NATIONAL OPEN UNIVERSITY OF NIGERIA

SCHOOL OF SCIENCE AND TECHNOLOGY

COURSE CODE: PHY 364

COURSE TITLE: PHY 364 ELECTRONICS II

PHY 364 ELECTRONICS II

COURSE GUIDE

NATIONAL OPEN UNIVERSITY OF NIGERIA

Contents

Introduction

INTRODUCTION

PHY 308 the prerequisite to this course has familiarised you with the basic concepts of Amplifiers, Classification of Amplifiers, Equivalent Circuit of Transistors, Operating Point, and Bias Stability, Small Signal Amplifiers, RF Amplifiers, Oscillators, Power Supplies, Power Sources, DC Power Units, Performance of Rectifiers, Filter Circuits, Regulation of Output Voltages, Linear Integrated Circuits, The OP Amp and its Applications, Amplifiers and Voltage Regulators.

This ought to have encouraged you to develop an enquiring attitude towards electronics which directly and indirectly you see around you every single day.

It is the objectives of this course to build upon the lessons learnt in the prerequisite course, and in this course, we shall be discussing amongst other concepts; Multistage Amplifiers, Power Amplifiers, Class A Amplifiers, Class B Amplifiers, Class C Amplifiers, Active and Passive Filters, Power Systems, use of Transistors in Stabilised Power Supplies and Field Effect Transistors.

This is with the view to further strengthening your understanding of the underlying concepts upon which developmental work and research in electronics are based and to build in you the confidence required to discuss professionally the concepts treated.

THE COURSE

PHY 364 Electronics II

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

Module 1 is composed of 6 Units

Module 2 is composed of 5 Units

Module 3 is composed of 5 Units

Module 4 is composed of 5 Units

Module 1 will introduce solid state active circuit elements and Multistage Amplifiers. In Unit 1 we will discuss Field Effect Transistors with emphasis laid on their operation, their terminals and the different types of Field Effect Transistors which you will encounter in the real world. Our discussion in Unit 2 will focus on specifically on Junction Field Effect Transistors; particularly their operation, their characteristic curves and their every day application as amplifiers.

Unit 3 will explain to you what Metal Oxide Field Effect Transistors are, their operation, output curves and the P-channel enhancement and depletion modes and the N-channel enhancement and depletion modes respectively as the different

MOSFET device types available for design purposes. You are encouraged to compare and contrast JFET and MOSFET transistors, their individual merits and demerits.

In Units 4, we will take a look at the different types and classification of amplifiers; particularly transistor amplifiers operational amplifiers and power amplifiers. We will see that amplifiers can be classified by their common terminal, their input and output variable and also by unilateral or bilateral properties. Finally in Unit 4 we will visit power amplifiers. In Unit 5 we shall be concerned with the common terminal configurations of bipolar junction transistors amplifiers; the common emitter, common base and the common collector Amplifiers. We will take a look at their properties and characteristics.

The last \Unit of Module 1 will focus on Multistage Amplifiers with emphasis laid on their classification, the merits of multistage amplification and finally, open loop and closed loop multistage amplifiers.

In Module 2 we shall exclusively discuss amplifiers proceeding with Power Amplifiers in Unit 1. Here we shall classify power amplifiers, review their specifications and state their practical limitations. In Units 2, 3 and 4 we will highlight class A, class B and AB as well as class C amplifiers. Here we will discover their maximum operating efficiencies, their gain, input and output impedances, level of distortion of the input signal and the practical uses to which they are frequently put. Also we will compare their performances, merits and demerits and in the case of class C amplifier; the two modes of operation.

We shall conclude Module 2 with Unit 5 in which we will treat low and high frequency power amplifiers. Of interest to us in this Unit are those specifications that qualify them as power electronic amplifiers, which we shall follow by spotlighting high frequency power amplifiers as a specific group of interest.

We shall take a critical look at electrical power and power supplies in Module 3. What is electrical energy? What are electrical power systems? Which of alternating current and direct current is more useful? What are their merits and demerits? These are the subject of our enquiry in Unit 1 in which we take on Power Systems.

Having established the sources and the transportation mechanism of this portable form of energy into our homes and industries in Unit 1, we will go further by studying Power Supplies in Unit 2. We will review and extend what we already know in the pre-requisite to this course about alternating current power supplies, direct current power supplies, linear power supplies and switching power supplies.

In Unit 3 I hope to capture your attention when we discuss constant voltage stabilised power supplies and active voltage regulators which are typified by linear and switching regulators. In Unit 4 it will be made clear why it is impossible to realise a switching regulators without using active circuit elements. Here we will see the important role transistors play in Stabilised Power Supplies exemplified by the solid state and operational amplifier voltage regulators.

Unit 5 of Module 3 will teach you Switched Mode Power Supply operation. You will have explained to you the subsystems which constitute, and the modular layout of the SMPS; particularly the rectifier, filter, inverter, converter, output rectifier, regulation, and the merits and demerits of SMPS.

The last module is Module 4 which is entirely made up of filter topics; Unit 1 will detail filter topology, Single element Filter, L Filter, T and π Filter, and the Multiple Element Filters.

Unit 2 will classify filters into passive and active filters while Unit 3 will explain passive filters, band-pass filters, band-reject filter, low-pass filter, high-pass filter and phase-shift filter otherwise known as the all pass filter. You will learn that these filters listed are passive filters because they do not feature any active circuit element in their design.

Unit 4 on the other hand is dedicated to Active Filters. Here we shall study the ideal filter approximations which will be illustrated by studying the unique properties of the Butterworth, Tschebyscheff and Bessel Filters. This is however preceded by the general criteria for active filter design.

