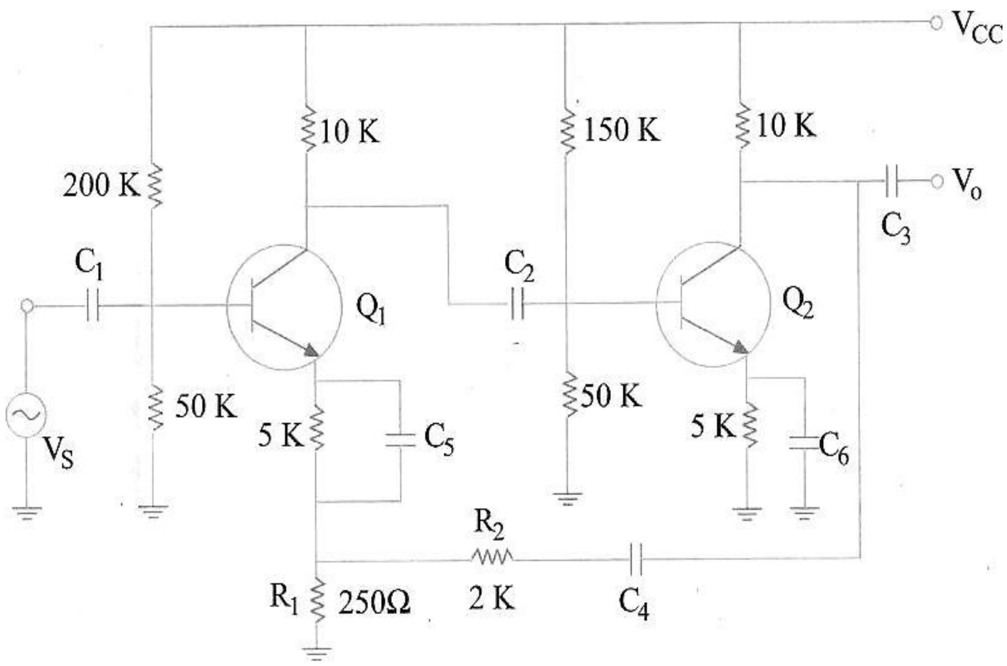


Fig. 3.10

(2) A certain non-inverting op-amp has $R_i = 1K, R_f = 99\ K$ and open-loop gain $A = 500{,}000$. Determine:

(i) β.

(ii) Loop gain.

(iii) Exact closed-loop gain and

(iv) Approximate closed-loop gain if it is assumed that open-loop gain $A = \infty$.

(3) For the series-parallel feedback amplifier shown in Fig. 3.11. Calculate

(*i*) open-loop gain,

(*ii*) gain of feedback loop,

(*iii*) closed-loop gain,

(*iv*) sacrifice factor

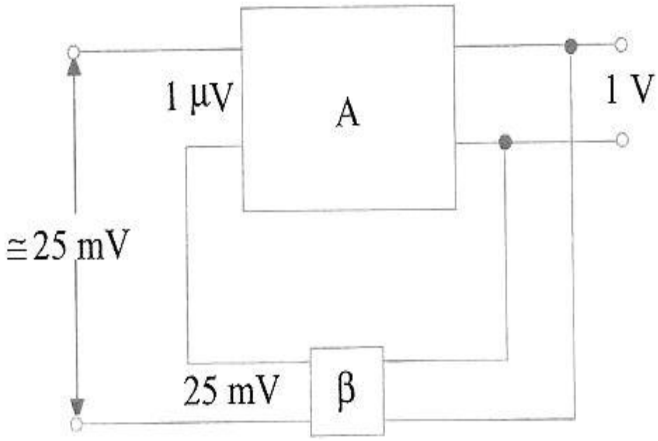


Fig. 3.11

(4) Give three reasons for using negative feedback.

In Fig. 3.12, the box represents an amplifier of gain -1000, input impedance $500\ k\Omega$ and negligible output impedance.

Calculate the voltage gain and input impedance of the amplifier with feedback.

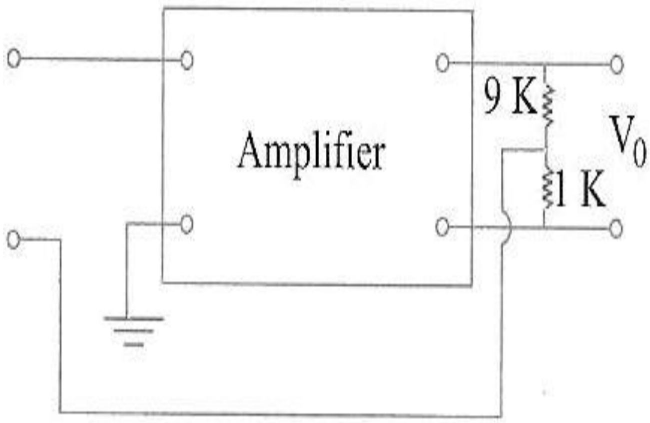


Fig. 3.12

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UNIT 2 POSITIVE FEEDBACK

CONTENTS

1.0 INTRODUCTION

Feedback is the process of transferring energy from a high-level point in a system to a low-level point in a system. This means transferring energy from the output of an amplifier back to its input. If the output feedback signal opposes the input signal, the signal is DEGENERATIVE or NEGATIVE FEEDBACK. However, if the feedback aids the input signal, the feedback is REGENERATIVE or POSITIVE FEEDBACK. Regenerative or positive feedback is one of the requirements to sustain oscillations in an oscillator. This feedback can be applied in any of several ways to produce a practical oscillator circuit.

Depending on the relative polarity of the signal being fed back into a circuit, one may have negative or positive feedback. Negative feedback results in decreased voltage gain, for which a number of circuit features are improved as summarized below. Positive feedback drives a circuit into oscillation as in various types of oscillator circuits.

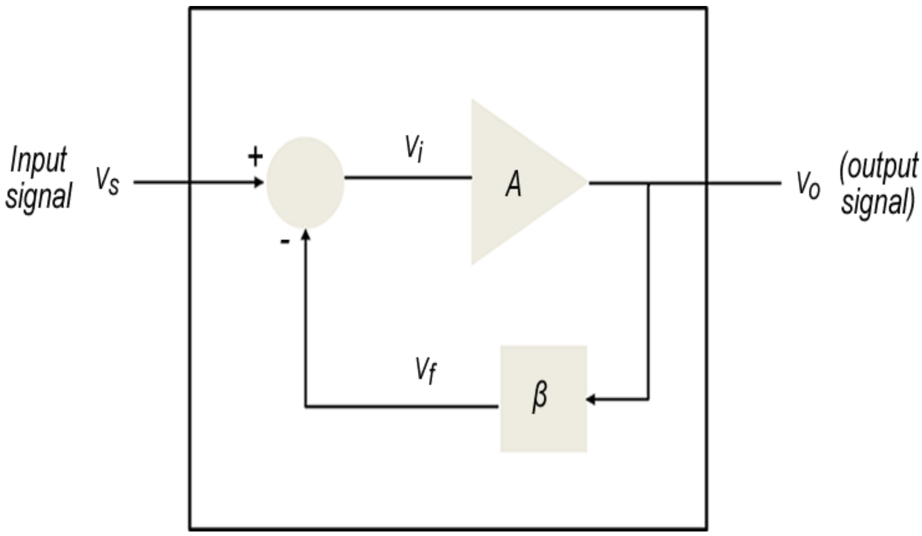

Figure 1.1- Simple block diagram of a feedback amplifier

A typical feedback connection is shown in Figure 1.1. The input signal, V_s, is applied to a mixer network, where it is combined with a feedback signal, A'. The difference of these signals, V_o, is connected to the feedback network (β), which provides a reduced portion of the output as feedback signal to the input mixer network.

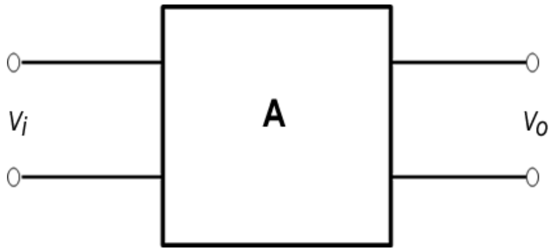

Figure 1.2

For an ordinary amplifier i.e. one without feedback, the voltage gain is given by the ratio of the output voltage Vo and input voltage Vi. As shown in the block diagram of Fig. 1.2, the input voltage Vi is amplified by a factor of A to the value Vo of the output voltage.

$$\therefore\ A = Vo\ /Vi$$

This gain A is often called *open-loop* gain.

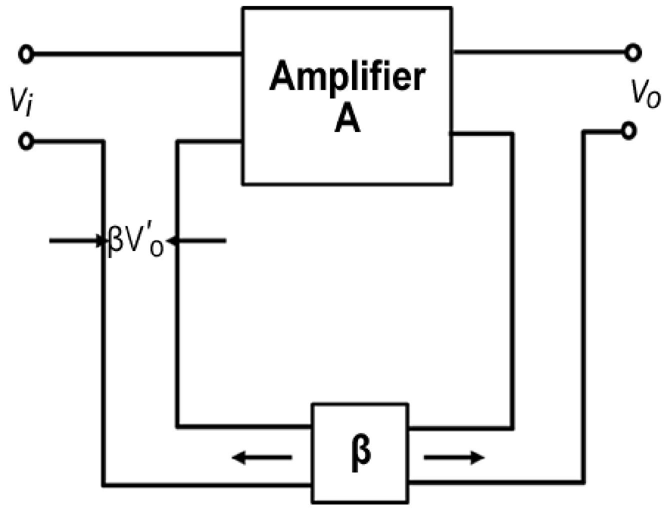

Fig. 1.3-Feedback Loop

Suppose a feedback loop is added to the amplifier (Fig. 1.3). If V_o' is the output voltage with feedback, then a fraction β (it is not the same as the β of a transistor) of this voltage is applied to the input voltage which, therefore, becomes $(V_i \pm \beta V_o')$ depending on whether the feedback voltage is in phase or anti-phase with it. Assuming positive feedback, the input voltage will become $(V_i \pm \beta V_o')$ When amplified A times, it becomes $A(V_i \pm \beta V_o')$

$$\therefore \quad A\,(V_i \pm \beta V_o') = V_o'$$

$$or \quad V_o'(1 - \beta A) = AV_i$$

The amplifier gain A' with feedback is given by

$$A' = \frac{V_o'}{V_i} = \frac{A}{1 - \beta A}$$

$$\therefore \quad A' = \frac{A}{1-\beta A}$$ — Positive feedback

$$= \frac{A}{1-(\beta A)} = \frac{A}{1+\beta A}$$ — Negative feedback

The term 'βA' is called *feedback factor* whereas β is known as *feedback ratio*. The expression $(1 \pm \beta A)$ is called loop gain. The amplifier gain A´ with feedback is also referred to *as closed-loop gain* because it is the gain obtained after the feedback loop is closed. The sacrifice factor is defined as $S = A/A'$.

2.0 OBJECTIVES

By the end of this unit, you should be able to:

- Understand the concept of feedback.
- Establish the fact that positive feedback is a criterion for oscillation.
- Understand the Nyquist criterion.

3.0 MAIN CONTENT

3.1 Positive Feedback

So far we have considered the operation of a feedback amplifier in which the feedback signal was opposite to the input signal - negative feedback (refer to unit 1 of this module). In any practical circuit, this condition occurs only for some mid-frequency range of operation. We know that an amplifier gain will change with frequency, dropping off at high frequencies from the mid-frequency value. In addition, the phase shift of an amplifier will also change with frequency.

If, as the frequency increases, the phase shift changes then some of the feedback signal will add to the input signal. It is then possible for the amplifier to break into oscillation due to positive feedback. If the amplifier oscillates at some low or high frequency, it is no longer useful as an amplifier. Proper feedback-amplifier design requires that the circuit be stable at all frequencies, not merely those in the range of interest. Otherwise a transient disturbance could cause a seemingly stable amplifier to suddenly start oscillating.

3.2 Nyquist Criterion

In judging the stability of a feedback amplifier, as a function of frequency, the βA product and the phase shift between input and output are the determining factors. One of the most popular techniques used to investigate stability is the Nyquist method. A Nyquist diagram is used to plot gain and phase shift as a function of frequency on a complex plane. The Nyquist plot, in effect, combine the two Bode plots of gain versus frequency and phase shift versus frequency and phase shift versus frequency on a single plot. A Nyquist plot is used to quickly show whether an amplifier is stable for all frequencies and how stable the amplifier is relative to some gain or phase-shift criteria.

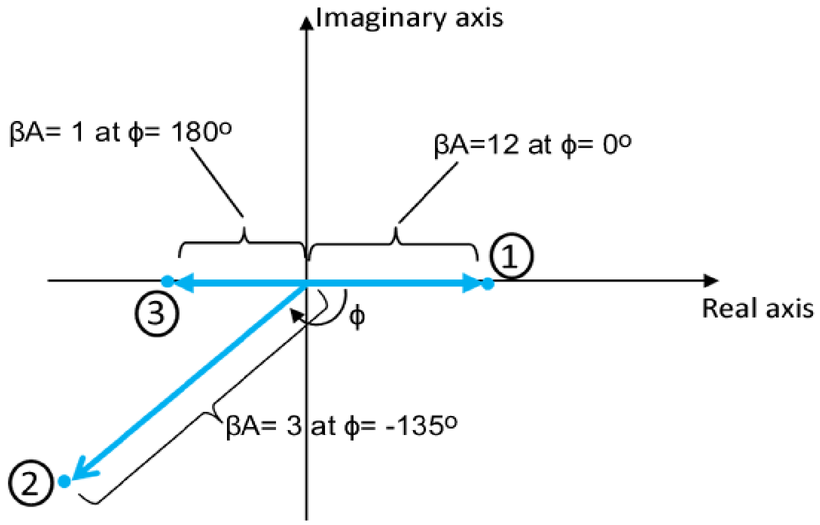

Fig 3.1 Complex plane showing typical gain-phase points.

As a start, consider the complex plane shown in fig 3.1. A few points of various gain (βA) values are shown at a few different phase-shift angles. By using the positive real axis as reference (0^o), a magnitude of βA = 2 is shown at a phase shift of 0^o at point 1. Additionally, a magnitude of βA = 3 at a phase shift of -135^o is shown at point 2 and a magnitude/phase of βA =1 at 180^o is shown at point 3. Thus points on this plot can represent both gain magnitude of βA and phase shift. If the point representing gain and phase shift for an amplifier circuit can be plotted at increasing frequency, then a Nyquist plot is obtained as shown by the plot in fig 3.2.

At the origin, the gain is 0 at a frequency of 0 (for RC-type of coupling). At increasing frequency, point f_1, f_2, and f_3 and the phase shift increased, as did the magnitude of βA. At a representing frequency f_4, the value of A is the vector length from the origin to point f_4 and the phase shift is the angle ϕ. At a frequency f_5, the phase shift is 180^o. At higher frequencies, the gain is shown to decrease back to 0.

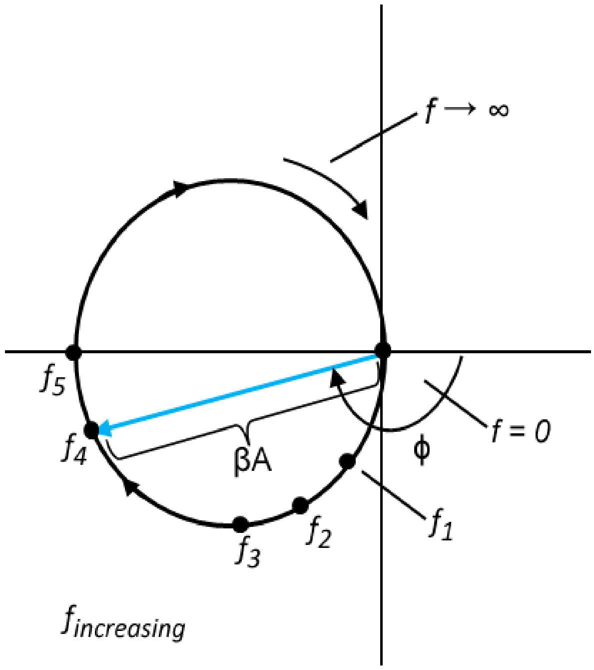

Fig 3.2 Nyquist plot

The Nyquist criterion for stability can be stated as follows:

The amplifier is unstable if the Nyquist curve plotted encloses (encircles) the -1 point, and it is stable otherwise.

The use of positive feedback that results in a feedback amplifier having closed-loop gain $|A_f|$ greater than 1 and satisfies the phase condition will result in operation as an oscillator circuit. An oscillator circuit then provides a varying output signal. If the output signal varies sinusoidally, the circuit is referred to as sinusoidal oscillator. If the output voltage rises quickly to one voltage level and later drops quickly to another voltage level, the circuit is generally referred to as a pulse or square-wave oscillator.

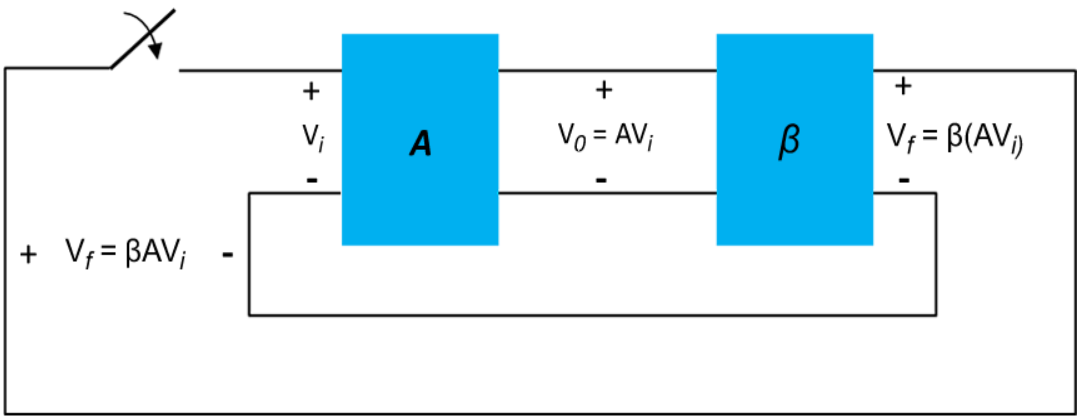

Fig 3.3 Feedback circuit used as an oscillator

To understand how a feedback circuit performs as an oscillator, consider the feedback circuit of Fig 3.3. When the switch at the amplifier input is open, no oscillation occurs. Consider that we have a fictitious voltage at the amplifier input V_i. This results in an output voltage $V_o = A V_i$ after the amplifier stage and in a voltage $V_f = \beta A V_i$ after the feedback stage. Thus, we have a feedback voltage $V_f = \beta(AV_i)$ where βA is referred to as the loop gain. If the circuits of the base amplifier and feedback network provide βA of a correct magnitude and phase, V_f can be made equal to V_i. Then, when the switch is closed and the fictitious voltage V_i is removed, the circuit will continue operating since the feedback voltage is sufficient to drive the amplifier and feedback circuits resulting in a proper input voltage to sustain the loop operation. The output waveform will still exist after the switch is closed if the condition

$$\beta A = 1$$

is met. This is known as ***Barkhausen criterio***n for oscillation.

In reality, no input signal is needed to start the oscillator going. Only the condition $\beta A = 1$ must be satisfied for self-sustained oscillations to result. In practice, βA is made greater than 1 and the system is started oscillating by amplifying noise voltage, which is always present. Saturation factors in the practical circuit provide an average value of βA of 1. The resulting waveforms are never exactly sinusoidal. However, the closer the value of βA is to exactly 1, the more nearly sinusoidal is the waveform.

3.3 Gain and Phase Margins

From the Nyquist criterion, we know that a feedback amplifier is stable if the loop gain (βA) is less than unity $(0\ dB)$ when its phase angle is 180^0. We can additionally determine some margin of stability to indicate how close to instability the amplifier is. That is, if the gain (βA) is less than unity but, say, 0.95 in value, this would not be as relatively stable as another amplifier having, say, $(\beta A) = 0.7$ (both measured at 180^0). Of course, amplifier with loop gain 0.96 and 0.7 are both stable, but one is closer to instability, if the loop gain increases, than the other. We can define the following terms:

Gain margin (GM) is defined as the negative value of $|\beta A|$ in decibels at the frequency at which the phase angle is 180^0. Thus, 0 dB, equal to a value of $\beta A = 1$, is on the border of stability and any negative decibel value is stable.

Phase margin (PM) is defined as the angle of 180^0 minus the magnitude of the angle at which the value of $|\beta A|$ is unity $(0\ dB)$.

4.0 CONCLUSION

In this unit, you have been introduced to the basic concept of positive feedback, Nyquist criterion and the ***Barkhausen criterion*** as the basic criteria for oscillation.

5.0 SUMMARY

Positive feedback drives a circuit into oscillation as in various types of oscillator circuits and Nyquist criterion which states that *The amplifier is unstable if the Nyquist curve plotted encloses (encircles) the* -1 *point, and it is stable otherwise* provides the condition for stability. The output waveform will still exist after the switch is closed if the condition $\beta A = 1$is met. This is known as ***Barkhausen criterio***n for oscillation.

6.0 TUTOR-MARKED ASSIGNMENT

1. With the aid of diagram(s), derive the expression for an amplifier with positive feedback and negative feedback. Indicate the feedback factor and feedback ratio in the expression.
2. What is Nyquist Criterion? Explain.
3. State the Barkhausen Criterion for oscillation.
4. Define the following:

(i) Gain Margin.

(ii) Phase margin.

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UNIT 3 LC OSCILLATORS

CONTENTS

1.0 INTRODUCTION

An electronic oscillator may be defined in any one of the following four ways:

1. It is a circuit which converts dc energy into ac energy at a very high frequency;

2. It is an electronic source of alternating current or voltage having sine, square or saw-tooth or pulse shapes;

3. It is a circuit which generates an ac output signal without requiring any externally applied input signal;

4. It is an unstable amplifier.

These definitions exclude electromechanical alternators producing 50 Hz ac power or other devices which convert mechanical or heat energy into electric energy.

1.1 Comparison between an Amplifier and an Oscillator

As discussed in the previous module, an amplifier produces an output signal whose waveform is similar to the input signal but whose power level is generally high. This additional power is supplied by the external dc source. Hence, an amplifier is essentially an energy convertor i.e. it takes energy from the dc power source and converts it into ac energy at signal frequency. The process of energy conversion is controlled by the input signal. If there is no input signal, there is no energy conversion and hence there is no output signal.

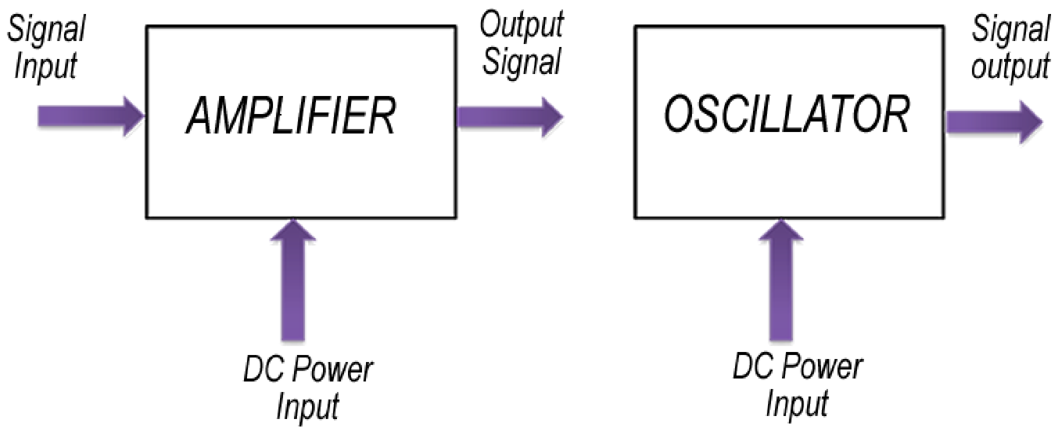


Fig.1.1-Comparison between an amplifier and an oscillator

An oscillator differs from an amplifier in one basic aspect: the oscillator does not require an external signal either to start or maintain energy conversion process (Fig. 1.1). It keeps producing an output signal so long as the dc power source is connected.

Moreover, the frequency of the output signal is determined by the passive components used in the oscillator and can be varied at will.

WAVE GENERATORS play a prominent role in the field of electronics. They generate signals from a few hertz to several gigahertz. Modern wave generators use many different circuits and generate such outputs as SINUSOIDAL, SQUARE, RECTANGULAR, SAWTOOTH, and TRAPEZOIDAL wave-shapes. These wave-shapes serve many useful purposes in the electronic circuits you will be studying. For example, they are used extensively throughout the television receiver to reproduce both picture and sound.

One type of wave generator is known as an OSCILLATOR. An oscillator can be regarded as an amplifier which provides its own input signal. Oscillators are classified according to the wave-shapes they produce and the requirements needed for them to produce oscillations.

1.2 Classification of Oscillators

Electronic oscillator can be classified into two broad categories according to their output wave-shapes:

(i) Sinusoidal (or harmonic) oscillators—which produce an output having sine waveform;

(ii) Non-sinusoidal (or relaxation) oscillators—they produce an output which has square, rectangular or saw-tooth waveform or is of pulse shape.

1.2.1 Sinusoidal Oscillators

A sinusoidal oscillator produces a sine-wave output signal. Ideally, the output signal is of constant amplitude with no variation in frequency. Actually, something less than this is usually obtained. The degree to which the ideal is approached depends upon such factors as class of amplifier operation, amplifier characteristics, frequency stability, and amplitude stability.

Sinusoidal oscillators may be further subdivided into:

(a) Tuned-circuits or LC feedback oscillators such as Hartley, Colpitts and Clapp etc.

(b) RC oscillators such as Wien-bridge oscillator;

(c) Negative-resistance oscillators such as tunnel diode oscillator;

(d) Crystal oscillators such as Pierce oscillator;

(e) Heterodyne or beat-frequency oscillator (BFO).

The active devices (bipolar, FETs or injunction transistors) in the above mentioned circuits may be biased class-A, B or C. Class-A operation is used in high-quality audio frequency oscillators. However, radio frequency oscillators are usually operated as class-C.

Sine-wave generators produce signals ranging from low audio frequencies to ultrahigh radio and microwave frequencies. Many low-frequency generators use resistors and capacitors to form their frequency-determining networks and are referred to as RC OSCILLATORS. They are widely used in the audio-frequency range.

Another type of sine-wave generator uses inductors and capacitors for its frequency-determining network. This type is known as the LC OSCILLATOR. LC oscillators, which use tank circuits, are commonly used for the higher radio frequencies. They are not suitable for use as extremely low-frequency oscillators because the inductors and capacitors would be large in size, heavy, and costly to manufacture.

A third type of sine-wave generator is the CRYSTAL-CONTROLLED OSCILLATOR.

The crystal-controlled oscillator provides excellent frequency stability and is used from the middle of the audio range through the radio frequency range.

1.2.2 Non-sinusoidal Oscillators

Non-sinusoidal oscillators generate complex waveforms, such as square, rectangular, trigger, sawtooth, or trapezoidal. Because their outputs are generally characterized by a sudden change, or relaxation, they are often referred to as RELAXATION OSCILLATORS. The signal frequency of these oscillators is usually governed by the charge or discharge time of a capacitor in series with a resistor. Some types, however, contain inductors that affect the output frequency. Thus, like sinusoidal oscillators, both RC and LC networks are used for determining the frequency of oscillation. Within this category of non-sinusoidal oscillators are MULTIVIBRATORS, BLOCKING OSCILLATORS, SAWTOOTH GENERATORS, and TRAPEZOIDAL GENERATORS.

1.3 The Basic Oscillator

An oscillator can be thought of as an amplifier that provides itself (through feedback) with an input signal. By definition, it is a no rotating device for producing alternating current, the output frequency of which is determined by the characteristics of the device. The primary purpose of an oscillator is to generate a given waveform at a constant peak amplitude and specific frequency and to maintain this waveform within certain limits of amplitude and frequency.

An oscillator must provide amplification. Amplification of signal power occurs from input to output. In an oscillator, a portion of the output is fed back to sustain the input, as shown in figure 1.2.Enough power must be fed back to the input circuit for the oscillator to drive itself as does a signal generator. To cause the oscillator to be self-driven, the feedback signal must also be REGENERATIVE (positive). Regenerative signals must have enough power to compensate for circuit losses and to maintain oscillations.

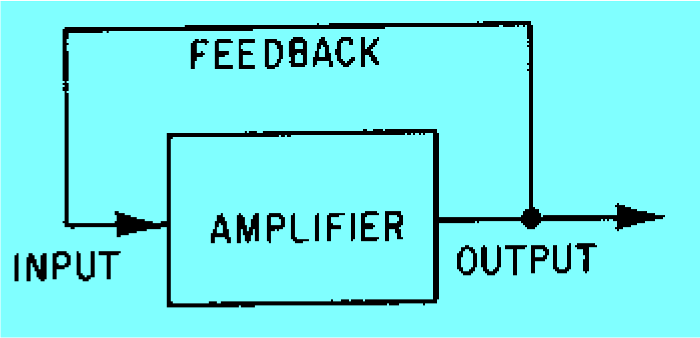


Figure 1.2 - Basic oscillator block diagram.

Since a practical oscillator must oscillate at a predetermined frequency, a FREQUENCY-DETERMINING DEVICE (F_{dd}), sometimes referred to as a FREQUENCY-DETERMINING NETWORK (F_{dn}), is needed. This device acts as a filter, allowing only the desired frequency to pass. Without a frequency-determining device, the stage will oscillate in a random manner, and a constant frequency will not be maintained.

Before discussing oscillators further, let's review the requirements for an oscillator. First, amplification is required to provide the necessary gain for the signal. Second, sufficient regenerative feedback is required to sustain oscillations. Third, a frequency-determining device is needed to maintain the desired output frequency.

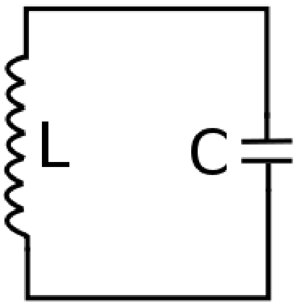
2.0 OBJECTIVES

By the end of this unit, you will be able to:

- Understand the basic operations of an LC oscillator.
- Familiarize with the various types of oscillators that use the LC oscillatory circuit.

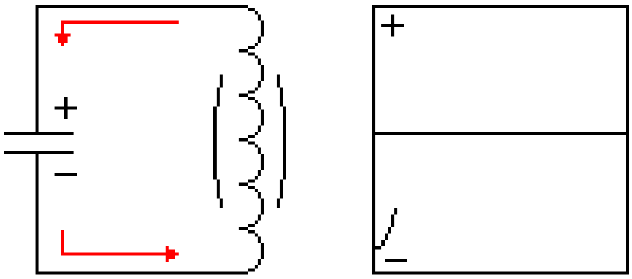
3.0 MAIN CONTENT

3.1 LC OSCILLATORS



An LC circuit can store electrical energy vibrating at its resonant frequency. A capacitor stores energy in the electric field between its plates, depending on the voltage across it, and an inductor stores energy in its magnetic field, depending on the current through it.

This oscillator consists of a capacitor and a coil connected in parallel. To understand how the LC oscillator basically works, let's start off with the basics. Suppose a capacitor is charged by a battery. Once the capacitor is charged, one plate of the capacitor has more electrons than the other plate, thus it is charged. Now, when it is discharged through a wire, the electrons return to the positive plate, thus making the capacitor's plates neutral, or discharged. However, this action works differently when you discharge a capacitor through a coil. When current is applied through a coil, a magnetic field is generated around the coil. This magnetic field generates a voltage across the coil that opposes the direction of electron flow. Because of this, the capacitor does not discharge right away. The smaller the coil, the faster the capacitor discharges. Now the interesting part happens. Once the capacitor is fully discharged through the coil, the magnetic field starts to collapse around the coil. The voltage induced from the collapsing magnetic field recharges the capacitor oppositely. Then the capacitor begins to discharge through the coil again, generating a magnetic field. This process continues until the capacitor is completely discharged due to resistance.



Technically this basic LC circuit generates a sine wave that loses voltage in every cycle. To overcome this, additional voltage is applied to keep the oscillator from losing voltage. However, to keep this oscillator going well, a switching method is used. A vacuum tube (or a solid-state equivalent such as a FET) is used to keep this LC circuit oscillating. The advantage of using a vacuum tube is that they can oscillate at specified frequencies such as a thousand cycles per second.

3.2 Time domain solution

By Kirchhoff's voltage law, the voltage across the capacitor, V_C, must equal the voltage across the inductor, V_L:

$$V_C = V_L.$$

From the constitutive relations for the circuit elements, we also know that

$$V_L(t) = L\frac{di_L}{dt}$$

and

$$i_C(t) = C\frac{dV_C}{dt}.$$

Rearranging and substituting gives the second order differential equation

$$\frac{d^2 i(t)}{dt^2} + \frac{1}{LC} i(t) = 0.$$

The parameter ω, the radian frequency, can be defined as:

$$\omega = \sqrt{\frac{1}{LC}}.$$

. Using this can simplify the differential equation

$$\frac{d^2 i(t)}{dt^2} + \omega^2 i(t) = 0.$$

The associated polynomial is $s^2 + \omega^2 = 0$, thus

$s = +j\omega$

or

$s = -j\omega$

where is the imaginary unit.

Thus, the complete solution to the differential equation is

$i(t) = Ae^{+j\omega t} + Be^{-j\omega t}$

and can be solved for A and B by considering the initial conditions.

Since the exponential is complex, the solution represents a sinusoidal alternating current.

If the initial conditions are such that $A = B$, then we can use Euler's formula to obtain a real sinusoid with amplitude 2*A* and angular frequency $\omega = \sqrt{\frac{1}{LC}}.$

Thus, the resulting solution becomes:

$i(t) = 2A\cos(\omega t).$

The initial conditions that would satisfy this result are:

$i(t=0) = 2A$

and

$\frac{di}{dt}(t=0) = 0.$

3.3 Resonance effect

The resonance effect occurs when inductive and capacitive reactance are equal in absolute value. (Notice that the LC circuit does not, by itself, resonate. The word resonance refers to a class of phenomena in which a small driving perturbation gives rise to a large effect in the system. The LC circuit must be driven, for example by an AC power supply, for resonance to occur (below).) The frequency at which this equality holds for the particular circuit is called the resonant frequency. The resonant frequency of the LC circuit is

$$\omega = \sqrt{\frac{1}{LC}}$$

Where **L** is the inductance in Henries, and **C** is the capacitance in Farads. The angular frequency ω has units of radians per second.

The equivalent frequency in units of hertz is

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi\sqrt{LC}}.$$

LC circuits are often used as filters; the L/C ratio is one of the factors that determines their "Q" and so selectivity. For a series resonant circuit with a given resistance, the higher the inductance and the lower the capacitance, the narrower the filter bandwidth. For a parallel resonant circuit the opposite applies. Positive feedback around the tuned circuit ("regeneration") can also increase selectivity.

Stagger tuning can provide an acceptably wide audio bandwidth, yet good selectivity.

3.3.1 Series LC circuit

Resonance

Here L and C are in series in an ac circuit. Inductive reactance magnitude (X_L) increases as frequency increases while capacitive reactance magnitude (X_C) decreases with the increase in frequency. At a particular frequency these two reactances are equal in magnitude but opposite in sign. The frequency at which this happens is the resonant frequency (f_r) for the given circuit.

Hence, at f_r :

$$X_L = -X_C$$

$$\omega L = \frac{1}{\omega C}$$

Converting angular frequency into hertz we get

$$2\pi f L = \frac{1}{2\pi f C}$$

Here *f* is the resonant frequency. Then rearranging,

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

In a series AC circuit, X_C leads by 90 degrees while X_L lags by 90. Therefore, they cancel each other out. The only opposition to a current is coil resistance. Hence in series resonance the current is maximum at resonant frequency.

- At f_r, current is maximum. Circuit impedance is minimum. In this state a circuit is called an *acceptor circuit*.
- Below f_r, $X_L \ll (-X_C)$. Hence circuit is capacitive.
- Above f_r, $X_L \gg (-X_C)$. Hence circuit is inductive.

Impedance

- First consider the impedance of the series LC circuit. The total impedance is given by the sum of the inductive and capacitive impedances:
- $Z = Z_L + Z_C$
- By writing the inductive impedance as $Z_L = j\omega L$ and capacitive impedance as $Z_C = \frac{1}{j\omega C}$ and substituting we have

$$Z = j\omega L + \frac{1}{j\omega C}.$$

Writing this expression under a common denominator gives

$$Z = \frac{(\omega^2 LC - 1)j}{\omega C}.$$

The numerator implies that if $\omega^2 LC = 1$ the total impedance Z will be zero and otherwise non-zero. Therefore the series LC circuit, when connected in series with a load, will act as a band-pass filter having zero impedance at the resonant frequency of the LC circuit.

3.3.2 Parallel LC circuit

Resonance

Here a coil (L) and capacitor (C) are connected in parallel with an AC power supply. Let R be the internal resistance of the coil. When X_L equals X_C, the reactive branch currents are equal and opposite. Hence they cancel out each other to give minimum current in the main line. Since total current is minimum, in this state the total impedance is maximum.

Resonant frequency given by: $f = \frac{1}{2\pi\sqrt{LC}}$.

Note that any reactive branch current is not minimum at resonance, but each is given separately by dividing source voltage (V) by reactance (Z). Hence I=V/Z, as per Ohm's law.

- At f_r, line current is minimum. Total impedance is maximum. In this state cct is called *rejector circuit*.
- Below f_r, circuit is inductive.
- Above f_r, circuit is capacitive.

Impedance

The same analysis may be applied to the parallel LC circuit. The total impedance is then given by:

$$Z = \frac{Z_L Z_C}{Z_L + Z_C}$$

and after substitution of Z_L and Z_C and simplification, gives

$$Z = \frac{-j\omega L}{\omega^2 LC - 1}.$$

Note that

$$\lim_{\omega^2 LC \to 1} Z = \infty$$

but for all other values of $\omega^2 LC$ the impedance is finite (and therefore less than infinity). Hence the parallel LC circuit connected in series with a load will act as band-stop filter having infinite impedance at the resonant frequency of the LC circuit.

3.3.3 Applications of resonance effect

1. Most common application is tuning. For example, when we tune a radio to a particular station, the LC circuits are set at resonance for that particular carrier frequency.
2. A series resonant circuit provides voltage magnification.
3. A parallel resonant circuit provides current magnification.
4. A parallel resonant circuit can be used as load impedance in output circuits of RF amplifiers. Due to high impedance, the gain of amplifier is maximum at resonant frequency.
5. Both parallel and series resonant circuits are used in induction heating.

3.4 The LC or Oscillatory Circuit

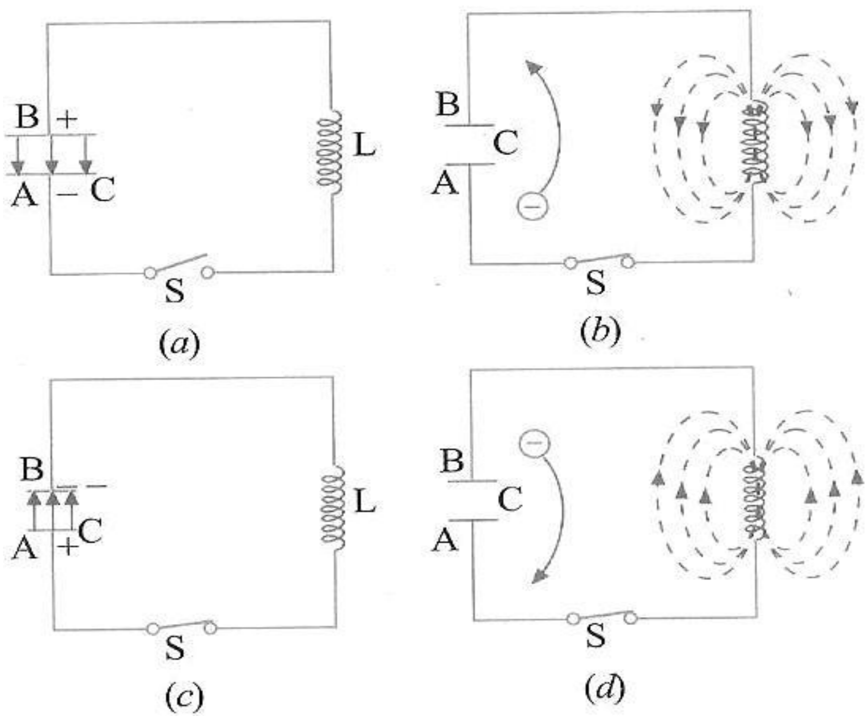


Fig 3.1

As shown in Fig. 3.1 (a), suppose the capacitor has been fully-charged from a dc source.

Since S is open, it cannot discharge through L. Now, let us see what happens when S is closed.

1. When S is closed [Fig. 3.1 (b)] electrons move from plate A to plate B through coil L as shown by the arrow (or conventional current flows from B to A). This electron flow reduces the strength of the electric field and hence the amount of energy stored in it.
2. As electronic current starts flowing, the self-induced emf in the coil opposes the current flow. Hence, rate of discharge of electrons is somewhat slowed down.

3. Due to the flow of current, magnetic field is set up which stores the energy given out by the electric field [Fig. 3.1 (b)].

4. As plate A loses its electrons by discharge, the electron current has a tendency to die down and will actually reduce to zero when all excess electrons on Aare driven over to plate B so that both plates are reduced to the same potential. At that time, there is no electric field but the magnetic field has maximum value.

5. However, due to self-induction (or electrical inertia) of the coil, more electrons are transferred to plate B than are necessary to make up the electron deficiency there. It means that now plate B has more electrons than A. Hence, capacitor becomes charged again though in opposite direction as shown in Fig. 3.1 (c).

6. The magnetic field L collapses and the energy given out by it is stored in the electric field of the capacitor.

7. After this, the capacitor starts discharging in the opposite direction so that, now, the electrons move from plate B to plate A [Fig. 3.1 (d)]. The electric field starts collapsing whereas magnetic field starts building up again though in the opposite direction. Fig.3.1 (d) shows the condition when the capacitor becomes fully discharged once again.

8. However, these discharging electrons overshoot and again an excess amount of electrons flow to plate A, thereby charging the capacitor once more.

9. This sequence of charging and discharging continues. The to and fro motion of electrons between the two plates of the capacitor constitutes an oscillatory current.

It may be also noted that during this process, the electric energy of the capacitor is converted into magnetic energy of the coil and vice versa.

These oscillations of the capacitor discharge are damped because energy is dissipated away gradually so that their amplitude becomes zero after sometime. There are two reasons for the loss of the energy:

(a) Some energy is lost in the form of heat produced in the resistance of the coil and connecting wires ;

(b) and some energy is lost in the form of electromagnetic (EM) waves that are radiated out from the circuit through which an oscillatory current is passing.

3.4.1 Frequency of LC circuit or Oscillatory Current

The frequency of time-period of the oscillatory current depends on two factors:

(a) Capacitance of the Capacitor

Larger the capacitor, greater the time required for the reversal of the discharge current i.e. lower its frequency.

(b) Self-inductance of the Coil

Larger the self-inductance, greater the internal effect and hence longer the time required by the current to stop flowing during discharge of the capacitor. The frequency of this oscillatory discharge current is given by

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{159}{\sqrt{LC}}\ kHz$$

where L = self-inductance in μH and C = capacitance in μF

It may, however, be pointed out here that damped oscillations so produced are not good for radio transmission purpose because of their limited range and excessive distortion. For good radio transmission, we need un damped oscillations which can be produced if some additional energy is supplied in correct phase and correct direction to the LC circuit for making up the I^2R losses continually occurring in the circuit.

3.5 Frequency Stability of an Oscillator

The ability of an oscillator to maintain a constant frequency of oscillation is called its frequency stability. Following factors affect the frequency stability:

1. Operating Point of the Active Device

   The Q-point of the active device (i.e. transistor) is so chosen as to confine the circuit operation on the linear portion of its characteristic. Operation on non-linear portion varies the parameters of the transistor which, in turn, affects the frequency stability of the oscillator.

2. Inter-element Capacitances

Any changes in the inter-element capacitances of a transistor particularly the collector- to emitter capacitance cause changes in the oscillator output frequency, thus affecting its frequency stability.

The effect of changes in inter-element capacitances can be neutralized by adding a swamping capacitor across the offending elements—the added capacitance being made part of the tank circuit.

3. Power Supply

Changes in the dc operating voltages applied to the active device shift the oscillator frequency.

This problem can be avoided by using regulated power supply.

4. Temperature Variations

Variations in temperature cause changes in transistor parameters and also change the values of resistors, capacitors and inductors used in the circuit. Since such changes take place slowly, they cause a slow change (called drift) in the oscillator output frequency.

5. Output Load

A change in the output load may cause a change in the Q-factor of the LC tuned circuit thereby affecting the oscillator output frequency.

6. Mechanical Vibrations

Since such vibrations change the values of circuit elements, they result in changes of oscillator frequency. This instability factor can be eliminated by isolating the oscillator from the source of mechanical vibrations.

3.6 Essentials of a Feedback LC Oscillator

The essential components of a feedback LC oscillator shown in Fig. 3.2 are:

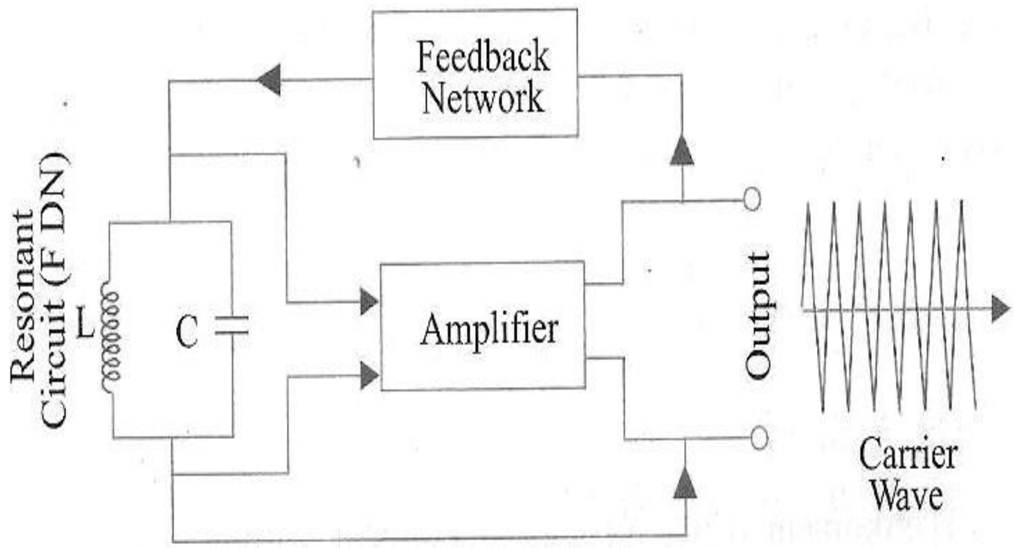


Fig. 3.2

1. A resonator which consists of an LC circuit. It is also known as frequency-determining network *(FDN)*or tank circuit.

2. An amplifier whose function is to amplify the oscillations produced by the resonator.

3. A positive feedback network *(PFN)* whose function is to transfer part of the output energy to the resonant LC circuit in proper phase. The amount of energy fed back is sufficient to meet I^2R losses in the LC circuit.

The essential condition for maintaining oscillations and for finding the value of frequency is

$$\beta A = 1 + j\,0 \qquad or \qquad \beta A \angle \phi = 1 \angle 0$$

It means that

(i) The feedback factor or loop gain $|\,\beta A\,| = 1$,

(ii) The net phase shift around the loop is 0° (or an integral multiple of 360°). In other words, feedback should be positive.

The above conditions form Barkhausen criterion for maintaining a steady level of oscillation at a specific frequency.

Majority of the oscillators used in radio receivers and transmitters use tuned circuits with positive feedback. Variations in oscillator circuits are due to the different way by which the feedback is applied. Some of the basic circuits are:

1. Armstrong or Tickler or Tuned-base Oscillator — it employs inductive feedback from collector to the tuned LC circuit in the base of a transistor.