Having understood the operating principle behind filters, you will see how filters are applied in the real world at audio frequencies, radio frequencies and as electrical noise suppressors. The final practical application of filters is more sophisticated than the preceding; it is the application of the narrow bandpass filter in spectrum sweeping.

COURSE AIMS AND OBJECTIVES

The aim of PHY 364 is to further intimate you with solid state active devices, power supplies and filters, to enable you discuss intelligently their parametric characteristics, to acquaint you with their electrical properties, their merits and demerits and to let you establish their indispensability in everyday living.

Specifically, after working through this course diligently, upon completing it you should be able to:

- Discuss with confidence the field effect transistor

- Explain why field effect transistors are unipolar devices
- Discus the electron and the hole as charge carriers
- Understand why bipolar transistors preceded field effect transistor
- Sketch the characteristic curve of junction field effect transistor
- Draw a functional sketch of N and P channel field effect transistors
- Know how field effect transistors control the flow of electrons
- Explain the meaning of N and P channel
- Discuss the ohmic mode of field effect transistor operation
- Recognise the saturation portion of the field effect transistor output curve
- Explain the meaning of threshold voltage when pplied to field effect transistors
- Describe the pinch-off point of field effect transistor characteristic curve
- Understand why junction field effect transistors are predominantly depletion mode devices.
- Explain the inversion process in field effect transistors
- Identify the terminals of field effect transistors
- Explain the significance of the field effect transistor substrate
- Draw analogy between the field effect transistor, triode valve and bipolar junction transistor terminals
- Realize why the field effect transistor is functionally closer to a triode valve than a bipolar transistor
- Recognise the substrate as a field effect transistor's fourth terminal
- Know that a MOSFET is the same as an IGFET
- Sketch and name the different configurations of field effect transistors
- Distinguish between depletion and enhancement modes of operation of FETs
- Explain the operation of a JFET

- Sketch a junction field effect transistor
- List the advantages of junction field effect transistors
- State why the JFET's input resistance is very high
- Explain the role of the JFET's gate junction diode
- Give a good reason why junction field effect transistors are difficult to manufacture
- Bias a junction field effect transistor
- Discus the effect of doping on channel depletion in the FET
- Explain charge separation in FET
- Design a simple JFET common source amplifier
- Draw a cross section view of a junction field effect transistor
- Sketch P and N channel JFET common drain amplifiers
- Refute the statement that JFETS are quite common in large scale integrated circuit chip design
- Explain why JFETS are imune to damage through electrostatic discharge
- State why MOSFETS are the most commonly used transistors
- Explain the role Shockley played in the development of the MOSFETs
- Discuss what is meant by conductively modulated device
- Contrast the process by which conduction is modulated in the MOSFET and JFET
- Say why MOSFET gate insulation is usually silicon dioxide
- Sketch a MOSFET output curve
- Explain the meaning of inversion in MOSFETs
- Sketch the different configuration of P and N channel MOSFETs
- Distinguish between the enhancement and depletion modes of operation in MOSFETs
- Draw transfer curves for all four MOSFET configurations

- Appreciate the benefits of MOSFETS over JFETS
- Recognise the transition from weak to strong inversion in MOSFETS
- Recognise the different amplifier types
- Identify classes A, B, AB and C amplifiers
- Discuss the attributes of power amplifiers
- Explain the causes of nonlinearity in non class A amplifiers
- Know why power amplifiers are often the last stage in a cascade
- Determine the efficiency of amplifiers
- Design simple amplifier circuits
- State the properties of operational amplifiers
- Apply common terminal classification to BJT, FET and triode amplifiers.
- Explain current, voltage and power gain
- Convert power, voltage and current ratio to decibel
- Describe transconductance
- Sketch the amplitude-frequency curve of an amplifier
- Know which amplifiers employ variable gain
- Enumerate the merits and demerits of BJT amplifiers
- Explain why all operational amplifiers are not differential amplifiers
- List why classes A, AB, B and C amplifiers are suitable for analogue applications
- Appreciate the relationship between amplifier efficiency and nonlinearity
- Sketch common emitter, common base and common collector amplifiers
- Know the relationship between emitter, base and collector currents
- Explain emitter degeneration and relate it to negative feedback
- Understand why emitter degeneration increases bandwidth

- Say why the emitter follower is best for high impedance input signal sources
- Recognise that the common collector amplifier is also called the emitter follower
- Know why the common base amplifier is best used as a voltage amplifier
- Calculate why the current gain of the common base amplifier is approximately unity
- Discover why the voltage gain of the common collector amplifier is almost unity
- Explain the meaning of current mirror
- Explain the term multistage amplifier
- List the merits demerits and of multistage amplifiers
- Distinguish between open loop and closed loop multistage amplifiers
- Associate instability with open loop multistage amplifiers
- See how bandwidth and negative feedback are related
- Find out why input and output impedances are better controlled in multistage amplifiers
- Understand open loop and closed loop gain
- Recognise operational amplifiers as multistage amplifiers
- Describe the process of cascading amplifier stages
- Sketch and name the four basic methods of applying negative feedback
- Understand that negative feedback reduces distortion
- Know how amplifier gain is rendered independent of parameters and is defined by passive elements through negative feedback
- Describe the operation of power amplifiers
- Classify power amplifiers
- Know the important specifications of power amplifiers