2. Tuned Collector Oscillator—it also employs inductive coupling but the LC tuned circuit is in the collector circuit.

3. Hartley Oscillator—Here feedback is supplied inductively.

4. Colpitts Oscillator—Here feedback is supplied capacitively.

5. Clapp Oscillator—it is a slight modification of the Colpitts oscillator.

3.7 Tuned Base Oscillator

Such an oscillator using a transistor in *CE* configuration is shown in Fig. 3.3. Resistors R_1, R_2 *and* R_3 determine the dc bias of the circuit.

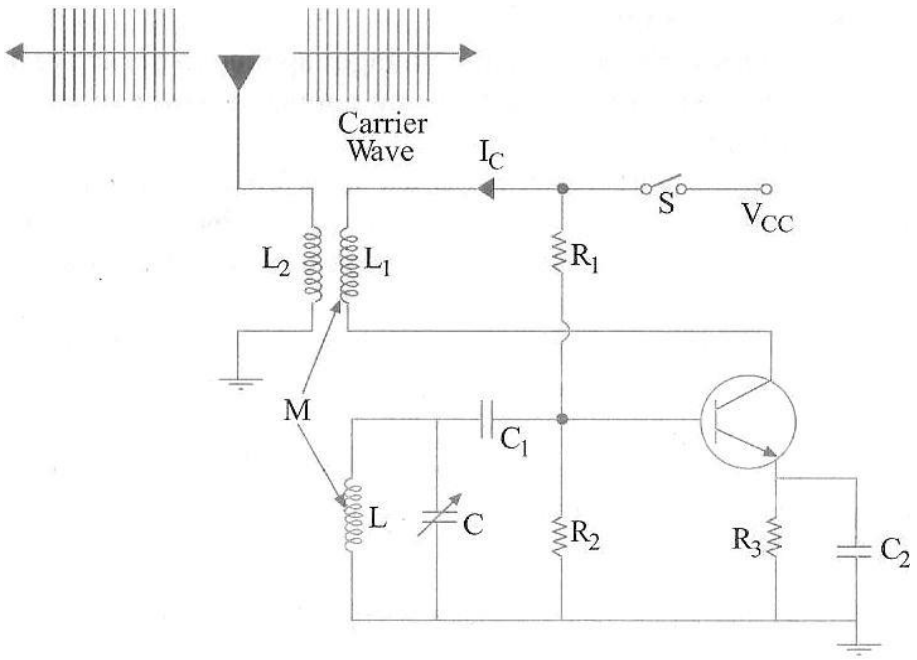


Fig. 3.3

The parallel R_3—C_2 network in the emitter circuit is a stabilizing circuit to prevent signal degeneration. As usual, C1 is the dc blocking capacitor. The mutually-coupled coilsL_1 *and* L forming primary and secondary coils of an *RF* transformer provide the required feedback between the collector and base circuits. The amount of feedback depends on the coefficient of coupling between the two coils. The CE connected transistor itself provides a phase shift of 180° between its input and output circuits. The transformer provides another $180°$ phase shift and thus producing a total phase shift of $360°$ which is an essential condition for producing oscillations. The parallel-tuned LC circuit connected between base and emitter is the frequency determining network *(FDN)* i.e. it generates the oscillations at its resonant frequency.

Circuit Action

The moment switch S is closed, collector current is set up which tends to rise to its quiescent value. This increase in I_C is accompanied by:

1. An expanding magnetic field through L_1 which links with L and

2. An induced $e.m.f.$ called feedback voltage in L.

Two immediate reactions of this feedback voltage are:

(i) Increase in emitter-base voltage (and base current) and

(ii) A further increase in collector current I_C.

It is followed by a succession of cycles of

1. An increase in feedback voltage,
2. An increase in emitter-base voltage and
3. An increase in I_C until saturation is reached.

Meanwhile, C gets charged. As soon as I_C ceases to increase, magnetic field of L_1 ceases to expand and thus no longer induces feedback voltage in L. Having been charged to maximum value, C starts to discharge through L. However, decrease in voltage across C causes the following sequence of reactions:

1. A decrease in emitter-base bias and hence in I_B ,
2. A decrease in I_C;
3. A collapsing magnetic field in L_1;
4. An induced feedback voltage in L though, this time, in opposite direction;
5. Further decrease in emitter-base bias and so on till I_C reaches its cut-off value.

During this time, the capacitor having lost its original charge, again becomes fully charged though with opposite polarity. Transistor being in cut-off, the capacitor will again begin to discharge through L. Since polarity of capacitor charge is opposite to that when transistor was in saturation, the sequence of reactions now will be

1. An increase in emitter-base bias,
2. An increase in I_C,
3. An expanding magnetic field in L_1,
4. An induced feedback voltage in L,
5. A further increase in emitter-base bias and
6. So on till I_C increases to its saturation value.

This cycle of operation keeps repeating so long as enough energy is supplied to meet losses in the LC circuit.

The output can be taken out by means of a third winding L_2 magnetically coupled to L_1. It has approximately the same waveform as collector current.

The frequency of oscillation is equal to the resonant frequency of the LC circuit.

3.8 Tuned Collector Oscillator

Such an oscillator using a transistor in CE configuration is shown in Fig. 3.4.

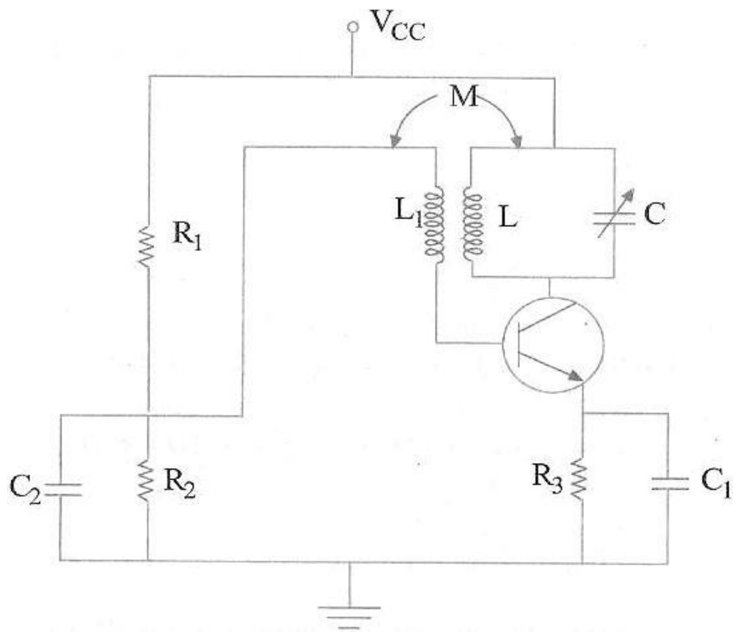


Fig. 3.4

(i) Frequency Determining Network *(FDN)*

It is made up of a variable capacitor C and a coil L which forms primary winding of a step-down transformer. The combination of Land C forms an oscillatory tank circuit to set the frequency of oscillation.

Resistors R_1, R_2 *and* R_3 are used to dc bias the transistor. Capacitors C_1 *and* C_2 act to bypass R_3 *and* R_2 respectively so that they have no effect on the ac operation of the circuit.

Moreover, C_2 provides ac ground for transformer secondary L_1.

(ii) Positive Feedback

Feedback between the collector-emitter circuit and base-emitter circuit is provided by the transformer secondary winding L_1 which is mutually-coupled to L. As far as ac signals are concerned, $L_1$is connected to emitter via low-reactance capacitorsC_2 and C_1.

Since transistor is connected in CE configuration, it provides a phase shift of 180° between its input and output circuits. Another phase shift of $180°$ is provided by the transformer thus producing a total phase shift of $360°$ between the output and input voltages resulting in positive feedback between the two.

(iii) Amplifying Action

The transistor amplifier provides sufficient gain for oscillator action to take place.

(iv) Working

When the supply is first switched on, a transient current is developed in the tuned LC circuit as the collector current rises to its quiescent value. This transient current initiates natural oscillations in the tank circuit. These natural oscillations induce a small emf into L_1 by mutual induction which causes corresponding variations in base current. These variations in IB are amplified β times and appear in the collector circuit. Part of this amplified energy is used to meet losses taking place in the oscillatory circuit and the balance is radiated out in the form of electromagnetic waves.

The frequency of oscillatory current is almost equal to the resonant frequency of the tuned circuit.

$$\therefore \quad f_o = \frac{1}{2\pi\sqrt{LC}}$$

Hartley Oscillator

In Fig. 3.5 (a) is shown a transistor Hartley oscillator using CE configuration.

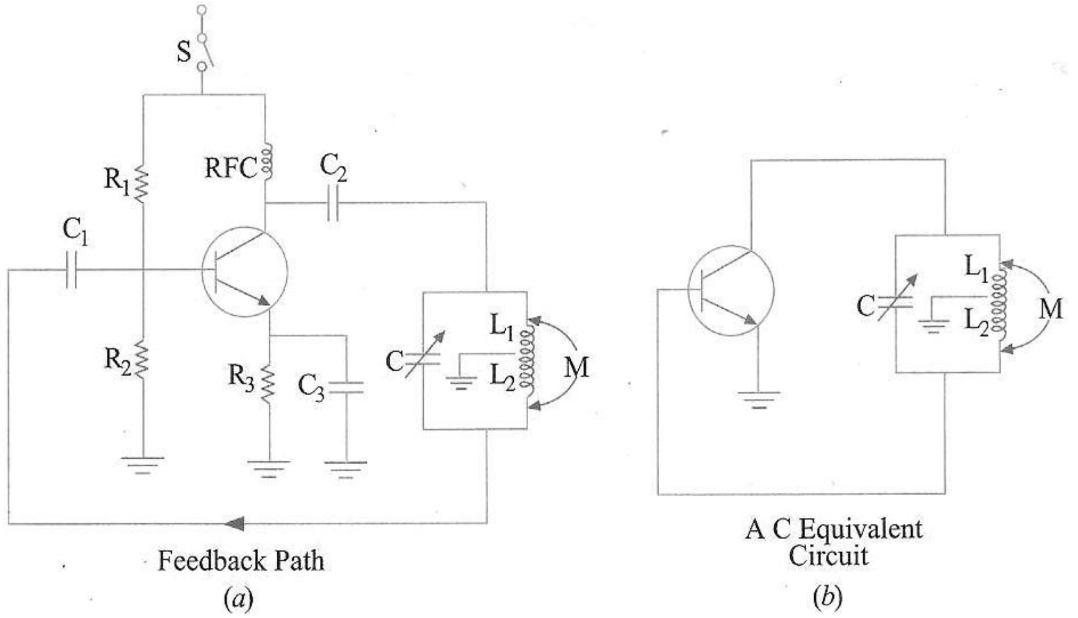


Fig. 3.5

It uses a single tapped-coil having two parts marked L_1 and L_2 instead of two separate coils. So far as ac signals are concerned, one side of L_2 is connected to base via C_1 and the other to emitter via ground and C_3. Similarly, one end of $L_1$is connected to collector via C_2 and the other to common emitter terminal via C_3. In other words, L_1 is in the output circuit i.e. collector-emitter circuit whereas L_2 is in the base-emitter circuit i.e. input circuit. These two parts are inductively-coupled and form an auto-transformer or a split-tank inductor. Feedback between the output and input circuits is accomplished through autotransformer action which also introduces a phase reversal of 180°. This phase reversal between two voltages occurs because they are taken from opposite ends of an inductor ($L_1 - L_2$ combination) with respect to the tap which is tied to common transistor terminal i.e. emitter which is ac grounded via C_3. Since transistor itself introduces a phase shift of 180°, the total phase shift becomes 360° thereby making the feedback positive or regenerative which is essential for oscillations. As seen, positive feedback is obtained from the tank circuit and is coupled to the base viaC1. The feedback factor is given by the ratio of turns in L_2 *and* L_1 *i.e. by* $N_2/N_1$and its value ranges from 0.1 *to* 0.5. Fig. 3.5(b) shows the equivalent circuit of Hartley oscillator.

Resistors R_1 *and* R_2form a voltage divider for providing the base bias and R_3 is an emitter swamping resistor to add stability to the circuit. Capacitor C_3 provides ac ground thereby preventing any signal degeneration while still providing temperature stabilization. Radio-frequency choke *(RFC)* provides dc load for the collector and also keeps ac currents out of the dc supply V_{CC}.

When V_{CC} is first switched on through S, an initial bias is established by $R_1 - R_2$ and oscillations are produced because of positive feedback from the LC tank circuit (L_1 and L_2constitute L). The frequency of oscillation is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad where \quad L = L_1 + L_2 + 2M$$

The output from the tank may be taken out by means of another coil coupled either to L_1 or L_2.

Example

Calculate the oscillation frequency for the transistor Hartley oscillator circuit(refer to Fig 65.8. Given the circuit values:
$L_{RFC} = 0.5\ mH,\ L_1 = 750\ \mu H,\ L_2 = 750\ \mu H,\ M = 150\ \mu H$ and $C = 150\ pF$.

Solution

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad where \quad L = L_1 + L_2 + 2M$$

$$\therefore \qquad L = 750\ \mu H + 750\ \mu H + 150\ \mu H = 1800\ \mu H$$

$$and \qquad f_o = \frac{1}{2\pi\sqrt{1800\ \mu H \times 150\ pF}} = \mathbf{320\ kHZ}$$

3.9 Colpitts Oscillator

This oscillator is essentially the same as Hartley oscillator except for one difference. Colpitts oscillator uses tapped capacitance whereas Hartley oscillator uses tapped inductance (‘*As an aid to memory, remember that Hartley begins with letter H for Henry i.e. coil and Colpitts begins with C for Capacitor*’).

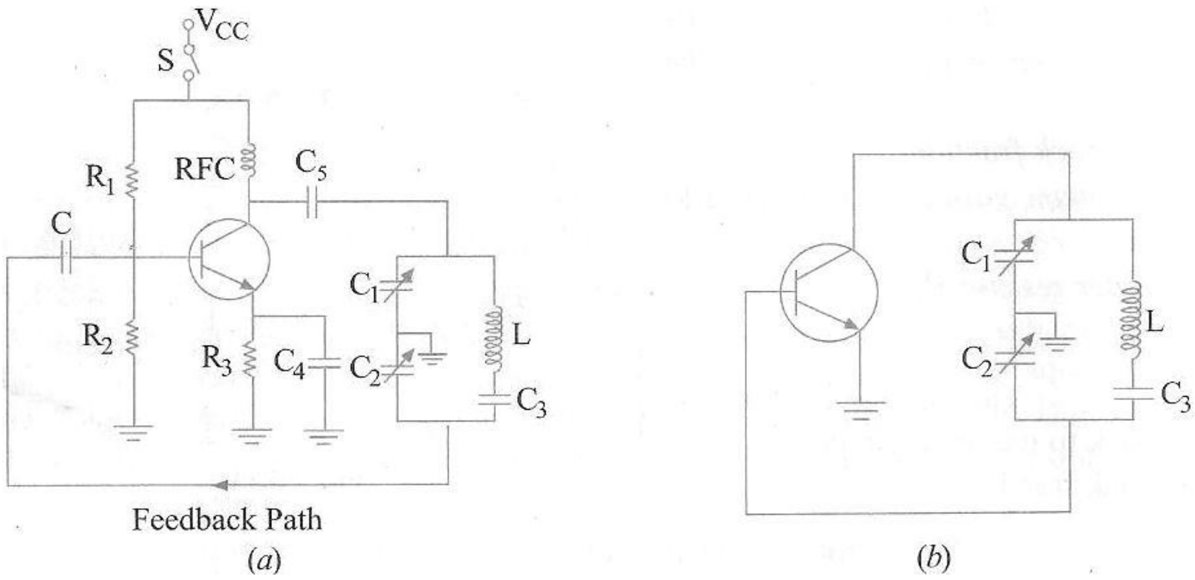


Fig. 3.6

Fig. 3.6 (a)shows the complete circuit with its power source and dc biasing circuit whereas Fig. 3.6 (b) shows its ac equivalent circuit. The two series capacitors C_1 *and* C_2 form the voltage divider used for providing the feedback voltage (the voltage drop across C2 constitutes the feedback voltage). The feedback factor is C_1/C_2. The minimum value of amplifier gain for maintaining oscillations is

$$A_{v(min)} = \frac{1}{C_1/C_2} = \frac{C_2}{C_1}$$

The tank circuit consists of two ganged capacitors C_1 *and* $C_2$and a single fixed coil. The frequency of oscillation (which does not depend on mutual inductance) is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad where \quad C = \frac{C_1 C_2}{C_1 + C_2}$$

Transistor itself produces a phase shift of $180°$.Another phase shift of $180°$ is provided by the capacitive feedback thus giving a total phase shift of $360°$ between the emitter-base and collector-base circuits.

Resistors R_1 *and* R_2 form a voltage divider across V_{CC} for providing base bias, R_3 is for emitter stabilization and *RFC* provides the necessary dc load resistance *RC* for amplifier action. It also prevents ac signal from entering supply $dc\ V_{CC}$. Capacitor C_5 is a bypass capacitor whereas C_4conveys feedback from the collector-to-base circuit.

When S is closed, a sudden surge of collector current shock-excites the tank circuit into oscillations which are sustained by the feedback and the amplifying action of the transistor.

Colpitts oscillator is widely used in commercial signal generators up to $1\ MHz$. Frequency of oscillation is varied by gang-tuning the two capacitors $C_1\ and\ C_2$.

3.10 Clapp Oscillator

It is a variation of Colpitts oscillator and is shown in Fig. 3.7 (a). It differs from Colpitts oscillator in respect of capacitor C_3 only which is joined in series with the tank inductor. Fig. 3.7(b) shows the ac equivalent circuit.

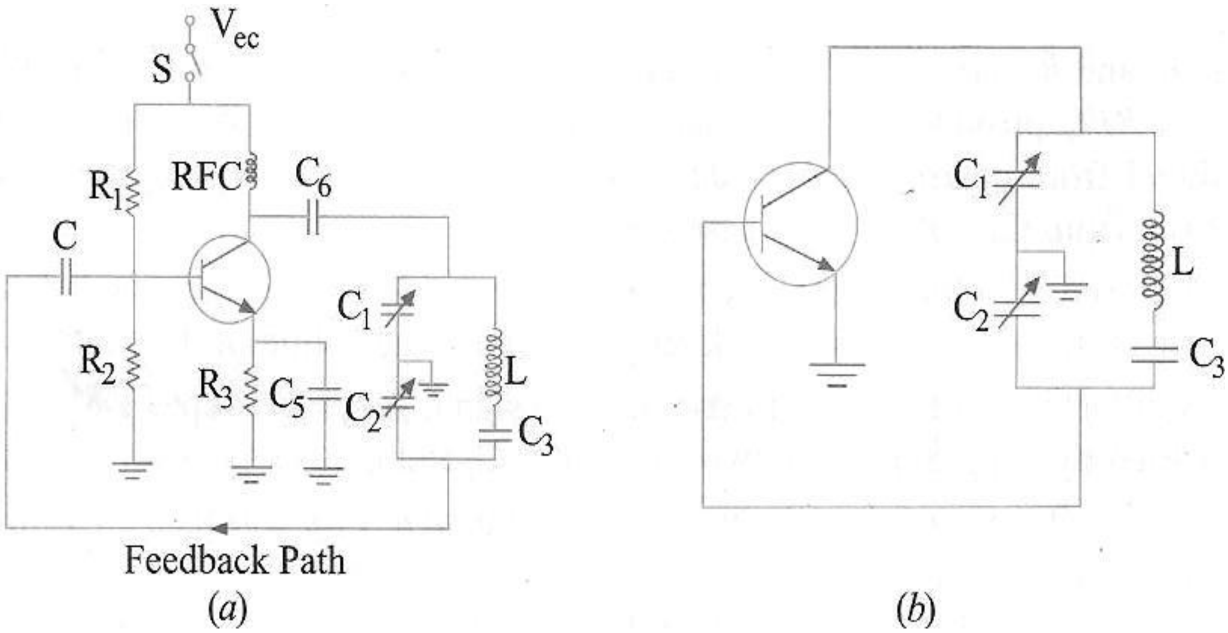


Fig. 3.7

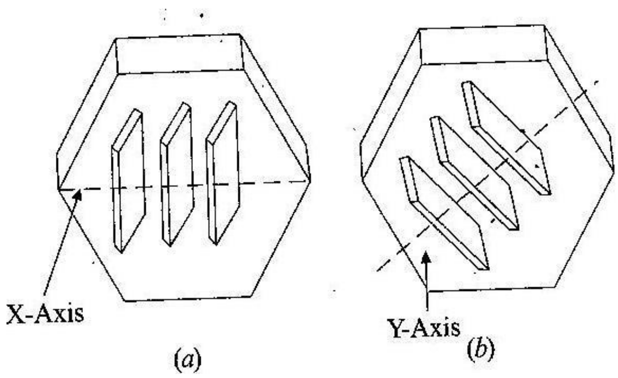
Addition of C_3 (i) improves frequency stability and (ii) eliminates the effect of transistor's parameters on the operation of the circuit.

The operation of this circuit is the same as that of the Colpitts oscillator.

The frequency of oscillation is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad where \quad \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

3.11 Crystals



For an exceptionally high degree of frequency stability, use of crystal oscillators is essential. The crystal generally used is a finely-ground wafer of translucent quartz (or tourmaline) stone held between two metal plates and housed in a package about the size of a postal stamp. The crystal wafers are cut from the crude quartz in two different ways. The method of 'cutting' determines the crystal's natural resonant frequency and its temperature coefficient. When the wafer is cut so that its flat surface is perpendicular to its electrical axis, it is called an X-cut crystal. But if the wafer is so cut that its flat surfaces are perpendicular to its mechanical axis, it is called Y-cut crystal.

(a) Piezoelectric Effect

The quartz crystal described above has peculiar properties. When mechanical stress is applied across its two opposite faces, a potential difference is developed across them. It is called piezoelectric effect. Conversely, when a potential difference is applied across its two opposite faces, it causes the crystal to either expand or contract. If an alternating voltage is applied, the crystal wafer is set into vibrations. The frequency of vibration is equal to the resonant frequency of the crystal as determined by its structural characteristics. Where the frequency of the applied ac voltage equals the natural resonant frequency of the crystal, the amplitude of vibration will be maximum. As a general rule, the thinner the crystal, the higher its frequency of vibration.

(b) Equivalent Electrical Circuit

The electrical equivalent circuit of the crystal is shown in Fig. 3.8 (b). It consists of a series RLC_1 circuit in parallel with a capacitor C_2.

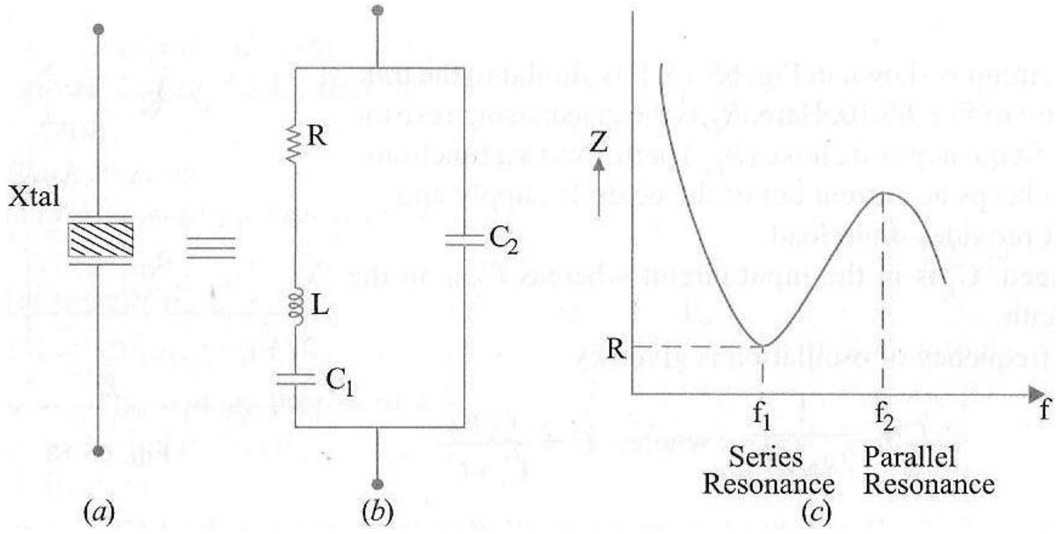


Fig. 3.8

The circuit has two resonant frequencies:

(i) One is the lower series resonance frequency f_1 which occurs when $X_L = X_{C1}$. In that case, $Z = R$.

$$f_1 = \frac{1}{2\pi\sqrt{LC_1}}$$

(ii) The other is the parallel resonance frequency f_2 which occurs when reactance of the series leg equals the reactance of C_2. At this frequency, the crystal offers very high impedance to the external circuit.

$$f_2 = \frac{1}{2\pi\sqrt{LC}}; \qquad where \qquad C = \frac{C_1 C_2}{C_1 + C_2}$$

The impedance versus frequency graph of the crystal is shown in Fig. 3.8 (c). Crystals are available at frequencies of 15 kHz and above. However, at frequencies above 100 MHz, they become so small that handling them becomes a problem.

(c) Q-factor

The equivalent inductance of a crystal is very high as compared to either its equivalent capacitance or equivalent resistance. Because of high L/R ratio, the Q-factor of a crystal circuit is 20,000as compared to a maximum of about 1000 for high-quality LC circuits. Consequently, greater frequency stability and frequency discrimination are obtained because of extremely high Q ($up\ to\ 10^6$) and high L/R ratio of the series RLC_1 circuit.

(d) Temperature Coefficient

Temperature variations affect the resonant frequency of a crystal. The number of cycles change per million cycles for a 1°C change in temperature is called the temperature coefficient (TC) of the crystal. It is usually expressed in parts per million (ppm) per °C. For example, a TC of 10 ppm per°C means that frequency variation is 0.001 per cent per °C change in temperature. It can also be expressed as 10 Hz/MHz/°C. When kept in temperature-controlled ovens, crystal oscillators have frequency stability of about $\pm 1\ ppm$.

Usually, X-cut crystals have negative TC whereas Y-cut crystals have positive TC.

3.12 Crystal Controlled Oscillator

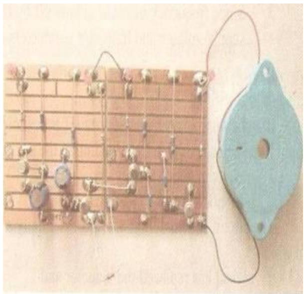

Crystal Controlled oscillator

Fig. 3.9 shows the use of a crystal to stabilize the frequency of a tuned-collector oscillator which has a crystal (usually quartz) in the feedback circuit.

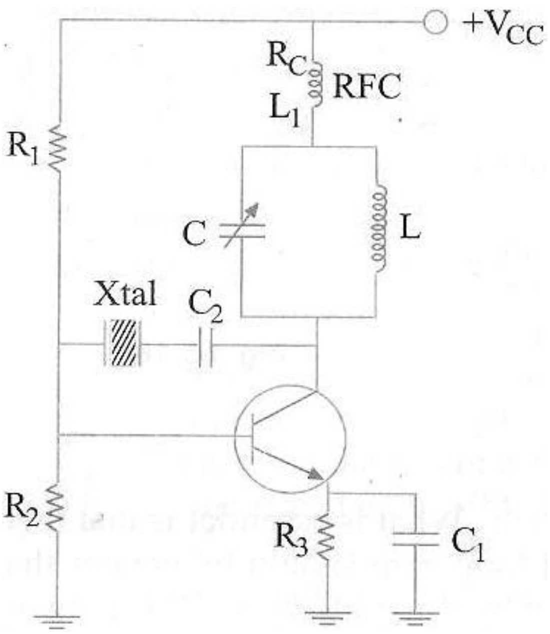


Fig. 3.9

The LC tank circuit has a frequency of oscillation

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

The circuit is adjusted to have a frequency near about the desired operating frequency but the exact frequency is set by the crystal and stabilized by the crystal. For example, if natural frequency of vibration of the crystal is 27 MHz, the LC circuit is made to resonate at this frequency.

As usual, resistors R_1, R_2 and R_3 provide a voltage-divider stabilized dc bias circuit. Capacitor $C_1$by passes R_3 in order to maintain large gain.RFCcoilL_1 prevents ac signals from entering dc line whereas RC is the required dc load of the collector. The coupling capacitor C_2 has negligible impedance at the operating frequency but prevents any dc link between collector and base. Due to extreme stability of crystal oscillations, such oscillators are widely used in communication transmitters and receivers where frequency stability is of prime importance.

3.13 Transistor Pierce Crystal Oscillator

A typical circuit originally suggested by Pierce is shown in Fig. 3.10. Here, the crystal is excited in the series resonance mode because it is connected as a series element in the feedback path from collector to the base. Since, in series resonance, crystal impedance is the smallest, the amount of positive feedback is the largest. The crystal not only provides the feedback but also the necessary phase shift.

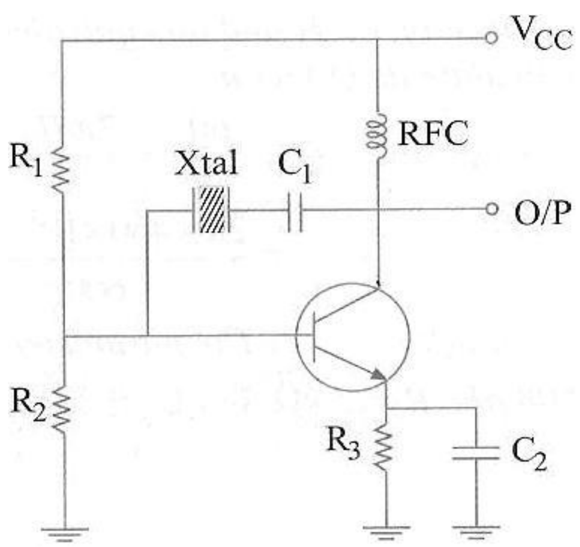


Fig. 3.10

As usual, R_1, R_2 and R_3 provide a voltage-divider stabilized dc bias circuit. C_2bypassesR_3 to avoid degeneration. The *RFC* coil provides dc collector load and also prevents any ac signal from entering the dc supply. The coupling capacitor C_1 has negligible reactance at circuit operating frequency but blocks any dc flow between collector and base. The oscillation frequency equals the series-resonance frequency of the crystal and is given by

$$f_o = \frac{1}{2\pi\sqrt{LC_1}}$$

Advantages

1 It is a very simple circuit because no tuned circuit other than the crystal itself is required.

2. Different oscillation frequencies can be obtained by simply replacing one crystal with another. It makes it easy for a radio transmitter to work at different frequencies.

3 Since frequency of oscillation is set by the crystal, it remains unaffected by changes in supply voltage and transistor parameters etc.

3.14 TEST

Question 1 A tuned-collector oscillator has a fixed inductance of $100\ \mu H$ and has to be tunable over the frequency band of $500\ kHz\ to\ 1500\ kHz$. Find the range of variable capacitor to be used.

Solution

Resonant frequency is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad or \qquad C = \frac{1}{4\pi^2 f_o^2 L}$$

Where L and C refer to the tank circuit.

$When\ f_o = 500\ kHz$

$$C = \frac{1}{4\pi^2} \times (500 \times 10^3)^2 \times 100 \times 10^{-6} = \mathbf{1015\ pF}$$

$When\ f_o = 1500\ kHz$

$$C = \frac{1015}{(1500/500)^2} = \mathbf{113\ pF}$$

Hence, capacitor range required is **113 – 1015 pF**

Question 2

(a) Calculate the oscillation frequency for the transistor Hartley oscillator circuit

(refer to Fig. 65.8). Given the circuit values to
be

$$L_{RFC} = 0.5\ mH, L_1 = 750\ \mu H, L_2 = 750\ \mu H, M = 150\ \mu H\ and\ C = 150\ pF$$

.

Solution

$$f_o = \frac{1}{2\pi\sqrt{LC}} \qquad where \quad L = L_1 + L_2 + 2M$$

$$\therefore L = 750\,\mu H + 750\,\mu H + 2 + 150\,\mu H = 1800\,\mu H$$

and

$$f_o = \frac{1}{2\pi\sqrt{180\,\mu H \times 150\,pF}} = 320\ kHz$$

(b) In a Hartley oscillator $if\ L_1 = 0.1\ mH$ and mutual inductance between the coils equal to $20\ \mu H$. Calculate the value of capacitor C of the oscillating circuit to obtain frequency of 4110 kHz.

Solution

$$L = L_1 + L_2 + 2M = 0.1\ mH + 10\ \mu H + 20\ \mu H = 130\mu\text{H}$$

Now the resonant frequency is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad or \quad C = \frac{1}{4\pi^2 f_o^2 L}$$

$$= \frac{1}{4\pi^2 \times 4110^2 \times 130\ \mu H}$$

$$C = 11.5\ pF$$

4.0 CONCLUSION

This unit has introduced to you the basic operation and circuitry of LC Oscillator. Various types of LC Oscillators were also discussed adequately.

5.0 SUMMARY

An LC oscillator consists of a capacitor and a coil connected in parallel which can store electrical energy vibrating at its resonant frequency. A capacitor stores energy in the electric field between its plates, depending on the voltage across it, and an inductor stores energy in its magnetic field, depending on the current through it. Majority of the oscillators used in radio receivers and transmitters use tuned circuits with positive feedback. Variations in oscillator circuits are due to the different way by which the feedback is applied. Some of the basic circuits are:

1. Armstrong or Tickler or Tuned-base Oscillator — it employs inductive feedback from collector to the tuned LC circuit in the base of a transistor.

2. Tuned Collector Oscillator—it also employs inductive coupling but the LC tuned circuit is in the collector circuit.

3. Hartley Oscillator—Here feedback is supplied inductively.

4. Colpitts Oscillator—Here feedback is supplied capacitively.

5. Clapp Oscillator—it is a slight modification of the Colpitts oscillator.

6.0 TUTOR-MARKED ASSIGNMENTS

(1) A tuned collector oscillator circuit is tuned to operate at $22\ kHz$ by a variable capacitor set to $2\ nF$.Find the value of tuned circuit inductance.

(2) In a transistorized Hartley oscillator, the tank circuit has the capacitance of $100\ pF$. The value of inductance between the collector and tapping point is $30\ \mu H$ and the value of inductance between the tapping point and the transistor base is $100\ \mu H$. Determine the frequency of oscillators. Neglect the mutual inductance.

(3) The frequency of oscillation of a Colpitts oscillator is given by,

$$f_o = \frac{1}{2\pi\sqrt{L\left(\frac{C_1 C_2}{C_1 + C_2}\right)}}$$

where $L, C_1\ and\ C_1$ are the frequency-determining components. Such a circuit operates at $450\ kHz$with $C_1 = C_2$. What will be the oscillation frequency if the value of $C_2$is doubled?

(4) A crystal has the following parameters: $L = 0.33\ H, C_1 = 0.065\ pF, C_2 = 1\ pF\ and\ R = 5.5\ K\Omega$. Find the series resonant frequency and Q-factor of the crystal.

7.0 REFERENCES/FURTHER READING

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UINT 4 RC OSCILLATORS

CONTENTS

1.0 INTRODUCTION

Oscillators are circuits that produce periodic waveforms. In oscillators, the only input requirement is of DC power supply which is required for operation of the active device. The frequency of the generated waveforms may vary from a few Hz to several KHz. It may be used to generate AC waveforms such as sinusoidal, rectangular or saw-tooth depending upon the type of oscillators used.

Sine-wave generators produce signals ranging from low audio frequencies to ultrahigh radio and microwave frequencies. Many low-frequency generators use resistors and capacitors to form their frequency-determining networks and are referred to as RC OSCILLATORS. They are widely used in the audio-frequency range.

2.0 OBJECTIVES

- Understand the basic operations of an RC oscillator.
- Familiarize with the various types of RC oscillators.
- Know the applications of RC network.
- Confirm that RC circuits are useful in the audio-frequency range

3.0 MAIN CONTENT

3.1 RC OSCILLATOR

An example of an oscillator circuit that follows the basic development of a feedback circuit is the RC or phase shift oscillator. Recall that the requirements for oscillation are that the loop gain, βA, is greater than unity and that the phase shift around the feedback network is 180^0 (providing positive feedback).

3.2 Phase Shift Principle

LC or Tuned circuits are not an essential requirement for oscillation. What is essential is that there should be a 180° phase shift around the feedback network (Total phase shift required is 360°. However, the balance of 180° is provided by the active device of the amplifier itself) and loop gain should be greater than unity. The 180° phase shift in the feedback signal can be achieved by using a suitable R-C network consisting of three or four R-C sections. The sine wave oscillators which use R-C feedback network are called phase-shift oscillators.

3.3 RC or Phase Shift Oscillator

Fig. 3.1, shows a transistor phase-shift oscillator which uses a three-section RC feedback network for producing a total phase shift of 180° (i.e. 60° per section) in the signal fed back to the base. Since CE amplifier produces a phase reversal of the input signal, total phase shift becomes 360° or 0° which is essential for regeneration and hence for sustained oscillations.

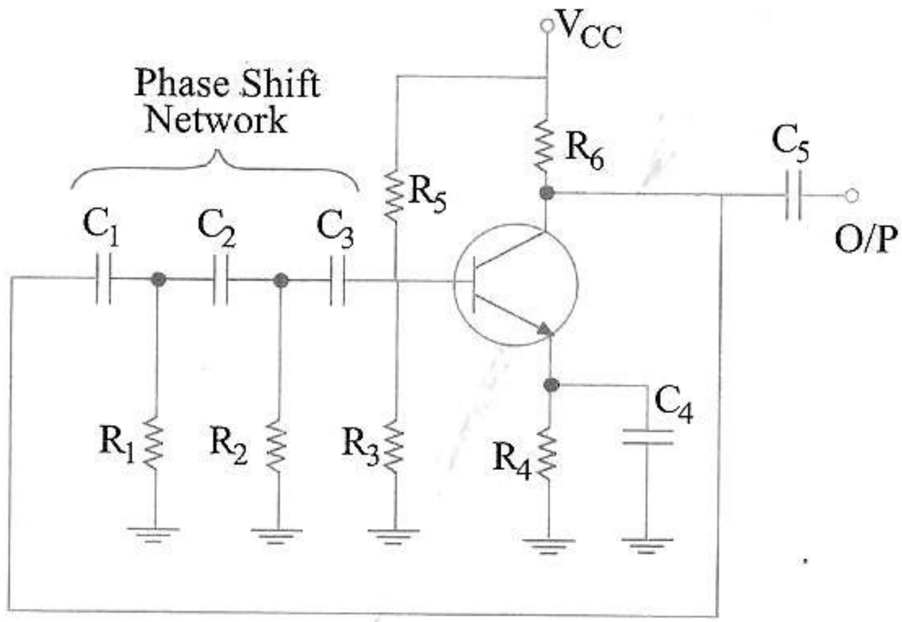

Fig. 3.1

Values of R and C are so selected that each RC section produces a phase advance of 60°. Addition of a fourth section improves oscillator stability. It is found that phase shift of 180° occurs only at one frequency which becomes the oscillator frequency.

(a) Circuit Action

The circuit is set into oscillations by any random or chance variation caused in the base current by

(i) noise inherent in a transistor or

(ii) minor variation in the voltage of the dc source.

This variation in the base current

1. is amplified in the collector circuit,
2. is then fed back to the RC network R_1C_2, R_2C_2 and R_3C_3,
3. is reversed in phase by the RC network,
4. is next applied to the base in phase with initial change in base current,
5. and hence is used to sustain cycles of variations in collector current between saturation and cut-off values.

Obviously, the circuit will stop oscillating the moment phase shift differs from 180°.

As is the case with such transistor circuits (i) voltage divider $R_5 - R_5$ provides dc emitter-base bias, (ii) R_6 controls collector voltage and (iii) R_4, C_4 provide temperature stability and prevent ac signal degeneration. The oscillator output voltage is capacitively coupled to the load by C_5.

(b) Frequency of Oscillation

The frequency of oscillation for the three-section RC oscillator when the three R and C components are equal is roughly given by

$$f_o = \frac{1}{2\pi\sqrt{6.RC}} Hz = \frac{0.065}{RC} Hz$$

Moreover, it is found that value of β is $1/29$. It means that amplifier gain must be more than 29 for oscillator operation.

(c) Advantages and Disadvantages

1. Since they do not require any bulky and expensive high-value inductors, such oscillators are well-suited for frequencies below $10\ kHz$.

2. Since only one frequency can fulfill Barkhausen phase-shift requirement, positive feedback occurs only for one frequency. Hence, pure sine wave output is possible.

3. It is not suited to variable frequency usage because a large number of capacitors will have to be varied. Moreover, gain adjustment would be necessary every time frequency change is made.

4. It produces a distortion level of nearly 5% in the output signal.

5. It necessitates the use of a high β transistor to overcome losses in the network.

3.4 Wien Bridge Oscillator

It is a low-frequency $(5\ Hz - 500\ kHz)$, low-distortion, tunable, high-purity sine wave generator, often used in laboratory work. As shown in the block diagrams of Fig.3.2 and Fig. 3.3, this oscillator uses two CE-connected RCcoupled transistor amplifiers and one RC-bridge (called Wien Bridge) network to provide feedback. Here,Q_1 serves as amplifier-oscillator and Q_2 provides phase reversal and additional amplification. The bridge circuit is used to control the phase of the feedback signal at Q_1.

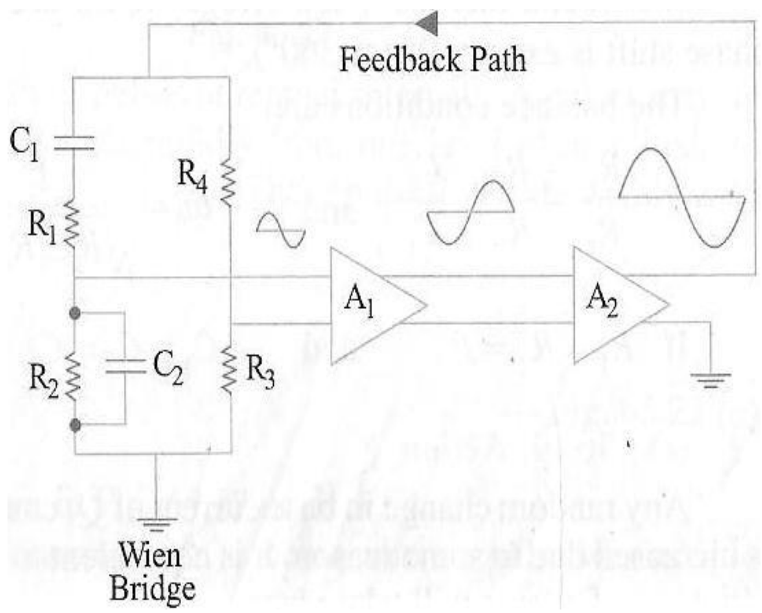

Fig.3.2

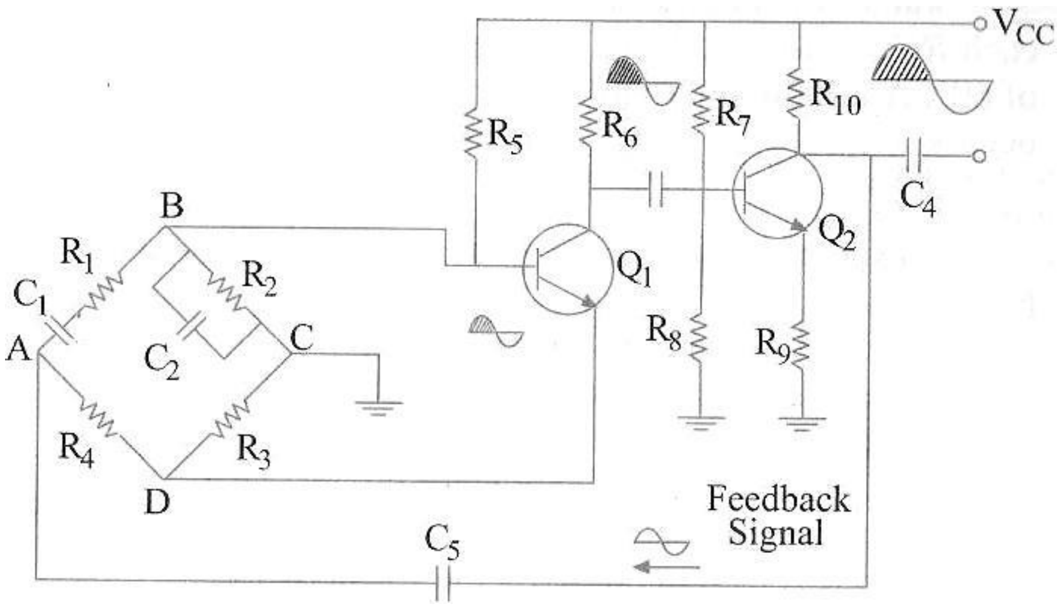

Fig. 3.3

(a) Phase Shift Principle

Any input signal at the base of Q_1 appears in the amplified but phase-reversed form across collector resistor R_6 (Fig. 65.21). It is further inverted by Q_2 in order to provide a total phase reversal of 360° for positive feedback. Obviously, the signal at R_{10} is an amplified replica of the input signal at Q_1 and is of the same phase since it has been inverted twice. We could feed this signal back to the base of Q_1 directly to provide regeneration needed for oscillator operation. But because Q_1 will amplify signals over a wide range of frequencies, direct coupling would result in poor frequency stability. By adding the Wien bridge, oscillator becomes sensitive to a signal of only one particular frequency. Hence, we get an oscillator of good frequency stability.

(b) Bridge Circuit Principle

It is found that the Wien bridge would become balanced at the signal frequency for which phase shift is exactly 0° (or 360°),

The balance conditions are

$$\frac{R_4}{R_3} = \frac{R_1}{R_2} + \frac{C_2}{C_1} \quad and \quad \omega_o = \frac{1}{\sqrt{R_1C_1R_2C_2}} \quad or \quad f_o = \frac{1}{2\pi\sqrt{R_1C_1R_2C_2}}$$

$$If \quad R_1 = R_2 = R \quad and \quad C_1 = C_2 = C \quad then \quad f_o = \frac{1}{2\pi RC} \quad and \quad \frac{R_4}{R_3} = 2$$

(c) Circuit Action

Any random change in base current of Q_1 can start oscillations. Suppose, the base current of Q_1 is increased due to some reason, it is equivalent to applying a positive going signal to Q_1. Following sequence of events will take place:

1. An amplified but phase-reversed signal will appear at the collector of Q_1

2. A still further amplified and twice phase-reversed signal will appear at the collector of Q_2.

   Having been inverted twice, this output signal will be in phase with the input signal at Q_1;

3. A part of the output signal at Q_2 is fed back to the input points of the bridge circuit (point $A - C$). A part of this feedback signal is applied to emitter resistor R_3 where it produces degenerative effect. Similarly, a part of the feedback signal is applied across base-bias resistor R_2 where it produces regenerative effect.

At the rated frequency f_o, effect of regeneration is made slightly more than that of degeneration in order to maintain continuous oscillations.

By replacing R_3 with a thermistor, amplitude stability of the oscillator output voltage can be increased.

(d) Advantages

Such a circuit has

1. Highly stabilized amplitude and voltage amplification,
2. Exceedingly good sine wave output,
3. Good frequency stability.