- State the practical limitations of power amplifiers
- Discuss the characteristics of amplifier classes A, AB, B and C
- Know which power amplifier classes are suitable for analogue applications
- Classify power amplifiers by device type
- Sketch power amplifier circuits
- Sketch the signal waveforms for classes A, AB, B and C amplifiers
- Discus the efficiency of classes A, AB, B and C amplifiers
- Confidently correlate efficiency and distortion in the various classes of power amplifiers
- Graphically discuss instability
- Describe the operation of class A amplifiers
- Know why class A audio amplifiers provide the highest fidelity
- See why class A amplifiers are the most energy inefficient class
- Understand the reason why class A amplifiers are rarely used in power output stages
- List the merits and demerits of class A amplifiers
- Compare performance of class A amplifiers with classes AB, B and C amplifiers
- Understand the term "single ended"
- Qualify the high frequency performance of class A amplifier
- Figure out why class A amplifiers have no crossover distortion
- Explain why an overloaded class A amplifier can suffer from non linearity
- Describe the operation of Class B and AB amplifiers
- State the range of efficiencies of classes B and AB amplifiers
- Sketch the output waveform of classes B and AB amplifiers

- Compare and contrast distortion in classes B and AB amplifies
- Describe biasing requirement for class AB amplifier
- Sketch classes AB and B amplifiers circuit layout
- Identify a class AB output stage in circuit diagram
- See the need to match output active elements in class AB amplifier
- Understand the meaning of push pull circuit
- Explain the meaning of complementary paired elements
- State the output phase relationship in classes B and AB amplifiers
- Compare and contrast classes AB and B amplifier performance with class A and class C amplifiers performances
- Appreciate the need for forced cooling in classes AB and B amplifiers
- Sketch the output characteristics of classes AB and B amplifiers
- Compare the low frequency responses of transformer coupled and transformerless class AB amplifiers
- Understand why biasing diodes are used in bipolar junction transistor class AB amplifiers
- Describe the operation of the class C amplifier
- Discuss the two modes of class C operation
- State the maximum efficiency of class C amplifiers
- Sketch the output waveform of class C amplifiers
- Understand how tuned mode class C amplifiers clamp DC level
- Explain why class C amplifiers are predominantly applied to radio frequency
- Sketch a class C output stage
- Say why class C stages do not require DC biasing
- Distinguish between low and high frequency power amplifiers

- List the most common power amplifier specifications
- Explain power amplifier signal bandwidth
- Sketch an audio power amplifier output stage
- Sketch a radio frequency power output stage
- Compare the efficiencies of low frequency and high frequency power amplifiers
- List the practical applications of low and high frequency power amplifiers
- Appreciate the importance of impedance matching in power amplifiers
- Express power gain in decibels
- Understand the need for forced cooling in power amplifier designs
- Understand the true nature of electrical energy
- Describe the various ways of generating electrical energy
- Explain the principle behind electrical storage and storage devices
- Describe electrical power transmission systems
- Distinguish between direct current and alternating current
- Sketch an electrical power distribution system
- State the difficulties associated with electrical energy distribution system
- Distinguish between electrical power generation, power transmission and power distribution systems
- Know why electrical energy is transmitted at very high voltages
- List the merits and demerits of direct current electrical transmission compared with alternating current transmission
- Explain the skin effect and the measures employed to limit its negative impact
- Explain why Aluminium conductors are preferred in electrical transmission systems
- Enumerate the properties of alternating current and voltage

- Sketch alternating current, direct current and pulsating direct current waveforms
- State the roles that notable scientists like Nikola Tesla and Thomas Edison played in the practical application of electrical energy
- List the domestic and industrial applications of direct current electrical energy
- Appreciate the reason why electrical power supplies are necessary
- Distinguish between alternating current and direct current power supplies
- Describe the functioning of the transformer
- Sketch a half wave and a full wave rectifier
- Sketch a half wave and a full wave rectifier output waveform
- Explain the need for a filter capacitor in power supplies
- Discuss methods for reduction of ripple in the output of power supplies
- Distinguish between linear and non linear power supplies
- Describe the operation of the switching power supply
- List the merits and the demerits of the switching power supply when compared with the linear power supply
- Compare the efficiencies of linear power supplies and switching power supplies
- State the economic advantages of switching power supplies
- Understand how constant voltage power supplies operate
- Describe the process of stabilisation in power supplies
- Discuss voltage regulators
- Distinguish between active and passive regulators
- Explain the significance of feedback loop in stabilisation
- Compare and contrast linear regulators and switching regulators
- Appreciate the significance of hybrid regulation

- Sketch the simplest regulator circuit
- Discuss series and shunt regulators
- Sketch an integrated circuit regulator
- Associate the output voltage of the 78xx and 79xx solid state regulators with their product number
- Explain drop-out voltage as applied to regulators
- Compare the frequency response of switching and linear regulators
- Recognise the importance of transistors in stabilised power supplies
- Realise that regulator power stages consist of at least one transistor which serve as the active element in the regulation or negative feedback loop
- See that the application of transistors in stabilised power supplies is almost always in association with negative feedback loop
- Understand why regulators require a reference voltage which is derived from a potential divider arrangement
- See how the current output of the basic regulator can be boosted with an active element such as a transistor
- Amplify the error signal of the regulator output with a transistor through a negative feedback loop to correct the regulator output
- Use the high open loop voltage gain of an operational amplifier along with its exceedingly high input impedance to buffer the output of an operational amplifier buffered regulator
- Appreciate why switched mode power supplies are in such widespread use
- Visually recognise switched mode power supplies
- See why switched mode power supply frequencies are supersonic
- Explain how switched mode power supplies derive their high conversion efficiencies
- Give reasons why it is impractical to have full implementation of a switched mode power supply as an integrated circuit
- Describe the different types of switched mode power supplies

- Sketch a switched mode power supply schematic diagram
- List the functional blocks of switched mode power supplies
- Understand why switched mode power supplies must include a reactive circuit element
- Discuss the source of switched mode power supply noise
- Appreciate why MOSFETs are preferred to bipolar devices in switched mode power supplies
- List the merits and demerits of switched mode power supplies when compared with linear power supplies
- Describe the electrical function of filters
- Sketch the common filter topologies
- Recognise a single element filter
- Sketch single element filters
- Explain why an LC pair is considered a single element in filter topology
- Sketch simple low pass, bandpass and high pass filter topologies
- Sketch L, T and π filter topologies
- Discuss multiple element filters
- Create multiple element filters from simple filter topologies
- Explain why bandpass filters can never be implemented with an L-filter topology
- Discuss the classification of filters
- Classify filters by topology, technology and methodology
- Distinguish between passive and active filters
- Explain how digital filters are implemented
- Understand the Q factor of a filter
- Sketch the frequency response of filters

- Explain the transfer function
- Work in the frequency domain
- Sketch passive and active filters
- Sketch twin T filters
- Sketch the transfer function of Wien bridge filters
- Explain active filter optimisation
- Understand the order of a filter
- Describe the effect of filter order on rolloff slope
- Sketch ideal filter response curves
- State the definition for passive filters
- Learn more about passive filters
- List five basic filter types
- Know that phase shift filters pass all frequencies without attenuation
- Know how to recognise filters which impact on your life very day
- Draw transfer function sketches of low pass, high pass, band pass, and reject and phase shift filters
- See the relationship between phase and frequency for the five types of filters
- Know how to use inductors, capacitors and resistors to design the five types of filters
- Distinguish between passband and stopband
- State many practical applications of passive filters
- Describe the characteristics of active filters.
- Sketch active filters
- Identify the role that active circuit elements play in active filters
- Identify practical applications of active filters

- List the advantages of active filters over passive filters
- Design active filters based on design criteria
- Remember the characteristic traits of Butterworth, Tschebyscheff and Bessel filters
- Compare the transfer functions of Butterworth, Tschebyscheff and Bessel filters
- Explain ideal filter approximation
- Recognise audio tone controls as filter implementation.
- List several applications of filters
- Categorise filters into continuous time and sampled data filters
- Recognise the role of filters in communications technology
- Appreciate that digital filters are implemented through computer software algorithms
- Discuss the negative effects of transients and radio frequency interference on electronic equipment
- Sketch a simple capacitive electrical noise suppressor
- Explain the function of snubber resistor in noise suppressors
- Understand the principle of operation of the spectrum analyser
- Appreciate the broad application of spectrum analysis
- Realise the difficulty entailed in totally eliminating mains frequency hum from audio equipment
- See typical applications of bandpass filters in radio frequency signal processing
- Understand how load impedance affects the response characteristics of filters

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 five units each, except for module 1 which has six Units.

Module 1 SOLID STATE AMPLIFIERS

Unit 1 Field Effect Transistors
Unit 2 Junction Field Effect Transistors
Unit 3 Metal Oxide Field Effect Transistor
Unit 4 Types and Classification of Amplifiers
Unit 5 Common Emitter, Common Base & Common Collector Amplifiers
Unit 6 Multistage Amplifiers

Module 2 POWER AMPLIFIERS

Unit 1 Power Amplifiers
Unit 2 Class A Amplifiers
Unit 3 Class B and AB Amplifiers
Unit 4 Class C Amplifiers
Unit 5 Low and High Frequency Power Amplifiers

Module 3 POWER SUPPLIES

Unit 1 Power Systems
Unit 2 Power Supplies
Unit 3 Stabilised Power Supplies
Unit 4 Uses of Transistors in Stabilised Power Supplies

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. L. Theraja and A. K. Theraja. Published By S. C. Chand

Electronic Devices and Circuit Theory 7th Edition
By Robert E. Boylestad and Louis Nashesky Published by Prentice Hall

Network Analysis with Applications 4th Edition
By William D. Stanley Published by Prentice Hall

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

Analog Filter Design
By M. E. Van Valkenburg Published by Holt, Rinehart and Winston

ASSESSMENT

Assessment of your performance is partly through 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 transistors, amplifiers, power supplies and filters and the presentation style will enable you to understand the content with relative ease and facilitate the translation of abstract theoretical concepts to real world subsystems and systems which you see around you all the time.

This coursework provides you invaluable insight into the discovery, development and the functioning of comparatively simple concepts and components which perhaps have been most catalytic in transforming the world to that which we live in today.

You will upon completion of this course confidently proffer realistic solutions and answers to everyday questions that arise such as:

- Is an audio equaliser really made up of bandpass filters and how does an audio equaliser really work?

- Why are power field effect transistors frequently discussed by technicians in the process of designing power inverters?

- Why can't I just use any filter topology for band reject filters?

- What happens when I connect two Zener diodes in parallel?

You just make sure that you have enough referential and study material available and at your disposal as this course will change the way you see the world around you in more ways than one.

On this note;

I wish you the very best in your quest for knowledge.

Table of Content **Page**

Module 1

UNIT 1 FIELD EFFECT TRANSISTORS

CONTENTS

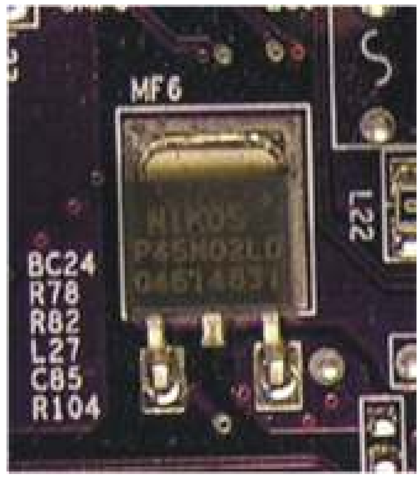
1.0 INTRODUCTION

A Field Effect Transistor (FET) is a unipolar device which conducts current using only one kind of charge carrier. If it is produced on an N-type semiconductor slab it uses electrons as carriers while conversely, a P-type based device uses only holes as carriers.