3.5 Non-sinusoidal Waveforms

Any waveform whose shape is different from that of a standard sine wave is called non-sinusoidal waveform. Examples are: square, rectangular, saw-tooth, triangular waveforms and pulses as shown in fig 3.4

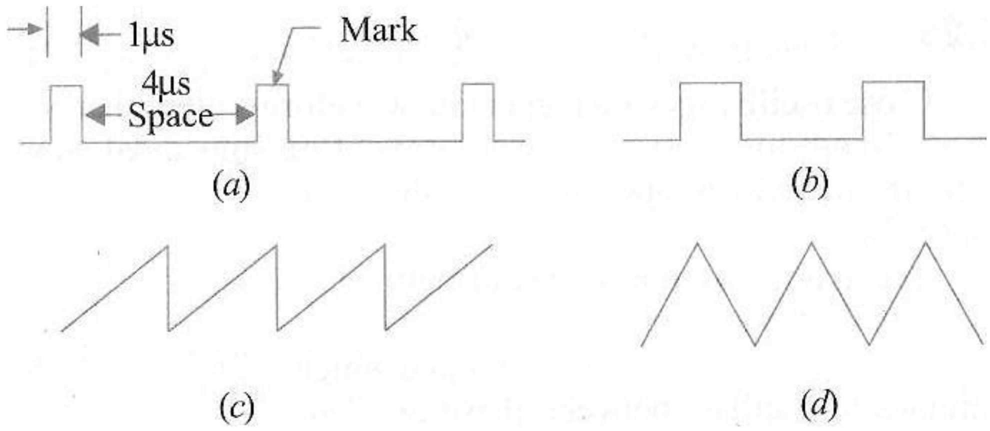

Fig. 3.4

(a) Pulses

Fig. 3.4 (a) shows a pulse train i.e. a stream of pulses at regular intervals. A pulse may, in general, be defined as a voltage or current that changes rapidly from one level of amplitude to another i.e. it is an abrupt discontinuity in voltage or current. These pulses are extensively used in digital electronics.

1. Mark-to-Space Ratio (MSR)

$$MRS = \frac{pulse\ width}{time\ between\ pulse} = \frac{1\ \mu s}{4\ \mu s} = \mathbf{0.25}$$

Hence, mark-to-space ratio of the pulse shown in Fig. 65.22 (a) is 1 : 4.

This name has come from early Morse-code transmission systems where a pulse was used to cause a pen to mark the paper.

2. Pulse Repetition Time *(PRT)*

It may be defined as the time between the beginning of one pulse and that of the other.

As seen from Fig. 3.4 (a), $PRT = 5\ \mu s$

3. Pulse Repetition Frequency (PRF)

It is given by the number of pulses per second.

$$PRT = \frac{1}{PRT} = \frac{1}{5\ \mu s} = \frac{10^6}{5} = 200{,}000Hz = 200Hz$$

Pulse circuits find applications in almost all electronic-based industries. Various types of pulse code modulations are employed in communication systems whereas radars utilize pulses to track targets. Digital computers require circuits that can be switched very rapidly between two states by using appropriate pulses.

(b) Square Wave.

It is shown in Fig. 3.4 (b) and is, in fact, a pulse waveform with a mark-to-space ratio of 1:1

Such square waves or pulses are used:

1. for audio frequency note generation,
2. for digital electronic switching as in computers
3. in radars,
4. as synchronizing pulses in TV,
5. for switching of high-power electronic circuits such as thyristor circuits.

(c) Saw-tooth Wave.

It is shown in Fig. 3.4 (c). Such waves are used:

1. In the scanning circuits of cathode-ray tubes (CRT),
2. In timing circuits where the time for the wave to proceed from one level to another is measured, such as that produced in an integrating circuit.

(d) Triangular Wave

It is shown in Fig. 3.4 (d). Such waves are often used

1. in scanning circuits where a uniform left-to-right scan is required as in computer displays,
2. for audio frequency note generation,
3. in timing circuits for electronic applications.

3.6 Multivibrators (MV)

These devices are very useful as pulse generating, storing and counting circuits. They are basically two-stage amplifiers with positive feedback from the output of one amplifier to the input of the other. This feedback (Fig. 3.5) is supplied in such a manner that one transistor is driven to saturation and the other to cut-off. It is followed by new set of conditions in which the saturated transistor is driven to cut-off and the cut-off transistor is driven to saturation.

There are three basic types of MVs distinguished by the type of coupling network employed.

1. Astable multivibrator (AVM),

2. Monostable multivibrator (MMV),

3. Bistable multivibrator (BMV).

The first one is the non-driven type whereas the other two are the driven type (also called triggered oscillators).

3.6.1 Astable Multivibrator (AMV)

It is also called free-running relaxation oscillator. It has no stable state but only two quasi-stable(half-stable) states between which it keeps oscillating continuously of its own accord without any external excitation.

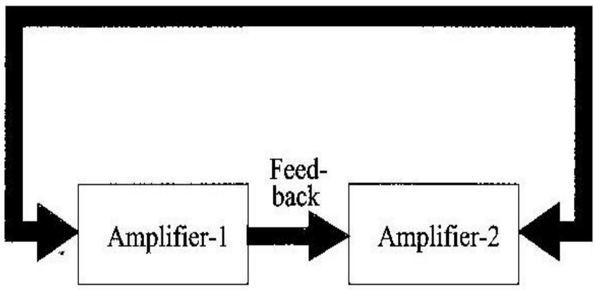

Fig. 3.5

In this circuit, neither of the two transistors reaches a stable state. When one is ON, the other is OFF and they continuously switch back and forth at a rate depending on the RC time constant in the circuit. Hence, it oscillates and produces pulses of certain mark-to-space ratio. Moreover, two outputs(180° out of phase with each other) are available.

It has two energy-storing elements i.e. two capacitors.

3.6.2 Monostable Multivibrator (MMV)

It is also called a single-shot or single swing or a one-shot multivibrator. Other names are : delay multivibrator and univibrator.

It has

(i) one absolutely stable (stand-by) state and (ii) one quasi-stable state.

It can be switched to the quasi-stable state by an external trigger pulse but it returns to the stable condition after a time delay determined by the value of circuit components. It supplies a single output pulse of a desired duration for every input trigger pulse.

It has one energy-storing element i.e. one-capacitor.

3.6.3 Bistable Multivibrator (BMV)

It is also called Eccles-Jordan or flip-flop multivibrator. It has two absolutely stable states. It can remain in either of these two states unless an external trigger pulse switches it from one state to the other. Obviously, it does not oscillate. It has no energy storage element.

Uses of Multivibrators

Some of their uses are:

1. as frequency dividers,
2. as sawtooth generators,
3. as square wave and pulse generators,
4. as a standard frequency source when synchronized by an external crystal oscillator,
5. for many specialized uses in radar and TV circuits,
6. as memory elements in computers.

3.7 TEST

Question 1

It is desired to design a phase-shift oscillator using a BJT and $R = 10\ k\Omega$.

Select the value of Cor oscillator operation at $1\ kHz$.

Solution

$$f_o = \frac{0.065}{RC} \quad or \quad C = \frac{0.065}{Rf_0}$$

$$= \frac{0.065}{10\ K \times 1\ KHz} = 0.0065 \times 10^{-6}\ F = 6.5\ nF$$

Question 2

Calculate the resonant frequency of a Wien Bridge oscillator (shown in Fig.

65.21) when $R = 10\ k\ \Omega\ and\ C = 2400\ pF.$

Solution

$$f_o = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 10\ K \times 2400\ pF}$$

$$= 6.63\ kHz$$

Fig. 65.21

Question 3

Determine the period and frequency of oscillation for an astable multivibrator with component values: $R_1 = 2\ K,\ \ R_2 = 20\ K,\ \ C_1 = 0.01\ \mu F\ and\ C_2 = 0.05\ \mu F.$

Solution

$$T_1 \ = 0.69\ \times\ 2\ K\ \times\ 0.01\,\mu F\ =\ 13.8\ \mu s$$

$$and\quad T_2 =\ 0.69\ \times\ 20\ k\ \times\ 0.05\ \mu F\ =\ 690\ \mu s$$

$$\therefore T\ =\ T_1\ +\ T_2\ =\ 13.8\,\mu s\ +\ 690\,\mu s\ =\ 703.8\ \mu s$$

4.0 CONCLUSION

This unit has introduced you to the basic working principles of the RC or Phase shift oscillators and has also confirmed that the usefulness of this RC network is greatly appreciated in the audio-frequency range as it meet the conditions of oscillation.

5.0 SUMMARY

RC oscillators also called phase shift oscillator produces the essential requirement for oscillation (i.e. loop gain, βA, greater than unity and that the phase shift around the feedback network is 180^0 (providing positive feedback)), hence finds application in a wide range of field with several modifications. They are widely used in the audio frequency range.

6.0 TUTOR-MARKED ASSIGNMENTS

(1) In an R-C phase shift oscillator $R\ =\ 5000\ \Omega\ and\ C\ =\ 0.1\ MF$. Calculate the frequency of oscillations.

(2) A Wien Bridge oscillator is used for operation at $f_o\ =\ 10\ kHz$.The value of $R\ is\ 100\ K,$ find the value of capacitor, *C.* Assume $R_1\ =\ R_2\ =\ R\ and\ C_1 =\ C_2\ = C.$

(3) A *RC* phase shift oscillator has $R\ =\ 1k\Omega\ and\ C\ =\ 0.01\ \mu F$. Calculate the frequency of oscillation.

(4) In an Hartley oscillator $if\ L_1\ =\ 0.1\ mH,\ L_2 = 10\ \mu H$ and mutual inductance between the coils equal to $20\ \mu H$. Calculate the value of capacitor *C* of the oscillatory circuit to obtain frequency of $4110\ kHz$ and also find the condition for sustained oscillations.

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MODULE 3 POWER SUPPLY

UNIT 1 POWER SOURCE

CONTENTS

1.0 INTRODUCTION

Power supply is a supply of electrical power. A device or system that supplies electrical or other types of energy to an output load or group of loads is called a power supply unit or PSU. The term is most commonly applied to electrical energy supplies.

A power supply may include a power distribution system as well as primary or secondary sources of energy such as:

- Conversion of one form of electrical power to another desired form and voltage, typically involving converting AC line voltage to a well-regulated lower-voltage DC for electronic devices. Low voltage, low power DC power supply units are commonly integrated with the devices they supply, such as computers and household electronics.
- Batteries
- Chemical fuel cells and other forms of energy storage systems

- Solar power
- Generators or alternators

Constraints that commonly affect power supplies are the amount of power they can supply, how long they can supply it without needing some kind of refueling or recharging, how stable their output voltage or current is under varying load conditions, and whether they provide continuous power or pulses.

A regulated power supply or stabilized power supply is one that includes circuitry to tightly control the output voltage and/or current to a specific value. The specific value is closely maintained despite variations in the load presented to the power supply's output, or any reasonable voltage variation at the power supply's input.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- Know what is meant by power supply.
- Know the major sources of power.
- Understand the environmental considerations of the sources of power.

3.0 MAIN CONTENT

POWER SOURCES - Sources of Electrical Energy

Electrical energy occurs naturally, but seldom in forms that can be used. For example, although the energy dissipated as lightning exceeds the world's demand for electricity by a large factor, lightning has not been put to practical use because of its unpredictability and other problems. Generally, practical electric-power-generating systems convert the mechanical energy of moving parts into electrical energy (e.g. generator). While systems that operate without a mechanical step do exist, they are at present either excessively inefficient or expensive because of a dependence on elaborate technology. While some electric plants derive mechanical energy from moving water (hydroelectric power), the vast majority derive it from heat engines in which the working substance is steam. The steam is generated with heat from combustion of fossil fuels or from nuclear fission. These energy resources fall into two main categories, often called renewable and non-renewable energy resources. Each of these resources can be used as a source to generate electricity, which is a very useful way of transferring energy from one place to another such as to the home or to industry.

3.1 Steam as an Energy Source

The conversion of mechanical energy to electrical energy can be accomplished with an efficiency of about 80%. In a hydroelectric plant, the losses occur in the turbines, bearings, penstocks, and generators. The basic limitations of thermodynamics fix the maximum efficiency obtainable in converting heat to electrical energy. The necessity of limiting the temperature to safe levels also helps to keep the efficiency down to about 41% for a fossil-fuel plant. Most nuclear plants use low-pressure, low-temperature steam operation, and have an even lower efficiency of about 30%. Nuclear plants have been able to achieve efficiency up to 40% with liquid-metal cooling. It is thought that by using magneto hydrodynamic “topping” generators in conjunction with normal steam turbines, the efficiency of conventional plants can be raised to close to 50%. These devices remove the restrictions imposed by the blade structure of turbines by using the steam or gasses produced by combustion as the working fluid.

Environmental Concerns

The heat generated by an electric-power plant that is not ultimately converted into electrical energy is called waste heat. The environmental impact of this waste is potentially catastrophic, especially when, as is often the case, the heat is absorbed by streams or other bodies of water. Cooling towers help to dispose waste heat into the atmosphere. Associated with nuclear plants, in addition to the problem of waste heat, are difficulties attending the disposal and confinement of reaction products that remain dangerously radioactive for many thousands of years and the adjustment of such plants to variable demands for power. Public concern about such issues—fueled in part by the accidents at the Three Mile Island nuclear plant in Harrisburg Pennsylvania in 1979, and the nuclear plant explosion in the Soviet Union at Chernobyl in 1986—forced the U.S. government to introduce extensive safety regulations for nuclear plants. Partly because of those regulations, nuclear plants are proving to be uneconomical. Several are being shut down and replaced by conventionally fueled plants.

3.2 Fossil fuels and nuclear fuel.

Fuel cells develop electricity by direct conversion of hydrogen, hydrocarbons, alcohol, or other fuels, with an efficiency of 50% to 60%. Although they have been used to produce electric power in space vehicles and some terrestrial locations, several problems have kept them from being widely used. Most important, the catalyst, which is an important component of a fuel cell, especially one that is operating at around room temperature, is very expensive. Controlled nuclear fusion could provide a virtually unlimited source of heat energy to produce steam in generating plants; however, many problems surround its development, and no appreciable contribution is expected from this source in the near future.

3.2.1 Fossil fuels

Sources of electricity include fossil fuels are found within the rocks of the Earth's surface. They are called fossil fuels because they are thought to have been formed many millions of years ago by geological processes acting on dead animals and plants, just like fossils.

Coal, oil and natural gas are fossil fuels. Because they took millions of years to form, once they are used up they cannot be replaced.

3.2.2 Oil and natural gas

Sources of electricity include oil and gases are chemicals made from molecules containing just carbon and hydrogen. All living things are made of complex molecules of long strings of carbon atoms. Connected to these carbon atoms are others such as hydrogen and oxygen. A simple molecule, called methane (CH4), is the main component of natural gas.

Crude oil (oil obtained from the ground) is a sticky, gooey black stuff. It contains many different molecules, but all are made of carbon and hydrogen atoms.

Advantages

These sources of energy are relatively cheap and most are easy to get and can be used to generate electricity.

Disadvantages

When these fuels are burned they produce the gas carbon dioxide, which is a greenhouse gas and is a major contributor to global warming. Transporting oil around the world can produce oil slicks, pollute beaches and harm wildlife.

3.2.3 Coal

Sources of electricity can include coal, which mainly consists of carbon atoms that come from plant material from ancient swamp forests. It is a black solid that is reasonably soft. You can scratch it with a fingernail. It is not as soft as charcoal, however, and is quite strong. It can be carved into shapes. There are different types of coal. Some contain impurities such as sulphur that pollute the atmosphere further when they burn, contributing to acid rain.

Advantages

Coal is relatively cheap, with large deposits left that are reasonably easy to obtain, some coal being close to the surface. It is relatively easy to transport because it is a solid.

Disadvantages

Some sources of coal are deep below the ground, as in the UK. They can be difficult, costly and dangerous to mine.

Burning coal without first purifying it contributes to global warming, as well as to the production of smog (smoke and fog), which is harmful to health. It is a finite resource and will eventually run out.

3.3 Solar energy

Solar energy has been recognized as a feasible alternative. It has been suggested that efficient collection of the solar energy incident on 14% of the western desert areas of the United States would provide enough electricity to satisfy current demands. Two main solar processes could be used. Photovoltaic cells (see solar cell) convert sunlight directly into electrical energy. Another method would use special coatings that absorb sunlight readily and emit infrared radiation slowly, making it possible to heat fluids to 1,000°F (540°C) by solar radiation. The heat in turn can be converted to electricity. Some of this heat would be stored to allow operation at night and during periods of heavy cloud cover. The projected efficiency of such a plant would be about 30%, but this fairly low efficiency must be balanced against the facts that energy from the sun costs nothing and that the waste heat from such a plant places virtually no additional burden on the environment. The principal problem with this and other exotic systems for generating electricity is that the time needed for their implementation may be considerable.

3.4 Windmills

Windmills, once widely used for pumping water, have become viable for electric-power generation because of advances in their design and the development of increasingly efficient generators. Windmill "farms," at which rows of windmills are joined together as the source of electrical energy, serve as a significant, though minor, source of electrical energy in coastal and plains areas. However, the vagaries of the wind make this a difficult solution to implement on a large scale.

4.0 CONCLUSION

This unit has given you a definition of power supply and has introduced you to some sources of electricity which play a major role or are widely used all over the world. Also the environmental considerations of the sources of power were considered.

5.0 SUMMARY

Power supply can be defined in relation to electrical energy supply as a supply of electrical power (electricity). Though electrical energy occurs naturally, but seldom in forms that can be used therefore has to be converted from other forms of energy to electrical energy and the sources includes amongst many: steam, fossil fuel, solar, windmill, hydro *etc.*

6.0 TUTOR-MARKED ASSIGNMENT

1. What is meant by power supply?
2. Enumerate the sources of power (electricity).
3. Give the environmental considerations of the sources of power.

4. List the merits and demerits of coal as a source of power supply.

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UNIT 2 DC POWER UNIT

CONTENTS

1.0 INTRODUCTION

Most of the electronic devices and circuits require a dc source for their operation. Dry cells and batteries are one form of dc source. They have the advantage of being portable and ripple-free.

However, their voltages are low; they need frequent replacement and are expensive as compared to conventional dc power supplies. Since the most convenient and economical source of power is the domestic ac supply, it is advantageous to convert this alternating voltage (usually, $220\ V\ rms$) to dc voltage (usually smaller in value). This process of converting ac voltage into dc voltage is called rectification and is accomplished with the help of a

(i) Rectifier
(ii) Filter and
(iii) Voltage regulator circuit.

These elements put together constitute dc power supply.

2.0 OBJECTIVES

By the end of this unit, you will be able to:

- Know the various types of power supply.
- Distinguish between regulated power supply and unregulated power supply.
- Enumerate the 5 stages of a dc power supply unit.

3.0 MAIN CONTENT

3.1 Power supply types

Power supplies for electronic devices can be broadly divided into linear and switching power supplies. (It is customary to refer to a simple unregulated supply as linear, although in fact is has no active electronic devices, either in linear or switched mode). The linear supply is usually a relatively simple design; it becomes increasingly bulky and heavy for high-current equipment due to the need for large mains-frequency transformers and heat-sinked electronic regulation circuitry. Linear voltage regulation circuitry reduces voltage by dissipating it, making efficiency low. A switched-mode supply of the same rating as a linear supply will be smaller, is usually more efficient, but will be more complex.

3.1.1 Battery Power Supply

A battery is a type of power supply that is independent of the availability of mains electricity, suitable for portable equipment and use in locations without mains power. A battery consists of several electrochemical cells connected in series to provide the voltage desired. Batteries may be primary (able to supply current when constructed, discarded when drained) or secondary (rechargeable; can be charged, used, and recharged many times)

The primary cell first used was the carbon-zinc dry cell. It had a voltage of 1.5 volts; later battery types have been manufactured, when possible, to give the same voltage per cell. Carbon-zinc and related cells are still used, but the alkaline battery delivers more energy per unit weight and is widely used. The most commonly used battery voltages are 1.5 (1 cell) and 9V (6 cells).

Various technologies of rechargeable battery are used. Types most commonly used are NiMH, and lithium ion and variants.

3.1.2 Unregulated Power Supply

An AC powered unregulated power supply usually uses a transformer to convert the voltage from the wall outlet (mains) to a different, nowadays usually lower, voltage. If it is used to produce DC, a rectifier is used to convert alternating voltage to a pulsating direct voltage, followed by a filter, comprising one or more capacitors, resistors, and sometimes inductors, to filter out (smooth) most of the pulsation. A small remaining unwanted alternating voltage component at mains or twice mains power frequency (depending upon whether half- or full-wave rectification is used)—ripple—is unavoidably superimposed on the direct output voltage. For purposes such as charging batteries the ripple is not a problem, and the simplest unregulated mains-powered DC power supply circuit consists of a transformer driving a single diode in series with a resistor.

Before the introduction of solid-state electronics equipment used valves (vacuum tubes) which required high voltages; power supplies used step-up transformers, rectifiers, and filters to generate one or more direct voltages of some hundreds of volts, and a low alternating voltage for filaments. Only the most advanced equipment used expensive and bulky regulated power supplies.

An unregulated power supply is one whose dc terminal voltage is affected significantly by the amount of load. As the load draws more current, the dc terminal voltage becomes less.

3.1.3 Regulated Power Supply

The voltage produced by an unregulated power supply will vary depending on the load and on variations in the AC supply voltage. For critical electronics applications a linear regulator may be used to set the voltage to a precise value, stabilized against fluctuations in input voltage and load. The regulator also greatly reduces the ripple and noise in the output direct current. Linear regulators often provide current limiting, protecting the power supply and attached circuit from over current.

Adjustable linear power supplies are common laboratory and service shop test equipment, allowing the output voltage to be adjusted over a range. For example, a bench power supply used by circuit designers may be adjustable up to 30 volts and up to 5 amperes output. Some can be driven by an external signal, for example, for applications requiring a pulsed output.

It is that dc power supply whose terminal voltage remains almost constant regardless of the amount of current drawn from it. An unregulated supply can be converted into a regulated power supply by adding a voltage regulating circuit to it.

3.1.4 AC/DC Supply

In the past, mains electricity was supplied as DC in some regions, AC in others. Transformers cannot be used for DC, but a simple, cheap unregulated power supply could run directly from either AC or DC mains without using a transformer. The power supply consisted of a rectifier and a filter capacitor. When operating from DC the rectifier was essentially a conductor, having no effect; it was included to allow operation from AC or DC without modification.

3.1.5 Switched-Mode Power Supply


A computer's switched mode power supply unit

A switched-mode power supply (SMPS) works on a different principle. AC input, usually at mains voltage, is rectified without the use of a mains transformer, to obtain a DC voltage. This voltage is then switched on and off at a high speed by electronic switching circuitry, which may then pass through a high-frequency, hence small, light, and cheap, transformer or inductor. The duty cycle of the output square wave increases as power output requirements increase. Switched-mode power supplies are always regulated. If the SMPS uses a properly-insulated high-frequency transformer, the output will be electrically isolated from the mains, essential for safety.

The input power slicing occurs at a very high speed (typically 10 kHz — 1 MHz). High frequency and high voltages in this first stage permit much smaller transformers and smoothing capacitors than in a power supply operating at mains frequency, as linear supplies do. After the transformer secondary, the AC is again rectified to DC. To keep output voltage constant, the power supply needs a sophisticated feedback controller to monitor current drawn by the load.

SMPSs often include safety features such as current limiting or a crowbar circuit to help protect the device and the user from harm. In the event that an abnormal high-current power draw is detected, the switched-mode supply can assume this is a direct short and will shut itself down before damage is done. For decades PC power supplies have provided a power good signal to the motherboard whose absence prevents operation when abnormal supply voltages are present.

SMPSs have an absolute limit on their minimum current output. They are only able to output above a certain power level and cannot function below that point. In a no-load condition the frequency of the power slicing circuit increases to great speed, causing the isolated transformer to act as a Tesla coil, causing damage due to the resulting very high voltage power spikes. Switched-mode supplies with protection circuits may briefly turn on but then shut down when no load has been detected. A very small low-power dummy load such as a ceramic power resistor or 10-watt light bulb can be attached to the supply to allow it to run with no primary load attached.

Power factor has become a recent issue of concern for computer manufacturers. Switched mode power supplies have traditionally been a source of power line harmonics and have a very poor power factor. Many computer power supplies built in the last few years now include power factor correction built right into the switched-mode supply, and may advertise the fact that they offer 1.0 power factor.

By slicing up the sinusoidal AC wave into very small discrete pieces, a portion of unused alternating current stays in the power line as very small spikes of power that cannot be utilized by AC motors and results in waste heating of power line transformers. Hundreds of switched mode power supplies in a building can result in poor power quality for other customers surrounding that building, and high electric bills for the company if they are billed according to their power factor in addition to the actual power used. Filtering capacitor banks may be needed on the building power mains to suppress and absorb these negative power factor effects.

3.1.6 Programmable Power Supply


Programmable power supplies

Programmable power supplies Programmable power supplies allow for remote control of the output voltage through an analog input signal or a computer interface such as RS232 or GPIB. Variable properties include voltage, current, and frequency (for AC output units). These supplies are composed of a processor, voltage/current programming circuits, current shunt, and voltage/current read-back circuits. Additional features can include over current, overvoltage, and short circuit protection, and temperature compensation. Programmable power supplies also come in a variety of forms including modular, board-mounted, wall-mounted, floor-mounted or bench top.

Programmable power supplies can furnish DC, AC, or AC with a DC offset. The AC output can be either single-phase or three-phase. Single-phase is generally used for low-voltage, while three-phase is more common for high-voltage power supplies.

Programmable power supplies are now used in many applications. Some examples include automated equipment testing, crystal growth monitoring, and differential thermal analysis.

3.1.7 Uninterruptible Power Supply

An uninterruptible power supply (UPS) takes its power from two or more sources simultaneously. It is usually powered directly from the AC mains, while simultaneously charging a storage battery. Should there be a dropout or failure of the mains, the battery instantly takes over so that the load never experiences an interruption. Such a scheme can supply power as long as the battery charge suffices, e.g., in a computer installation, giving the operator sufficient time to effect an orderly system shutdown without loss of data. Other UPS schemes may use an internal combustion engine or turbine to continuously supply power to a system in parallel with power coming from the AC mains. The engine-driven generators would normally be idling, but could come to full power in a matter of a few seconds in order to keep vital equipment running without interruption. Such a scheme might be found in hospitals or telephone central offices.

3.1.8 High-voltage power supply

High voltage refers to an output on the order of hundreds or thousands of volts. High-voltage supplies use a linear setup to produce an output voltage in this range.

Additional features available on high-voltage supplies can include the ability to reverse the output polarity along with the use of circuit breakers and special connectors intended to minimize arcing and accidental contact with human hands. Some supplies provide analog inputs (i.e. 0-10V) that can be used to control the output voltage, effectively turning them into high-voltage amplifiers albeit with very limited bandwidth.

3.2 Components of a dc supply unit

A typical dc power supply consists of five stages as shown in Figure 3.1.

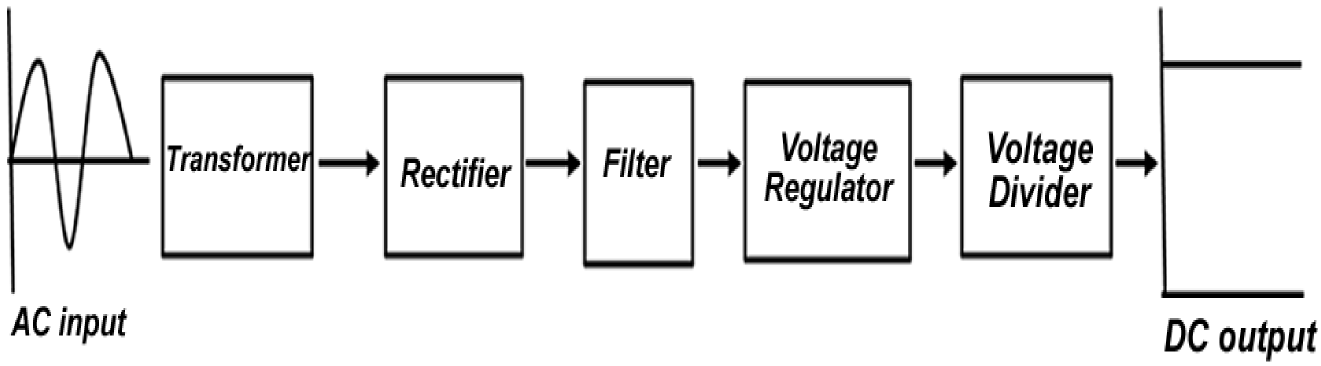

Fig 3.1 dc power supply unit

1. **Transformer:** Its job is either to step up or (mostly) step down the ac supply voltage to suit the requirement of the solid-state electronic devices and circuits fed by the dc power supply. It also provides isolation from the supply line–an important safety consideration.

2. **Rectifier:** It is a circuit which employs one or more diodes to convert ac voltage into pulsating dc voltage.

3. **Filter**: The function of this circuit element is to remove the fluctuations or pulsations (called ripples) present in the output voltage supplied by the rectifier. Of course, no filter can, in practice, gives an output voltage as ripple-free as that of a dc battery but it approaches it so closely that the power supply performs as well.

4. **Voltage Regulator:** Its main function is to keep the terminal voltage of the dc supply constant even when

   (i) ac input voltage to the transformer varies (deviations from $220\ V$ are common); or

   (ii) the load varies.

   Usually, Zener diodes and transistors are used for voltage regulation purposes. Again, it is impossible to get 100% constant voltage but minor variations are acceptable for most of the jobs.

5. **Voltage Divider:** Its function is to provide different dc-voltages needed by different electronic circuits. It consists of a number of resistors connected in series across the output terminals of the voltage regulator. Obviously, it eliminates the necessity of providing separate dc power supplies to different electronic circuits working on different dc levels.

Strictly speaking, all that is really required for conversion from ac to dc is a transformer and a rectifier (in fact, even the transformer could be eliminated if no voltage transformation is required). The filter, voltage regulator and voltage divider are mere refinements of a dc power supply though they are essential for most applications except for battery charging and running small dc motors etc.

4.0 CONCLUSION

This unit has introduced you to the types of dc power supply available and also to the various components of a dc power supply and a brief description of each components. A detailed description of the components will be provided in the other units.

5.0 SUMMARY

The conventional dc power supply unit has been a great solution to the constraints of dry cell batteries *i.e.* low voltage supply, constant need for replacement and relative high cost. The alternating voltage can be converted to dc voltage through the components of the dc power supply unit.

6.0 TUTOR-MARKED ASSIGNMENT

1. With the aid of a block diagram, list the components of a dc supply unit.
2. Enumerate the types of power supply.
3. What is the difference between Regulated power supply and unregulated power supply?
4. What device or circuit is needed to convert an unregulated supply to a regulated supply?
5. Explain the disadvantages of the switched-mode power supply and propose solutions to the problem.
6. Name the applications of Programmable power supply.
7. What is meant by UPS scheme?

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UNIT 3 PERFORMANCE OF RECTIFIER

CONTENTS

1.0 INTRODUCTION

A rectifier circuit is necessary to convert a signal having zero average value to one that has a non-zero average. The output resulting from a rectifier is a pulsating dc voltage and not as a battery replacement. Such a voltage could be used in, say, a battery charger, where the average dc voltage is large enough to provide a charging current for the battery. For dc supply voltage, as those used in a radio, stereo system, computer, and so on, the pulsating dc voltage from a rectifier is not good enough. A filter circuit is necessary to provide a steadier dc voltage.

2.0 OBJECTIVES

By the end of this unit, you will be able to:

- Understand and describe the rectifier circuits.
- Describe the output of each rectifier circuits
- Solve problems related to rectification of ac signal

3.0 MAIN CONTENT

Many semiconductor devices or systems (like car stereo systems) require a negative dc source or both a negative and a positive dc source. For the sake of simplicity, we will analyze only the positive dc power supplies. However, a positive dc supply can be converted into a negative one by simply reversing the two leads in the same way as we reverse the polarity of a dry cell.

Quite a number of integrated circuits (ICs) require both positive and negative source with common ground. In that case, the polarized components in the negative portion of the supply will have to be reversed. For example, its rectifier, filter capacitor and voltage/current regulation devices will have to be reversed as compared to the positive supply.

We will consider the following circuits:

1. Half-wave rectifier,
2. Full-wave rectifier,
3. Full-wave bridge circuit.

3.1 Half-Wave Rectifier

The basic circuit of a half-wave rectifier with a resistive load (but no filter circuit) is shown in Fig. 3.1 (a). The alternating secondary voltage is applied to a diode connected in series with a load resistor R_L. Let the equation of the alternating secondary voltage be:

$$V_s = V_{sm}\, wt$$

(a) Working

During the positive half-cycle of the input ac voltage, the diode D is forward-biased (ON) and conducts. While conducting, the diode acts as a short-circuit so that circuit current flows and hence, positive half-cycle of the input ac voltage is dropped across R_L. It constitutes the output voltage V_L as shown in Fig. 3.1 (b). Waveform of the load voltage is also shown in Fig. 3.1 (b). It consists of half-wave rectified sinusoids of peak value V_{LM}.

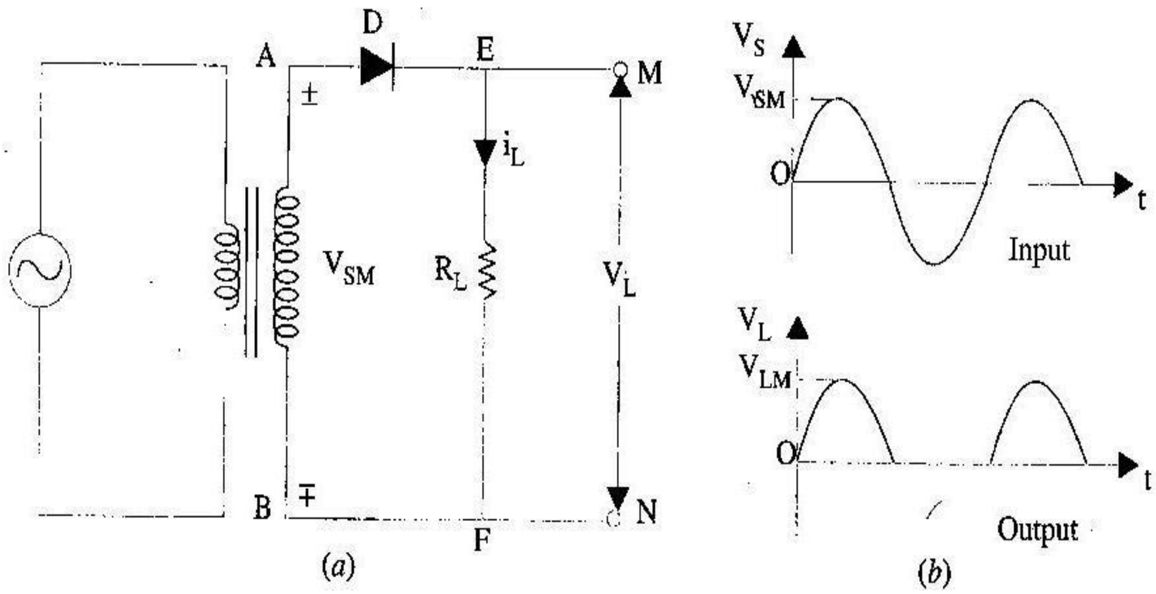

Fig. 3.1

During the negative input half-cycle, the diode is reverse-biased(OFF) and so, does not conduct *i.e.* there is no current flow. Hence, there is no voltage drop across R_L. In other words $i_L = 0$ and $V_L = 0$. Obviously, the negative input half-cycle is suppressed *i.e.* it is not utilized for delivering power to the load. As seen, the output is not a steady dc but only a pulsating dc wave having a ripple frequency equal to that of the input voltage frequency. This wave can be observed by an oscilloscope connected across R_L. When measured by a dc meter, it will show some average positive value both for voltage and current. Since only one half-cycle of the input wave is used, it is called a half-wave rectifier. It should be noted that forward voltage drop across the diode has been neglected in the above discussion. We have, in fact, assumed an ideal diode (having zero forward resistance and infinite reverse resistance).

(b) Average and RMS Values

Let V_{sm} = maximum value of transformer secondary voltage

V_s = rmsvalue of secondary voltage

V_{LM}. = maximum value of load voltage

$= V_{sm}$ − diode drop − secondary resistance drop

V_L = rms value of load voltage

I_L = rms value of load current

$V_{L(dc)}$ = average value of load voltage

$I_{L(dc)}$ = average value of load current

I_{LM} = maximum value of load current

R_L = load resistance

R_s = transformer secondary resistance

r_d = diode forward resistance

$R_0 = R_s + r_d$

$$I_{LM} = \frac{V_{sm} - V_B}{(R_S + r_d) + R_L} = \frac{V_{sm} - V}{R_O + R_L}, \qquad V_{LM} = I_{LM}.R_L$$

$$v_{L(dc)} = \frac{V_{LM}}{\pi} = 0.318V_{LM}, \quad I_{L(dc)} = \frac{I_{LM}}{\pi} = 0.318I_{LM}$$

$$I_L = I_L M_n/2 = 0.5\, I_{LM} = 0.5\, V_{LM}/R_L$$

(c) Efficiency

The efficiency of rectification is given by the ratio of the output dc power to the total amount of input power supplied to the circuit. It is also called the conversion efficiency.

$$\eta = \frac{P_{dc}}{P_{in}} = \frac{power\ in\ the\ load}{input\ power}$$

Now, $P_{dc} = I^2_{L(dc)} R_L = \left(\frac{I_{LM}}{\pi}\right)^2 \quad ; \quad R_L = \frac{I^2_{LM}}{\pi^2} \cdot R_L$

$$P_{in} = I^2_{L(dc)}(R_L + R_0) = \left(\frac{I_{LM}}{\pi}\right)^2 (R_L + R_0) = \frac{I^2_{LM}}{4}(R_L + R_0)$$

$$\therefore \quad \eta = \frac{P_{dc}}{P_{in}} = \left(\frac{4}{\pi^2}\right)\frac{R_L}{(R_L + R_0)} = \frac{0.406}{1 + R_0/R_L} = \frac{409.6\%}{1 + R_0/R_L}$$

If R_0 is neglected $\eta = 40.6\%$. Obviously, it is the maximum possible efficiency of a half-wave rectifier.

(d) Ripple Factor

Although the rectified voltage is not a filtered voltage, it nevertheless contains a dc component and a ripple component. We shall find out that the full wave rectified signal has a larger dc component and fewer ripples than the half-wave rectified voltage.

For a half-wave rectified signal, the output dc voltage is

$$V_{dc} = 0.318 V_m$$

The rms value of the ac component of the output signal can be calculated to be

$$V_r(rms) = 0.385 V_m$$

The percent ripple of a half-wave rectified signal can then be calculated as

$$\gamma = \frac{V_r(rms)}{V_{dc}} \times 100\% = \frac{0.385 V_m}{0.318 V_m} \times 100\% = 121\%$$

(e) Peak Inverse Voltage (PIV)

It is the maximum voltage that occurs across the rectifying diode in the reverse direction. As seen from Fig. 3.1, the diode is reverse-biased during the negative half-cycle and the maximum voltage applied across it equals the maximum secondary voltage i.e. V_{sm}.

(f) Transformer Utilization Factor (TUF)

While designing any power supply, it is necessary to determine the rating of the transformer. It can be done provided TUF is known. The value of TUF depends on the amount of power to be delivered to the load and the type of rectifier circuit to be used.

$$TUF = \frac{dc\ power\ delivered\ to\ the\ load}{ac\ rating\ of\ transformer\ secondary}$$

$$= \frac{P_{dc}}{P_{ac.rated}} = \frac{P_{dc}}{P_{in.rated}}$$

At first sight it might appear as if the above ratio is the same as the conversion efficiency. Actually, it is not so because the rating of the transformer secondary is different from the actual power delivered by the secondary.

$$P_{dc} = V_{L(dc)} \cdot I_{L(dc)} = \frac{V_{LM}}{\pi} \cdot \frac{V_{LM}}{R_L} = \frac{V_{LM}^2}{\pi R_L}$$

$$= \frac{V_{sm}^2}{\pi R_L} \qquad - if\ drop\ over\ R_0\ is\ neglected$$

Now, the rated voltage of transformer secondary is $V_{sm}/\sqrt{2}$but the actual current flowing through the secondary is $I_L = I_{LM}/2$ (and not $I_{LM}/\sqrt{2}$) since it is a half-wave rectified current.

$$P_{ac.rated} = \frac{V_{sm}}{\sqrt{2}} \cdot \frac{I_{LM}}{2} = \frac{V_{sm}}{\sqrt{2}} \cdot \frac{V_{LM}}{2R_L} = \frac{V_{sm}^2}{2\sqrt{2}R_L}$$

$$TUF = \frac{V_{sm}^2/\pi R_L}{V_{sm}^2/2\sqrt{2}R_L} = \frac{2\sqrt{2}}{\pi} = 0.287$$

However, due to saturation effects produced by the flow of direct current through the transformer secondary, the value of TUFis further reduced to 0.2.

Obviously, dc power delivered to the load = ac transformer rating × TUF

If, we have a 1 kVA transformer, then the power which it would be able to deliver to a resistive load in a half-wave rectifier without over-heating would be = $0.2 \times 1000 = 200\,W$.

3.1.1 Equivalent Circuit of a HW Rectifier

Such a circuit is shown in Fig. 3.2. Here, the diode has been replaced by its equivalent circuit. The transformer secondary of Fig. 55.2 has been replaced by an ac sinusoidal generator having a peak value of V_{sm}. Resistance R_S represents transformer secondary resistance.

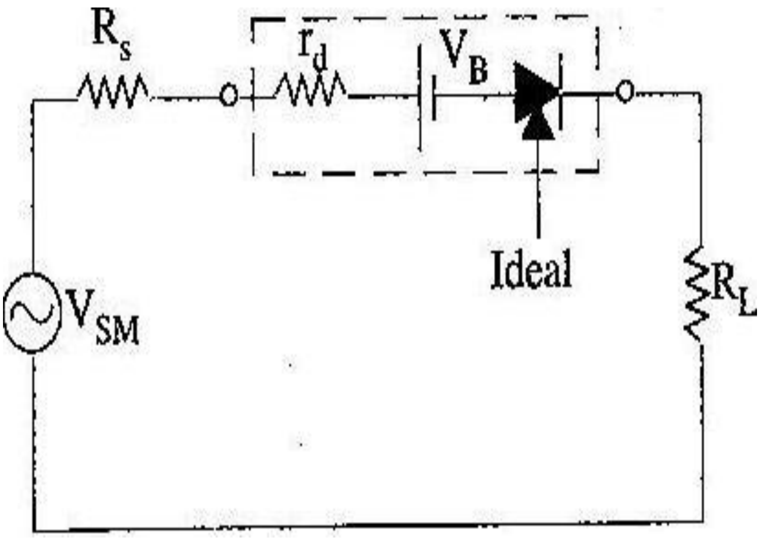

Fig. 3.2

Obviously,

$$I_{LM} = \frac{V_{sm} - V_B}{(R_S + r_d) + R_L} = \frac{V_{sm} - V_B}{R_0 + R_L}$$

$$V_{LM} = I_{LM} \,.R_L$$

$$V_{L(dc)} = V_{LM}/\pi \quad , \quad I_{L(dc)} = I_{LM}/\pi$$

$$V_L = V_{LM}/2 \quad and \quad I_L = I_{LM}/2$$

(i) $\eta = \left(\frac{4}{\pi^2}\right)\frac{R_L}{(R_S + r_d) + R_L}$

$$= \left(\frac{4}{\pi^2}\right)\frac{R_L}{R_0 + R_L}\frac{40.6\%}{1 + R_0/R_L}$$

(ii) Voltage regulation is given by

$$V_R = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

(iii) Under no-load condition i.e. when no output current flows, the voltage has maximum value.

When rectifier is fully loaded *i.e.* when output current flows, there is drop over R_0. Hence, output voltage is decreased by this much amount.

$$V_{FL} = V_{NL} \frac{R_L}{R_0 + R_L}$$

Substituting this value in the above equation, we get

$$VR = \frac{R_o}{R_L}$$

Example

A half-wave rectifier using silicon diode has a secondary emf of $14.14\ V\ (rms)$ with a resistance of $0.2\ \Omega$. The diode has a forward resistance of $0.05\ \Omega$ and a threshold voltage of $0.7\ V$. If load resistance is $10\ \Omega$, determine

(i) dc load current,
(ii) dc load voltage,
(iii) voltage regulation and
(iv) efficiency.

Solution

$$V_{sm} = \sqrt{2} \times 14.14 = 20\ V \quad , \qquad R_o = 0.2 + 0.05 = 0.25\Omega$$

(i) $$I_{LM} = \frac{V_{sm} - V_B}{R_0 + R_L} = \frac{20 - 0.7}{10.25} = 1.88\ A$$

$$I_{L(dc)} = \frac{I_{LM}}{\pi} = \frac{1.88}{\pi}\ 0.6\ A$$

(ii) $$V_{L(dc)} = I_{L(dc)}.R_L = 0.6 \times 10 = 6\ V$$

(iii) $$V_R = R_0/R_L = 0.25/10 = 0.025 \quad or\ 25\%$$

(iv) $\eta = \frac{40.6}{1+0.25/10} = 39.6\%$

3.2 Full-wave Rectifier

In this case, both half-cycles of the input are utilized with the help of two diodes working alternately. For full-wave rectification, use of a transformer is essential (though it is optional for half-wave rectification).

The full-wave rectifier circuit using two diodes and a center-tapped transformer is shown in 3.3(a). The center-tap is usually taken as the ground or zero voltage reference point.

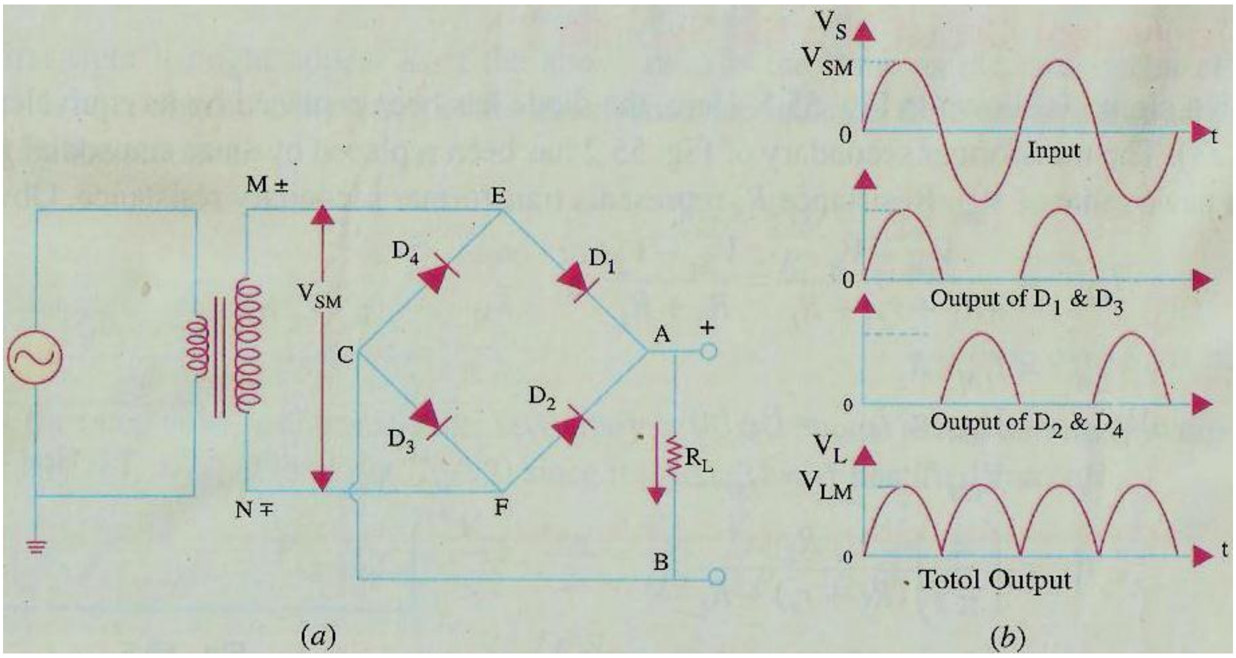

Fig 3.3

Fig. 3.4 shows two different ways of drawing the circuit. In Fig. 3.4 (a), R_L becomes connected to point G *via* the earth whereas in Fig. 3.4 (b). It is connected directly to G.