The principle behind the operation of field-effect transistors was first patented by Julius Edgar Lilienfeld in 1925 and by Oskar Heil in 1934, however practical semi-conducting devices such as the Junction Gate Field Effect Transistor, were only developed much later after the transistor effect was observed and explained by William Shockley's research team at Bell Laboratories in 1947.

Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFET), which superseded the Junction Field Effect Transistor and had a more profound effect on electronic development, was first proposed by Dawon Kahng in the year 1960

The operation of the field-effect transistor which is commonly referred to as the FET depends on an electric field to control the shape and subsequently the conductivity of a channel of one of the two types of charge carriers in a semiconductor material.



High-power N-channel field-effect Transistor

Field Effect Transistors are sometimes called unipolar transistors to reflect their single-carrier-type operation with the dual-carrier-type operation of Bipolar Junction Transistors (BJT) and while the concept of the FET precedes that of the Bipolar Junction Transistor, it was not physically implemented before the Bipolar Junction Transistor due to the limitations of semiconductor materials and the relative ease of manufacturing Bipolar Junction Transistors compared to Field Effect Transistors at the time.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. Discuss with confidence the device known as the field effect transistor
2. Explain why field effect transistors are unipolar devices
3. Discus the electron and the hole as charge carriers
4. Understand why the bipolar transistors preceded field effect transistor

5 Sketch the characteristic curve of junction field effect transistor

6 Draw a functional sketch of N and P channel field effect transistors

7 Know how field effect transistors control the flow of electrons

8 Explain the meaning of N and P channel

9 Discuss the ohmic mode of field effect transistor operation

10 Recognise the saturation portion of the field effect transistor output curve

11 Explain the meaning of threshold voltage

12 Describe the pinch-off point of field effect transistor

13 Understand why junction field effect transistors are predominantly depletion mode devices.

14 Explain the inversion process in field effect transistors

15 Identify the terminals of field effect transistors

16 Explain the significance of the substrate

17 Draw analogy between field effect transistor, triode valve and Bipolar transistor terminals

18 Realize why the field effect transistor is functionally closer to a triode valve than a bipolar transistor

19 Recognise the substrate as a field effect transistor's fourth terminal

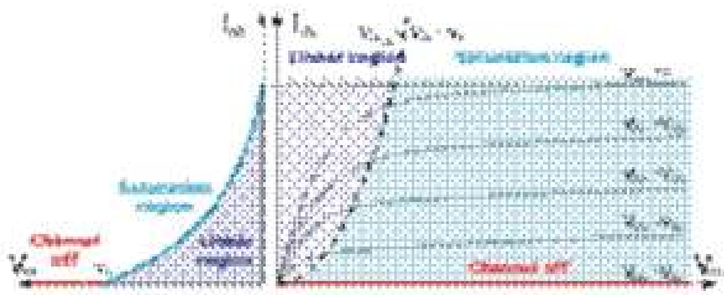
20 Know that a MOSFET is the same as an IGFET

21 Sketch and name the different configurations of field effect transistors

22 Distinguish between depletion and enhancement modes of operation

3.0 MAIN CONTENT

3.1 FIELD EFFECT TRANSISTOR OPERATION



I–V characteristics and output plot of a JFET n-channel transistor.

The easiest way for you to understand the operation of the Field Effect Transistor is for you to visualize it as a device which controls the flow of electrons (which may also be visualised in conventional current terms as electron holes) from the source to the drain by affecting the size and shape of a conductive channel created and influenced by a voltage, or the lack of voltage applied across the gate and source terminals – with the conductive channel acting as the medium through which electrons flow from the source to the drain.

In the n-channel depletion-mode Field Effect transistor device, a negative gate-to-source voltage causes the depletion region to increase its width and encroach on the channel from the sides; this narrow the channel creating greater impedance to electron flow through the channel. If the depletion region expands to completely close the channel, the resistance of the channel from source to drain becomes very large, and the Field Effect Transistor is effectively turned off – just like a switch. If you were to apply a positive gate-to-source voltage, you would be increasing the channel size and this allows more electrons to flow easily across the channel; which presents lower impedance to electron flow.

As you would correctly guess, in an n-channel enhancement-mode Field Effect transistor, a positive gate-to-source voltage is necessary to create, and to increase the conductive channel since the channel does not exist naturally within the transistor. The positive voltage attracts free-floating electrons within the body towards the gate, forming a conductive channel. Enough electrons must be attracted near the gate to counter the ions used in doping the semiconductor of the Field Effect Transistor and this forms a region free of mobile carriers which you must remember – as the depletion region. The phenomenon is referred to as the threshold voltage of the FET. Any additional gate-to-source voltage will attract even more electrons towards the gate which are able to create a conductive channel from source to drain in a process called inversion.

When you are dealing with either the enhancement or the depletion-mode Field Effect Transistors, if drain-to-source voltages is much less than gate-to-source voltages, changing the gate voltage will alter the channel resistance, and drain current will be proportional to drain voltage when referenced to source voltage. In this mode the Field Effect Transistor functions like a variable resistor and the operation of the device can be said to be in linear mode or ohmic mode.

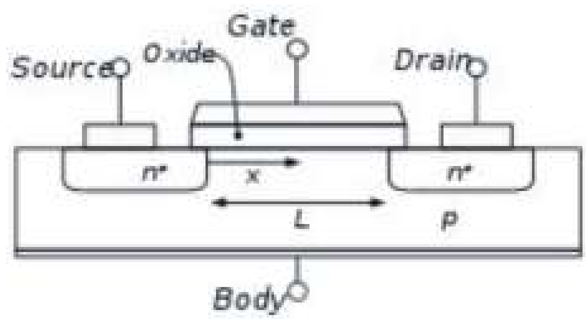
If drain-to-source voltage is increased, a significant asymmetrical change in the shape of the channel is created due to a gradient of voltage potential from source to drain. The shape of the inversion region becomes constricted and is said to be "pinched-off" near the drain end of the channel. If drain-to-source voltage is increased further, the pinch-off point of the channel begins to move away from the drain towards the source. The Field Effect Transistor is said to be in saturation mode; or active mode.

The saturation mode, or the region between ohmic and saturation, is used when amplification is required and the region between is sometimes considered to be part of the ohmic or linear region, even where drain current is not approximately linear with drain voltage.

Even though the conductive channel formed by gate-to-source voltage no longer connects source to drain during saturation mode, charge carriers are not blocked from flowing. If you consider again an n-channel device, depletion regions exists in the p-type body, surrounding the conductive channel and drain and source regions. Electrons which comprise the channel electrons are free to move out of the channel through the depletion region if attracted to the drain by drain-to-source voltage. The depletion region is free of carriers and has a resistance similar to silicon. Any increase of the drain-to-source voltage will increase the distance from drain to the pinch-off point, increasing resistance due to the depletion region proportionally to the applied drain-to-source voltage. This proportional change causes the drain-to-source current to remain relatively fixed independent of changes to the drain-to-source voltage and quite unlike the linear mode operation. Thus in saturation mode, the FET behaves as a constant-current source rather than as a resistor and can be used most effectively as a voltage amplifier. In this case, the gate-to-source voltage determines the level of constant current through the channel.

3.2 TERMINALS OF THE FIELD EFFECT TRANSISTOR

There are three terminals which you will always find on all Field Effect Transistors as illustrated in the diagram below; they are:



Cross section of an n-type MOSFET

- Gate terminal
- Drain terminal
- Source terminal

They bear the analogous relationship of base, collector, and emitter with the terminals of the Bipolar Junction Transistors. With the exception of the Junction Field Effect Transistor, all Field Effect Transistors possess fourth terminal which is severally referred to as the body, base, bulk, or substrate; and which serves to bias the Field Effect Transistor into operation. Take special note that this fourth terminal should not be trivialized in circuit designs as its presence is important in the physical layout of integrated circuits. The size of the gate is the distance between the source and the drain.

The width is the extension of the Field Effect Transistor perpendicular to its cross section and typically the width is much larger than the length of the gate. For a gate length of 1 µm you may assume an upper operating frequency limit of about 5 GHz while an 0.2 µm gate length sets an upper frequency limit in the region of 30 GHz.

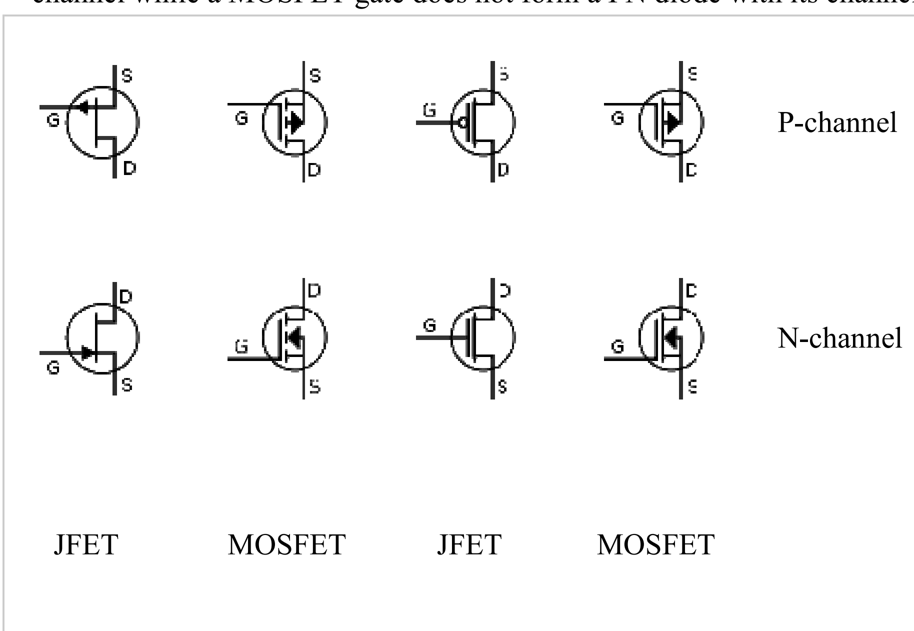
Just like in Bipolar Junction Transistors, the names of the terminals refer to their functions you can therefore imagine the gate terminal as though it were controlling the opening and the closing of a physical gate through which electrons passes. This gate permits electrons to flow through or blocks their passage by creating or eliminating a channel between the source and drain.

Electrons flow from the source terminal towards the drain terminal if influenced by an applied voltage. The body simply refers to the bulk of the semiconductor in which the gate, source and drain lie. Usually the body terminal is connected to the highest or lowest voltage within the circuit, depending on type. The body terminal and the source terminal are sometimes connected together since the source is also sometimes connected to the highest or lowest voltage within the circuit; however there are several uses of the Field Effect Transistor which do not have such a configuration, such as in the cases of transmission gates and cascode circuits.

3.3 TYPES OF FIELD EFFECT TRANSISTORS

It is suggested that you consult the diagram below to appreciate that there exist only two families of Field Effect Transistors – the Junction Field Effect Transistors commonly referred to as JFET on the one hand, and the Insulated Gate Field Effect Transistors or IGFET for short.