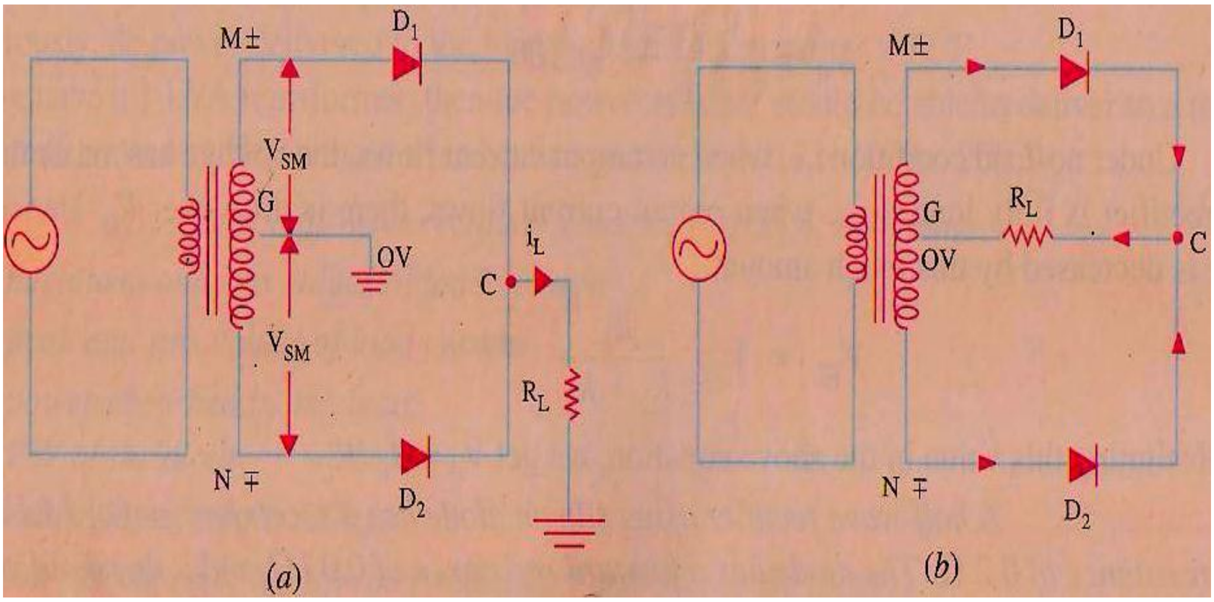

Fig. 3.4

(a) Working

When input ac supply is switched on, the ends M and N of the transformer secondary become $+ve$and $-ve$ alternately. During the positive half-cycle of the ac input, terminal M is $+ve$, G is at zero potential and N is at $-ve$ potential. Hence, being forward-biased, diode D_1 conducts (but not D_2which is reverse-biased) and current flows along MD_1CABG. As a result, positive half-cycle of the voltage appears across R_L.

During the negative half-cycle, when terminal N becomes $+ve$, then D_2 conducts (but notD_1) and current flows along ND_2CABG. So, we find that current keeps on flowing through R_L in the same direction (*i.e.* fromA to B) in both half-cycles of ac input. It means that both half-cycles of the input ac supply are utilized as shown in Fig. 3.3(b). Also, the frequency of the rectified output voltage is twice the supply frequency. Of course, this rectified output consists of a dc component and many ac components of diminishing amplitudes.

(b) Average and RMS Values

As proved earlier in and now shown in Fig. 3.5

$$V_L = \frac{V_{LM}}{\sqrt{2}} = 0.707V_{LM} \quad ; \quad V_{L(dc)} = 2V_{LM}/\pi = 0.636\,V$$

$V_{L(ac)}$ = rms value of ac components in the output voltage

$$= \sqrt{V_L^2 - V_{L(dc)}^2}$$

Similarly, $I_{LM} = \frac{V_{LM}}{R_L}$

$$I_L = \frac{I_{LM}}{\sqrt{2}} = 0.707 I_{LM}$$

$$I_{L(dc)} = \frac{2I_{LM}}{\pi} = 0.636 I_{LM}$$

$$I_{L(ac)} = \sqrt{I_L^2 - I_{L(dc)}^2}$$

Incidentally, $I_{L(ac)}$is the same thing as$I_{r(rms)}$.

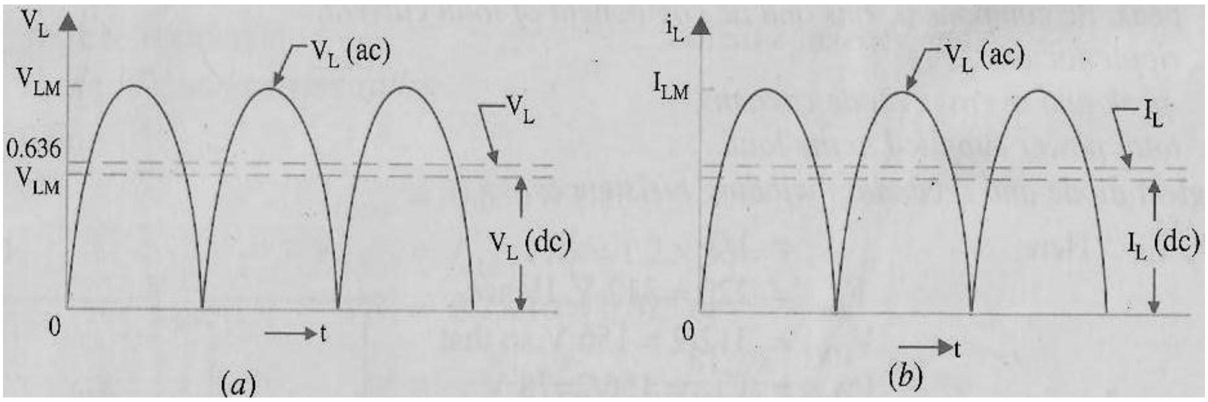

Fig 3.5

(c) Efficiency

$$P_{in} = I_L^2(R_0 + R_L) = \left(\frac{I_{LM}}{\sqrt{2}}\right)^2 (R_0 + R_L) = \frac{1}{2} I_{LM}^2 (R_0 + R_L)$$

$$P_{dc} = I_{L(dc)}^2 (R_0 + R_L) = \left(\frac{2I_{LM}}{\pi}\right)^2 (R_0 + R_L) = \frac{4I_{LM}^2}{\pi^2} (R_0 + R_L)$$

$$\eta = \frac{P_{dc}}{P_{in}} = \left(\frac{8}{\pi^2}\right)\left(\frac{R_L}{R_0 + R_L}\right) = \frac{0.812}{(1 + R_0/R_L)} = \frac{81.2\%}{(1 + R_0/R_L)}$$

It is twice the value for the half-wave rectifier for the simple reason that a full-wave rectifier utilizes both half-cycles of the input ac supply.

(d) Ripple Factor

For a full-wave rectified voltage, the dc value is

$$V_{dc} = 0.636\ V_m$$

The rms value of the ac component of the output signal can be calculated to be

$$V_r(rms) = 0.308\ V_m$$

The percent ripple of a full-wave rectified signal can be calculated as

$$\gamma = \frac{V_r(rms)}{V_{dc}} \times 100\% = \frac{0.308\ V_m}{0.636\ V_m} \times 100\% = 48\%$$

It is much less as compared to 121% for half-wave rectifier.

(e) PIV

Its value is = 2 V_{sm}

(f) TUF

Its value is found by considering the primary and secondary windings of the transformer separately. Its value is 0.693 (as compared to 0.287 for a half-wave rectifier). In such a rectifier, there is no problem due to dc saturation of flux in the core because the dc currents in the two halves of the secondary flow in opposite directions.

3.3 Full-Wave Bridge Rectifier

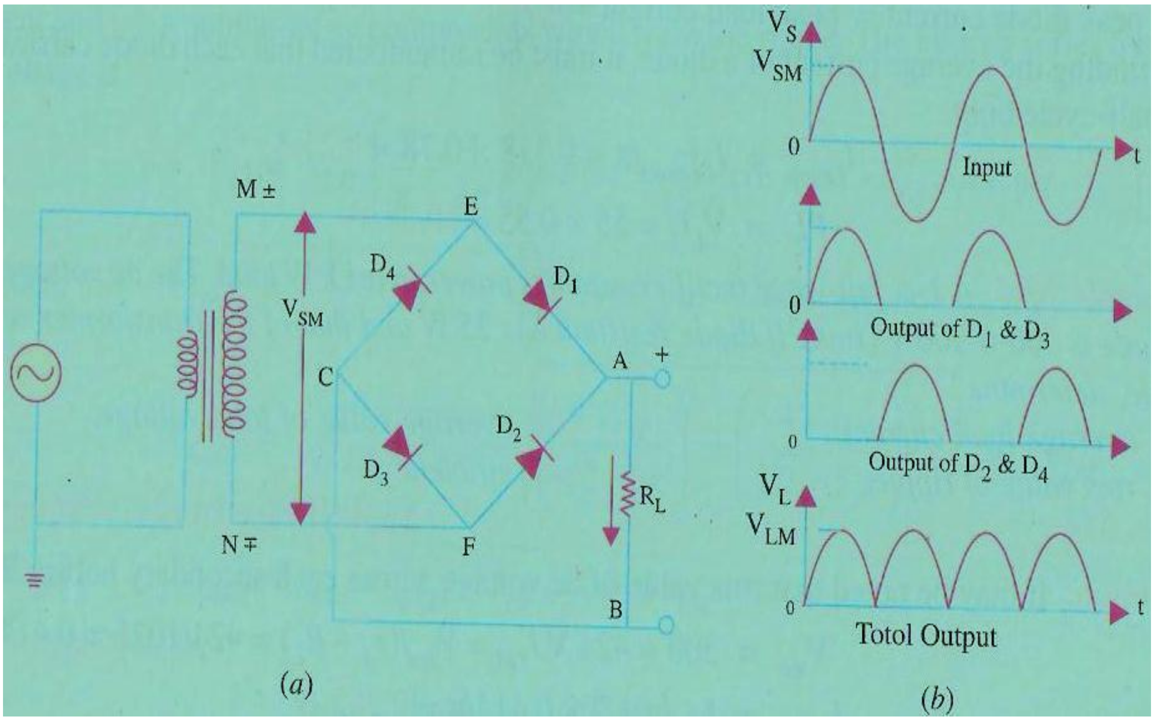

Fig. 3.6

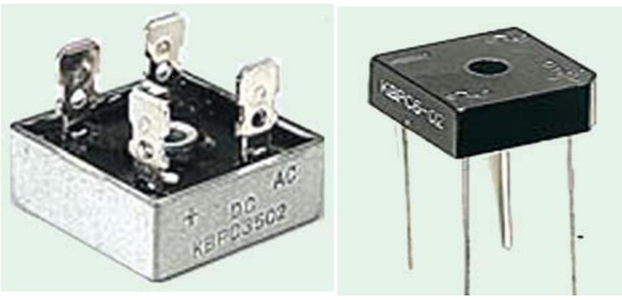

Fig 3.6c

It is the most frequently-used circuit for electronic dc power supplies. It requires four diodes but the transformer used is not center-tapped and has a maximum voltage ofV_{sm}. The full-wave bridge rectifier is available in three distinct physics forms.

1. Four discrete diodes.
2. One device inside a four-terminal case.
3. As part of an array of diodes in an IC.

The circuit using four discrete diodes is shown in Fig. 3.6 (a) and 3.6 (c) shows some pictures of the bridge rectifier available as one device in a four terminal case.

(a) Working

During the positive input half-cycle, terminal M of the secondary is positive and N is negative as shown separately in Fig. 3.7 (a). Diodes D_1 and D_3 become forward-biased (ON) whereas D_2 and D_4 are reverse-biased (OFF). Hence, current flows along $MEABCFN$ producing a drop acrossR_L.

During the negative input half-cycle, secondary terminal N becomes positive and M negative.

Now, D_2 and D_4 are forward-biased. Circuit current flows along $NFABCEM$ as shown in Fig. 3.7(b)

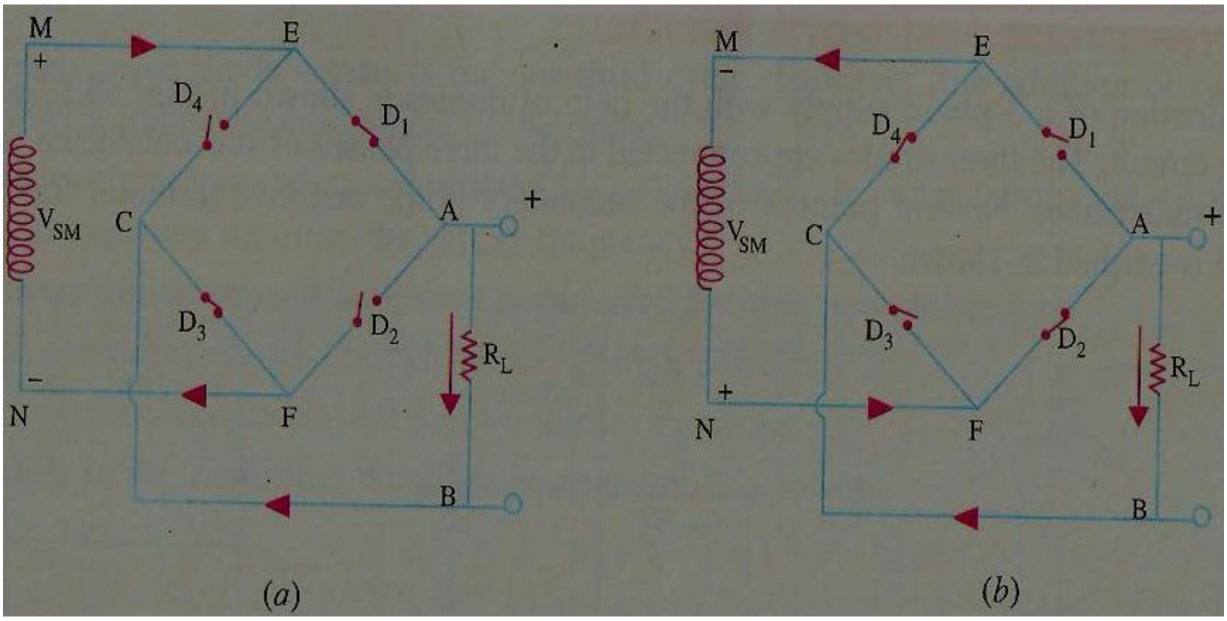

Fig 3.7

Hence, we find that current keeps flowing through load resistance R_L in the same direction ABduring both half-cycles of the ac input supply. Consequently, point A of the bridge rectifier alwaysacts as an anode and point C as cathode. The output voltage across R_L is as shown in Fig. 3.6(b).

Its frequency is twice that of the supply frequency.

(b) Average and RMS Values

These are the same as for the center-tapped full-wave rectifier discussed earlier.

(c) Efficiency

$$\% \eta = \frac{81.2}{1 + 2r_d/R_L}$$

(d) Ripple Factor

It is the same as for a full-wave rectifier i.e. $\gamma = 48\%$

(e) PIV

The PIV rating of each of the four diodes is equal to V_{SM}—the entire voltage across the secondary.

When Secondary and Diode Resistances are considered

(i) $I_{LM} = \frac{V_{sm} - 2V_B}{(R_S + 2r_d) + R_L} = \frac{V_{sm} - 2V_B}{R_o + R_L}$

(ii) $V_{LM} = I_{LM} . R_L$

(iii) $\eta = \left(\frac{8}{\pi^2}\right)\left(\frac{R_L}{R_o + 2r_d + R_L}\right) = \left(\frac{8}{\pi^2}\right)\left(\frac{R_L}{R_o + R_L}\right)$

(iv) $V_R = \frac{R_S + 2r_d}{R_L} = \frac{R_o}{R_L}$

(f) Advantages

After the advent of low-cost, highly-reliable and small-sized silicon diodes, bridge circuit has become much more popular than the center-tapped transformer full-wave rectifier. The main reason for this is that for a bridge rectifier, a much smaller transformer is required for the same output because it utilizes the transformer secondary continuously unlike the 2-diode full-wave rectifier which uses the two halves of the secondary alternately.

So, the advantages of the bridge rectifier are.

1. No center-tap is required on the transformer.
2. Much smaller transformers are required.
3. It is suitable for high-voltage applications.
4 It has less PIV rating per diode.

The obvious disadvantage is the need for twice as many diodes as for the center-tapped transformer version. But ready availability of low-cost silicon diodes has made it more economical despite its requirement of four diodes.

3.4 TEST

Question 1

In the half-wave rectifier circuit of Fig. 3.8, determine

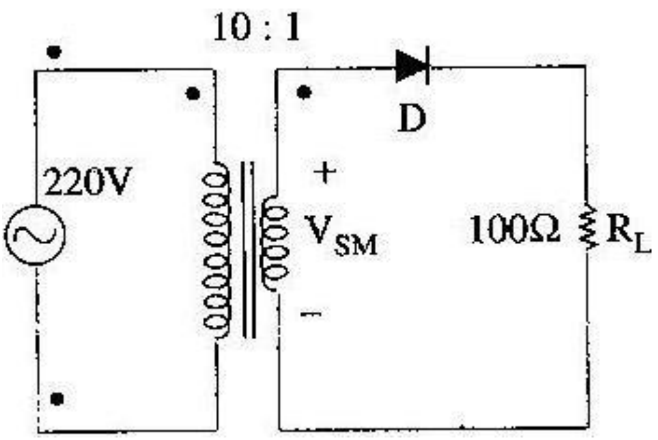

Fig. 3.8

(i) Maximum and rms values of load voltage,

(ii) Peak and rms values of load current,

(iii) Power absorbed by the load,

(iv) PIV of the diode,

(v) rms value of ripple voltage.

Neglect resistance of transformer secondary and that of the diode.

Solution

Here $K = \frac{N_2}{N_1} = 1/10$. Peak primary voltage is $V_{pm} = 220\sqrt{2} = 310\ V$.

Hence, $V_{sm} = KV_{pm}$

$= 310/10 = \mathbf{31\ V}$

(i) $V_{LM} = V_{sm} = \mathbf{31\ V}$

$$V_L = \frac{V_{LM}}{2} = \frac{31}{2} = \mathbf{15.5\ V}$$

(ii) $$I_{LM} = \frac{V_{LM}}{R_L} = \frac{31}{100} = \mathbf{0.31\ A}$$

$$I_L = \frac{I_{LM}}{2} = 0.31/2 = \mathbf{0.155\ A}$$

(iii) $P_L = V_L I_L = 15.5 \,.0.155 = \mathbf{2.4\ W}$

(iv) $PIV = 2\,V_{sm} = 2\,.31 = \mathbf{62\ V}$

(iv) $$V_{L(ac)} = \sqrt{V_L^2 - V_{L(dc)}^2}$$

$$Now, V_L = \frac{V_{LM}}{2} \quad and \quad V_{L(dc)} = \frac{V_{LM}}{\pi}$$

$$\therefore \quad V_{L(ac)} = \sqrt{\left(\frac{V_{LM}}{2}\right)^2 - \left(\frac{V_{LM}}{\pi}\right)^2} = 0.385\,V_{LM}$$

$$\therefore \quad V_{r(rms)} = V_{L(ac)} = 0.385 \times 31 = \mathbf{11.9\ V}$$

It represents the rms value of the ripple voltage.

Question 2

A 1-Φ, full-wave rectifier supplies power to a $1\ kW$ load. The ac voltage applied to the diode is $300\text{-}0\text{-}300\ V$ (rms). If diode resistance is $25\ W$ and that of the transformer secondary negligible, determine:

(i) average load current

(ii) average value of load voltage

(iii) rms value of ripple

(iv) Efficiency

Solution

It may be noted that rms value of ac voltage across each secondary half is $300\ V$.

(i) $$V_{sm} = 300 = 424\ V$$

$$I_{LM} = \frac{V_{sm}}{(r_d + R_L)} = 424/1025 = 0.414\ A$$

$$I_{L(dc)} = \frac{I_{LM}}{\pi} = 2 \times \frac{0.414}{\pi} = 0.263\ A$$

(ii) $$V_{L(dc)} = I_{L(dc)} . R_L = 0.263 \times 1000 = 263\ V$$

(iii) $$\gamma = \frac{V_{L(ac)}}{V_{L(dc)}} \frac{V_{r(rms)}}{V_{L(dc)}}$$

∴ $$V_{r(rms)} = \gamma . V_{L(dc)} = 0.482 \times 263 = 126.8\ V$$

(iv) $$\eta = \frac{81.2\ \%}{1 + r_d/R_L} = \frac{81.2\ \%}{1 + 25/1000} = 72.9\ \%$$

4.0 CONCLUSION

This unit has introduced you to the fundamentals of rectifier circuits; the half-wave rectifier, full-wave rectifier and the full-wave bridge rectifier for single phase rectification. Here, average $d.c.$ current is 0.827 times the peak current as compared to 0.318 times for 1-ϕ,half-wave circuit and 0.636 times for 1-ϕ, full-wave circuit. Moreover, Vdc is also correspondingly high, it is 51.17 times the $r.m.s.$ voltage of each secondary leg $(1.414 \times 0.827 = 1.17)$. Conversely,$r.m.s.$ voltage (VS) across each leg of the secondary need only be $1/1.17 = 0.855$ times the average desired $d.c.$ output voltage across the load. This leaves a good foundation upon which rectification of other types of phases (three phase, polyphase) can be built. The most important and commonly used is the full-wave bridge rectifier as it possesses some advantages over the others.

5.0 SUMMARY

The rectifier circuit is a very useful and important circuit in the dc power supply unit as it does the major conversion of the ac voltage to a pulsating dc voltage. It is a circuit which employs one or more diodes to convert ac voltage into pulsating dc voltage. For some sensitive equipment, the pulsating dc voltage from a rectifier is not good enough; hence filter circuit is necessary to provide a steadier dc voltage.

6.0 TUTOR-MARKED ASSIGNMENT

1. Explain the usefulness of a rectifier circuit in a dc supply unit.
2. Draw the circuit diagram of the following rectifier circuit and indicate the respective input and output waveforms.

   (a) Half-wave rectifier.

   (b) Full-wave rectifier.

(c) Full-wave Bridge rectifier.

3. A single-phase half-wave rectifier supplies power to a $1\ K$ load. The rectifier voltage is $200\ \mathrm{V}$ (rms).Neglecting diode resistance, calculate:

(i) dc load voltage

(ii) dc load current and

(iii) $\mathrm{r.m.s}$.ripple voltage.

4. A single-phase half-wave diode rectifier supplies power to a $2\ \mathrm{k\Omega}$ resistive load. The input ac supply voltage has a peak value of $300\ V$. Neglecting forward drop of the diode, calculate:

(a) V_{dc}

(b) I_{dc}

(c) power delivered to the load

(d) ripple voltage (rms value)

5. A full-wave diode rectifier supplies a load of $10\ k\Omega$. The ac voltage applied to the diode is $300\text{-}0\text{-}300V_{rms}$. Its diode resistance is neglected, calculate:

(a) V_{dc}

(b) I_{dc}

(c) I_{rms}

(d) form factor

(e) ripple voltage.

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UNIT 4 FILTER CIRCUITS

CONTENTS

1.0 INTRODUCTION

Before going into the details of a filter circuit, it would be appropriate to consider the usual methods of rating filter circuits so that we can compare a circuit's effectiveness as a filter. Figure 1.1 shows a typical filter output voltage, which will be used to define some of the signal factors. The filtered output of fig 1.1 has a dc value and some ac variation (ripple). Although a battery has essentially a constant or dc output voltage, the dc derived from an ac source signal by rectification will have some ac variation (ripple). The smaller the ac variation with respect to the dc level, the better the filter circuit's operation.

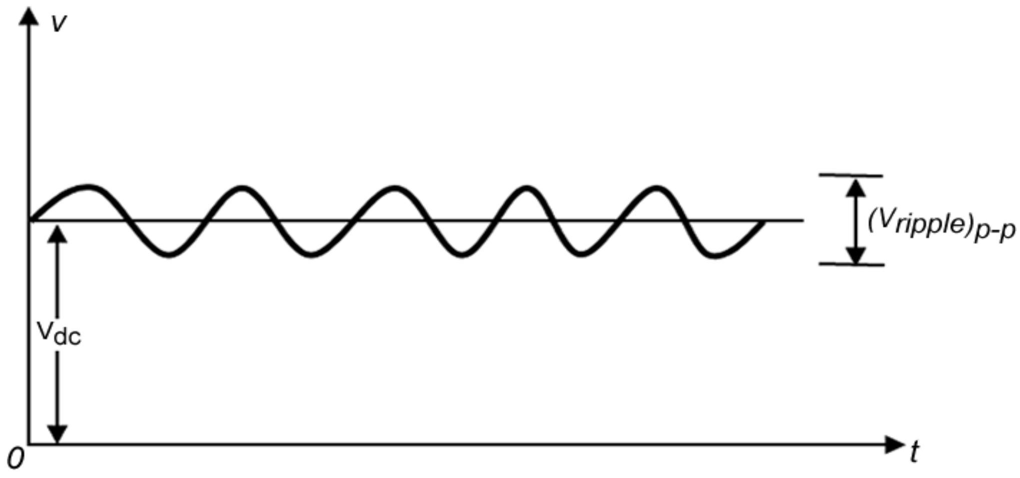


Figure 1.1 Filter voltage waveform showing dc and ripple voltages

Consider measuring the output voltage of a filter circuit using a dc voltmeter and an ac (rms) voltmeter. The dc voltmeter will read only the average or dc level of the output voltage. The ac (rms) meter will read the rms value of the ac component of the output voltage (assuming the ac signal is coupled through a capacitor to block out the dc level).

Ripple:

$$\gamma = \frac{ripple\ voltage\ (rms)}{dc\ voltage} = \frac{V_{r(rms)}}{V_{dc}} \times 100\%$$

Voltage Regulation:

Another factor of importance in a power supply is the amount the dc output voltage changes over a range of circuit operation. The voltage provided at the output under no-load condition (no current drawn from the supply) is reduced when load current is drawn from the supply (under load), the amount of dc voltage changes between no-load and load condition is described by a factor called voltage regulation.

$$\text{Voltage regulation} = \frac{\text{no} - \text{load voltage} - \text{full} - \text{load voltage}}{\text{full} - \text{load voltage}}$$

$$\%\ V.R. = \frac{V_{NL} - V_{FL}}{V_{FL}}$$

2.0 OBJECTIVES

By the end of this unit, you will be able to:

- Understand the function of filter circuit in the dc supply unit.
- Know the various types of filter circuits.
- Solve related problems.

3.0 MAIN CONTENT

3.1 Filter Circuits

The main function of a filter circuit (Fig 3.1) is to minimize the ripple content in the rectifier output.

As seen, output of various rectifier circuits is pulsating. It has a dc value and some ac components called ripples. This type of output is not useful for driving sophisticated electronic circuits/ devices. In fact, these circuits require a very steady dc output that approaches the smoothness of a battery's output.

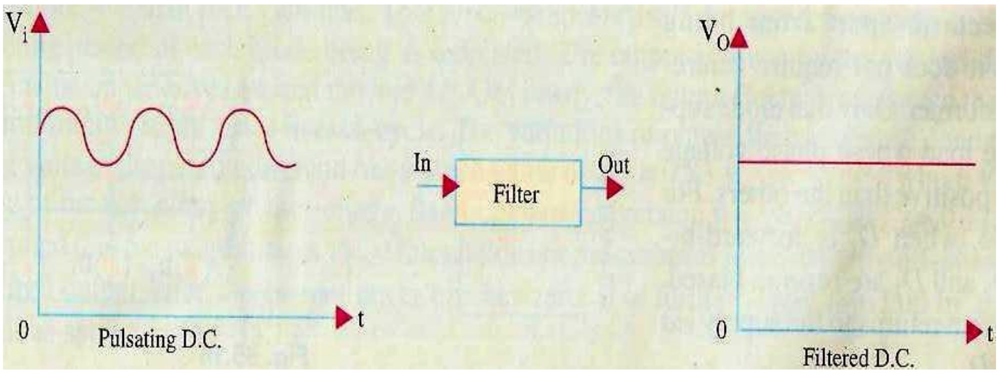


Fig. 3.1

A circuit that converts a pulsating output from a rectifier into a very steady dc level is known as filter because it filters out or smoothens out the pulsations in the output.

We will consider the following popular filter circuits:

1. Shunt capacitor filter
2. Series inductor filter
3. L-C filter (or L-type)
4. R-C filter
5. C-L-C filter.

3.1.1 Shunt Capacitor Filter

In this circuit, a suitable single capacitor C is connected across the rectifier and in parallel with the load R_L to achieve filtering action. This type of filter is known as capacitor input filter.

This filter circuit depends for its operation on the property of a capacitor to charge up (i.e. store energy) during conducting half-cycle and to discharge (*i.e.* deliver energy) during the non-conducting half-cycle. In simple words, a capacitor opposes any change in voltage. When connected across a pulsating $d.c.$ voltage, it tends to smoothen out or filter out the voltage pulsations (or ripples). The filtering action of the simple capacitor filter when used in a half-wave rectifier can be understood with the help of Fig. 3.2.

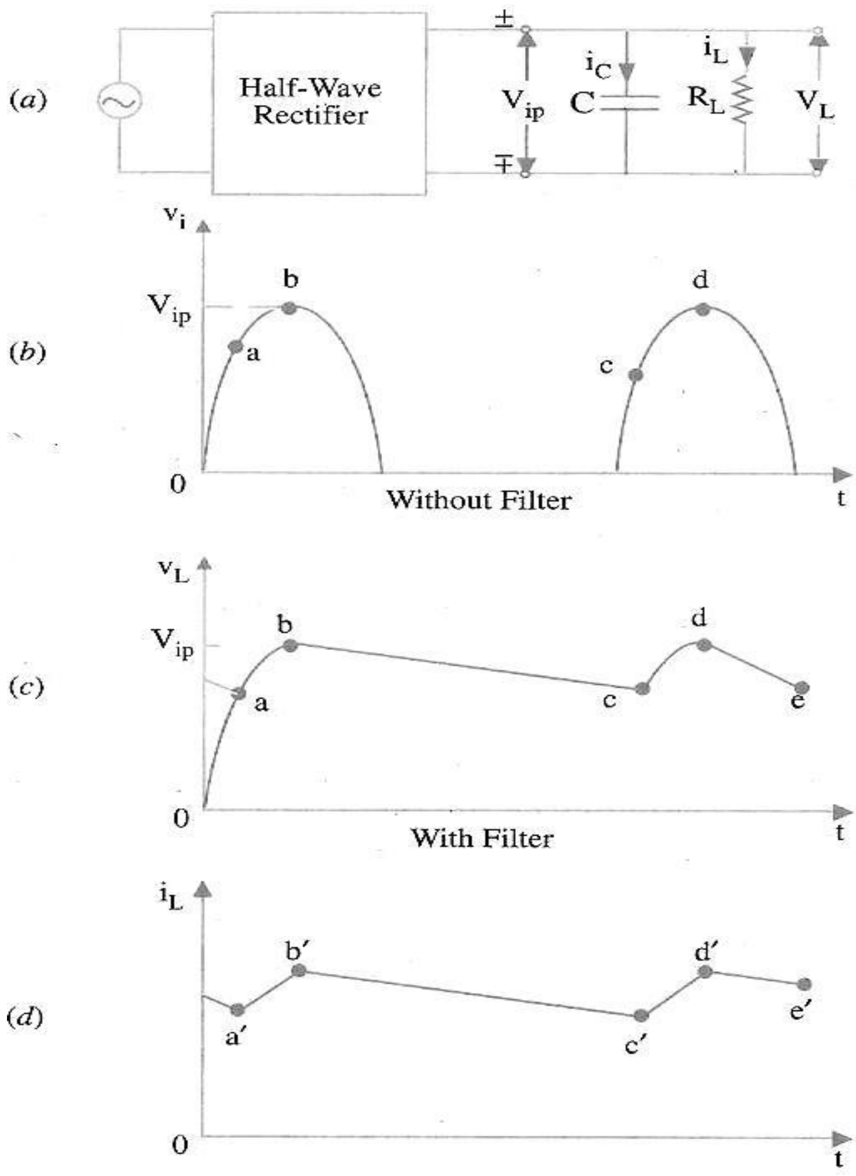


Fig. 3.2

(a) Circuit Analysis

When positive half-cycle of the ac input is applied, the diode is forward-biased and hence is turned ON. This allows C to quickly charge up to peak value of input voltage V_{ip} [point b in Fig. 3.2 (b)] because charging time constant is almost zero. It is so because there is no resistance in the charging path except diode forward resistance which is negligible. Hence, capacitor follows the charging voltage as shown. After being fully charged, the capacitor holds the charge till input ac supply to the rectifier goes negative. During the negative half-cycle, the capacitor attempts to discharge. However, it cannot discharge through diode which, being now reverse-biased, is OFF. Hence, it discharges through R_L from point b to c in Fig. 3.2 (c) and its voltage decreases somewhat. The discharging time constant $(= CR_L)$ is usually 100 times more than the charging time. Hence, C does not have sufficient time to discharge appreciably. It is seen that even during negative half-cycle of the input supply, the capacitor maintains a sufficiently large voltage across R_L.

During the next positive half-cycle, when rectifier voltage exceeds the capacitor voltage represented by point c in Fig. 3.2 (c), C is again charged quickly to V_{ip} as represented by point d. Once more, input voltage goes negative, opening the diode and forcing C to discharge through R_L during the interval de. In this way, R_L sees a nearly constant dc voltage across it at all times.

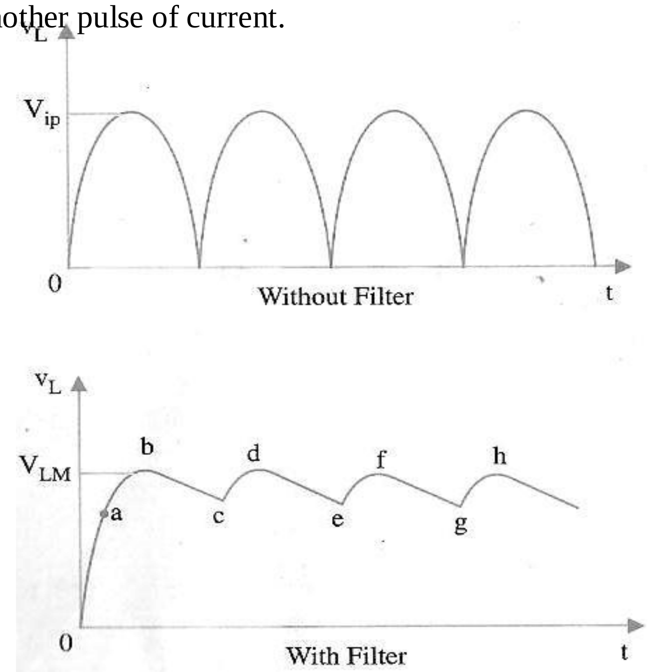
The filtering action of this simple capacitor filter on a full-wave rectifier is shown in Fig. 3.3. It is seen that as compared to a half-wave rectifier.

(i) dc load voltage increases slightly towards V_{ip},

(ii) Ripple voltage has been reduced by half.

The decreased ripple is because of shorter discharge time before the capacitor is re-energized by another pulse of current.

Fig. 3.3



(b) Load Current

The load current has the same wave-shape as v_L because load is purely resistive. It is shown in Fig. 3.2(d). During periods $a'b'$ and $c'd'$ etc., current is supplied by the diode and during periods $b'c'$ and $d'e'$ etc. by the capacitor.

(c) Diode Current

Diode current flows during short intervals of time like ab and cd etc. in Fig. 3.2 (c) which is reproduced in Fig. 3.4. During these intervals, diode output voltage is greater than the capacitor voltage which is also the load voltage. Hence, diode current is a surging current i.e. it takes the form of short-duration pulses as shown in Fig. 3.4. A small resistor is always connected in series with the diode to limit this surge current. It is known as surge limiting resistor.

The sole function of the diode is to recharge C and the sole function of C is to supply load current by discharge.

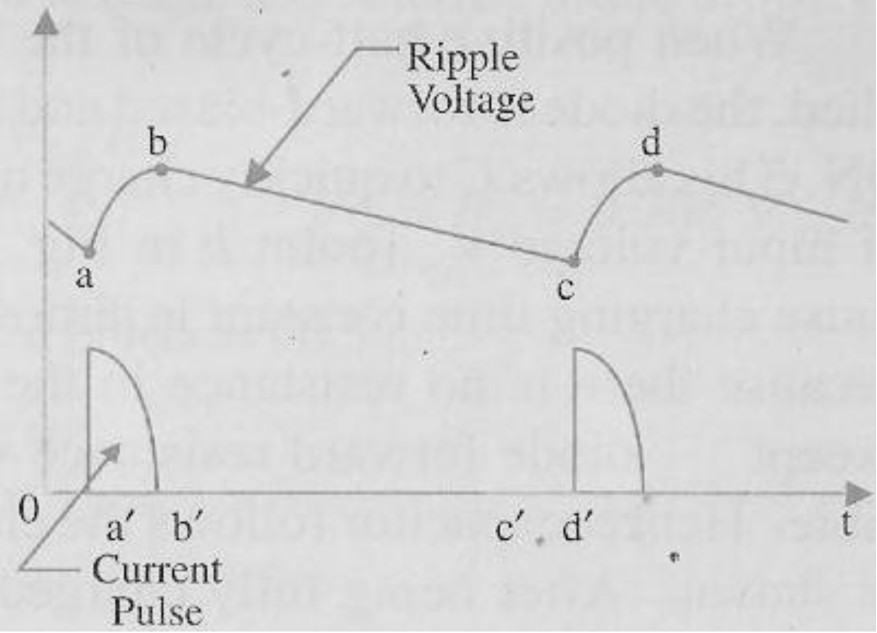


Fig. 3.4

3.1.1.1 Effect of Increasing Filter Capacitance

A capacitor has the basic property of opposing changes in voltage. Hence, a bigger capacitor would tend to reduce the ripple magnitude. It has been found that increasing the capacitor size.

1. increases V_{dc} towards the limiting value V_{ip} ;

2. reduces the magnitude of ripple voltage;

3. reduces the time of flow of current pulse through the diode;

4. increases the peak current in the diode.

3.1.1.2 Calculations of Shunt Capacitor Filter

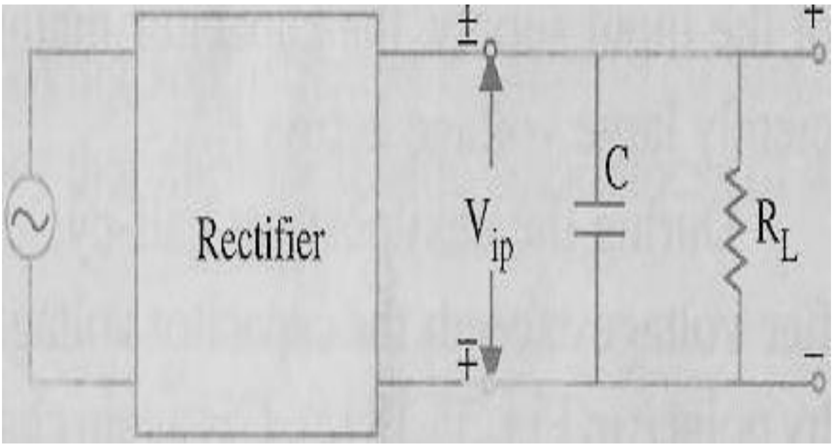


Fig. 3.5

Consider the rectifier and filter circuit of Fig. 3.5where a capacitor has been connected acrossR_L. The output voltage waveforms of a half-wave rectifier with a shunt capacitor filter are shown in Fig. 3.6 (a) whereas Fig. 3.6 (b) shows those for a full-wave rectifier. The ripple voltage which occurs under light load conditions can be approximated by a triangular wave which has a peak-to-peak value of $V_{r(p-p)}$and a time period of T_r. (Since charging time is negligibly small, the approximate discharging time represents the full time-period.) centered around the dc level.

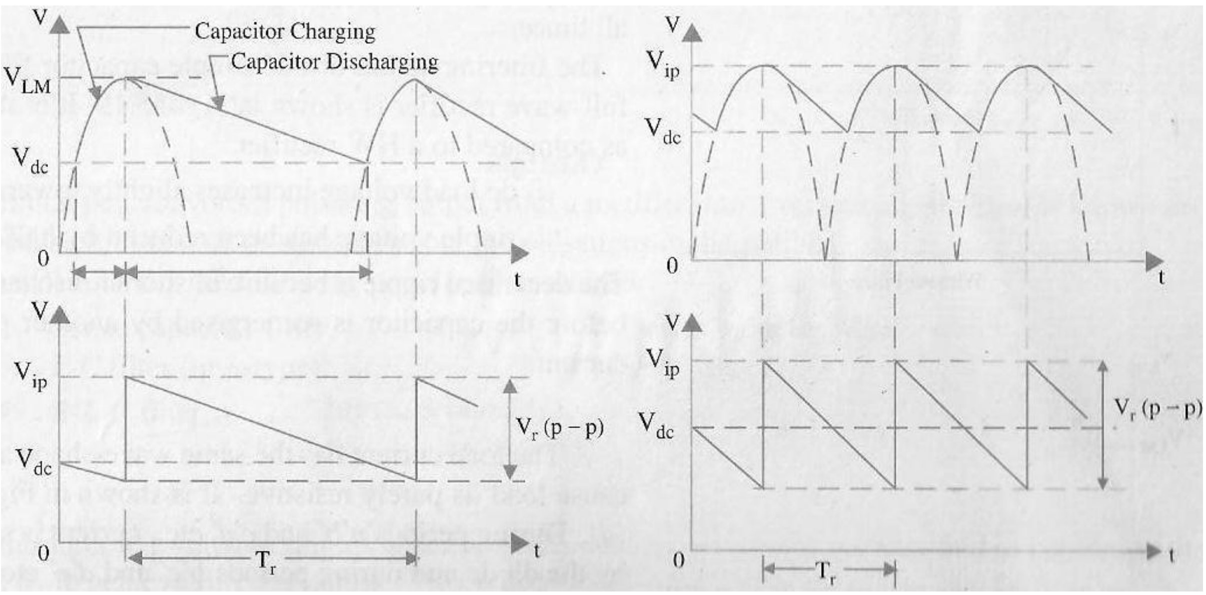


Fig. 3.6

In fact, $V_{r(p-p)}$ is the amount by which capacitor voltage falls during discharge period T_r. This discharge is actually exponential (given by $V_c = V_{ip}e^{-t}/CR_L$) but can be approximated by a straight line discharge if we assume the discharge rate to remain constant at the dc level I_{dc}. In that case, charge lost dQ in time T_r is $I_{dc}\ T_r$.

$$\therefore \qquad V_{r(p-p)} = \frac{dQ}{C} = \frac{I_{dc}T_r}{C} = \frac{V_{dc}}{f_r CR_L}$$

$$\because \qquad I_{dc} = \frac{V_{dc}}{R_L}$$

The triangle ripple has an rms value given by $V_{r(rms)} = V_{r(p-p)}/2\sqrt{3}$

$$\therefore \qquad V_{r(rms)} = \frac{V_{r(p-p)}}{2\sqrt{3}} = \frac{V_{dc}}{2\sqrt{3}f_r CR_L} \qquad \therefore \quad \gamma = \frac{V_{r(rms)}}{V_{dc}} = \frac{1}{2\sqrt{3}f_r CR_L}$$

Now, f_r is the frequency of the ripple voltage. For a half-wave rectifier, f_r equals the rectifier line input frequency whereas it is double the line input frequency for a full-wave rectifier. If f is the line frequency, then

$$\gamma \cong \frac{1}{2\sqrt{3}fCR_L} \qquad - for\ Halfwave\ rectifier$$

$$\cong \frac{1}{4\sqrt{3}fCR_L} \qquad - for\ fullwave\ rectifier$$

It can be further proved that

$$\gamma \cong \frac{1}{2\sqrt{3}fCR_L} = \frac{I_{dc}}{4\sqrt{3}fC}\left(\frac{1}{V_{ip}} - \frac{1}{V_{dc}}\right) \qquad - for\ Halfwave\ rectifier$$

$$= \frac{1}{4\sqrt{3}fCR_L} = \frac{I_{dc}}{4\sqrt{3}fCV_{ip}} \qquad - for\ fullwave\ rectifier$$

It is seen from above that ripple increases with increase in load (*i.e.* output) current.

Incidentally, $\qquad V_{dc} = V_{ip} - \frac{V_{r(p-p)}}{2}$

where $\qquad V_{ip}$ = peak rectifier output voltage.

Substituting the value of $\quad V_{r(p-p)} = \frac{V_{dc}}{f_r CR_L}$, $\quad$ we get

$$V_{dc} = V_{ip} - \frac{V_{dc}}{2f_r CR_L} \qquad or \qquad V_{dc} = -\frac{V_{ip}}{1 + \frac{1}{2f_r CR_L}}$$

$$V_{dc} = V_{ip} = \left(\frac{2fCR_L}{1+2fCR_L}\right) = \frac{V_{ip} - I_{dc}/4fC}{1+ I_{dc}/4fCV_{ip}}$$ - half-wave rectifier

$$= V_{ip}\left(\frac{4fCR_L}{1+4fCR_L}\right) = \frac{V_{ip}}{1+I_{dc}/4fC\,V_{ip}}$$ - full-wave rectifier

Example

A half-wave rectifier has a peak output voltage of 12.2 V at 50 Hz and feeds a resistive load of 100 Ω. Determine

(i) *The value of the shunt capacitor to give 1 percent ripple factor and*
(ii) *The resulting dc voltage across the load resistor.*

Solution

(i)
$$\gamma \cong \frac{1}{2\sqrt{3}fCR_L}$$

$$\therefore \qquad C = \frac{1}{2\sqrt{3}f\gamma R_L} = \frac{1}{2\sqrt{3}\times 0.01\times 100\times 50} = 5770\ \mu F$$

(ii)
$$V_{dc} = -\frac{V_{ip}}{1+\frac{1}{2f_r CR_L}} = \frac{12.2}{1+1/2\times 5770\times 10^{-6}\times 100} = 12\ V$$

3.1.2 Series Inductor Filter

The filter consists of a choke in series with the load resistor R_L as shown in Fig. 3.7. The operation of such a filter depends on the fundamental property of an inductor to oppose any sudden changes in the current flowing through it. Since this inductor presents high impedance to the ac components in the filter output, it reduces their amplitude with respect to the dc component thereby producing only a small ripple as shown in Fig. 3.7 (*b*).

The Fourier series for the rectifier output voltage is

$$v_i = V_{ip}\left(\frac{2}{\pi} - \frac{4}{3\pi}\cos 2\,\omega t - \frac{4}{15\pi}\cos 4\,\omega t - \cdots\right)$$

For finding the ripple factor, we will calculate the dc as well as ac drop over R_L. If we neglect choke resistance (RC), then the entire dc component of filter output is available across R_L and its value is $V_{dc} = 2\,V_{ip}/\pi$.

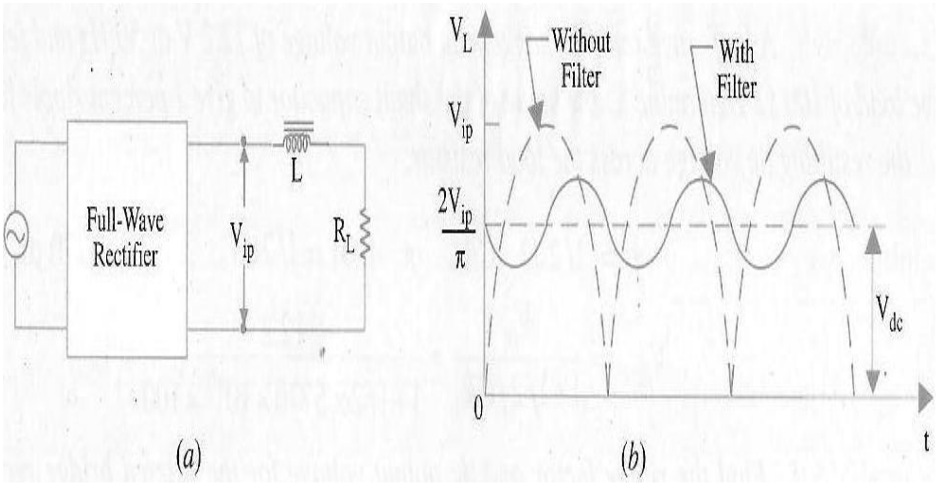


Fig. 3.7

We will consider only the second harmonic voltage $(4V_{ip}/3\pi)\ cos\ 2\ \omega t$ of frequency 2ω and neglect higher harmonic voltages. This ac voltage partly drops over X_L and partly over R_L. Since choke and R_L are connected in series, the maximum value of drop over R_L is

$$= \frac{4V_{ip}}{3\pi} \cdot \frac{R_L}{\sqrt{R_L^2 + X_L^2}}$$

The rms value of this ac voltage drop across R_L is

$$V_{ac} = \frac{4V_{ip}}{\sqrt{2}.3\pi} \frac{R_L}{\sqrt{R_L^2 + X_L^2}}$$

$$\gamma = \frac{V_{ac}}{V_{dc}} = \frac{4V_{ip}}{\sqrt{2}.3\pi} \frac{R_L}{\sqrt{R_L^2 + X_L^2}} \times \frac{\pi}{2V_{ip}}$$

$$= \frac{\sqrt{2}R_L}{3\sqrt{R_L^2 + X_L^2}} = \frac{\sqrt{2}}{3(1 + X_L^2/R_L^2)^{1/2}}$$

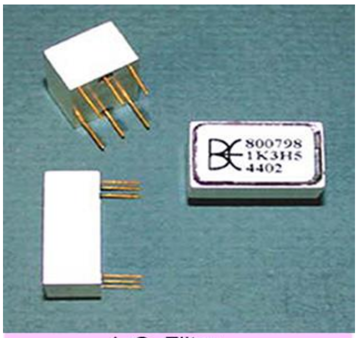
Since $X_L = 2\omega L$, hence

$$\gamma = \frac{\sqrt{2}}{3(1 + \frac{4\omega^2 L^2}{R_L^2})^{1/2}}$$

If $\frac{4\omega^2 L^2}{R_L^2} \gg 1$, then $\gamma = \frac{\sqrt{2}R_L}{3 \times 2\omega L} = \frac{R_L}{\sqrt{2}.3\omega L}$

It is seen that ripple decreases as R_L decreases or load current increases (just the opposite of what happens in the case of shunt capacitor filter).

3.1.3 The Choke Input or L-C Filter



L.C. Filter

It is a combination of two filters and provides a lower ripple than is possible with either Lor C alone. As is known, in an inductor filter, ripple increases with $R_L$but decreases in a capacitor filter. The combination of $L$and C(*i.e.*$L-$section) filter makes the ripple independent of R_L. Fig. 3.8 (*a*)shows the filter and (*b*) the voltage variations

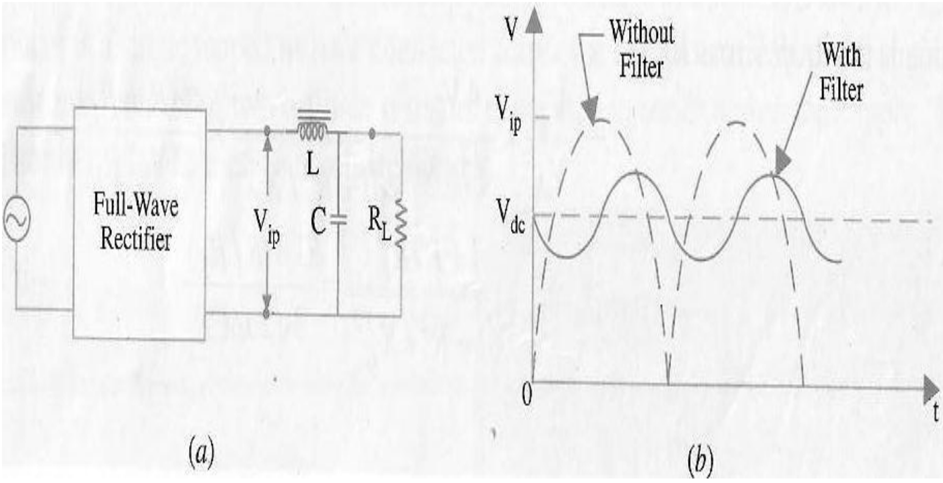


Fig. 3.8

Ripple Factor

If choke resistance $R_C$is neglected, then dc voltage available across $R_L = 2\,V_{ip}/\pi$. The ac drop over $R_L$is the same as across C. Since $X_C \ll R_L$, the parallel combination of *RL* and *XC* has impedance$\cong X_C$. The second harmonic voltage $(\,4\,V_{ip}\,/3\pi)\,cos\,2\omega t$ can be assumed to drop over the $L-C$ series combination because $R_L$is effectively not there.

Maximum value of ac drop over $C$is

$$\frac{4V_{ip}}{3\pi}\cdot\frac{X_C}{(X_L + X_C)}$$

$$rms\ value = \frac{4V_{ip}}{\sqrt{2}3\pi}\cdot\frac{X_C}{(X_L + X_C)}$$

$$\gamma = \frac{V_{ac}}{V_{dc}}\frac{4V_{ip}}{\sqrt{2}3\pi}\cdot\frac{X_C}{(X_L + X_C)} \times \frac{\pi}{2V_{ip}} = \frac{\sqrt{2}X_C}{2X_L} - \text{if} X_c \ll X_L$$

$$= \frac{\sqrt{2}}{3(2\omega C)(2\omega L)} = \frac{\sqrt{2}}{12\omega^2 LC} = \frac{1.19}{LC}$$ – if C is in μF and L in henrys

Now, $I_{dc} = 2V_{ip}/\pi RL$; maximum value of second harmonic current $I_{2h} = 4V_{ip}/3\pi \times 2\omega L$. The critical (or minimum) value of choke inductance essential for proper working of the filter is reached when $I_{dc} = I_{2h}$ or $2V_{ip}/\pi R_L = 4V_{ip}/3\pi.2\omega_L$ or $L = R_L/3\omega_L$. For $f = 50\ Hz, L = R_L/940.$

3.1.4 The R-C Filter

Such a filter is shown in Fig. 3.9. Suppose that it is connected to a full-wave rectifier having a filtered output voltage of V_{ip}. The dc component voltage which drops over R_L is

$$= \frac{2V_{ip}}{\pi} . \frac{R_L}{R + R_L}$$

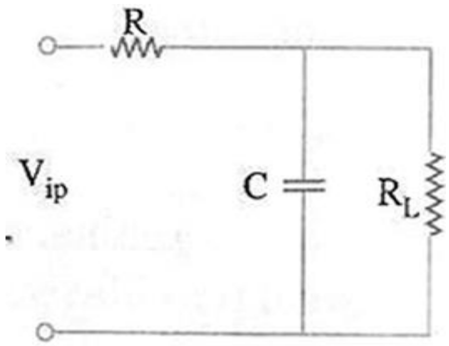


Fig 3.9

Again, we would consider only the second harmonic voltage $(4V_{ip}/3\pi) \cos 2\omega t$. As before, it will be assumed that $X_C \ll R_L$ so that $R_L || X_C \cong XC$. Inthat case, ac voltage would be assumed to drop across *R-C* combination.

$$V_{ac} = \frac{1}{\sqrt{2}} . \frac{4V_{ip}}{3\pi} . \frac{X_C}{\sqrt{R^2 + X_C^2}} = \frac{4V_{ip}}{\sqrt{2}.3\pi} . \frac{1}{\sqrt{1 + R^2/X_C^2}}$$

Same is the drop across R_L.

$$\gamma = \frac{V_{ac}}{V_{dc}} = \frac{4V_{ip}}{\sqrt{2}.3\pi} . \frac{1}{\sqrt{1 + R^2/X_C^2}} \times \frac{\pi(R + R_L)}{2V_{ip}.R_L}$$

$$= \frac{\sqrt{2}}{3} . \frac{1 + R/R_L}{\sqrt{1 + R^2/X_C^2}} = \frac{(1 + R/R_L)}{3\sqrt{2}\omega CR}$$ - if $R^2/X_C^2 \gg 1$

3.1.5 The C-L-C or Pi Filter

As shown in Fig. 3.10, it consists of one inductor and two capacitors connected across its each end. The three components are arranged in the shape of the Greek letter π. It is also called capacitor input π-filter. The input capacitor C_1 is selected to offer very low reactance to the ripple frequency.

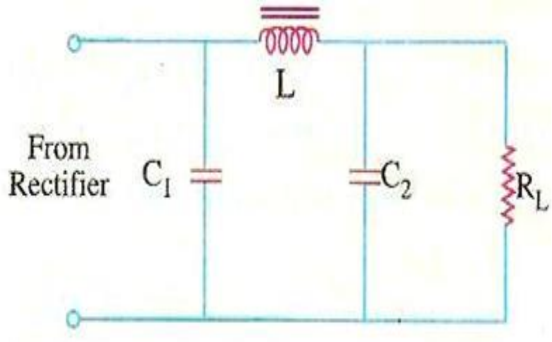


Fig. 3.10

Hence, major part of filtering is done by C_1. Most of the remaining ripple is removed by the combined action of L and C_2.

The charging and discharging action of C_1 is exactly the same as described earlier. The output voltage waveform is also like that shown in Fig. 3.8 (*b*).

This circuit gives much better filtering than LC filter circuit. However, C_1 is still directly connected across the supply and would need high pulses of current if load current is large.

Since these high peak current pulses are likely to damage the rectifier diode, this filter is used with low-current equipment.

Though this filter-gives somewhat higher output voltage, its voltage regulation is inferior to that of the LC filter.

The ripple factor of this filter is given by

$$\gamma = \sqrt{2}\frac{X_{C_1}X_{C_2}}{R_L X_L} = \frac{\sqrt{2}}{8\omega^3 C_1 C_2 L R_L} = \frac{5700}{LC_1 C_2 R_L} \qquad \text{- when } f = 50Hz$$

Here, $C_1 C_2$ are in μF, L in henrys and R_L in ohms.

3.2 Bleeder Resistor

Very often, a resistor (called bleeder resistor) is placed across the filter output (Fig. 55.28) because it provides the following advantages:

1. It improves voltage regulation of the supply.

   By acting as a pre-load on the supply, it causes an initial voltage drop. When the real load is connected, there so only a small amount of

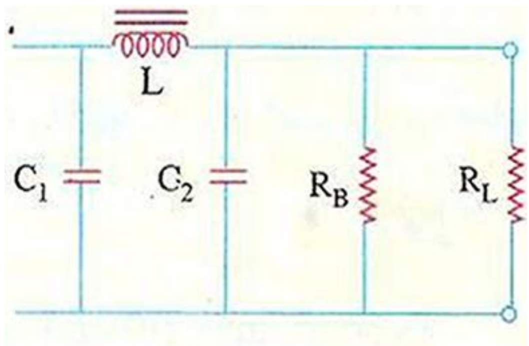


Fig. 3.11

additional drop. In this way, difference between no-load and full-load voltage is reduced thereby improving the regulation.

2. It provides safety to the technicians handling the equipment.

When power supply is switched off, it provides a path for the filter capacitor to discharge through. That is why it is called bleeder resistor. Without it, the capacitor will retain its charge for quite sometime even when the power supply is switched off. This high voltage can be dangerous for people working with the equipment.

3. By maintaining a minimum current through the choke, it improves its filtering action. Value of R_B should be such as to conduct 10 per cent of the total load current.

3.3 Voltage Dividers

Often more than one dc voltage is needed for the operation of electronic circuits. A single power supply can provide as many voltages as are needed by using a voltage divider. As shown in Fig. 3.12a voltage divider is a single tapped resistor connected across the output terminals of the supply. The tapped resistor may consist of two or three resistors connected in series across the supply. In fact, bleeder resistor may also be used as a voltage divider.

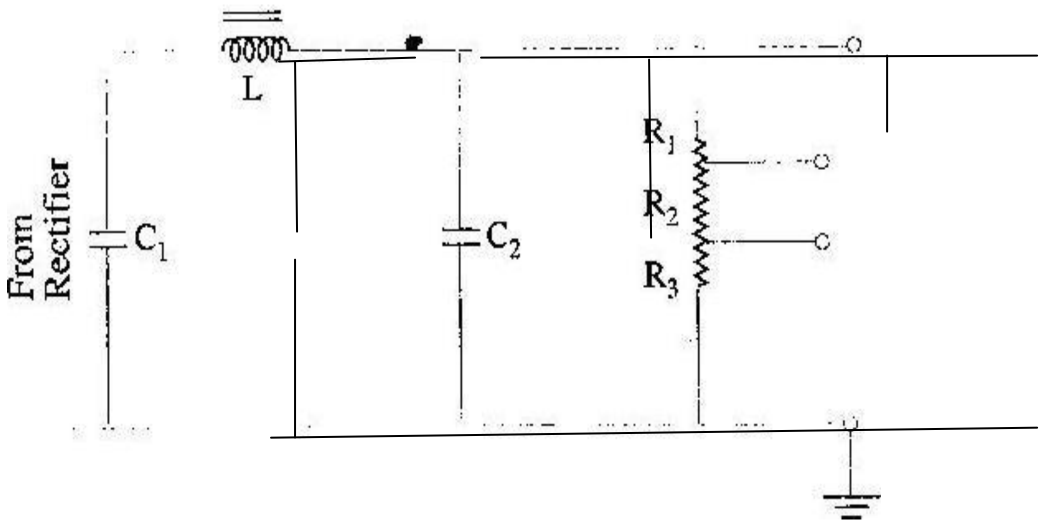


Fig. 3.12

3.4 Complete Power Supply

Fig. 3.13 shows a complete solid-state power supply. From left to right, it consists of a transformer with a current-limiting resistor R_1, rectifier diodes for full-wave rectification, a π-type filter, a transistor series voltage regulator and a voltage divider.

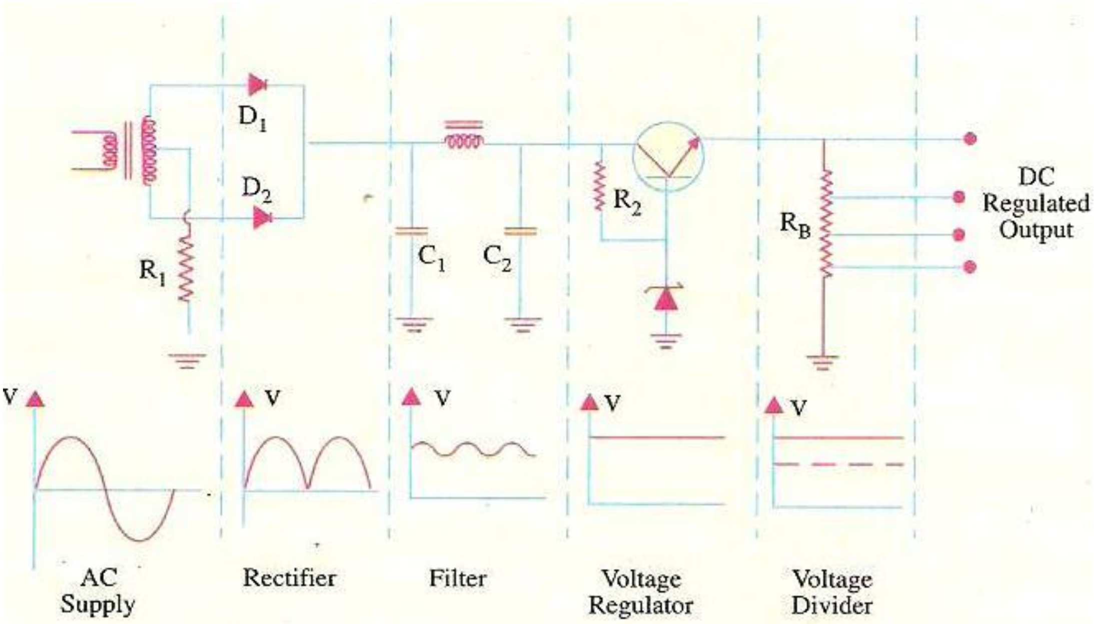


Fig. 3.13

As seen, unregulated ac voltage is fed from the transformer through a full-wave rectifier. It is then filtered by the CLC filter and finally regulated by a transistor regulator. The regulated dc supply becomes available across voltage divider resistance R_B. The output is practically ripple-free.

3.5 Troubleshooting Power Supplies

There are usually two types of problems with power supplies *i.e.* either no dc output or low dc output.

The situation of no dc output can occur due to any one of the following reasons:

1. when there is no output from the rectifiers,

2. when there is no ac input to power supply,

3. when filter choke is open,

4. when the first input capacitor shorts.

A low dc output can occur in the following situations:

1. decreased input ac voltage,

2. open input capacitor of the filter circuit,

3. partial short across the load.

3.6 TEST

Question 1

Find the ripple factor and dc output voltage for the filtered bridge rectifier shown in Fig. 3.14. Each silicon diode has a threshold voltage of $0.7\ V$.

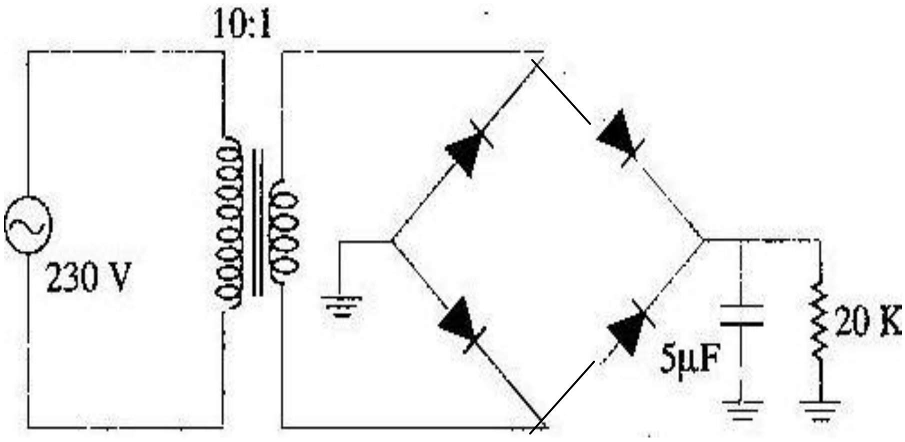


Fig. 3.14

Solution

Peak primary voltage = $230 \times 3 = 325\ V$

Peak secondary voltage = $325 \times 1/10 = 32.5\ V$

Peak full-wave rectified voltage at the filter input $V_{ip} = 32.5 - 2 \times 0.7 = 31.1\ V$

$$\gamma = \frac{1}{4\sqrt{3}fCR_L}$$

$$= \frac{1}{4\sqrt{3} \times 50 \times 5 \times 10^{-6} \times 20 \times 10^{3}}$$

$= 0.028\ or\ \mathbf{28\%}$

$$V_{dc} = \frac{V_{ip}}{1 + \frac{1}{4fCR_L}}$$

$$= \frac{31.1\ V}{4 \times 50 \times 5 \times 10^{-6} \times 20 \times 10^{3}}$$

$$= 29.6\ V$$

Question 2

A single-phase full-wave rectifier uses $300\text{-}0\text{-}300\ V$, $50\ \text{Hz}$ transformer. For a load current of $60\ mA$, design an L-filter using $10\ H$ coil and a suitable capacitor to ensure a ripple factor of not more than 1%.

Solution

$$\gamma = \frac{1.19}{LC}$$

$$0.01 = \frac{1.19}{LC}; \qquad \therefore\ LC = 119$$

Hence, $$10 \times C = 119$$

$$C = 11.9\ \mu F \cong 12\ \mu F.$$

4.0 CONCLUSION

This unit has introduced you to the basic types of Filter Circuits and has also made you understand the basic function of the filter circuit in a dc supply unit.

5.0 SUMMARY

The filter circuit is a circuit that converts a pulsating output from a rectifier into a very steady dc level as it filters out or smoothens out the pulsations in the output. The main function of a filter circuit is to minimize the ripple content in the rectifier output.

Although a battery has essentially a constant or dc output voltage, the dc derived from an ac source signal by rectification will have some ac variation (ripple). The smaller the ac variation with respect to the dc level, the better the filter circuit's operation.

6.0 TUTOR-MARKED ASSIGNMENT

1. Derive an expression for the ripple in the output of a full-wave rectifier circuit, with a simple capacitor element as the filter.

The load current from the above circuit operating from 200-V, 50-Hz supply is 12 mA. Calculate minimum value of filter capacitor which is required to keep the ripple voltage below 2%.

2. A $1\text{-}\varphi$ half-wave rectifier using a $10:1$ transformer supplies power to a $9\ \Omega$ load. If the primary input voltage has an $r.m.s.$ value of $200\ V$ and forward diode resistance is $0.2\ \Omega$ and transformer secondary resistance is 0.8 W, determine:

(i) $I_{\mathrm{L(dc)}}$

(ii) $r.m.s.$ ripple voltage and

(iii) Efficiency

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MODULE 4 LINEAR INTERGRATED CIRCUITS

UNIT 1 THE OPERATIONAL AMPLIFIER (OP-AMP)

CONTENTS

1.0 INTRODUCTION

Electronic circuitry has undergone tremendous changes since the invention of a triode by Lee De Forest in 1907. In those days, the active components (like triode) and passive components (like resistors, inductors and capacitors etc.) of the circuits were separate and distinct units connected by soldered leads.

The invention of transistors in 1948 by W.H Brattain and I. Bardeen, and the development of printed circuit board (PCB) made the entire circuit very small.

In the early 1960s, a new field of microelectronics was born primarily to meet the requirements of the Military which wanted to reduce the size of its electronic equipment to approximately one-tenth of its then existing volume. This drive for extreme reduction in the size of electronic circuits has led to the development of microelectronic circuits called integrated circuits (ICs) which are so small that their actual construction is done by technicians using high powered microscopes.

1.1 What is an Integrated Circuit (IC)?

To put it very briefly, an integrated circuit (IC) is just a packaged electronic circuit.

A more detailed definition is as under:

An IC is a complete electronic circuit in which both the active and passive components are fabricated on a tiny single chip of silicon.

Active components are those which have the ability to produce gain. Examples are: transistors and FETs.

Passive components or devices are those which do not have this ability. Examples are: resistors, capacitors and inductors.

Integrated Circuits (ICs) can be classified into two based on the function. They are:

(1) Digital ICs

Digital ICs contain circuits whose input and output voltages are limited to two possible levels – high or low. It is so because digital signals are usually binary.

Examples of Digital ICs include:

1. Logic gates
2. Flip-flop
3. Calculator chip
4. Memory chip

Amongst others.

(2) Linear ICs (LICs)

Linear ICs are also referred to as analog ICs because their inputs and outputs can take on a continuous range of values and the outputs are generally proportional to the inputs. As compared to digital ICs, LICs are used much less. But LICs are quickly displacing their discrete circuit counterparts in many applications as their cost becomes competitive. They also possess much higher reliability because so many external connections (major source of circuit failure) are eliminated.

LICs find wide use in military and industrial applications as well as in consumer products. They are frequently used in

1. Operational amplifiers,
2. Small-signal amplifiers,
3. Power amplifiers,
4. RF and IF amplifiers,
5. Microwave amplifiers,
6. Multipliers,
7. Voltage comparators,
8. Voltage regulators etc.

Operational amplifier is by far the most versatile form for an LIC and is discussed separately.

2.0 OBJECTIVES

- After going through this unit, you should be able to:
- Define and identify operational amplifiers.
- Understand the manipulations of the input of an operational amplifier to produce a desired output.
- Understand various connection modes of an operational amplifier
- Solve related problems

3.0 MAIN CONTENT

3.1 What is an Operational Amplifier (OP-AMP)?

An operational amplifier, or op-amp is a very high gain, high input impedance directly coupled positive feedback amplifier with low output impedance, which can amplify signals having frequency ranging from 0 Hz to a little beyond 1 MHz. They are made with different internal configurations in linear ICs. An OP-AMP is so named because it was originally designed to perform mathematical operations like summation, subtraction, multiplication, differentiation and integration etc. in analog computers. Present day usage is much wider in scope but the popular name OP-AMP continues.

Although an OP-AMP is a complete amplifier, it is so designed that external components (resistors, capacitors etc.) can be connected to its terminals to change its external characteristics. Hence, it is relatively easy to tailor this amplifier to fit a particular application and it is, in fact, due to this versatility that OP-AMPs have become so popular in industry.

An OP-AMP IC may contain two dozen transistors, a dozen resistors and one or two capacitors.

The OP-AMP's input can be single-ended or double-ended (or differential input) depending on whether input voltage is applied to one input terminal only or to both. Similarly, amplifier's output can also be either single-ended or double-ended. The most common configuration is two input terminals and a single output.

3.2 THE BASIC OP-AMP

Figure 3.1 shows a basic op-amp with two inputs and one output as would result using a differential amplifier input stage. Each input results is either the same or an opposite polarity (or phase) output, depending on whether the signal is applied to the plus (+) or the minus (-).

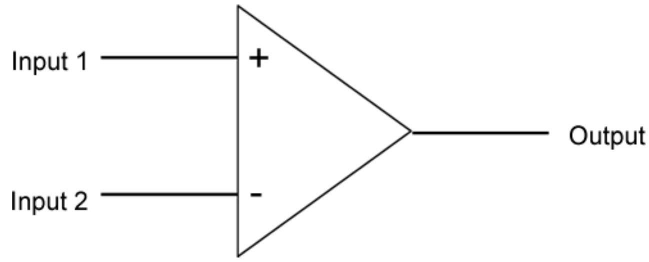

Fig 3.1 Basic op-amp

3.2.1 Single-Ended Input

Single-ended input operation results when the input signal is connected to one input with the other input connected to the ground. Figure 3.2 shows the signals connected for this operation.

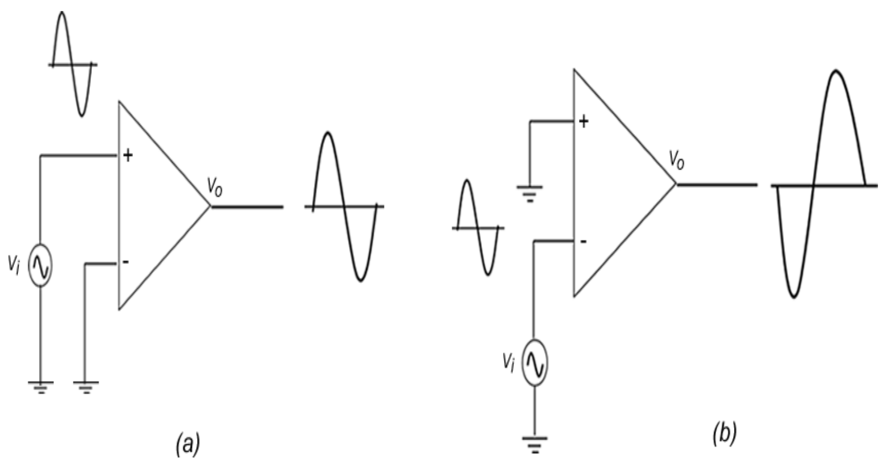

Figure 3.2 Single-ended operations

In Fig3.2a, the input is applied to the plus input (with minus input at ground), which results in an output having the same polarity as the applied input signal. Fig 3.2b shows an input signal applied to the minus input, the output then being opposite in phase to the applied signal.

3.2.2 Double-Ended (Differential) Input

In addition to using only one input, it is possible to apply signals at each input – this being a double-ended operation. Fig 3.3a shows an input, V_d, applied between the two input terminal (recall that neither input is at ground), with the resulting amplified output in phase with that applied between the plus and minus inputs. Fig 3.3b shows the same action resulting when two separate signals are applied to the inputs, the difference signal being $V_{i_1} - V_{i_2}$.

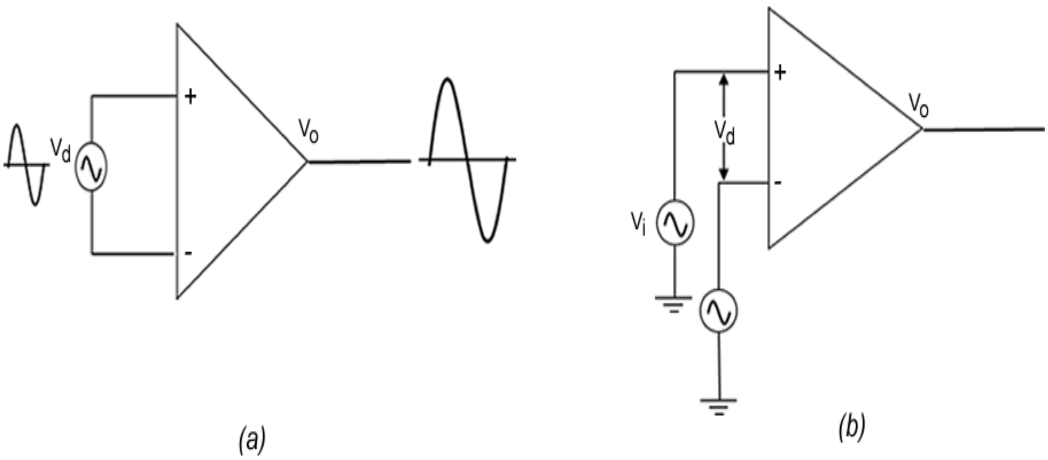

Fig 3.3 Double-ended (differential) operation

3.2.3 Double-Ended Output

While the operation discussed so far had a single output, the op-amp can also be operated with opposite outputs, as shown in fig 3.4. An input applied to either inputs will result in outputs from both output terminals, these output always being opposite in polarity.

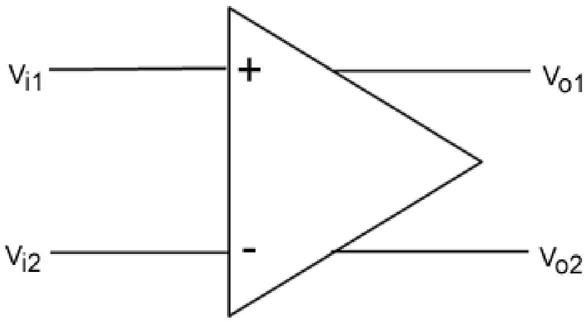

Fig 3.4 Double-ended

Fig 3.5 shows a single-ended input with double ended output. As shown, the signal applied to the plus input results in two amplified outputs of opposite polarity.

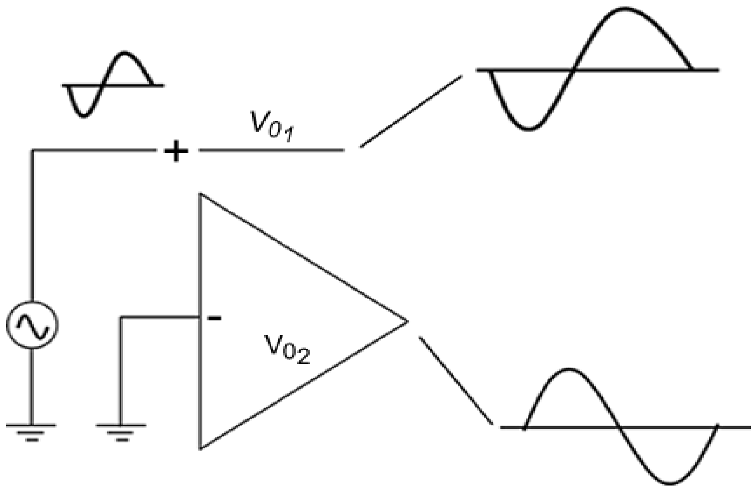

Fig 3.5 Double-ended output with single ended input

Fig 3.6 shows the same operation with a single output measured between output terminal (not with respect to ground). This difference output signal is $V_{o_1} - V_{o_2}$. The difference output is also referred to as a floating signal since neither output terminal is the ground (reference) terminal. Notice that the difference output is twice as large as either V_{o_1} *or* V_{o_2}, since they are of opposite polarity and subtracting them is twice the amplitude $[i.e., 10\ V - (-10V) = 20]$.

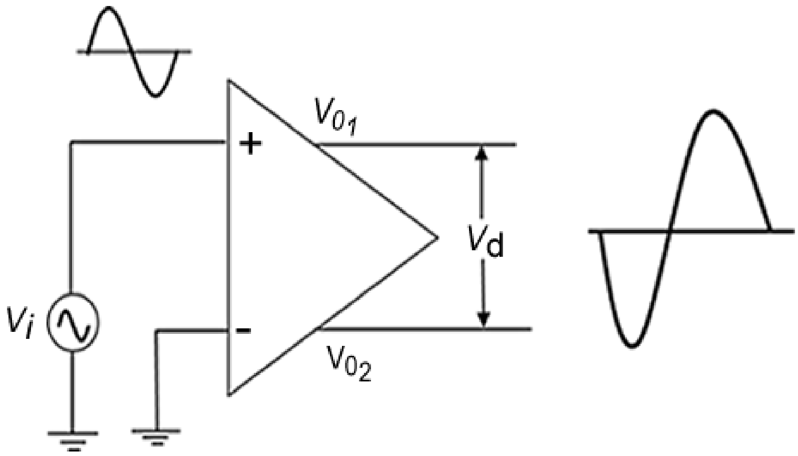

Fig 3.6Double-ended output.

Figure 3.7 shows a differential input, differential output operation. The input is applied between the two input terminals and the output taken from between the two output terminals. This is fully differential operation.

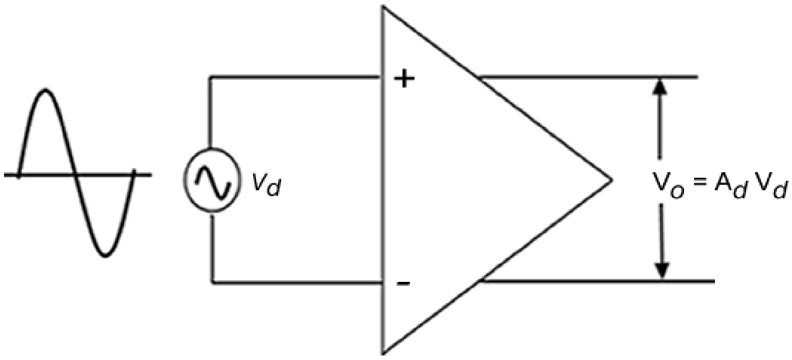

Figure 3.7 Differential-input, differential output operation.

3.2.4 Common-Mode Operation

When the same input signals are applied to both inputs, common-mode operation results, as shown in fig 3.8. Ideally, the two inputs are equally amplified, and since they result in opposite polarity signals at the output, these signals cancel, resulting in 0-V output. Practically, a small signal will result.

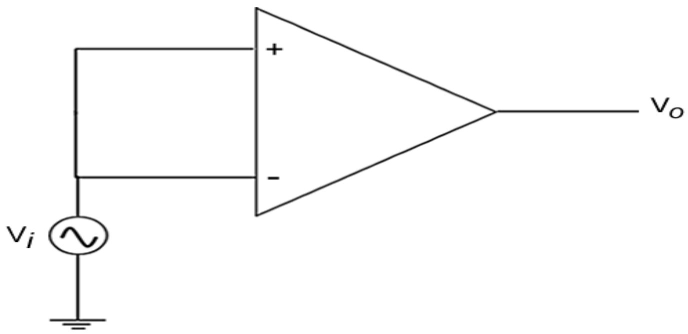

Fig3.8 Common-mode operation.

3.2.5 Common-Mode Rejection

A significant feature of a differential connection is that the signal which are opposite at the input are highly amplified, while those which are common to the two inputs are only slightly amplified – the overall operation being to amplify the difference signal while rejecting the common signal at the two inputs. Since noise (any unwanted input signal) is generally common to both inputs, the differential connection tends to provide attenuation of this unwanted input while providing an amplified output of the difference signal applied to the inputs. This operating feature, referred to as a common mode rejection is discussed more fully in this unit.

3.3 Differential and Common-Mode Operation

One of the more important features of a differential circuit connection, as provided in an op-amp, is the circuit's ability to greatly amplify signals that are opposite at the two inputs, while only slightly amplifying signals that are common to both inputs. An op-amp provides an output component that is due to the amplification of the difference of signals applied to the plus and minus inputs and a component due to the signal common to both inputs. Since amplification of the opposite signals is much greater than that of the common input signals, the circuit provides a common-mode rejection as described by a numerical value called the common-mode rejection ratio (CMRR).

3.3.1 Differential Inputs

When separate inputs are applied to the op-amp, the resulting difference signal is the difference between the two inputs.

$$V_d = V_{i_1} - V_{i_2}$$

3.3.2 Common Inputs

When both input signals are the same, a common signal element due to the two inputs can be defined as the average of the sum of the two signals.

$$V_c = \frac{1}{2}\left(V_{i_1} + V_{i_2}\right)$$

3.3.3 Output Voltage

Since any signals applied to an op-amp in general have both in-phase and out-of-phase components, the resulting output can be expressed as:

$$V_o = A_d V_d + A_c V_C$$

whereV_d = difference voltage

V_C = common voltage

A_d = difference gain of amplifier

A_c = common-mode gain of amplifier

3.3.4 Opposite Polarity Inputs

If opposite polarity inputs applied to an op-amp are ideally opposite signals, $V_{i_1} = -V_{i_2} = V_s$, the resulting difference voltage is:

$$V_d = V_{i_1} - V_{i_2} = V_s - (-V_s) = 2V_s$$

while the resulting common voltage is:

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \frac{1}{2}[V_s + (-V_S)] = 0$$

so that the resulting output voltage is:

$$V_o = A_d V_d + A_c V_C = A_d(2V_s) + 0 = 2A_d V_s$$

This shows that when the inputs are ideal opposite signal (no common element), the output is the differential gain times twice the input signal applied to one of the inputs.

3.3.5 Same Polarity Inputs

If the same polarity inputs are applied to an op-amp, $V_{i_1} = V_{i_2} = V_s$, the resulting difference voltage is:

$$V_d = V_{i_1} - V_{i_2} = V_s - V_s = 0$$

while the resulting common voltage is:

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \frac{1}{2}[V_s + V_s] = V_s$$

so that the resulting output voltage is:

$$V_o = A_d V_d + A_c V_C = A_d(0) + A_c V_s = A_c V_s$$

This shows that when the inputs are ideal in-phase signals (no difference signal), the output is the common-mode gain times the input signal, V_s, which shows that only common-mode operation occurs.

3.3.6 Common-Mode Rejection Ratio

We can calculate a value for the common-mode rejection ratio (CMRR) with respect to $A_d \text{and} A_c$ which is defined by the following equation:

$$CMRR = \frac{A_d}{A_c}$$

The value of CMRR can also be expressed in logarithm term as;

$$CMRR\ (log) = 20\ \log_{10}\frac{A_d}{A_c} \quad (dB)$$

It should be clear that the desired operation will have A_d very large with A_c very small. That is, the signal components of opposite polarity will appear greatly amplified at the output, whereas the signal component that are I phase will mostly cancel out so that the common-mode gain, A_c, is very small. Ideally, the value of the CMRR is infinite. *Practically, the larger the value of CMRR, the better the circuit operation.*

We can express the output voltage in terms of the value of CMRR as follows:

$$V_o = A_dV_d + A_cV_C = A_dV_d\left(1 + \frac{A_cV_c}{A_dV_d}\right)$$

This can be re-written as:

$$V_o = A_dV_d\left(1 + \frac{1}{CMRR}\frac{V_c}{V_d}\right)$$

Even when both V_d and V_c components of signal are present, it shows that for large values of CMRR, the output voltage will be due mostly to the difference signal, with the common-mode component greatly reduced or rejected.

Example

Determine the output voltage of an op-amp for input voltages of $V_{i_1} = 150\ \mu V\ V_{i_2} = 140\ \mu V$. The amplifier has a differential gain of $A_d = 4000$ and the value of CMRR is:

(a) 100.
(b) 10^5

Solution

$$V_d = V_{i_1} - V_{i_2} = (150 - 140)\mu V = 10\ \mu V$$

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \frac{150\mu V + 140\ \mu V}{2} = 145\ \mu V$$

(a) $V_o = A_dV_d\left(1 + \frac{1}{CMRR}\frac{V_c}{V_d}\right)$

$$= (4000)(10\ \mu V)\left(1 + \frac{1}{100}\frac{145\ \mu V}{10\ \mu V}\right)$$

$$= 40\ mV(1.145) = 45.8\ mV$$

(b) $V_0 = (4000)(10\ \mu V)\left(1 + \frac{1}{10^5}\frac{145\ \mu V}{10\ \mu V}\right)$

$$= 40\ mV(1.000145) = 40.006\ mV$$

This shows that the larger the value of CMRR, the closer the output voltage is to the difference input times the difference gain with the common-mode signal being rejected.

3.3.7 Virtual Ground and Summing Point

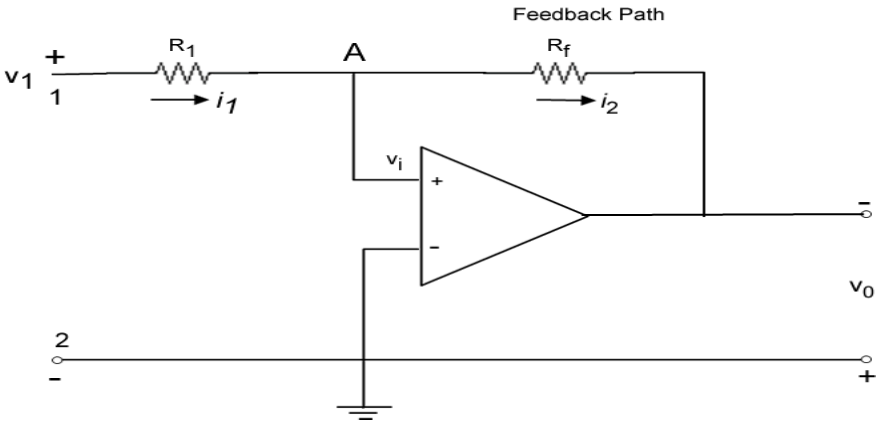

Fig. 3.9

In Fig. 3.9 is shown an OP-AMP which employs negative feedback with the help of resistor R_f which feeds a portion of the output to the input. Since input and feedback currents are algebraically added at point A, it is called the summing point.

The concept of virtual ground arises from the fact that input voltage V_1 at the inverting terminal of the OP-AMP is forced to such a small value that, for all practical purposes, it may be assumed to be zero. Hence, point A is essentially at ground voltage and is referred to as virtual ground. Obviously, it is not the actual ground, which, as seen from Fig. 3.9, is situated below.

3.4 PRACTICAL OP-AMP CIRCUITS

The op-amp can be connected in a large number of circuits to provide various operating characteristics. We will cover a few of the most common of these circuit connections.

3.4.1 Inverting Amplifier

The most widely used constant-gain amplifier circuit is the inverting amplifier, as shown in fig 3.10. The output is obtained by multiplying the input by a fixed or constant gain, set by the input resistor (R_1) and feedback resistor (R_F) – this output also being inverted from the input. We can write that:

$$V_o = -\frac{R_f}{R_1}V_1$$

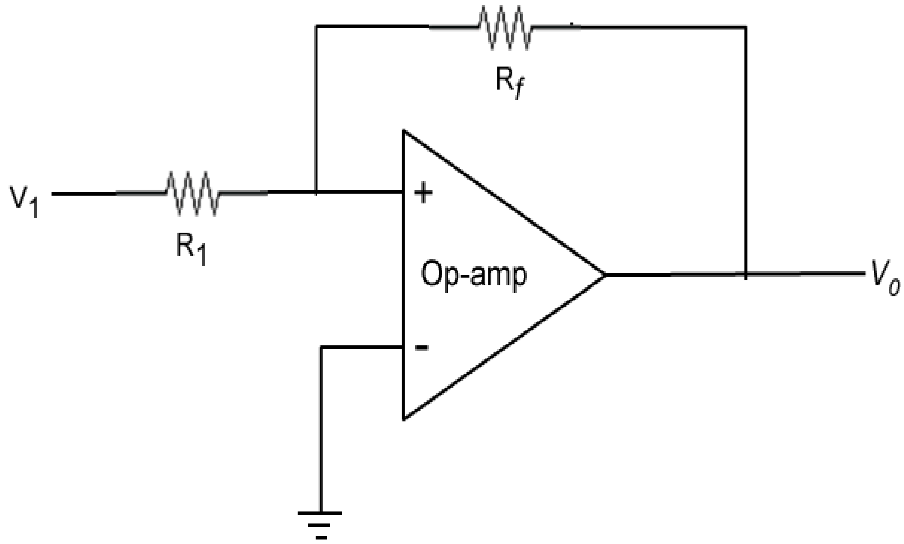

Fig 3.10 Inverting constant-gain multiplier

Example

If the circuit of fig 14.15 has $R_1 = 100\ k\Omega$and $R_f = 500\ k\Omega$, what output voltage result for an input of $V_1 = 2\ V$.

Solution

$$V_o = -\frac{R_f}{R_1}V_1 = -\frac{500\ k\Omega}{100\ k\Omega}(2\ V) = -10\ V$$

3.4.2 Non-Inverting Amplifier

The connection of fig 3.11 shows an op-amp circuit that works as a non-inverting amplifier or constant gain multiplier. It should be noted that the inverting amplifier connection is more widely used because it has better frequency stability. To determine the voltage gain of the circuit, we can use the equivalent representation shown in fig 3.11b. Note that the voltage across R_1 is V_1since $V_i = 0\ V$. This must be equal to the output voltage, through a voltage divider of $R_1$and R_f, so that

$$V_1 = \frac{R_1}{R_1 + R_f} V_o$$

which results in

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

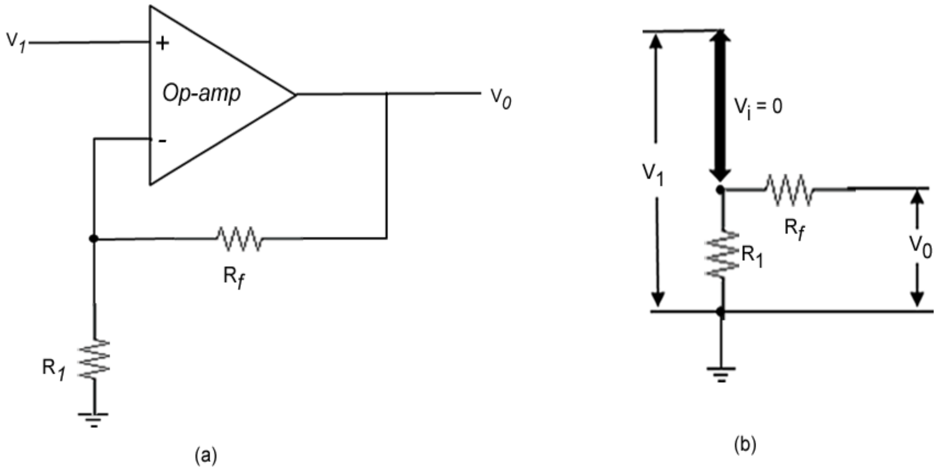

Fig 3.11 Non-inverting constant-gain multiplier

EXAMPLE

Calculate the output voltage of a non-inverting amplifier (as shown in fig 3.11) for values of $V_1 = 2\ V,\ R_f = 500 k\Omega, and\ R_1 = 100\ k\Omega$.

SOLUTION

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 = \left(1 + \frac{500\ K\Omega}{100\ K\Omega}\right)(2\ V) = \ 6(2\ V) = \ +12\ v$$

3.4.3 Unity Follower

The unity follower circuit, as shown in fig 3.12a, provides a gain of unity (1) with no polarity or phase reversal. From the equivalent circuit, fig 3.12b, it is clear that

$$V_o = V_i$$

And that the output is the same polarity and magnitude as the input. The circuit operates like an emitter- or source-follower circuit except that the gain is exactly unity.