You will come across a very common transistor called the MOSFET which stands for Metal–Oxide–Semiconductor Field Effect Transistor. The MOSFET and the IGFET are the same thing and the name MOSFET only reflects the original construction of the IGFET from layers of metal which formed the gate, an insulating oxide layer and semiconductor material. Take special note that a JFET gate forms a PN diode with the channel while a MOSFET gate does not form a PN diode with its channel.



Classification of Field Effect Transistors

A further classification divides Field Effect Transistors into depletion-mode and enhancement-mode subject to the channel being turned on or off with zero gate-to-source voltage.

For enhancement mode Field Effect Transistors, the channel is non conductive at zero bias voltage and a gate potential is used to "enhance" conduction. Depletion mode Field Effect Transistors' channel are conductive at zero bias voltage and a gate potential of the opposite polarity will "deplete" the channel, reducing conduction.

Most Junction Field Effect Transistors are depletion-mode devices as the diode junctions would forward bias and conduct if they were enhancement mode devices. You should note this fact and contrast with that of most Insulated gate Field Effect Transistors which operate in the enhancement-mode.

4.0 CONCLUSION

In this unit we have learnt that Field Effect Transistors are unipolar devices which conduct current using only one kind of charge carrier, and are broadly classified into Junction Field Effect transistors and Insulated Gate Field Effect Transistors which may either be a P Channel or an N channel device operating in the Enhancement or in the Depletion mode.

Also we have learnt that Field Effect Transistors offer superior operating qualities to bipolar transistors

5.0 SUMMARY

- Field Effect Transistors are unipolar devices
- Electron and the hole as charge carriers
- Bipolar transistors preceded Field Effect Transistors
- There are N and P channel Field Effect Transistors
- Field Effect Transistors control the flow of electrons

- Linear Field Effect Transistor amplification is in the ohmic mode of operation
- Junction field effect transistors are predominantly depletion mode devices
- Field effect transistors are basically three terminal devices
- Field Effect Transistors are functionally closer to a triode valve than a Bipolar Junction Transistor
- The Field Effect Transistors substrate is not neglected in circuit design and is considered the fourth terminal
- Field Effect Transistors operate either in depletion or enhancement mode
- The MOSFET is an Insulated Gate Field Effect Transistor

6.0 TUTOR MARKED ASSIGNMENTS

1 Why do you think field effect transistors are called unipolar devices? Could you compare this with bipolar junction transistors?

2 Describe the role electrons and holes play as charge carriers in field effect transistor conduction? Do you have minority carriers in field effect transistors?

3 Can you remember the very first scientist to patent the principle behind the operation of field-effect transistors? Was it Shockley, was it Lilienfeld or was it Heil, and in which year?

4 Which came first, the JGFET or the MOSFET?

5 Sketch the cross section of a P-channel MOSFET and label its four terminals. State the significance of the fourth terminal and explain why it is not trivial.

6 In the field effect transistor, what is severally referred to as the body, the base and the bulk?

7 If a field effect transistor gate length lies between 1 micro µm and 2 micro µm, what upper operating frequency limit range can we assume that this gate length range set?

8 Descriptively compare the enhancement and depletion modes of field effect transistor operation?

9 Sketch and label the different types of field effect transistors you know?

10 Which is the odd one out, JGFET, IGFET and MOSFET? Why?

11 Can you recall the most common insulating material used in the construction of MOSFETs?

12 "With the exception of the junction field effect transistor, all field effect transistors possess fourth terminal" True or false? Why.

13 Sketch the output characteristic curve of a field effect transistor and label the different regions. What happens during pinch off?

14 By what other name can the linear region of the field effect transistor operation be called?

15 Describe in detail the phenomenon referred to as the threshold voltage of the field effect transistor?

16 Most Junction Field Effect Transistors are depletion-mode devices. Discuss?

7.0 REFERENCES/FURTHER READINGS

A Textbook of Electrical Technology 2010
By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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

Electronic Devices and Circuit Theory 7th Edition
By Robert E. Boylestad and Louis Nashesky Published by Prentice Hall

UNIT 2 JUNCTION FIELD EFFECT TRANSISTORS

CONTENTS

1.0 INTRODUCTION

If we take a trip down memory lane, in 1947, Shockley, Brattain, and Bardeen were investigating the field effect transistor but extreme difficulties diverted them into inventing the Bipolar Transistor instead of the Field Effect Transistor.

Prior to 1960, material processing technology had not attained the maturity requires to produce a functional Field Effect Transistor, therefore Shockley's field effect transistor theory was only published in 1952 and the working device had to wait until 1960 when John Atalla produced a working Field Effect Transistor for the first time.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Explain the operation of a JFET

2 Sketch a junction field effect transistor

3 List the advantages of junction field effect transistors

4 State why the JFET's input resistance is very high

5 Explain the role of the JFET's gate junction diode

6 Give a good reason why junction field effect transistors are difficult to manufacture

7 Bias a junction field effect transistor

8 Discus the effect of doping on channel depletion

9 Explain charge separation

10 Design a simple JFET common source amplifier

11 Draw a cross section view of a junction field effect transistor

12 Sketch P and N channel JFET common drain amplifiers

13 Refute the statement that JFETS are quite common in large scale integrated circuit chip design

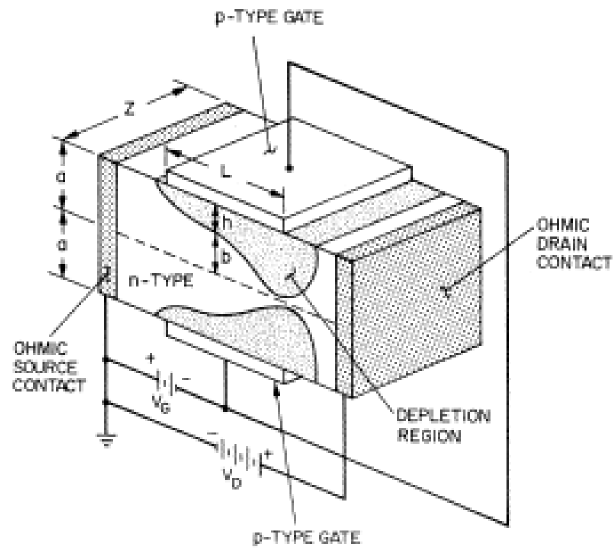
14 Explain why JFETS are immune to damage through electrostatic discharge