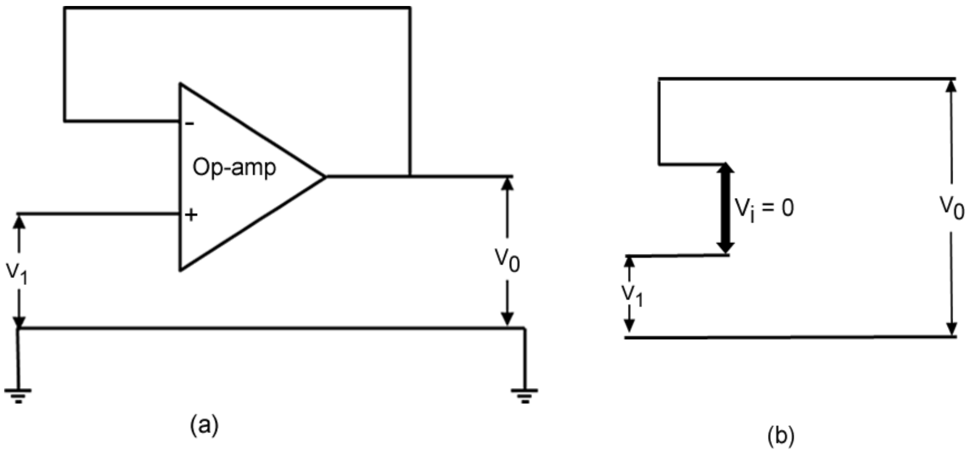

Figure3.12 (a) Unity follower, (b) virtual-ground equivalent circuit

3.4.4 Summing Amplifier

Probably, the most used of the op-amp circuit is the summing amplifier circuit shown in fig 3.13a. The circuit shows a three-input amplifier circuit, which provides a means of algebraically summing (adding) three voltages, each multiplied by a constant-gain factor. Using the equivalent representation shown in fig 3.13b, the output voltage can be expressed in terms of the inputs as:

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_1}V_3\right)$$

In other words, each input adds a voltage to the output multiplied by its separate constant-gain multiplier. If more inputs are used, they each add additional component to the output.

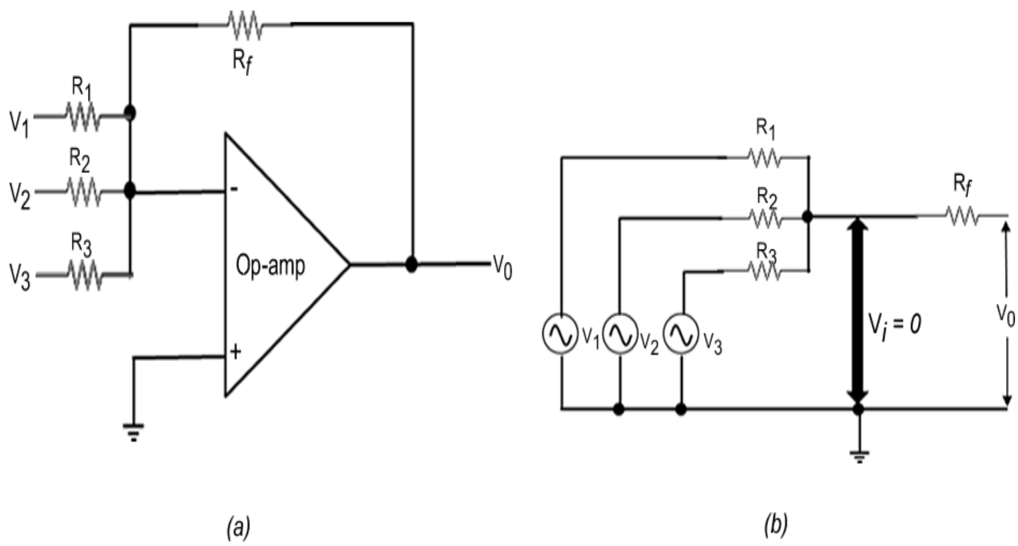

Figure 3.13 (a) Summing amplifier; (b) virtual-ground equivalent circuit.

3.4.5 Integrator

So far, the input and feedback components have been resistors. If the feedback component used is a capacitor, as shown in fig 3.14a, the resulting connection is called an integrator. The virtual ground equivalent circuit (fig 3.14b) shows that an expression for the voltage between input and output can be derived in terms of current I, from input to output. Recall that virtual ground means that we can consider the voltage at the junction of R and X_C to be ground (since $V_i \approx 0\ V$) but that no current goes into ground at that point. The capacitive impedance can be expressed as

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC}$$

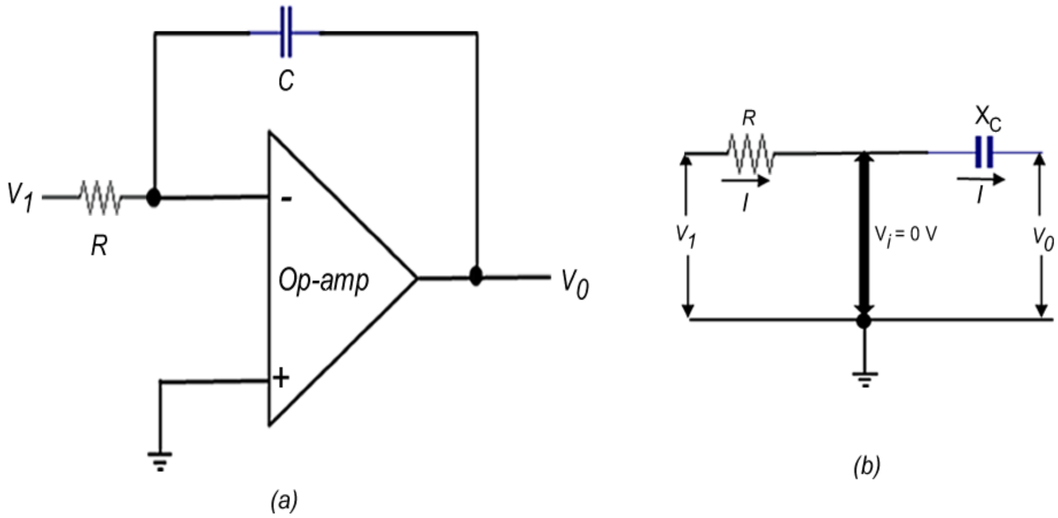

Figure 3.14 Integrator

where $s = j\omega$ is in the Laplace notation. Solving for V_o/V_1 yields

$$I = \frac{V_1}{R} = -\frac{V_o}{X_C} = \frac{-V_o}{1/sC} = -sCV_o$$

$$\frac{V_o}{V_1} = \frac{-1}{sCR}$$

The expression above can be rewritten in the time domain as

$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$

It shows that the output is the integral of the input, with an inversion and scale multiplier of $1/RC$. The ability to integrate a given signal provides the analog computer with the ability to solve differential equations and therefore provides the ability to electrically solve analogs of physical system operation.

3.4.6 Differentiator

A differentiator circuit is shown in fig 3.15 while not as useful as the circuit forms covered above, the differentiator does provide a useful operation, the resulting relation for the circuit being

$$V_o(t) = -RC\frac{dv_1(t)}{dt}$$

Where the scale factor is $-RC$.

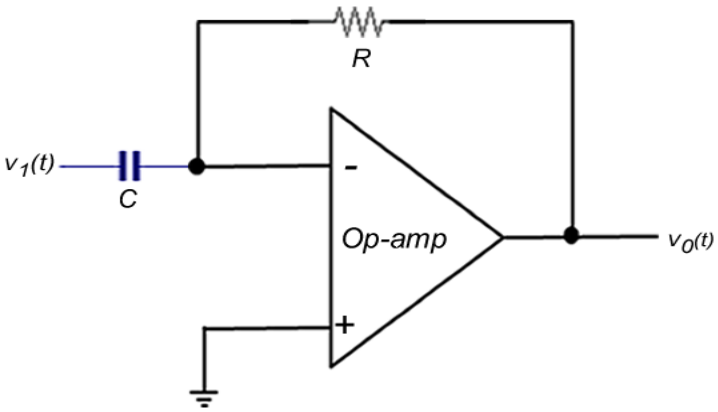

Figure 3.15 Differentiator circuit.

3.5 TEST

Question 1

What input voltage will result in an output of 2 V in the circuit of Fig 3.16?

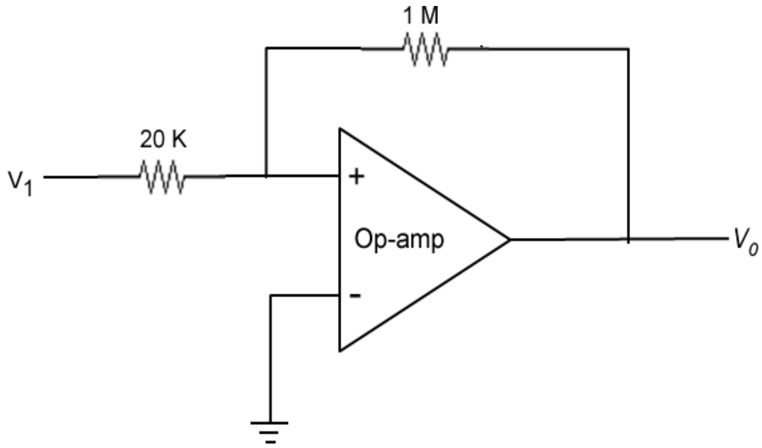

Fig 3.16

Solution

$$V_o = -\frac{R_f}{R_1}V_1$$

Hence,

$$V_1 = -\frac{R_1}{R_f}V_o$$

$$V_1 = -\frac{20 \times 10^3}{1 \times 10^6} = \mathbf{-0.2\ V}$$

Question 2

Calculate the output of the circuit in Fig 3.17 for $R_f = 68\ k\Omega$.

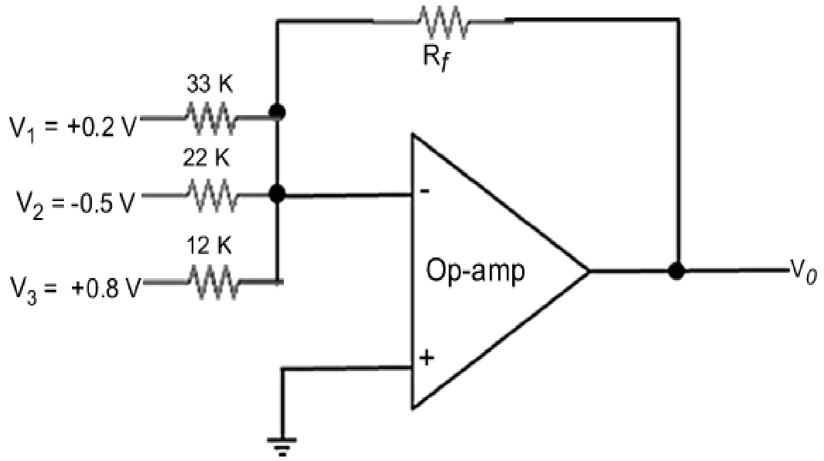

Fig 3.17

Solution

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_1}V_3\right)$$

$$V_o = -\left[\frac{68\ k\Omega}{33\ k\Omega}(0.2) + \frac{68\ k\Omega}{22\ k\Omega}(-0.5) + \frac{68\ k\Omega}{12\ k\Omega}(0.8)\right]$$

$$= -[0.412 + (-1.545) + 4.533]$$

$$= -3.4\ V$$

Question 3

The input to the differentiator circuit of the figure below is a sinusoidal voltage of peak value of $5\ mV$ and frequency $1\ kHz$. Find out the output if $R = 1000\ K$ and $C = 1\ \mu F$.

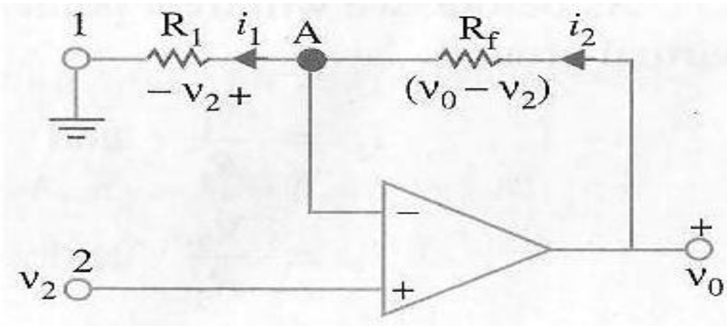

Fig 3.18

Solution

The equation of the input voltage is

$$v_1 = 5\sin 2\pi \times 1000t = 5\sin 2000\pi t \ mV$$

Scale factor $= RC = 10^{-6} \times 10^{5} = 0.1$

$$v_0 = 0.1\frac{d}{dt}(5\sin 2000\pi t) = (0.5 \times 2000\pi)\cos 2000\pi t$$

$$= 1000\pi \cos 2000\pi t \ mV$$

As seen, the output is a co sinusoidal voltage of frequency of 1 kHz and peak value $1000\pi \ mV$.

4.0 CONCLUSION

This unit has introduced you to the basic operation of an operational amplifier and also treated the various connection modes and the practical op-amp circuits

5.0 SUMMARY

The operational amplifier or op-amp is a very high gain amplifier having a very high input impedance and low output impedance (less than 10 Ω). The basic circuit is made using a difference amplifier having two inputs (plus (+) and minus (-)) and at least one output.

An ideal op-amp circuit will have infinite input impedance, zero output impedance and infinite voltage gain.

6.0 TUTOR-MARKED ASSINGMENT

1. (i) When in a negative scalar, both R_1 and R_f are reduced to zero, the circuit functions as

(*a*) integrator

(*b*) subtractor

(*c*) comparator

(*d*) unity follower.

(ii) The two input terminals of an OP-AMP are known as

(*a*) Positive and negative.

(*b*) Differential and non-differential.

(*c*) Inverting and non-inverting.

(*d*) High and low.

2. Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $R_f = 1\ M\Omega$ in all cases.

(a)
$V_1 = +1\ \text{V}, V_2 = +2\ \text{V}, V_3 = +3\ \text{V}, R_1 = 500\ k\Omega, R_2 = 1\ M\Omega, R_3 = 1\ M\Omega.$

(b)
$V_1 = -2\ \text{V}, V_2 = +3\ \text{V}, V_3 = +1\ \text{V}, R_1 = 200\ k\Omega, R_2 = 200\ k\Omega, R_3 = 1\ M\Omega$

3. Calculate the CMRR (in dB) for the circuit measurement of $V_d = 1\ mV, V_o = 120\ mV,\ and\ V_C = 1\ mV, V_o = 20\ \mu V.$

4. Calculate the voltage output of fig 3.19.

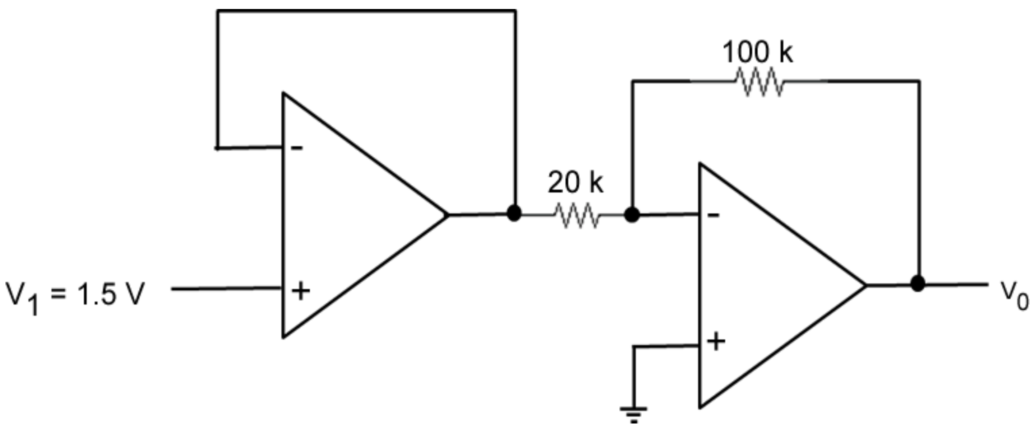

Figure3.19

5. In an inverting amplifier, the two input terminals of an ideal OP-AMP are at the same potential because

(*a*) The two input terminals are directly shorted internally (*b*) The input impedance of the OP-AMP is infinity

(*c*) Common-mode rejection ratio is infinity

(*d*) The open-loop gain of the OP-AMP is infinity

7.0 REFERENCES/FURTHER READING

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UNIT 2 OP-AMP APPLICATIONS

CONTENTS

1.0 INTRODUCTION

Although an op-amp is a complete amplifier, it is so designed that external components (resistors, capacitors, etc.) can be connected to its terminals to change its external characteristics. Hence, it is relatively easy to tailor this amplifier to fit a particular application and it is in fact, due to this versatility that the op-amp has become so popular in industry.

2.0 OBJECTIVES

At the end of this unit, you should be able to

- Identify and familiarize with the various application of op-amp
- Solve related problems

3.0 MAIN CONTENT – APPLICATIONS OF OP-AMP

3.1 CONSTANT-GAIN MULTIPLIER

One of the most common op-amp circuits is the inverting constant-gain multiplier, which provides a precise gain or amplification. Fig 3.1 shows a standard circuit connection with the resulting gain being given by:

$$A = -\frac{R_f}{R_1}$$

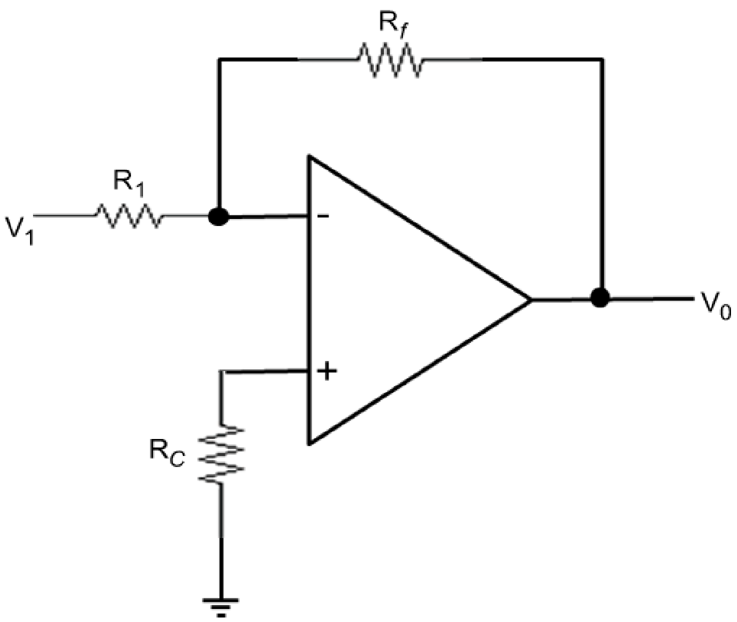


Fig 3.1 Fixed-gain amplifier

A non-inverting constant-gain multiplier is provided by the circuit of fig 3.2 with the gain given by:

$$A = 1 + \frac{R_f}{R_1}$$

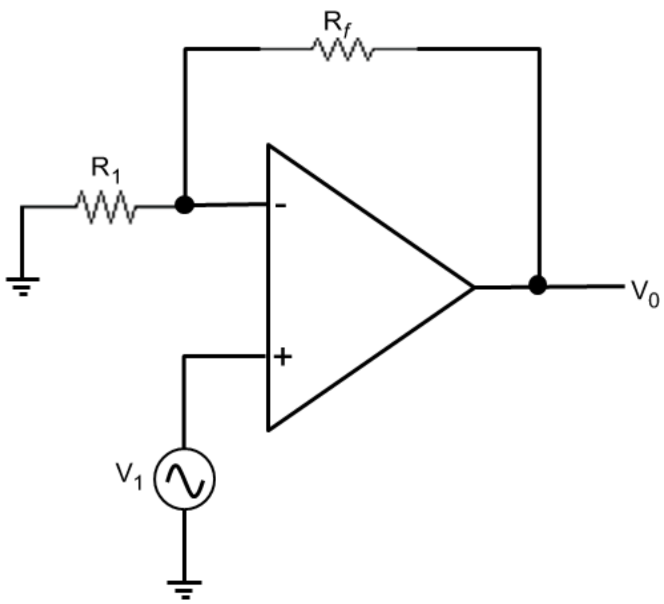


Figure3.2Noninverting fixed-gain amplifier.

Multiple-stage Gains

When a number of stages are connected in series, the overall gain is the product of the individual stage gains. Figure 3.3 shows a connection of three stages. The first stage is connected to provide non-inverting gain. The next two stages provide an inverting gain. The overall gain is then non-inverting and calculated by

$$A = A_1 A_2 A_3$$

Where

$$A_1 = 1 + \frac{R_f}{R_1}, \qquad A_2 = -\frac{R_f}{R_2} \;\; and \;\; A_3 = -\frac{R_f}{R_3}$$

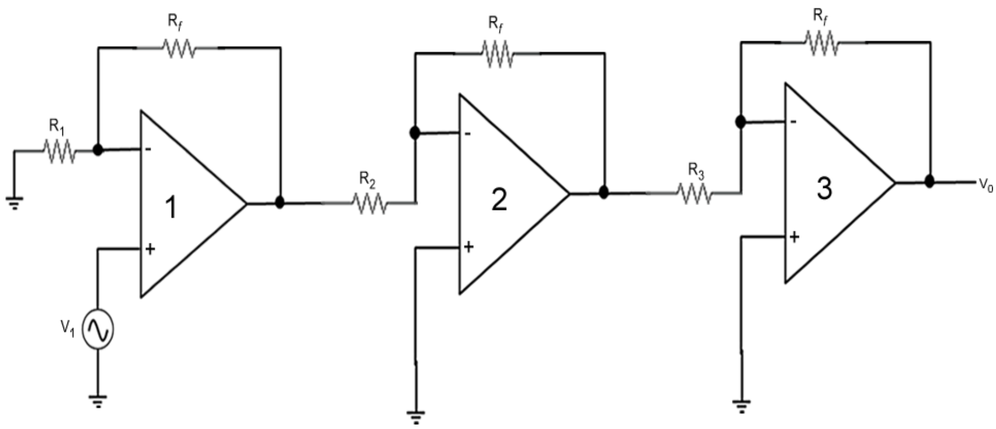


Figure 3.3 Constant-gain connections with multiple stages

Example

Calculate the output voltage using the circuit of Figure 3.3 for resistor component of value $R_f = 470\ k\Omega, R_1 = 4.3\ k\Omega\ , R_2 = 33\ k\Omega, and\ R_3 = 33\ k\Omega$ for an input of *80 μV.*

Solution

The amplifier gain is calculated to be

$$A = A_1A_2A_3 = \left(1 + \frac{R_f}{R_1}\right)\left(-\frac{R_f}{R_2}\right)\left(-\frac{R_f}{R_3}\right)$$

$$= \left(1 + \frac{470}{4.3}\right)\left(-\frac{470}{33}\right)\left(-\frac{470}{33}\right) k\Omega$$

$$= (110.3)(-14.2)(-14.2) = 22.2 \times 10^3$$

So that

$$V_o = AV_i = 22.2 \times 10^3(80\ \mu V) = 1.78\ V$$

3.2 VOLTAGE SUMMING

Another popular use of an op-amp is as a summing amplifier. Fig 3.4 shows the connection with the output being the sum of the three inputs each multiplied by a different gain. The output voltage is

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

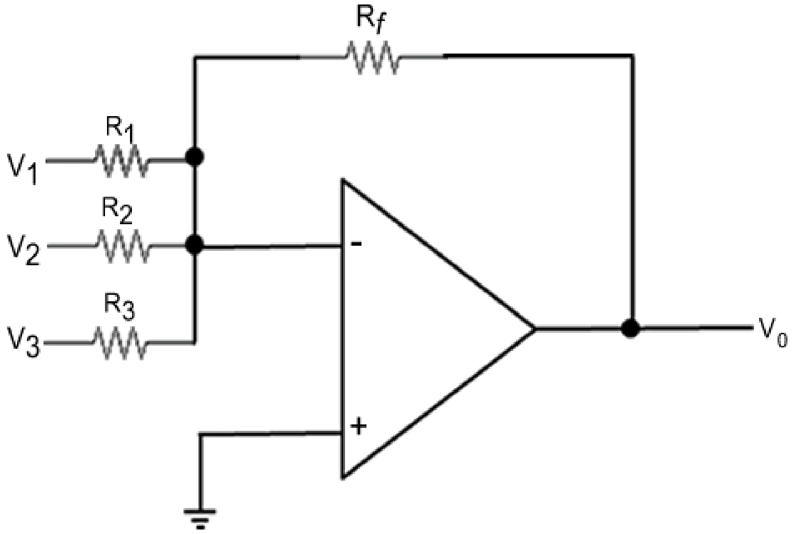


Fig 3.4 Summing amplifier

Voltage Subtraction

Two signals can be subtracted, one from another, in a number of ways. Figure 3.5 shows two op-amp stages used to provide subtraction of input signals. The resulting output is given by:

$$V_o = -\left[\frac{R_f}{R_3}\left(-\frac{R_f}{R_1}V_1\right) + \frac{R_f}{R_2}V_2\right]$$

$$V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)$$

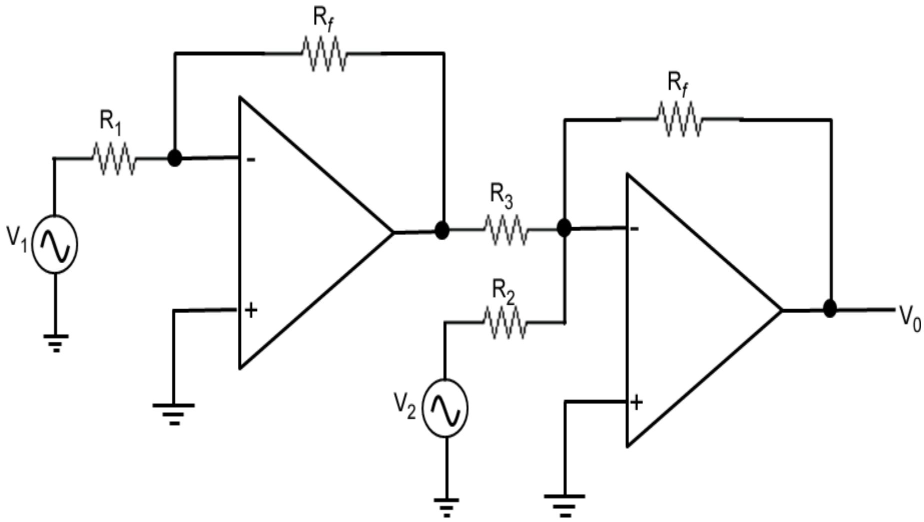


Fig 3.5 Circuit to subtract two signals.

Example

Determine the output for the circuit of Fig 3.5 with components $R_f = 1\ M\Omega, R_1 = 100\ k\Omega\ , R_2 = 50\ k\Omega, and\ R_3 = 500\ k\Omega$

Solution

The output voltage is calculated to be

$$V_o = -\left(\frac{1\ M\Omega}{50\ k\Omega}V_2 - \frac{1\ M\Omega}{500\ k\Omega}\frac{1\ M\Omega}{100\ k\Omega}V_1\right)$$

$$= -(20\ V_2 - 20V_1) = -20(V_2 - V_1)$$

The output is seen to be the difference of V_2 and V_1 multiplied by a gain factor of -20.

Another connection to provide subtraction of two signals is shown in fig 3.6.

This connection uses only one op-amp stage to provide subtracting two input signals. Using superposition the output can be shown to be

$$V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2$$

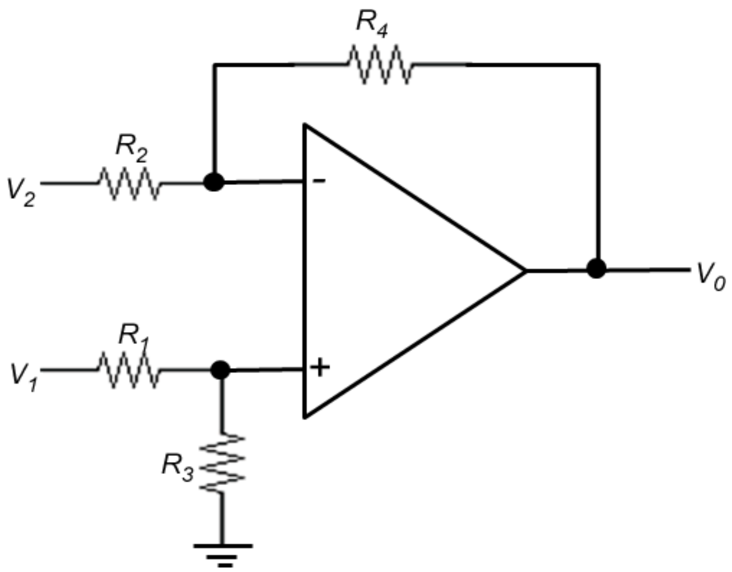


Fig 3.6 Subtraction circuit.

Example

Determine the output for the circuit of fig 3.7

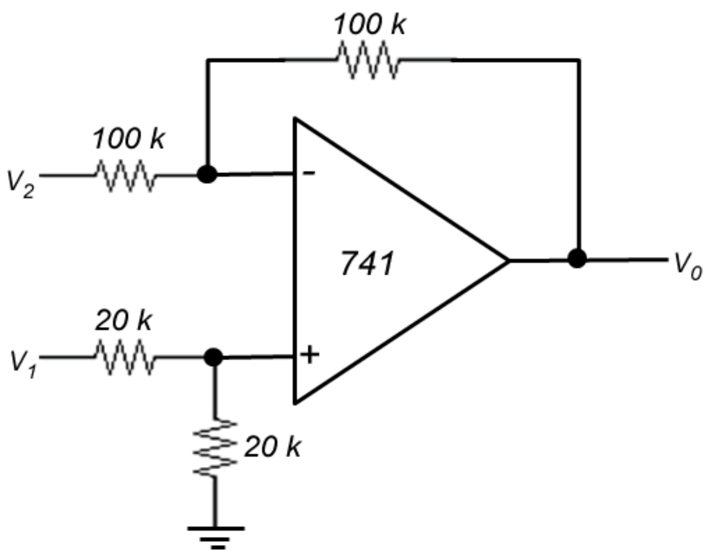


Fig 3.7

Solution

The resulting output voltage can be expressed as

$$V_o = \left(\frac{200\ k\Omega}{20\ k\Omega + 20k\Omega}\right)\left(\frac{100\ k\Omega + 100k\Omega}{100\ k\Omega}\right)V_1 - \frac{100\ k\Omega}{100\ k\Omega}V_2$$

$$= V_1 - V_2$$

The resulting output voltage is seen to be the difference of the two voltages.

3.3 VOLTAGE BUFFER

A voltage buffer circuit provides a means of isolating an input signal from a load by using a stage having unity voltage gain, with no phase or polarity inversion, and acting as an ideal circuit with very high input impedance and low output impedance. Fig 3.8 shows an op-amp connected to provide this buffer amplifier operation. The output voltage is given by

$$V_0 = V_1$$

Fig 3.9 shows how an input signal can be provided to two separate outputs. The advantage of this connection is that the load connected across one output has no (or little) effect on the other output. In effect, the outputs are buffered or isolated from each other.

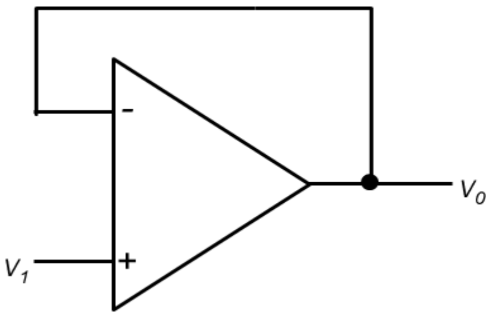


Fig 3.8 Unity-gain (buffer) amplifier

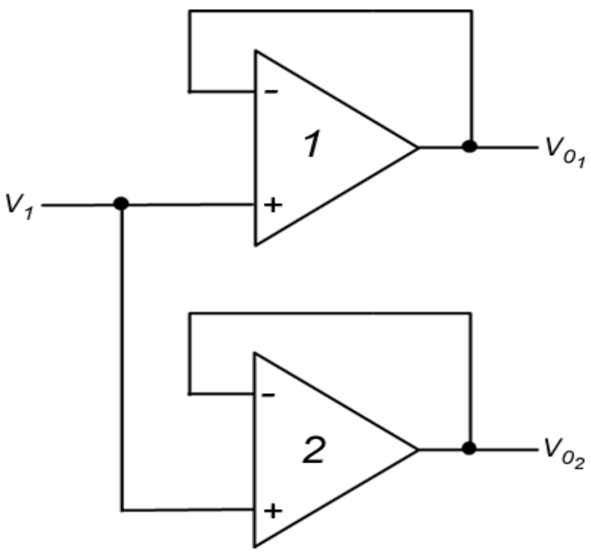


Fig 3.9 Use of buffer amplifier to provide output signals.

3.4 CONTROLLED SOURCES

Operational amplifiers can be used to form various types of controlled sources. An input voltage can be used to control an output voltage or current. These types of connections are suitable for use in various instrumentation circuits. A form of each type of controlled source is provided next.

3.4.1 Voltage-Controlled Voltage Source

An ideal form of voltage source whose output V_0 is controlled by an input voltage V_1 is shown in fig 3.10.

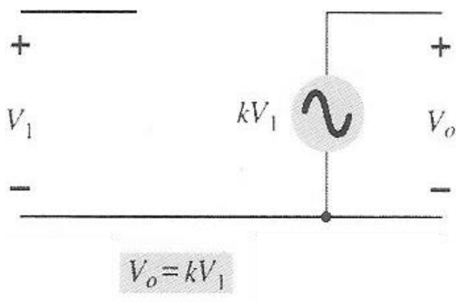


Figure 3.10 Ideal voltage-controlled voltage source.

The output voltage is seen to be dependent on the input voltage (times a scale factor *k*). This type of circuit can be built using an op-amp as shown in Fig 3.11. Two versions of the circuit are shown, one using inverting input and the other using non-inverting input. For connection of Fig 3.11, the output voltage is

$$V_o = -\frac{R_f}{R_1}V_1 = kV_1$$

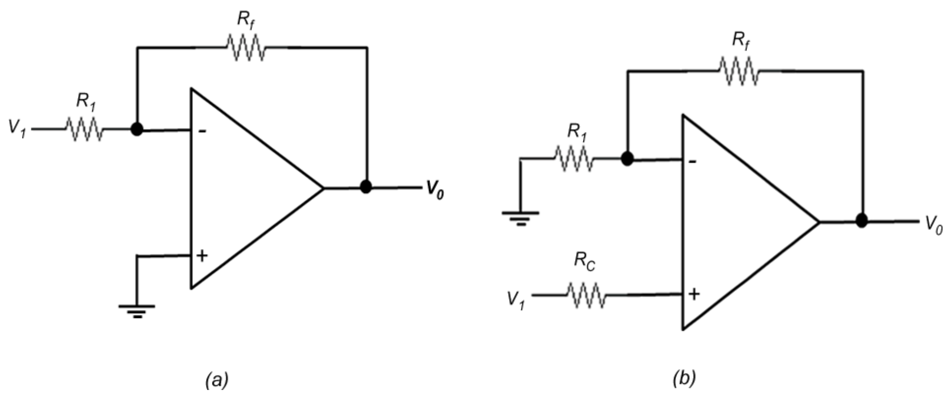


Fig 3.11 Practical voltage-controlled voltage source circuits

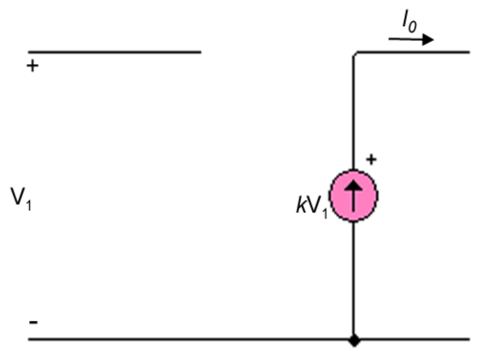
While that of Fig 3.11b results in

$$V_o = \left(1 + \frac{R_f}{R_1}\right)V_1 = kV_1$$

3.4.2 Voltage-Controlled Current Source

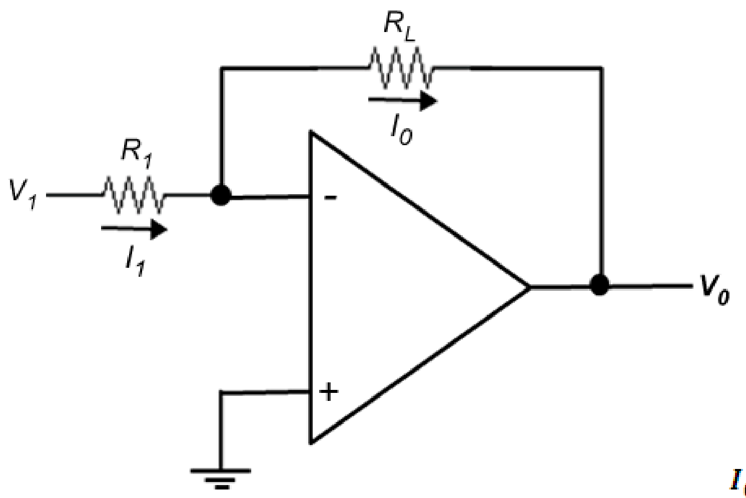
An ideal form of circuit providing an output current controlled by an input voltage is that of fig 3.12. The output current is dependent on the input voltage. A practical circuit can be built as in Fig 3.13, with the output current through load resistor R_L controlled by the input voltage V_1. The current through load resistance R_L can be seen to be

$$I_0 = \frac{V_1}{R_1} = kV_1$$



$$I_0 = kV_1$$

Fig 3.12 Ideal voltage-controlled current source.



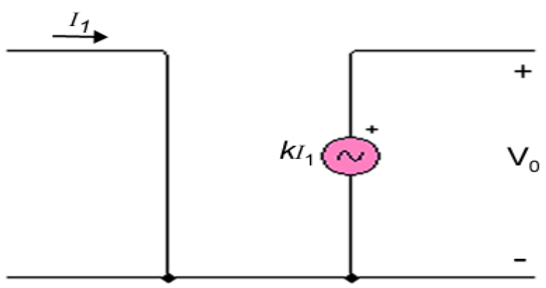
$$I_0 = \frac{V_1}{R_1}$$

Fig 3.13 Practical voltage-controlled current source

3.4.3 Current-Controlled Voltage Source

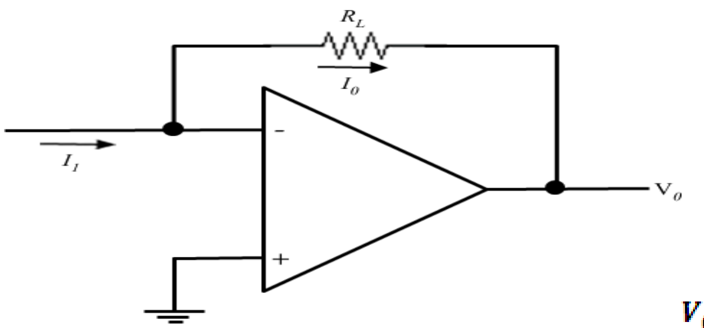
An ideal form of a voltage source controlled by an output current is shown in Fig 3.14. The output voltage is dependent on the input current. A practical form of the circuit is built using an op-amp as shown in Fig 3.15. The output voltage is seen to be

$$V_0 = -I_1 R_L = kI_1$$



$$\boldsymbol{V_0 = kI_1}$$

Fig 3.13 Ideal current-controlled voltage source

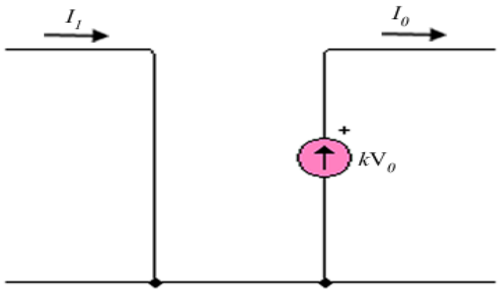


$$\boldsymbol{V_0 = (-I_1 R_L)}$$

Fig 3.14 Practical form of current-controlled voltage source.

3.4.4 Current-Controlled Current Source

An ideal form of a circuit providing an output current dependent on an input current is shown in Fig 3.15. In this type of circuit, an output current is provided dependent on the input current. A practical form of the circuit is shown in Fig 3.16. The input current I_1 can be shown to result in the output current I_0 so that



$$I_0 = kI_1$$

Fig 3.15 Ideal current-controlled current source

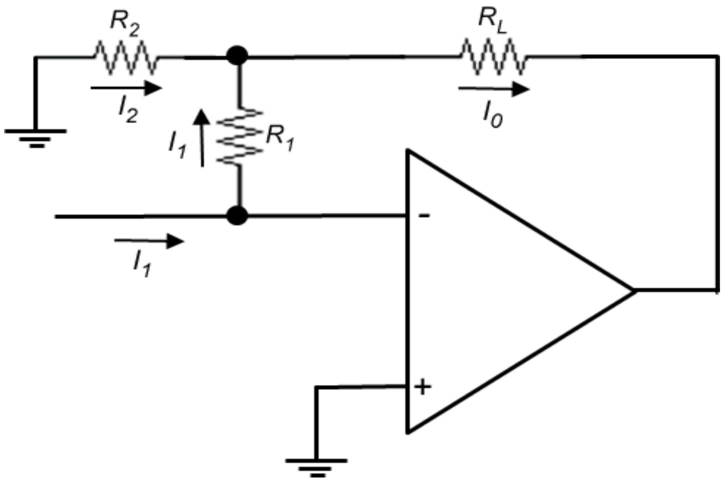


Fig 3.16 Practical form of current-controlled current source

$$I_0 = I_1 + I_2 = I_1 + \frac{I_1 R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right) I_1 = kI_1$$

Example

(a) For the circuit of fig 3.17a, calculate I_L.

(b) For the circuit of fig 3.17b, calculate V_o.

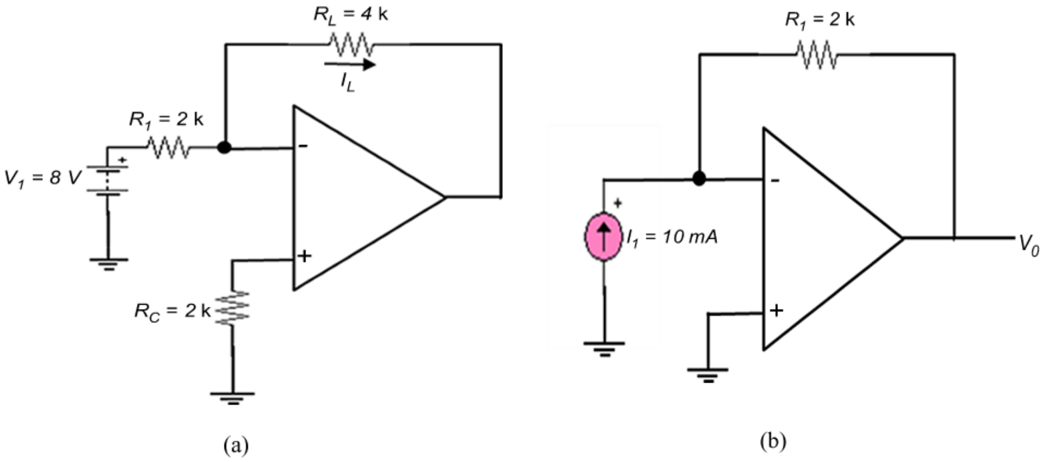


Fig 15.24

Solution

(a) For the circuit of fig 3.17a,

$$I_L = \frac{V_1}{R_1} = \frac{8\ V}{2\ k\Omega} = 4\ mA$$

(b) For the circuit of Fig 3.17b

$$V_o = -I_1 R_1 = -(10\ mA)(2\ k\Omega) = -20\ V$$

3.5 INTRUMENTATION CIRCUITS

A popular area of op-amp application is in the instrumentation circuits such as dc or ac voltmeters. A few typical circuits will demonstrate how op-amp can be used.

3.5.1 DC Millivoltmeter

Figure 3.18 shows a 741 op-amp used as the basic amplifier in a dc Millivoltmeter. The amplifier provides a meter with high input impedance and scale factor dependent only on resistor value and accuracy. Notice that the meter reading represents millivolts of signal at the circuit input. An analysis of the op-amp circuit provides the circuit transfer function

$$\left|\frac{I_o}{V_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_s}\right) = \left(\frac{100\ k\Omega}{100\ k\Omega}\right)\left(\frac{1}{10\ k\Omega}\right) = \frac{1\ mA}{10\ mV}$$

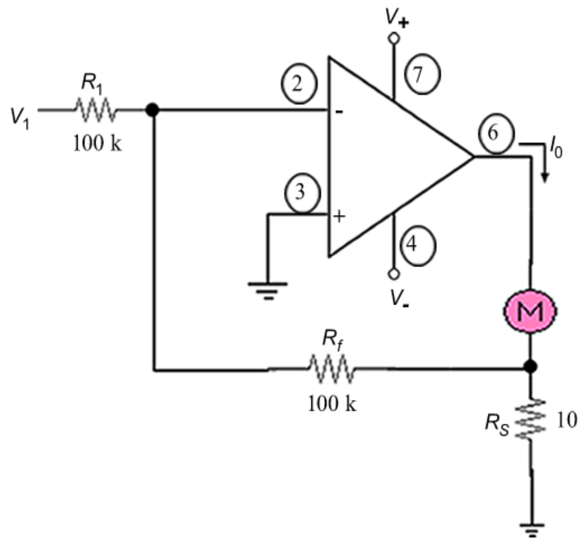


Figure 3.18 Op-amp dc Millivoltmeter

Thus, an input of 10 mA will result in a current through the meter of 1 mA. If the input is 5 mV, the current through the meter will be 0.5 mA, which is half-scale deflection. Changing R_f to $200\ k\Omega$, for example, would result in a circuit scale factor of

$$\left|\frac{I_o}{V_1}\right| = \left(\frac{200\ k\Omega}{100\ k\Omega}\right)\left(\frac{1}{10\ k\Omega}\right) = \frac{1\ mA}{5\ mA}$$

Showing that the meter now reads 5 mA, full scale. It should be kept in mind that building such a Millivoltmeter requires purchasing an op-amp, a few resistors, diodes, capacitors, and a meter movement.

3.5.2 AC Millivoltmeter

Another example of an instrumentation circuit is the ac Millivoltmeter shown in fig 3.19. the circuit transfer function is

$$\left|\frac{I_o}{I_1}\right| = \frac{R_f}{R_1}\left(\frac{1}{R_S}\right) = \left(\frac{100\ k\Omega}{100\ k\Omega}\right)\left(\frac{1}{10\ \Omega}\right) = \frac{1\ mA}{10\ mA}$$

this appears the same as the dc Millivoltmeter, except that in this case the signal handled is an ac signal. The meter indicator provides a full-scale deflection for an ac input signal of 10 mA, while an ac input of 5mA will result in half-scale deflection with the meter reading interpreted in millivolts unit.

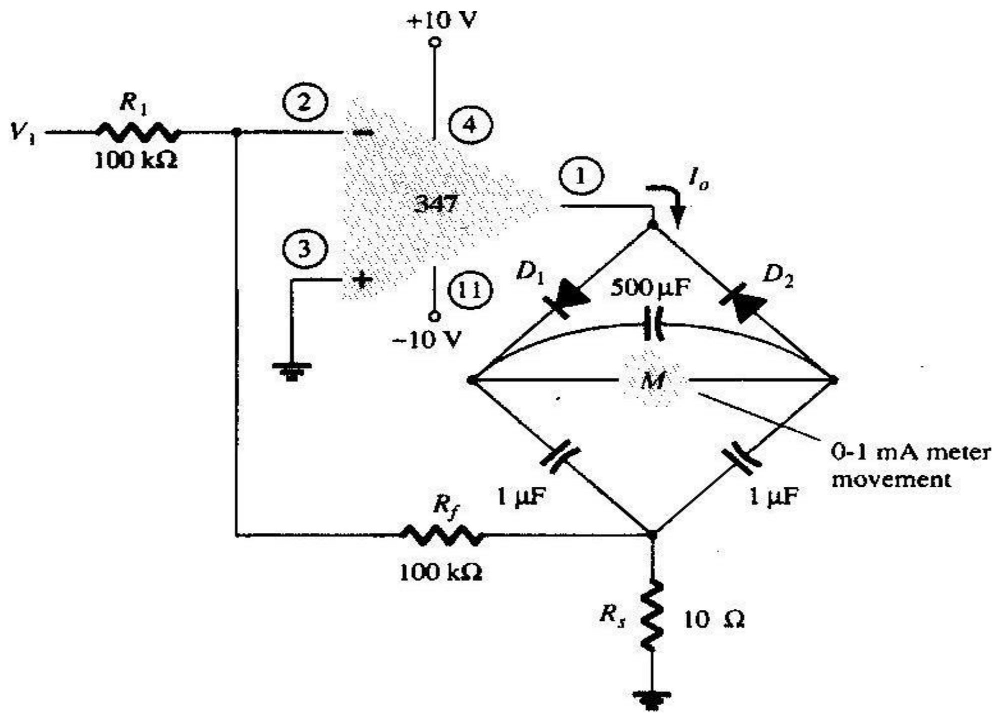


Fig 3.19 Ac Millivoltmeter using op-amp

3.5.3 Display Divider

Fig 3.20 shows op-amp circuit that can be used to drive a lamp display or LED display. When the non-inverting input to the circuit in fig 3.20a goes above the inverting input, the output at terminal 1 goes to the positive saturation level (near +5V in this example) and the lamp is driven on when transistor Q_1 conducts. As shown in the circuit, the output of the op-amp provides 30 mA of current to the base of transistorQ_1, which then drives 600 mA through a suitably selected transistor (with$\beta > 20$) capable of handling that amount of current. Fig 3.20b shows an op-amp circuit that can supply 20 mA to drive an LED display when the non-inverting input goes positive compared to the inverting input.

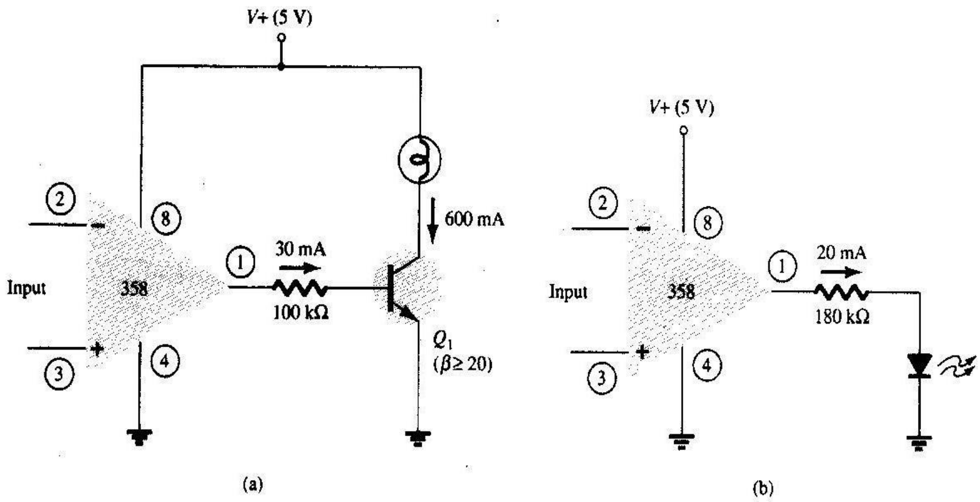


Fig 3.20 Display driver circuits:

3.5.4 Instrumentation Amplifier

A circuit providing an output based on the difference between two inputs (times a scale factor) is shown in fig 3.21. A potentiometer is provided to permit adjusting the scale factor of the circuit. While three op-amps are used, a single-quad op-amp IC is all that is necessary (other than the resistor components.) The output voltage can be shown to be

$$\frac{V_o}{V_1 - V_2} = 1 + \frac{2R}{R_p}$$

So that the output can be obtained from

$$V_o = \left(1 + \frac{2R}{R_p}\right)(V_1 - V_2) = k(V_1 - V_2)$$

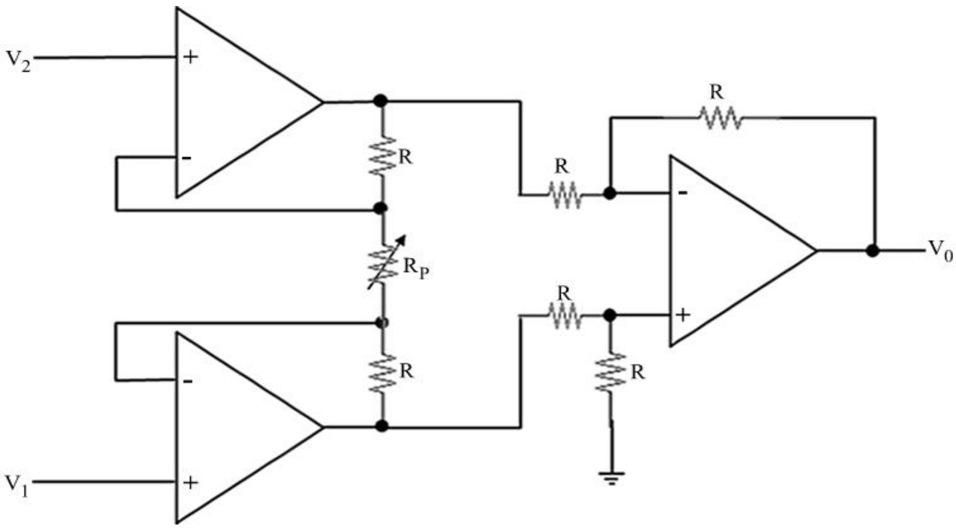


Fig 3.21 Instrumentation amplifier.

Example

Calculate the output voltage expression for the circuit of fig 3.22

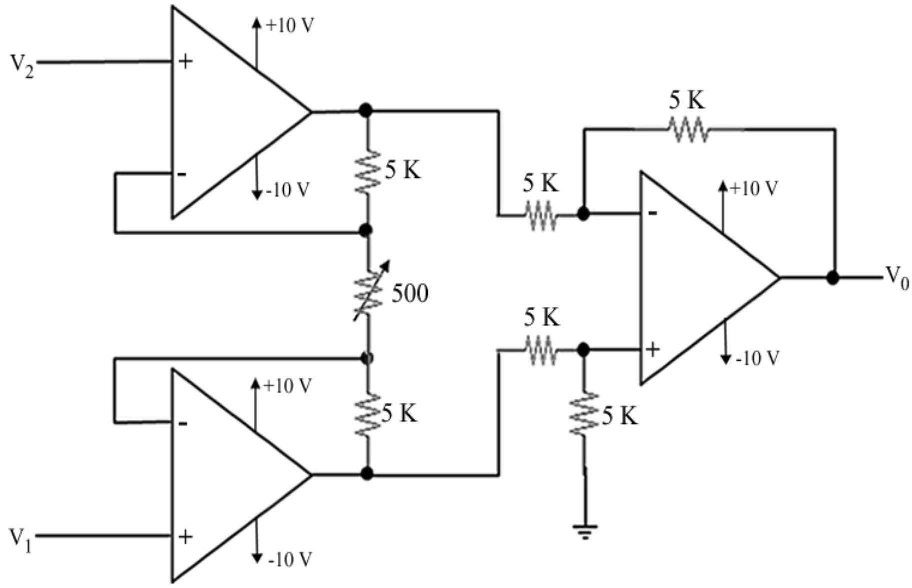


Fig 3.22

Solution

The output voltage can then be expressed using:

$$V_o = \left(1 + \frac{2R}{R_p}\right)(V_1 - V_2) = \left[1 + \frac{2(5000)}{500}\right](V_1 - V_2)$$

$$= 21(V_1 - V_2)$$

3.6 ACTIVE FILTERS

A popular application uses op-amp to build active filters. We have already discussed in Module II, about tuned amplifiers. Such amplifiers are designed to amplify only those frequencies that are within certain range. As long as the input signal is within the specified range, it will be amplified. If it goes outside of this frequency range, amplification will be drastically reduced. The tuned amplifier circuits using *OP-AMP* are generally referred to as active filters. Such circuits do not require the use of inductors. The frequency response of the circuit is determined by resistor and capacitor values.

A filter circuit can be constructed using passive components like resistors and capacitors. But an active filter, in addition to the passive components makes use of an *OP-AMP* as an amplifier. The amplifier in the active filter circuit may provide voltage amplification and signal isolation or buffering.

There are four major types of filters namely, low-pass, filter-high-pass filter, and band-pass filter and band-stop or notch filter. All these four types of filters are discussed one by one in the following pages.

3.6.1 Low-Pass Filter

A filter that provides a constant output from dc up to a cut-off frequency (f_{OH}) and then passes no signal above that frequency is called an ideal low-pass filter. The ideal response of a low-pass filter is as shown in Fig. 3.23 (*a*). Notice that the response shows that the filter has a constant output(indicated by a horizontal line AB) from dc or zero frequency up to a cut-off frequency (f_{OH})And beyond f_{OH}, the output is zero as indicated by the vertical line 'BC' in the figure.

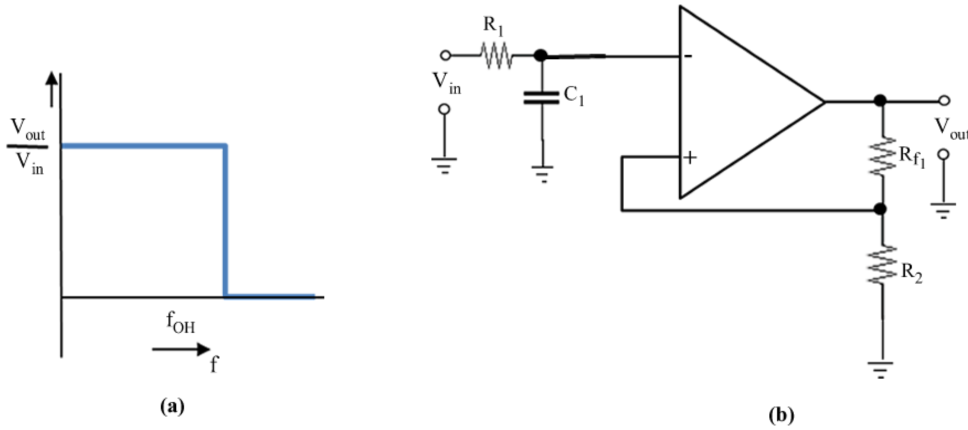
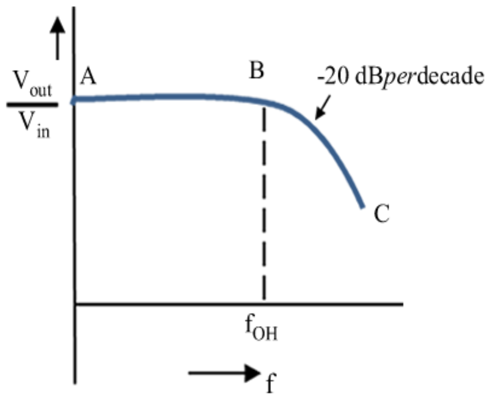


Fig. 3.23

Fig. 3.24 (*b*) shows the circuit of a low-pass active filer using a single resistor and capacitor. Such a circuit is also referred to as first-order (or single-pole)low-pass filter. It is called first-order because it makes use of a single resistor and a capacitor. The response of such a first-order low pass filter is as shown in Fig. 3.25. Notice that the response below the cut-off frequency (f_{OH}) shows a constant gain (indicated by a horizontal line



'AB')

However, beyond the cut-off frequency, the gain does not reduce immediately to zero as expected in Fig. 3.24 (*a*) but reduces with a slope of 20 dB/decade (means that the output voltage reduces by a factor of 100 when the frequency increases by a factor of 10). The voltage gain for a low-pass filter below the cut-off frequency (f_{OH}) is given by the relation.

$$A_v = 1 + \frac{R_3}{R_1}$$

And the cut-off frequency is determined by the relation

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

It is possible to connect two sections of the filter together as shown in Fig. 3.26 (*a*). Such a circuit is called second-order (or two-pole) low pass filter. Fig. 3.26 shows configuration of the second-order low-pass filter.

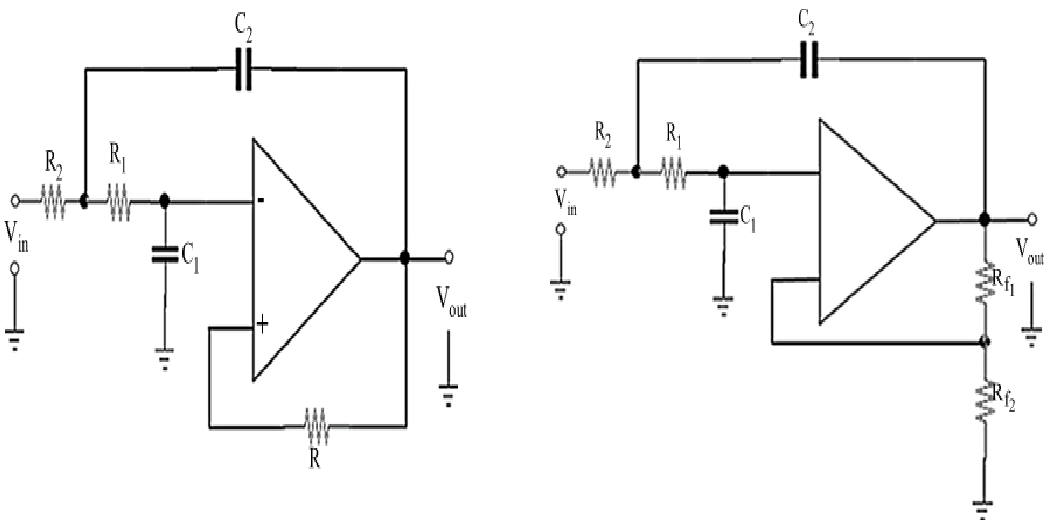


Fig. 3.26

Each circuit shown in Fig. 3.26 has two RCcircuits,$R_1 - C_1$ and $R_2 - C_2$. As the operating frequency increases beyond f_2, each circuit will be dropping the closed-loop gain by 20 dB, giving a total roll-off rate of $40\ dB/\mathrm{decade}$when operated above f_2. The cut-off frequency for each of the circuit is given by,

$$f_2 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

Example

Calculate the cut-off frequency of a first-order low-pass filter for $R_1 = 1.2\ k\Omega\ and\ C_1 = 0.02\ \mu F$.

Solution

$$f_{OH} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(1.2 \times 10^3)(0.02 \times 10^{-6})} = 6.63\ kHz$$

3.6.2 High-pass Filter

As a matter of a fact, there is very little difference between the high-pass filter and the low-pass filter. Fig. 3.27 (*a*) shows the circuit of a first order (or single-pole) high-pass filter and Fig. 3.27(*b*), the circuit of a second-order (or two-pole) high-pass filter. Notice that the only thing that has changed is the position of the capacitors and resistors. The value of cut-off frequencies f_1 *and* f_2 is obtained by using the same equations we used for low-pass filter.

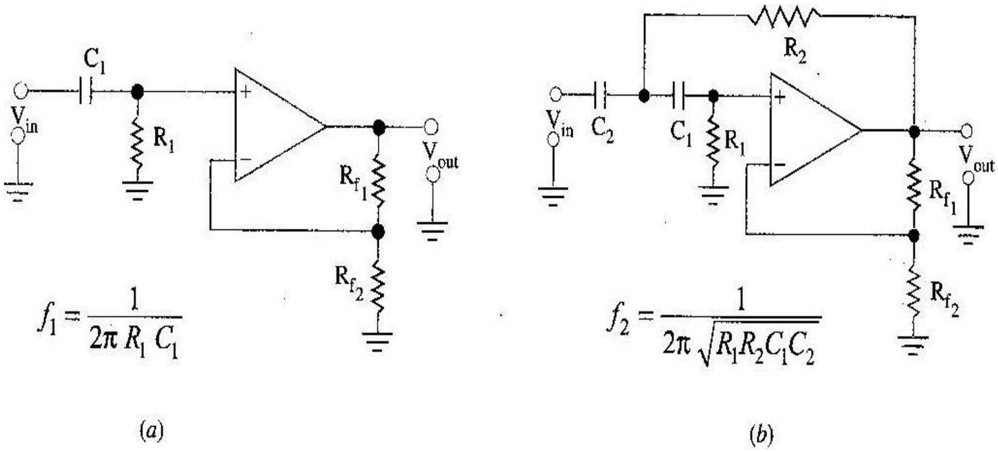


Fig. 3.27

Fig. 3.28 shows the gain versus frequency response of a high-pass filter. Notice that the solid line indicates the ideal response while the dashed line, corresponds to the actual response of the filter circuit. The ideal curve indicates that the filter has a zero output for the frequencies below f_{OL} (indicated by the line 'AB').And beyondf_{OL}, it has a constant output. The actual response curve may correspond to the roll-off gain by $20\ dB/decade$ for first order to $40\ dB/decade$ for second-order low-pass filters.

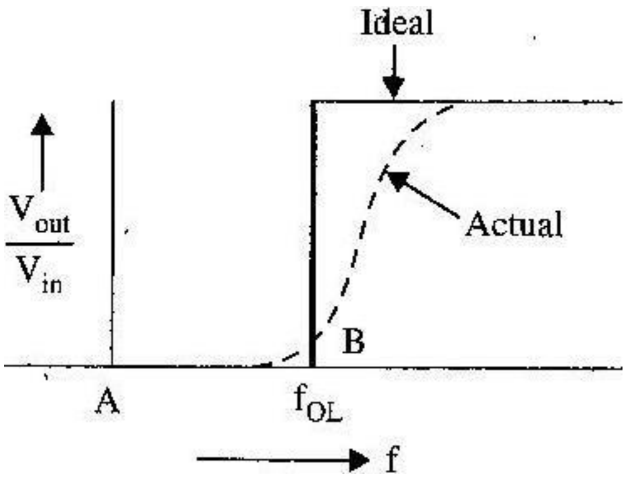


Fig. 3.28

3.6.3 Band-pass Filters

A band-pass filter is the one that is designed to pass all frequencies within its bandwidth. A simple way to construct a band-pass filter is to cascade a low-pass filters and a high-pass filter as shown in Fig. 3.29. The first stage of the band-pass filter will pass all frequencies that are below its cut-off value, f_2. All the frequencies passed by the first stage will head into the second stage. This stage will pass all frequencies above its value of f_1. The result of this circuit action is as shown in Fig 3.30.

Note that the only frequencies that all will pass through the amplifier are those that fall within the pass band of both amplifiers. The values of f_1 and f_2 can be obtained by using the relations: $1/2\pi R_1 C_1$ and $1/2\pi R_2 C_2$. Then bandwidth,

$$BW = f_2 - f_1$$

And the center frequency,

$$f_0 = f_2 . f_1$$

The Quality-factor (or Q-factor) of the band-pass filter circuit:

$$Q = \frac{f_o}{BW}$$

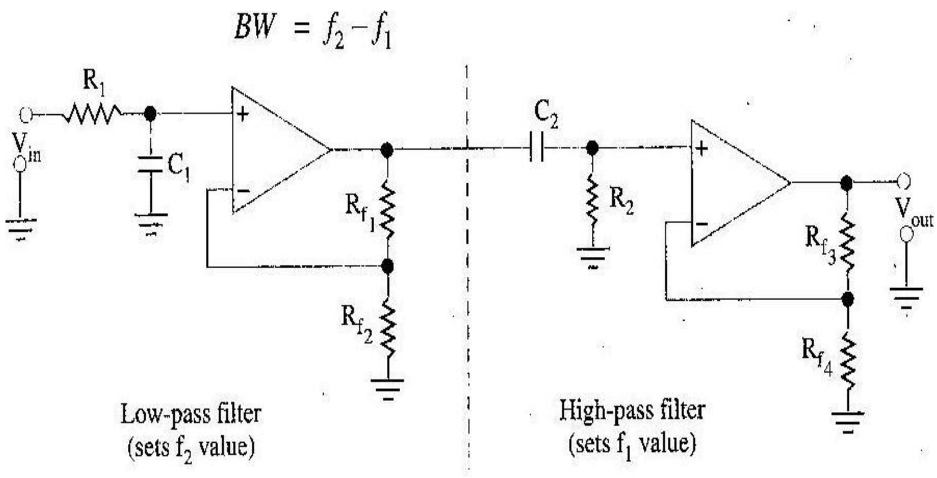


Fig. 3.29

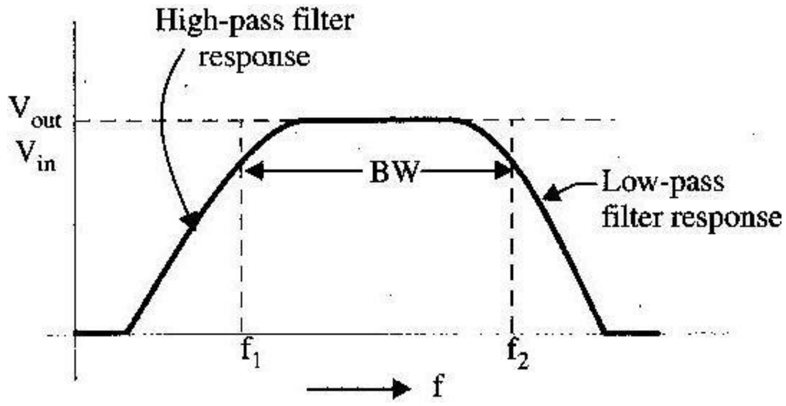


Fig. 3.30

3.6.4 Notch Filter

The notch filter is designed to block all frequencies that fall within its bandwidth Fig. 3.31(*a*) shows a block diagram and 3.31 (*b*), the gain versus frequency response curve of a multistage notch filter.

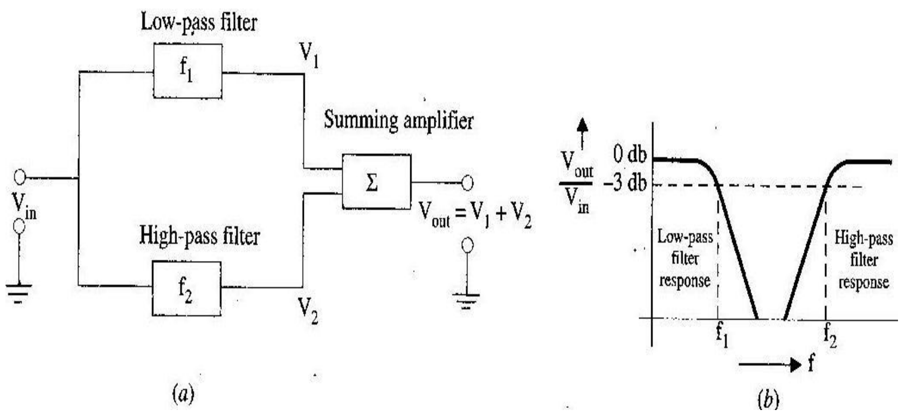


Fig. 3.31

The block diagram shows that the circuit is made up of a high-pass filter, a low-pass filter and assuming amplifier. The summing amplifier produces an output that is equal to a sum of the filter output voltages. The circuit is designed in such a way so that the cut-off frequency, f_1 (which is set by a low-pass filter) is lower in value than the cut-off frequency, f_2 (which is set by high-pass filter). The gap between the values of f_1 and f_2 is the bandwidth of the filter.

When the circuit input frequency is lower thanf_1, the input signal will pass through low-pass filter to the summing amplifier. Since the input frequency is below the cut-off frequency of the high-pass filter, v_2 will be zero. Thus the output from the summing amplifier will equal the output from the low-pass filter. When the circuit input frequency is higher thanf_2, the input signal will pass-through the high-pass filter to the summing amplifier. Since the input frequency is above the cut-off frequency of the low-pass filter,v_1 will zero. Now the summing amplifier output will equal the output from the high-pass filter.

It is evident from the above discussion that frequencies below f_1 and those above f_2, have been passed by the notch filter. But when the circuit frequency between $f_1$and f_2, neither of the filters will produce an output. Thus v_1 and v_2 will be both zero and the output from the summing amplifier will also be zero.

The frequency analysis of the notch filter is identical to the band-pass filter. First, determine the cut-off frequencies of the low-pass and the high-pass filters. Then using these calculated values, determine the bandwidth, center frequency and *Q* values of the circuit.

3.7 TEST

Question 1

Determine the output voltage for the circuit of Fig. 3.32 with a sinusoidal input of $2.5\ mV$.

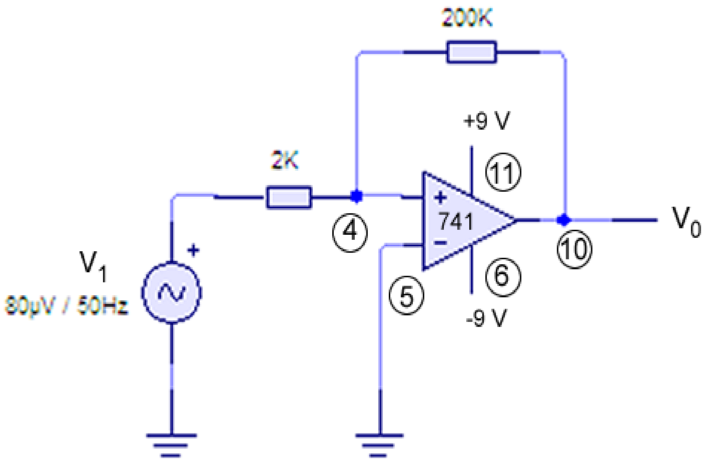


Figure 3.32

Solution

The circuit of fig 3.32 uses a 741 Op-amp to provide a constant or fixed gain,

$$A = -\frac{R_f}{R_1} = -\frac{200\ k\Omega}{2\ k\Omega} = -100$$

The output voltage is then

$$V_o = AV_i = -100(2.5\ mV) = -250\ mV = \mathbf{-0.25\ V}$$

Question 2

Show the connection for a $LM\ 124$ quad op-amp as a three-stage amplifier with gain of $+10, -18, and - 27$. Use a $270\ k\Omega$ feedback resistor for all three circuits. What output voltage will result for an input of $150\ \mu$V?

Solution

For the gain of $+10$:

$$A_1 = 1 + \frac{R_f}{R_1} = +10$$

$$\frac{R_f}{R_1} = 10 - 1 = 9$$

$$R_1 = \frac{R_f}{9} = \frac{270\ k\Omega}{9} = 30\ k\Omega$$

For the gain of -18

$$A_2 = 1 + \frac{R_f}{R_2} = -18$$

$$R_2 = \frac{R_f}{18} = \frac{270\ k\Omega}{18} = 15\ k\Omega$$

For the gain of -27

$$A_3 = 1 + \frac{R_f}{R_3} = -27$$

$$R_3 = \frac{R_f}{27} = \frac{270\ k\Omega}{27} = 10\ k\Omega$$

The circuit showing the pin connections and all components used is in fig 3.33. For an input of $V_1 = 150\ \mu V$, the output voltage will be

$$V_o = A_1 A_2 A_3 V_1 = (10)(-18)(-27)(150\ \mu V) = 4860(150\ \mu V)$$

$$= \mathbf{0.729\ V}$$

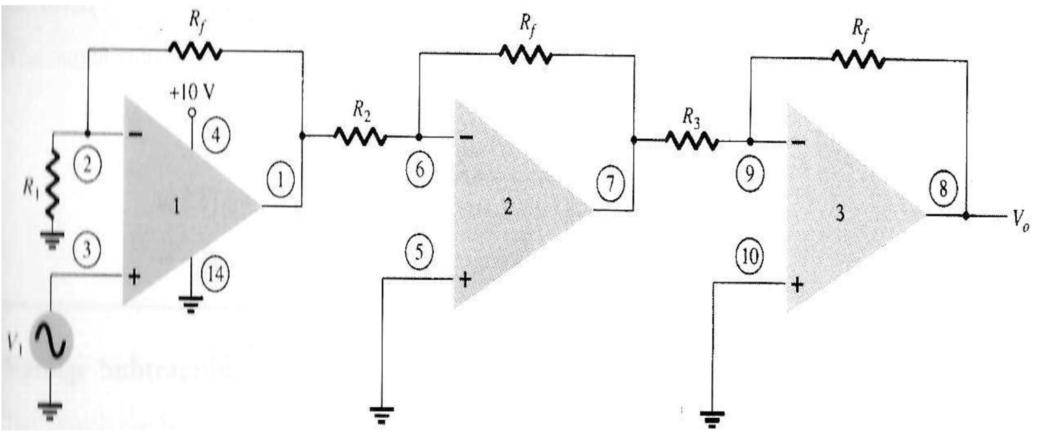


Fig 15.6

4.0 CONCLUSION

This unit has introduced you to the basic operation of an operational amplifier and also treated the various applications of the op-amp.

5.0 SUMMARY

The Operational Amplifier is a very popular active device due to the fact that it is relatively easy to tailor to fit any particular application. Hence, many ICs contain various connection modes of op-amp which has been fabricated for flexible connections making it very versatile in many applications.

The operational amplifier or op-amp is a very high gain amplifier having a very high input impedance and low output impedance (less than 10 Ω). The basic circuit is made using a difference amplifier having two inputs (plus (+) and minus (-)) and at least one output.

6.0 TUTOR-MARKED ASSINGMENT

1. Calculate the output voltage of the circuit of fig. 3.34 for input of $150\ mV\ rms$.

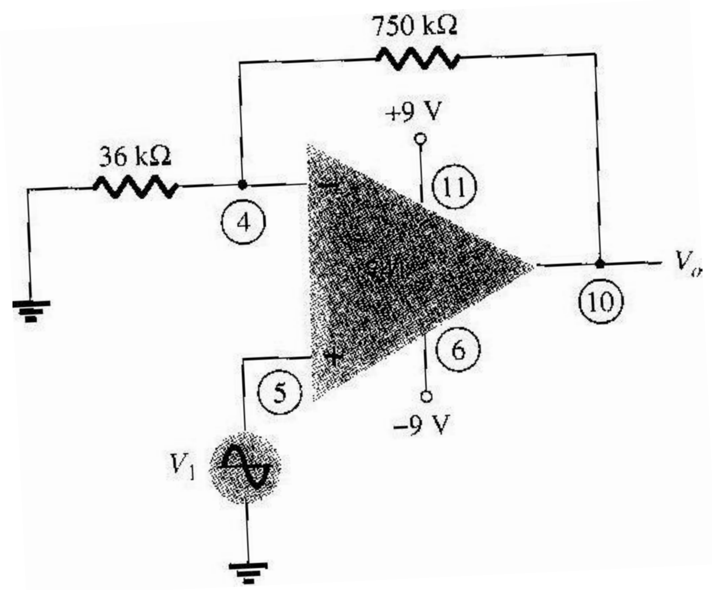


Fig. 3.34

2. Show the connection of two op-amp stages using an $LM358\ IC$ to provide outputs that are 15 and -30 times larger than the input. Use feedback resistor,$R_f = 150\ k\Omega$ in all stages.

3. Determine the output voltage for the circuit of fig 3.35.

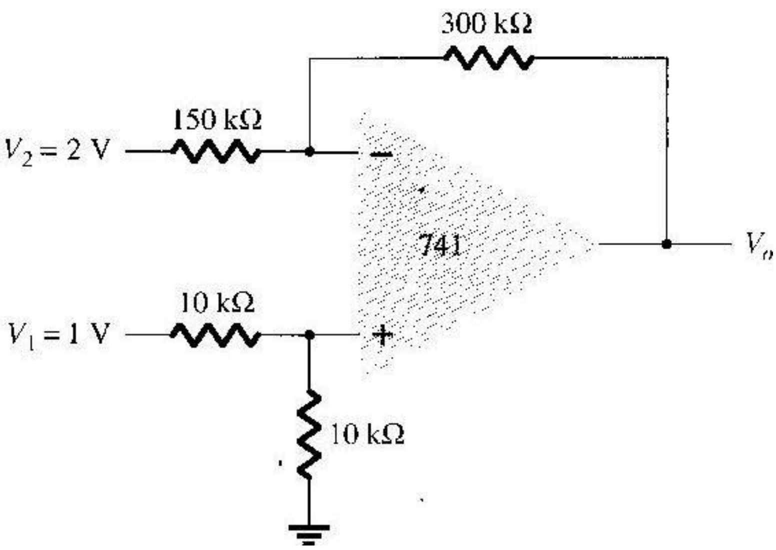


Fig 3.35

4. Show the connection (including pin information) of LM124 IC stage connected as a unity-gain amplifier.

5. For the circuit of fig 3.36,calculate I_L.

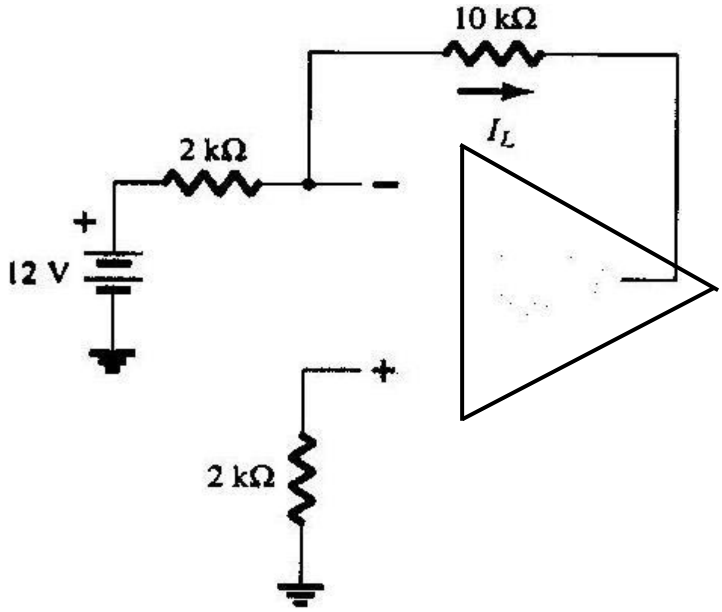


Fig 3.36

6. Calculate the cutoff frequency of the high-pass filter circuit in fig 3.37.

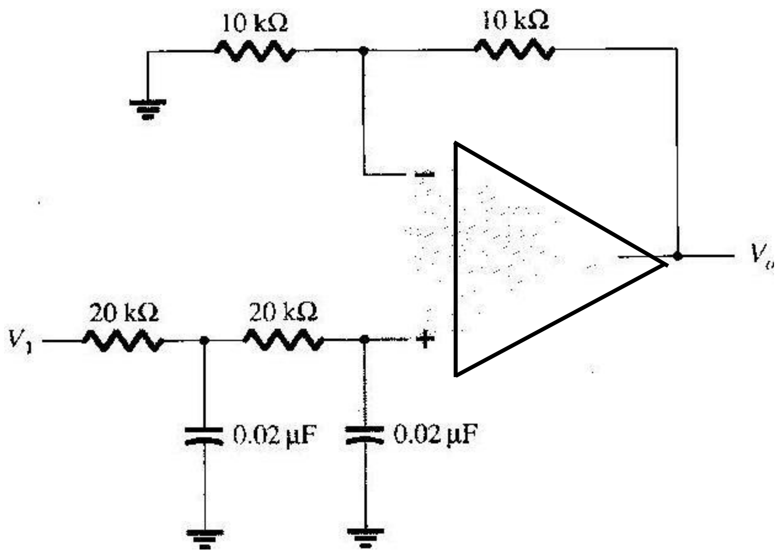


Fig 3.37

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UNIT 3 REGULATION OF OUTPUT VOLTAGE

CONTENTS

1.0 INTRODUCTION

The various power-supply circuits considered in the previous unit suffer from the drawback that their dc output voltage changes with changes in load or input voltage. Such a dc power supply is called unregulated power supply. Regulated power supply can be obtained by using a voltage regulator circuit. A regulator is an electronic control circuit which is capable of providing a nearly constant dc output voltage even when there are variations in load or input voltage. A source of regulated dc power is essential for all communication, instrumentation, computers or any other electronic system.

We will consider both ***linear*** regulators and ***switching*** regulators which are also available in integrated circuit form. In linear regulators, the transistor operates somewhere between saturation and cut-off. It is always ON and dissipates power. Hence, its efficiency (output power/input power)is 50 per cent or less. In switching regulators, the transistor operates like a switch *i.e.* it is either saturated or cut-off. Hence, its power efficiency is 90 per cent or more.

The linear regulators are of two basic type *i.e.* series regulators and shunt regulators. Likewise switching regulators can be of three basic types **(*i*)** step-down type, **(*ii*)** step-up type and **(*iii*)** inverting type.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- Understand the function of Voltage regulators and the effect in a dc supply unit.
- Know the various types of voltage regulators.
- Know the application and forms of voltage regulators.
- Solve related problems

3.0 MAIN CONTENT

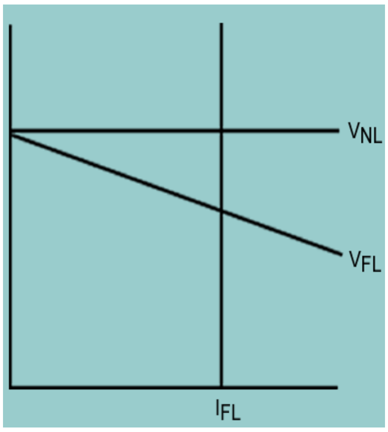
3.1 Voltage Regulation

As stated above, in an unregulated power supply, output voltage changes whenever input supply voltage or load resistance changes. It is never constant. The change in voltage from no-load to full-load condition is called ***voltage regulation***. The aim of a voltage regulator circuit is to reduce these variations to zero or, at least, to the minimum possible value.

The percentage regulation or, simply, regulation of a power supply is given by

$$\%\, regulation = \frac{V_{max} - V_{min}}{V_{max}} \times 100$$

minimum dc output voltage.



When we say that $10\ V$ regulated dc power supply has a regulation of 0.005 per cent, it means that dc output voltage will vary within an envelope 0.005 per cent of $10\ V$.

Now, $0.005\%\ of\ 10\ V = \frac{0.005 \times 10}{100}$

$$= 0.0005\ V = 0.5\ mV$$

Hence, output voltage will vary by $\pm\ 0.25\ mV$. So, we see that instead of expressing voltage regulation by unwieldy expression 0.005 per cent, we can express it by a simple figure of $\pm\ 0.25\ mV$.

In general, $\%\, regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$

where, V_{NL} = no-load or open-circuit terminal voltage of the supply

V_{FL} = full-load terminal voltage of the supply

In an ideal or perfectly regulated dc power supply, the percentage voltage regulation is zero.

This voltage regulation is also called ***load regulation.***

3.2 Zener Diode Shunt Regulator

A simple shunt voltage regulating system using a Zener diode is shown in Fig. 3.1. The input voltage V_{in}, in fact, is the unregulated output of a rectifier. This simple regulator restricts output voltage variations within reasonable limits around V_z in the face of changing load current or changing input voltage. Obviously, the Zener diode will regulate so long as it is kept in reverse conduction.

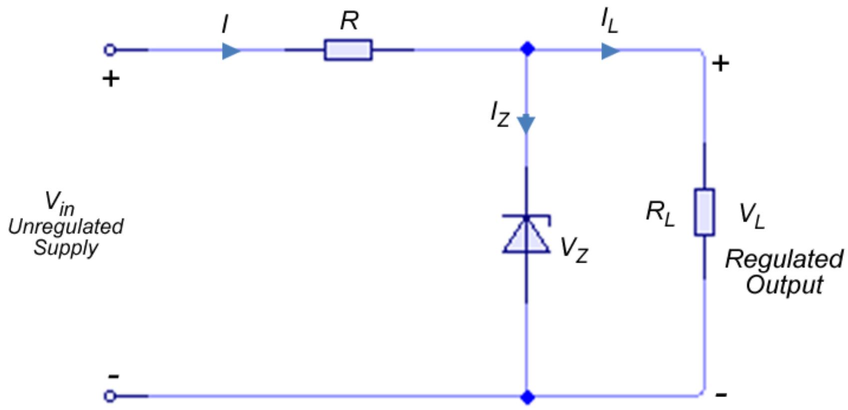


Fig. 3.1

Example *The Zener diode ofFig. 56.2 has the following ratings:*

$V_z = 6.8\ V \quad at \quad I_z = 50\ mA$

$r_z = 2\ \Omega \quad at \quad I_z = 50\ mA$

$I_{z(min)} = 5\ mA \qquad I_{z(max)} = 150\ mA$

What would be the load voltage when load current IL varies from 10 mA to 120 mA? Also, calculate voltage regulation of the regulator.

Solution. We will call $V_z = 6.8\ V$ and $I_z = 50\ mA$ as reference values and calculate changes in voltage with respect to these values.

(i) $\boldsymbol{I_L = 120\ mA}$

Obviously, $I_z = 150 - 120 = 30\,mA$

Deviation from 50 mA $= 30 - 50 = -20\,mA$

Drops across diode $= I_z.r_z = -20 \times 2 = -40\,mV$

$$V_L = V_z + I_z.r_z = 6.8 + (-40 \times 10^{-3}) = \mathbf{6.76\,V}$$

(*ii*) $\boldsymbol{I_L = 10\,mA}$

Now, $I_z = 150 - 10 = 140\,mA$

Deviation from reference value$= 140 - 50 = 90\,m$A

Diode drop $= I_z r_z = 90 \times 10^{-3} \times 2 = 0.18\,V$

$$V_L = V_z + I_z r_z = 6.8 + 0.18 = \mathbf{6.98\,V}$$

$$\%\,regulation = \frac{6.98 - 6.76}{6.98} \times 100 = 3.15\,\%$$

For many applications, a change in load voltage of 3.15% is acceptable but, in some, it may be intolerable. This regulation can be reduced to 1% or less with the help of circuits discussed below.

3.3 Transistor Series Voltage Regulator

The circuit is shown in Fig. 3.2. It is also called ***emitter-follower*** regulator because the voltage at the emitter follows the base voltage.

In this set-up, the transistor behaves like a variable resistor whose resistance is determined by the base current. It is called ***pass*** transistor because total current to be regulated passes through it.

Keeping in mind the polarities of different voltages, they are related by the equation derived from *KVL*

$$V_L + V_{BE} - V_z = 0$$

$$\therefore \quad V_{BE} = V_z - V_L$$

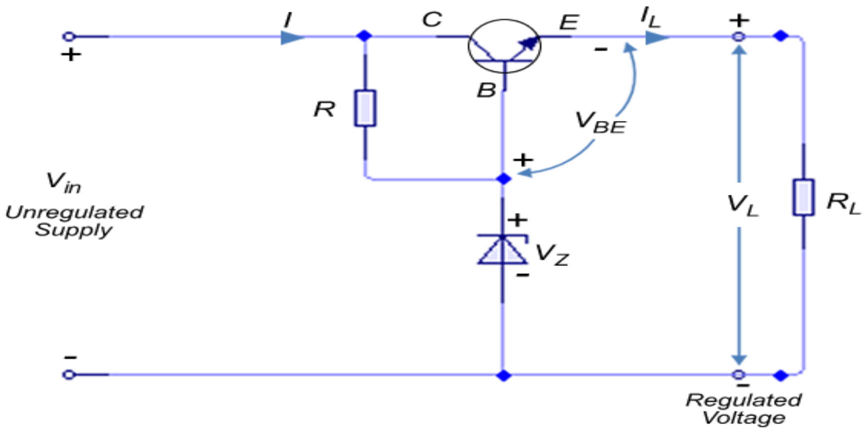


Fig. 3.2

When current demand is increased by decreasing R_L, V_L tends to decrease. As seen from the above equation, it will increase V_{BE} because V_z is fixed. This will increase forward bias of the transistor thereby increasing its level of conduction. This, is turn, will lead to decrease in the collector-emitter resistance of the transistor which will slightly increase the input current in order to compensate for decrease in R_L so that $V_L = (I_L R_R)$ will remain at a constant value. Incidentally, R is used for limiting current passing through the Zener diode.

3.4 Controlled Transistor Series Regulator

The circuit employing a second transistor T_2 as a sensing element is shown in Fig. 3.3. It has the additional feature of control with the help of potentiometer $R_1 - R_2$. In the discussion to follow, it will be assumed that I is much greater than I_{B2}. Now, there is a drop of V_L on $(R_1 + R_2)$ and a drop of $(V_z + V_{BE2})$ across R_2.

$$\frac{V_L}{V_z + V_{BE2}} = \frac{R_1 + R_2}{R_2} \qquad or \qquad V_L = \frac{R_1 + R_2}{R_2}(V_z + V_{BE2})$$

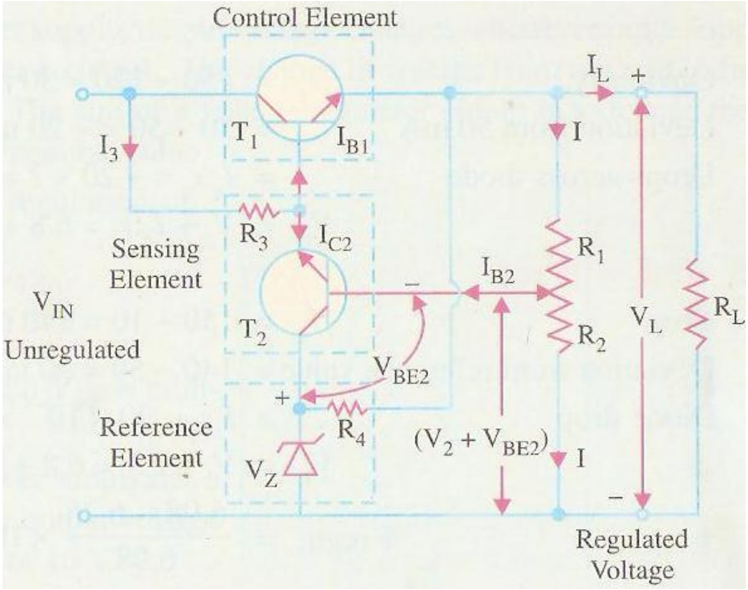


Fig. 3.3

Now, $(R_1 + R_2)$and $(V_z + V_{BE2})$both have constant values so that $V_L \propto 1/R_2$.

If the potentiometer is adjusted so thatR_2 decreases, then V_L increases and *vice versa*.

Suppose $R_L$is decreased, then, $I_L$increases but $V_L$decreases. Decrease in $V_L$decreases $I_{B2}$and I_{C2}. AssumingI_3 to be relatively constant (or decreasing only slightly), I_{B1} is increased thereby decreasing the terminal (collector-emitter) resistance of T_1. This leads to decrease in V_{CE1} thereby offsetting the decrease in $V_L$which is, therefore, returned to its original value.

In sequential logic, we have

$V_L \downarrow$ $\quad$ $I_{B2} \downarrow$ $\quad$ $I_{C2} \downarrow$ $\quad$ $I_{B1} \uparrow$ $\quad$ $V_{CE1} \downarrow$ $V_2 \uparrow$

3.5 Transistor Shunt Voltage Regulator

It employs the transistor in shunt configuration as shown in Fig. 3.4.

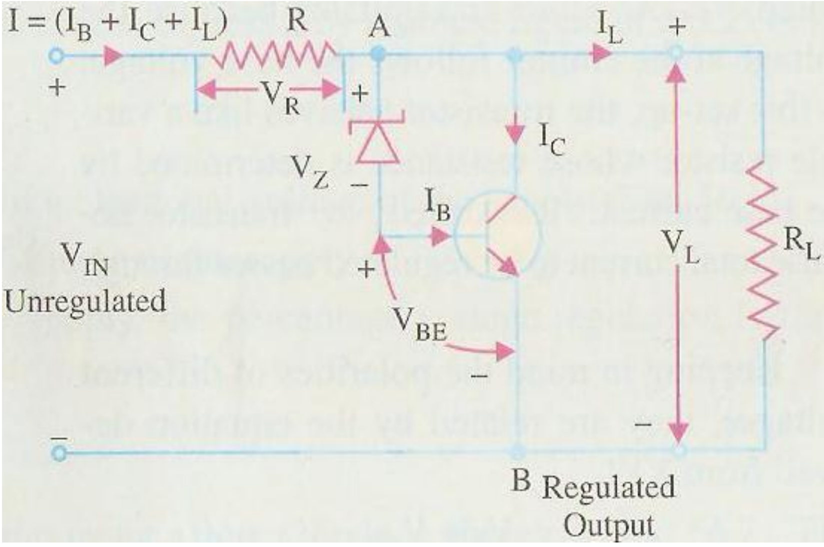


Fig. 3.4

Since path *AB* is in parallel across *VL*, we have from Kirchhoff's Voltage Law

$$V_L - V_z - V_{BE} = 0$$

or $$V_{BE} = V_L - V_z \ (fixed)$$

Since V_z is fixed, any decrease or increase in V_L will have a corresponding effect on V_{BE} Suppose, V_L decreases, then as seen from the above relation, V_{BE} also decreases. As a result, I_B decreases, hence, $I_C\ (= \beta I_B)$ decreases, thereby decreasing I and hence $V_R\ (= IR)$. Consequently, V_L increases because at all times

$$V_{in} = V_R + V_L \ or \quad V_L = V_{in} - V_R$$

In sequential logic,

$V_z\downarrow$ $V_{BE}\downarrow$ $I_B\downarrow$ $I_C\downarrow$ $I_R\downarrow$ $V_R\downarrow$
$V_L\uparrow$

Same line of logic applies in case V_L tries to increase.

3.6 Transistor Current Regulator

The main function of a current regulator is to maintain a fixed current through the load despite variations in the terminal voltage. Such a circuit employing a Zener diode and a PNP transistor is shown in Fig. 3.5. Suppose, due to drop in V_L, current $I_L\ (= I_C)$ is decreased. This will decrease $I_E\ (\cong I_C)$. Hence, drop across R_E i.e. V_{RE} will decrease. As per Kirchhoff's Voltage Law

$$-V_{RE} - V_{BE} + V_z = 0 \quad or \quad V_{BE} = V_z - V_{RE}$$

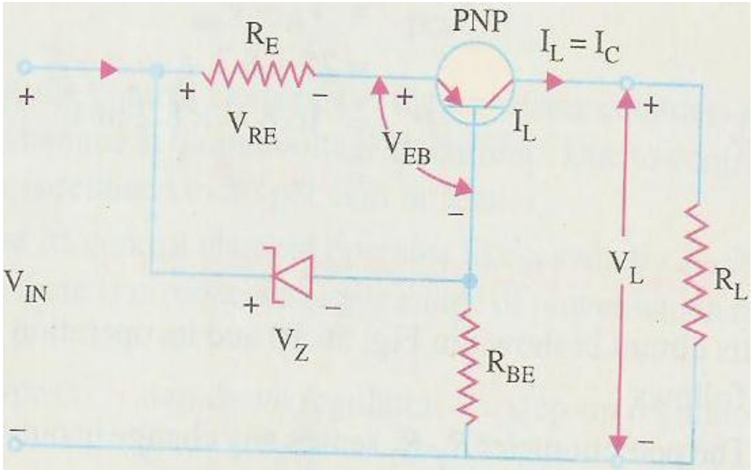


Fig. 3.5

Hence, a decrease in V_{RE} will increase V_{BE} and, hence, the conductivity of the transistor thereby keeping I_L at a fixed level.

A similar logic applies when there is increase in V_L.

3.7 Variable Feedback Regulator

The regulators considered so far provide a non-adjustable output voltage. This would be fine if only single value of regulated voltage is required. Fig. 3.6 shows a feedback regulator which provides different values of regulated dc voltage. In Fig. 3.6, T_1 is the pass transistor and T_2 is the feedback transistor whose job is to provide ands ample output (*i.e.* load) voltage. It offsets any change in the output voltage. Since potentiometer R_3 is connected in parallel with Zener diode D, it has Zener voltage V_z applied across it. Voltage across the wiper varies from 0 to V_z. Capacitor C ensures that voltage across D and R_3 does not change suddenly.

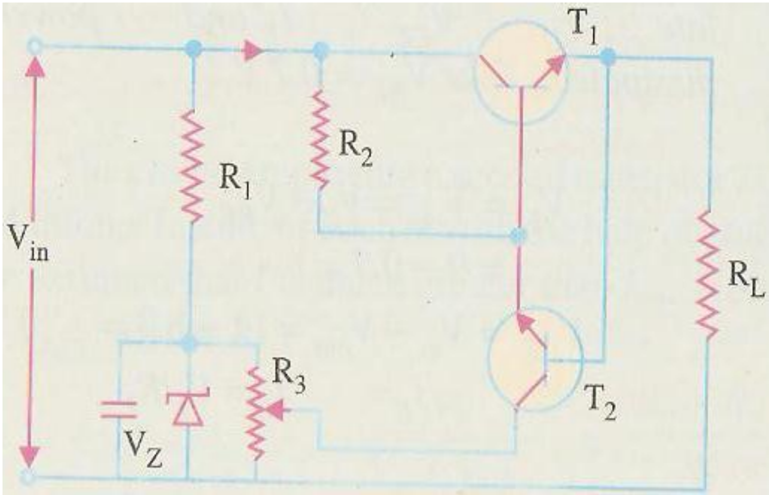


Fig. 3.6

Voltage at the base of T_2 is $0.7\ V$ more positive than the voltage at its emitter. Its emitter voltage and hence the base voltage can be changed with the help of R_3. Since base of T_2 is tied to the output, it is responsible for providing output or load voltage. The voltage V_{CE1} across the pass transistor is given by the difference of input voltage and output voltage. The current through T_1 is equal to the load current. $R2$ prevents saturation of transistors whereas $R1$ limits the current flowing through D.

The working of feedback transistor can be explained as follows:

Since base voltage of T_2 is directly related to V_{out} it will change if V_{out} changes. The base and collector of T_2 are 180^0 out of phase with each other. If base voltage increases due to increase in V_{out} collector voltage would decrease. Now, collector of T_2 controls base of T_2. As the base voltage of $T1$decreases, its collector-emitter resistance increases which lowers the load current. This, in turn, lowers the output voltage thereby offsetting the attempted increases in V_{out}. The opposite of these steps provides the action of an attempted decrease in output voltage.

Example

In the variable feedback regulator circuit of Fig. 3.5, $V_{in} = 25\ V, V_z = 15\ V$ *and*

$R_L = 1\ K$. *If the wiper of* R_3 *is adjusted half-way and assuming silicon transistor, compute*

(i) V_{out}
(ii) I_L
(iii) I_{E1}
(iv) P_1

Solution

(i) $V_{out} = voltage\ at\ wiper + V_{BE2} = (15/2) + 0.7 = \mathbf{8.2\ V}$

(ii) $I_L = V_{out}/R_L = 8.2\ V/1\ K = \mathbf{8.2\ mA}$

(iii) $I_{E1} = I_L = \mathbf{8.2\ mA}$

(iv) $V_{CE1} = V_{in} - V_{out}$

$= 25 - 8.2 = \mathbf{16.8\ V}$

$\therefore P_1 = 16.8\ V \times 8.2\ mA$

$= \mathbf{140\ mW}$

3.8 Basic Op-amp Series Regulator

Its circuit is shown in Fig. 3.7 and its operations as follows:

The potentiometer $R_2 - R_3$ senses any change in out-put voltage V_{out}. When V_{out} attempts to decrease because of decrease in V_{in} or because of the increase in I_L, a proportional voltage decrease is applied to the inverting output of the op-amp by the potentiometer. Since, the other op-amp input is held by the Zener voltage at a fixed reference voltage V_{REF}, a small difference voltage (called error voltage) is developed across the two inputs of the op-amp. This difference voltage is amplified and op-amp's output voltage increases. This increase in voltage is applied to the base of T_1 causing the emitter voltage $(= V_{out})$ to increase till the voltage to the inverting input again equals the reference (Zener) voltage. This action offsets attempted decrease in the output voltage thus keeping it almost constant. The opposite action occurs if the output voltage tries to increase.

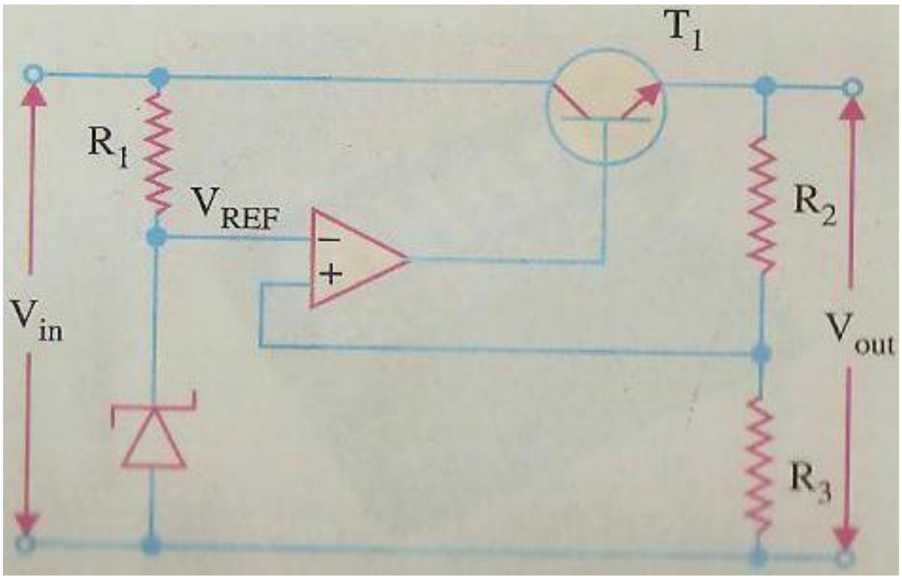


Fig. 3.7

Calculations

It will be seen that the op-amp of Fig. 3.7 is actually connected as a non-inverting amplifier where V_{REF} is the input at the non-inverting terminal and the R_2/R_3 voltage divider forms the negative feed-back network. The closed-loop voltage gain is given by $A = 1 + (R_2/R_3)$. Neglecting base-emitter voltage of T_1, we get

$$V_{out} = V_{REF}\ (1 + R_2/R_3)$$

It is seen that V_{out} depends on Zener voltage and potential divider resistors R_2 and R_3 but is independent of input voltage V_{in}.

3.9 Basic Op-amp Shunt Regulator

Such a shunt type linear regulator is shown in Fig. 3.8. Here, the control element is a series resistor R_1 and a transistor T_1 in parallel with the load. In such a regulator, regulation is achieved by controlling the current through T_1.

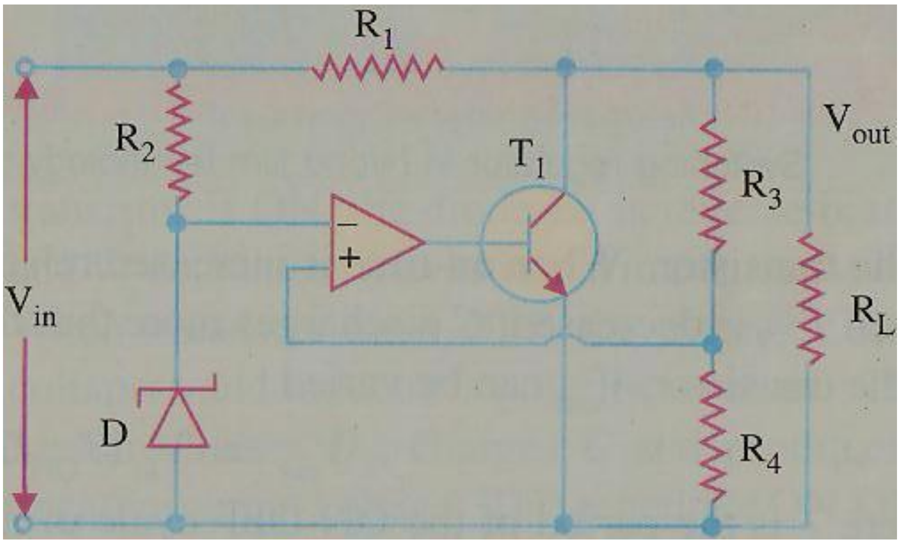


Fig. 3.8

Working

When output voltage tries to decrease due to change in either the input voltage or load current or temperature, the attempted decrease is sensed by R_3 and $R_4$and applied to the non-inverting input of the op-amp. The resulting difference in voltage reduces the op-amp's output, driving T_1 less thus reducing its collector current(shunt current), and increasing its collector-to-emitter resistance. Since collector-to-emitter resistance acts as a voltage divider with R_1, this action offsets the attempted decrease in output voltage and hence, maintains it at a constant value. The opposite action occurs when output voltage tries to increase. The shunt regulator is less efficient than the series type but offers inherent short-circuit protection.

3.10 Switching Regulators

In the linear regulators considered so far, the control element *i.e.* the transistor conducts all the time, the amount of conduction varying with changes in output voltage or current. Due to continuous power loss, the efficiency of such a regulator is reduced to $50\ per\ cent$ or less.

A switching regulator is different because its control element operates like a switch *i.e.* either it is saturated (closed) or cut-off (open). Hence, there is no unnecessary wastage of power which results in higher efficiency of 90% or more.

Switching regulators are of three basic types:

(i) Step-down regulator
(ii) Step-up regulator and
(iii) Inverting regulator.

3.10.1 Step-down Switching Regulator

In this regulator (Fig. 3.9), V_{out} is always less than V_{in}. An unregulated positive dc voltage is applied to the collector of the NPN transistor. A series of pulses from an oscillator is sent to the base of transistor T which gets saturated(closed) on each of the positive pulses. It is so because an NPN transistor needs a positive voltage pulse on its base in order to turn ON. A saturated transistor acts as a closed switch, hence it allows V_{in} to send current through L and charge C to the value of output voltage during the on-time (T_{ON}) of the pulse. The diode D_1 is reverse-biased at this point and hence, does not conduct.

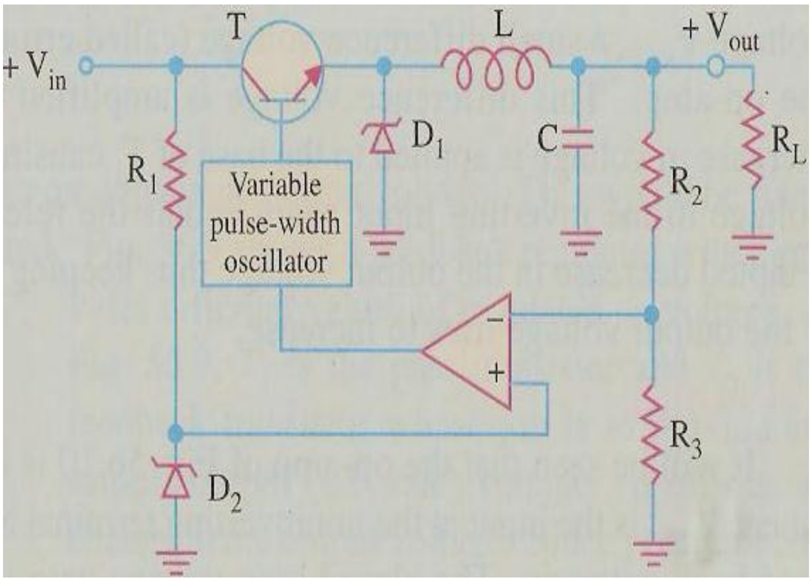


Fig. 3.9

Eventually when positive pulse turns to zero, T is cut-off and acts like an open switch during the off period (T_{OFF}) of the pulse. The collapsing magnetic field of the coil produces self-induced voltage and keeps the current flowing by returning energy to the circuit.

The value of output voltage depends on input voltage and pulse width *i.e.* on-time of the transistor. When on-time is increased relative to off-time, *C* charges more thus increasing V_{out}.When T_{ON} is decreased, C discharges more thus decreasing V_{out}. By adjusting the duty cycle (T_{ON}/T) of the transistor, V_{out} can be varied.

$$\therefore V_{out} = V_{in}\,(T_{ON}/T)$$

where T is the period of the $ON - OFF$ cycle of the transistor and is related to frequency by $T = 1/f$.

Also, $T = T_{ON} + T_{OFF}$ and the ratio $(T_{ON}/T)$is called the ***duty cycle.***

The regulating action of the circuit is as follows:

When V_{out}tries to decrease, on-time of the transistor is increased causing an additional charge on the capacitor $C$to offset the attempted decrease. When V_{out}tries to increase, T_{ON} of the transistor is decreased causing $C$to discharge enough to offset the attempted increase.

3.10.2 Step-up Switching Regulator

The circuit is shown in Fig. 3.10. When transistor Tturns ON on the arrival of the positive pulse at its base, voltage across L increases quickly to$V_{out} - V_{CE(sat)}$ and magnetic field of L expands quickly. During on-time of the transistor,V_L keeps decreasing from its initial maximum value. The longer transistor is ON, the smaller V_L becomes.

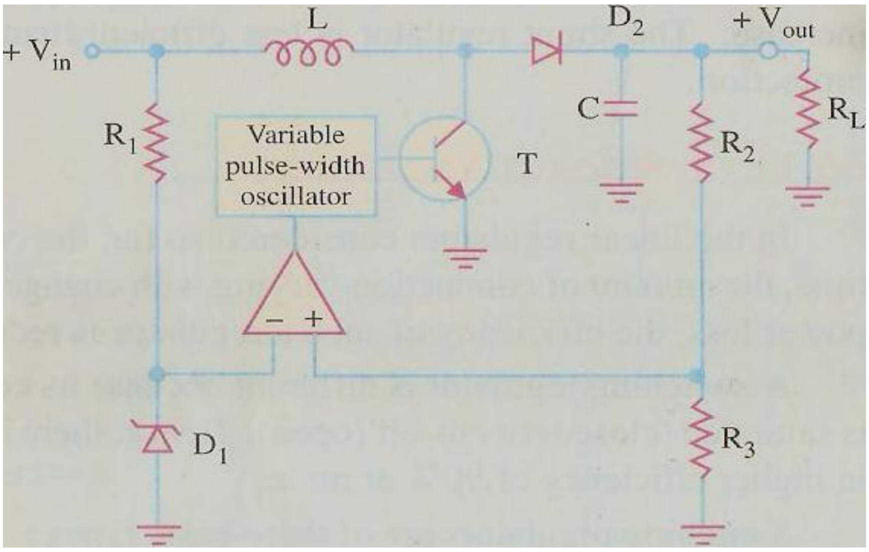


Fig. 3.10

When transistor turns OFF, magnetic field of Lcollapses and its polarity reverses so that its voltage adds to the input voltage thus producing an output voltage greater than the input voltage. During off-time of the transistor, D_2 is forward-biased and allows $C$to charge. The variations in V_{out}due to charging and discharging action are sufficiently smoothed by filtering action of $L$and C.

It may be noted that shorter the on-time of the transistor, greater the inductor voltage and hence greater the output voltage (because greater $V_L$adds toV_{in}). On the other hand, the longer the on-time, the smaller the inductor voltage and hence, lesser the output voltage (because smaller V_L adds to V_{in}).

The regulating action can be understood as follows:

When V_{out} tries to decrease (because of either increasing load or decreasing V_{in}), transistor on time decreases thereby offsetting attempted decrease in V_{out}. When V_{out} tries to increase, on-time increases and attempted increase in V_{out} is offset.

As seen, the output voltage is inversely related to the duty cycle.

$$\therefore \quad V_{out} = V_{in}\,(T/T_{ON})$$

3.10.3 Inverting Switching Regulator

The basic diagram of such a regulator is shown in Fig. 3.11. This regulator provides an output voltage that is opposite in polarity to the input voltage.

When transistor T turns ON by the positive pulse, the inductor voltage V_L jumps to $V_{in} - V_{CE(sat)}$ and the magnetic field of the inductor expands rapidly. When transistor is ON, the diode D_2 is reverse-biased and V_L decreases from its initial maximum value.

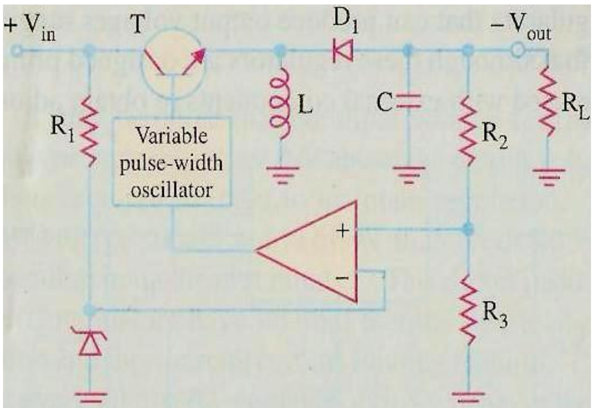


Fig. 3.11

When transistor turns OFF, the magnetic field collapses and inductor's polarity reverses. This forward-biases D_2, charges C and produces a negative output voltage. This repetitive $ON - OFF$ action of the transistor produces a repetitive charging and discharging that is smoothed by LC filter action. As in the case of a step-up regulator, lesser the time for which transistor is ON, greater the output voltage and vice versa.

3.11 TEST

Question 1

In the NPN emitter-follower regulator circuit of fig 3.12, calculate

(i) V_L

(ii) V_{CE}

(iii) I_E and

(iv) Power dissipated. Take V_{BE} = 0.7 V.

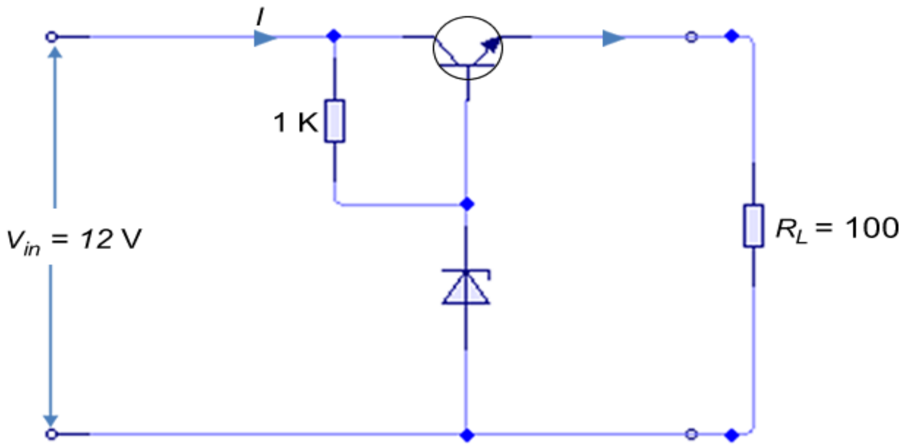


Fig 3.12

Solution

(i) $V_L = V_{out} = V_Z - V_{BE}$

$= 9 - 0.7 = \mathbf{8.3\ V}$

(ii) $V_{CE} = V_{in} - V_{out} = 12 - 8.3 = \mathbf{3.7\ V}$

(iii) $I_E = I_L = \frac{V_L}{R_L}$

$= \frac{8.3}{100} = \mathbf{83\ mA}$

(iv) Power dissipated $= V_{CE} I_E$

$= 3.7\ V \times 83\ mA = \mathbf{310\ mW}$

Question 2

Compute the output voltage V_{out} for the op-amp series regulator shown in

Fig 3.13

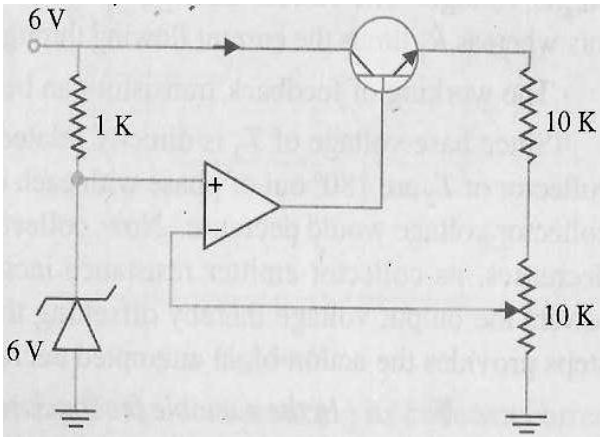


Fig 3.13

Solution

We are given that $V_{REF} = 6\,V \quad and\, R_2 = R_3 = 1\,K$

$$V_{out} = V_{REF}(1 + \frac{R_2}{R_3})$$

$$= 6(1 + \frac{10}{10})$$

$$= 6 \times 2 = 12\,V$$

4.0 CONCLUSION

This unit has introduced to the basic types of voltage regulators and their respective operations as they are capable of providing a nearly constant dc output voltage even when there are variations in load or input voltage.

5.0 SUMMARY

The various voltage regulator circuits has brought about a tremendous solution to the major draw-back of the unregulated power supply and it has made it possible to obtain a stable or nearly constant dc output voltage even when there are variations in load or input voltage. A regulated dc power supply is essential for sensitive electronic systems used in communication, instrumentation, computers and many other areas.

6.0 TUTOR-MARKED ASSIGNMENT

1. The Zener diode of Fig. 3.14 has the following ratings:

$V_z = 15\,V$ at $I_z = 17\,mA$

$r_z = 14\,\Omega$ at $I_z = 17\,mA$

$I_{z(min)} = 0.25\,mA$ $I_{z(max)} = 66\,mA$

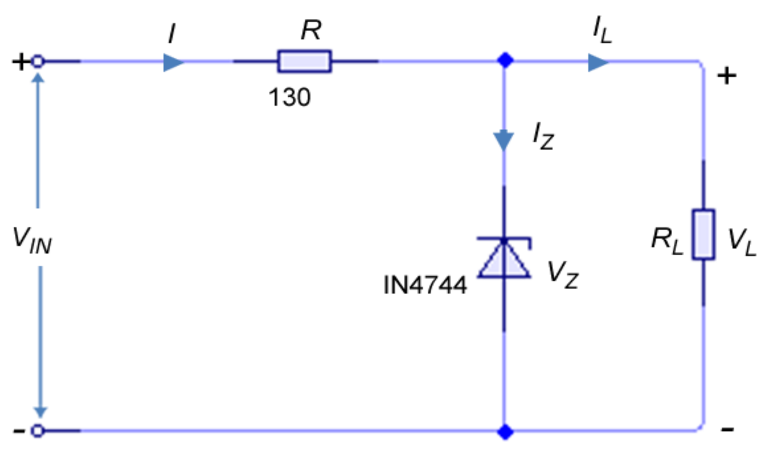


Fig. 3.14

What would be the load voltage when load current IL varies from 1 mA to 60 mA. Also calculate the voltage regulation of the regulator.

2. Determine the output voltage, V_{out} for the op-amp series regulator shown in Fig. 3.15.

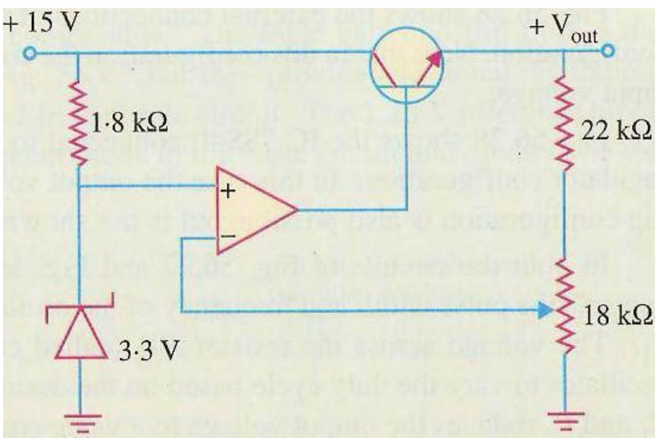


Fig. 3.15

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UNIT 4 VOLTAGE REGULATORS

CONTENTS

1.0 INTRODUCTION

Due to low-cost fabrication technique, many commercial integrated-circuit (*IC*) regulators are available since the past two decades. These include fairly simple, fixed-voltage types of high-quality precision regulators. These *IC* regulators have much improved performance as compared to those made from discrete components. They have a number of unique build-in features such as current limiting, self-protection against over-temperature, and remote control operation over a wide range of input voltages and fold-back current limiting.

2.0 OBJECTIVES

By the end of this unit, you should be able to:

- Know the various type of voltage regulator ICs and their respective functions.
- Know the connection modes with regard to the pins.
- Identify the voltage regulator IC series.

3.0 MAIN CONTENT

Voltage regulators comprise a class of widely used ICs. Regulator IC units contain the circuitry for reference source, comparator amplifier, control device, and overload protection all in a single IC. Although the internal construction of the IC is somewhat different from that of the discrete voltage regulator circuits, the external operation is much the same. IC units provide regulation of a fixed positive voltage, a fixed negative voltage or an adjustable set voltage.

A power supply can be built using a transformer connected to the ac supply line to step the ac voltage to a desired amplitude, then rectifying that ac voltage, filtering with a capacitor and RC filter, if desired, an finally regulating the dc voltage using an IC regulator. The regulators can be selected for operation with load current from hundreds of milli-amperes to tens of amperes, corresponding to power ratings from milli-watts to tens of watts.

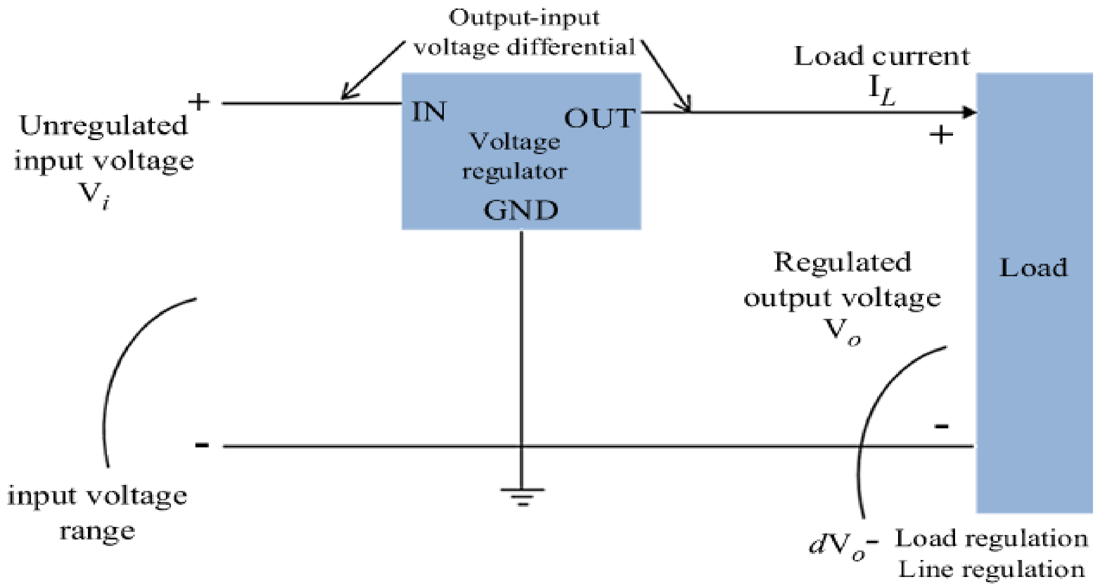

Figure 3.1 Block representation of three terminal voltage regulator

3.1 Three-Terminal Voltage Regulators

Figure 3.1 shows the basic connection of a three-terminal voltage regulator IC to a load. The fixed voltage regulator has an unregulated dc input voltage, V_i, applied to one terminal, a regulated output dc voltage, V_o, from a second terminal, with the third terminal connected to ground. For a selected regulator, IC device specification list a voltage range over which the input voltage can vary to maintain a regulated output voltage over a range of current load. The specifications also list the amount of output voltage change resulting from a change in load current (load regulation) or in input voltage (line regulation).

3.2 Fixed Positive Voltage Regulators

The series 78 regulators provide fixed regulated voltages from $5\ to\ 24\ V$. Figure 3.2 shows how one such IC, a 7812, is connected to provide voltage regulation with output from this unit of $+12\ V\ dc$. An unregulated input voltage V_i is filtered by capacitor C_1 and connected to the IC's IN terminal. The $IC's\ OUT$ terminal provides a regulated $+12\ V$, which is filtered by capacitor C_2 (mostly for any high-frequency noise).

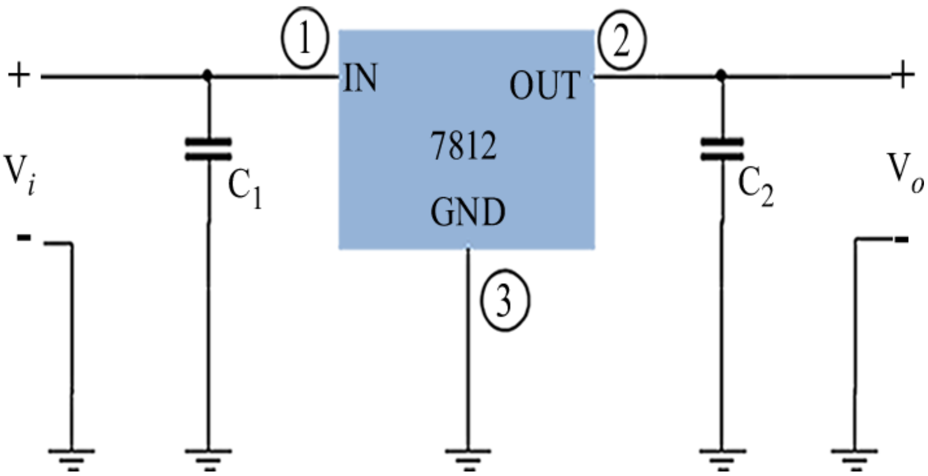

Figure 3.2 Connection of 7812 voltage regulator.

The third IC terminal is connected to ground (GND). While the input voltage may vary over some permissible voltage range and the output load may vary over some acceptable range, the output voltage remains constant within specified voltage variation limits. These limitations are spelled out in the manufacturer's specification sheets.

A table of positive voltage regulator ICs is provided in the table below.

Table 3.1 Positive Voltage Regulator in 7800 Series

IC Part	*Output Voltage (V)*	*Minimum V_i (V)*
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

The connection of 7812 in a complete voltage supply is shown in the connection of fig 3.3. The ac line voltage ($120\ V\ rms$) is stepped down to $18\ V$ rms across each half of the center-tapped transformer. A full-wave rectifier and capacitor filter then provides an unregulated dc voltage, shown as a dc voltage of about $22\ V$, with ac ripple of a few volts as the input to the voltage regulator. The $7812\ IC$ then provides an output that is a regulated $+12\ V\ dc$.

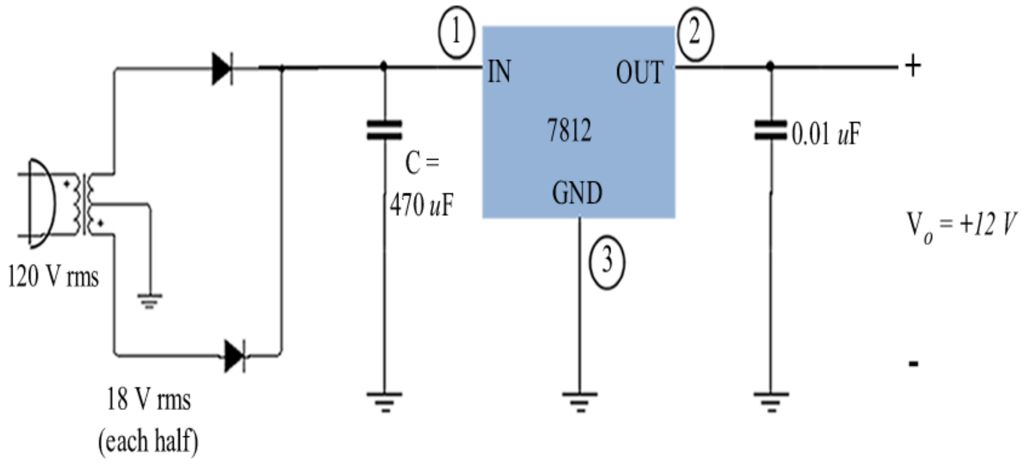

Fig 3.3 $+12\ V$ *power supply.*

POSITIVE VOLTAGE REGULATOR SPECIFICATIONS

The specification sheet of voltage regulators is typified by that shown in the table below for the group of series 7800 positive voltage regulators. Some consideration of a few of more important parameters should be made.

Nominal output voltage	Regulators
5	7805
6	7806
8	7808
10	7810
12	7812
15	7815
18	7818
24	7824

Absolute maximum ratings:

Input voltage	40 V
Continuous total dissipation	2 W
Operating free-air temperature range	$-65 \text{to} 150°C$

μA 7812C electrical characteristics:

Parameters	**Min.**	**Typ.**	**Max.**	**Unit**
Output voltage	11.5	12	12.5	V
Input regulation		3	120	mV
Ripple rejection	55	71		dB
Output regulation		4	100	mV
Output resistance		0.018		Ω
Dropout voltage		2.0		V
Short-circuit output current		350		mA
Peak output current		2.2		A

Table 2 Specification sheet data for voltage regulator ICs

Output voltage: The specification for the 7812 shows that the output voltage is typically $+12\ V$ but could be as low as $11.5\ V$ or high as $12.5\ V$.

Output regulation: The output voltage regulation is seen to be typically $4\ mV$, to a maximum of $100\ mV$ (at output current from $0.25\ to\ 0.75\ A$). This information specifies that the output voltage can typically vary only $4\ mV$ from the rated $12\ V$ dc.

Short-circuit output current: The typical amount of current is limited to typically $0.35\ A$ if the output were to be short-circuited (presumably by accident or by another faulty component).

Peak output current:while the rated maximum current is 1.5 A for this series of IC, the typical peak output current that might be drawn by a load is $2.2\ A$. This shows that although the manufacturer rates the IC as capable of providing $1.5\ A$, one could draw somewhat more current (possibly for a short period of time).

Dropout voltage: The drop out voltage, typically $2\ V$, is the minimum amount of voltage across the input-output terminals that must be maintained if the IC is to operate as a regulator. If the input voltage drops too low or the output rises so that at least $2\ V$ is not maintained across the IC input-output, the IC will no longer provide voltage regulation. One therefore maintains an input voltage enough to ensure that the dropout voltage is provided.

3.3 Fixed Negative Voltage Regulator

The series $7900\ ICs$ provide negative voltage regulators, similar to those providing positive voltages. A list of negative voltage regulators ICs is provided in the table below. As shown. ICregulators are available for a range of fixed negative voltages; the selected IC providing the rated output voltage as long as the input voltage is maintained greater than the minimum input value. For example, the 7912 provides an output of $-12\ V$ as long as the input to the regulator IC is more than negative $-14.6\ V$.

Table 3.3 Negative Voltage Regulator in 7900 Series

IC Part	*Output Voltage (V)*	*Minimum V_i (V)*
7905	-5	-7.3
7906	-6	-8.4
7908	-8	-10.5
7909	-9	-11.5
7912	-12	-14.6
7915	-15	-17.7
7918	-18	-20.8
7924	-24	-27.1

Example

Draw a voltage supply using a full-wave bridge rectifier, capacitor filter and IC regulator to provide an output of $+5\ V$.

Solution

The resulting circuit is shown in fig 3.4

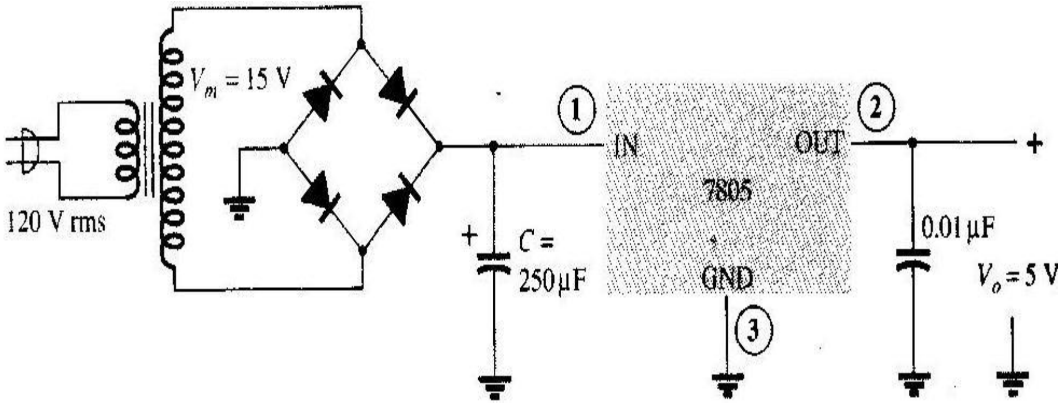

Fig3.4

3.4 Adjustable Voltage Regulators

Voltage regulators are also available in circuit configurations that allow the user to set the output voltage to a desired regulated value. The $LM317$, for example, can be operated with the output voltage regulated at any setting over the range of voltage from $1.2\ to\ 37\ V$. Figure 3.5 shows how the regulated output of an $LM317$ can be set.

Resistor $R_1\ and\ R_2$ set the output to any desired voltage over the adjustment range (1.2 to 37 V). The output voltage desired can be calculated using

$$V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2$$

With typical IC values of

$$V_{ref} = 1.25\ V \text{ and} I_{adj} = 100\ \mu A$$

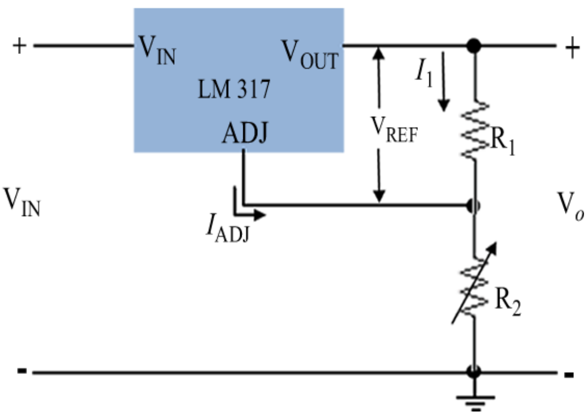

Figure 3.5 Connection of $LM317$ adjustable-voltage regulator

Example

Determine the regulated voltage in the circuit of Figure 19.30 with $R_1 = 240\ \Omega$ and $R_2 = 2.4\ k\Omega$

Solution

Using

$$V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2$$

$$V_o = 1.25\ V\left(1 + \frac{2.4\ k\Omega}{240\ \Omega}\right) + (100\ \mu A)(2.4\ k\Omega)$$

$$= 13.75\ V + 0.24\ V\ = 13.99\ V$$

3.5 TEST

Question 1

Determine the regulated output voltage of the circuit in figure 3.6

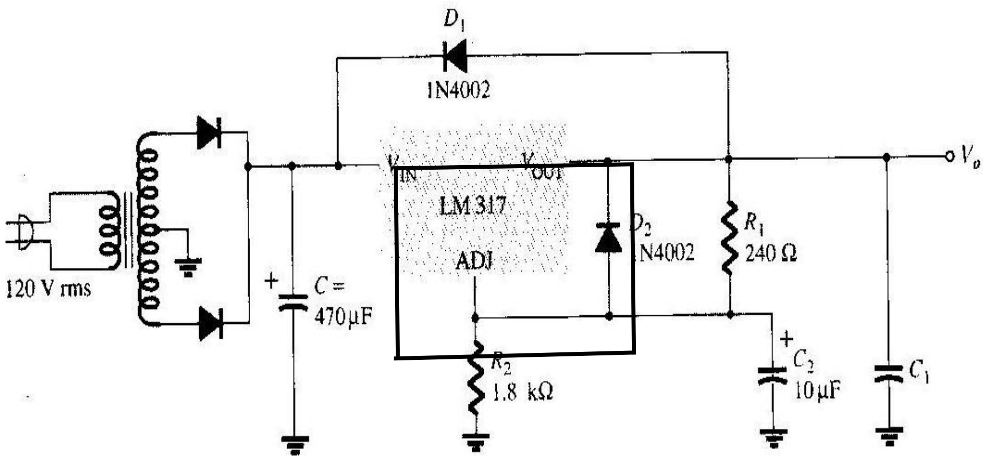

Figure 3.6

Solution

The output voltage calculated using

$$V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2$$

$$V_o = 1.25\left(1 + \frac{1.8\ k\Omega}{240\ \Omega}\right) + (100\ \mu A)(1.8\ k\Omega) \approx 10.8\ V$$

A check of the filter capacitor voltage shows that an input-output difference of 2 V can be maintained up to at least 200 mA load current.

Question 2

For a transformer output of $15\ V$ and a filter capacitor of $250\ \mu F$, calculate the minimum input voltage when connected to a load drawing $400\ mA$.

Solution

The voltages across the filter capacitor are:

$$V_r(peak) = \sqrt{3}V_r(rms) = \sqrt{3}\frac{2.1 I_{dc}}{C} = \sqrt{3}\frac{2.4(400)}{250} = 6.65\ V$$

$$V_{dc} = V_m - V_r(peak) = 15\ V - 6.65\ V = 8.35\ V$$

Since the input swing around this dc level, the minimum voltage can drop to as low as

$$V_i(low) = V_{dc} - V_r(peak) = 15\ V - 6.65\ V = 8.35\ V$$

Since this voltage is greater than the minimum required for the IC regulator (from table 3.2. $V_i = 7.3\ V$), the IC can provide a regulated voltage for the given load.

Question 3

Determine the regulated voltage in the circuit of fig 19.30 with $R_1 = 240\Omega$and $R_2 = 1.8\ k\Omega$.

Solution

Using

$$V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{adj}R_2$$

$$V_o = 1.25\ V\left(1 + \frac{1.8\ k\Omega}{240\ \Omega}\right) + (100\ \mu A)(1.8\ k\Omega)$$

$$= 13.75\ V + 0.24\ V = 13.99\ V$$

4.0 CONCLUSION

This unit has introduced you to the various regulator ICs, their various functions and connection modes. It also introduced you to some voltage regulator IC series and their usage.

5.0 SUMMARY

Voltage regulator circuits has brought about a tremendous solution to the major draw-back of the unregulated power supply and it has made it possible to obtain a stable or nearly constant dc output voltage even when there are variations in load or input voltage. Due to low-cost fabrication technique, many commercial integrated-circuit (*IC*) regulators are available since the past two decades. These include fairly simple, fixed-voltage types of high-quality precision regulators. These *IC* regulators have much improved performance as compared to those made from discrete components. A regulated dc power supply is essential for sensitive electronic systems used in communication, instrumentation, computers and many other areas.

6.0 TUTOR-MARKED ASSIGNMENT

1. Draw the circuit of a voltage supply comprised of a full-wave bridge rectifier, capacitor filter, and IC regulator to provide an output of $+12\ V$.

2. Calculate the minimum input voltage of the full-wave rectifier and filter capacitor network in fig 3.7 when connected to a load drawing $250\ mA$.

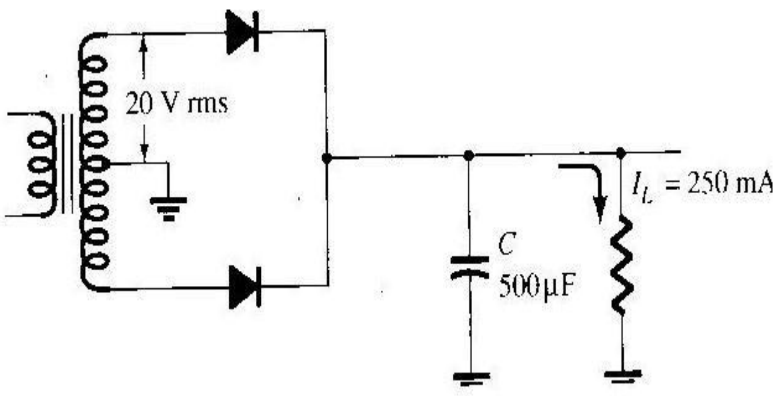

Fig 3.7

3. Determine the regulated output voltage from the circuit of Fig 3.8.

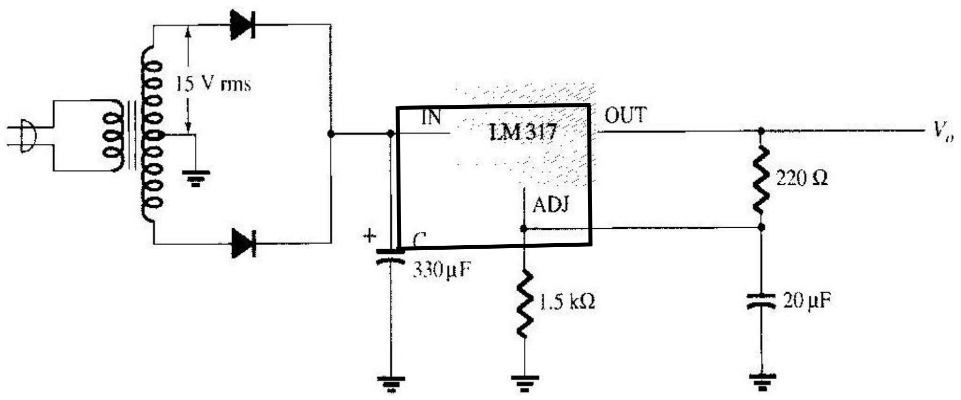

Fig 3.8

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