3.0 MAIN CONTENT

3.1 JUNCTION FIELD EFFECT TRANSISTORS (JFET)

Development and employment of transistors on a large scale started with the Bipolar Junction Transistor and this is the most common transistor which you will most likely find on a printed circuit board populated with transistors. It serves as a key device in, and has led to the solid state electronics revolution. The major drawback of the Bipolar Junction Transistor however is its very low input impedance which results from the forward bias of the Emitter-Base junction when in normal operation.

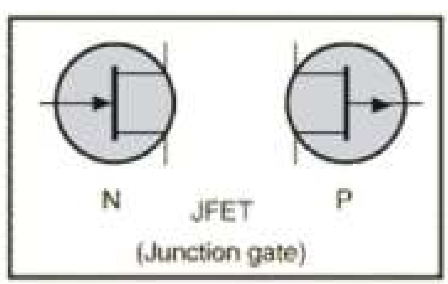
Now if you can imagine a junction device similar to the Bipolar Junction Transistor which operates with the input diode junction reversed biased, then you have imagined a Junction Field Effect Transistor or JFET in short, which with its reverse biased input junction presents very high input impedance.



Junction Field Effect Transistor

Several advantages are associated with high input impedance. For instance, having high input impedance minimizes the interference with or loading of the signal source when measurements are made and this is very useful in instrumentation.

An n-channel FET is constructed from a bar of n-type material, with the shaded areas composed of a p-type material as a Gate. Between the Source and the Drain, the n-type material acts as a resistor. The current flow consists of the majority carriers (electrons for n-type material) Since the Gate junction is reverse biased and because there is no minority carrier contribution to the flow through the device, the input impedance is extremely high.



N-channel and P Channel JFET

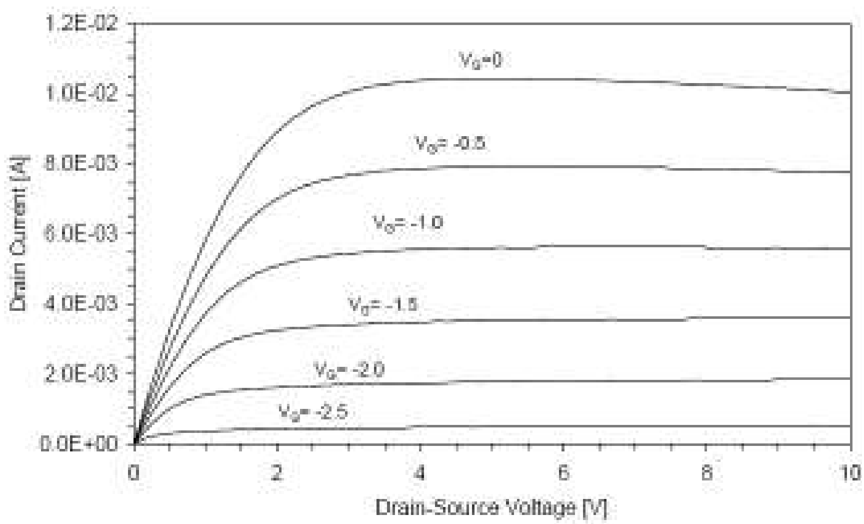
The control element for the JFET comes from depletion of charge carriers from the n-channel. When the Gate is made more negative, it depletes the majority carriers from a larger depletion zone around the gate. This reduces the current flow for a given value of Source-to-Drain voltage.

Modulating the Gate voltage modulates the current flow through the device. The unipolar field effect transistor is conceptually simple, but difficult to manufacture. Why?

Well, it is possible to make bipolar transistors outside a strictly controlled production environment such as a clean room; it is absolutely necessity for field effect transistors to be prepared in a rigidly controlled and clean environment and with strict contamination control to prevent.

3.2 JFET CHARACTERISTIC CURVES

When you take a look at the characteristic curves for the JFET overleaf you will see that for a given value of Gate voltage, the current is very nearly constant over a wide range of Source-to-Drain voltages. The control element for the JFET comes from depletion of charge carriers from the n-channel. When the Gate is made more negative, it depletes the majority carriers from a larger depletion zone around the gate. This reduces the current flow for a given value of Source-to-Drain voltage. Modulating the Gate voltage modulates the current flow through the device.

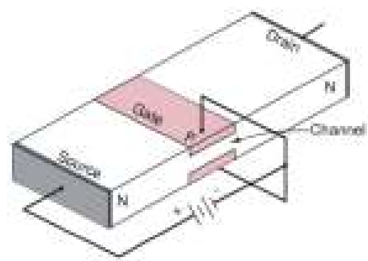


JFET Characteristic Curve

The transfer characteristic for the JTET is useful for visualizing the gain from the device and identifying the region of linearity. The gain is proportional to the slope of the transfer curve. The current value I_{DSS} represents the value when the Gate is shorted to ground, the maximum current for the device. This value will be part of the data supplied by the manufacturer. The Gate voltage at which the current reaches zero is called the "pinch voltage", V_P. Note that the dashed line representing the gain in the linear region of operation strikes the zero current line at about half the pinch voltage

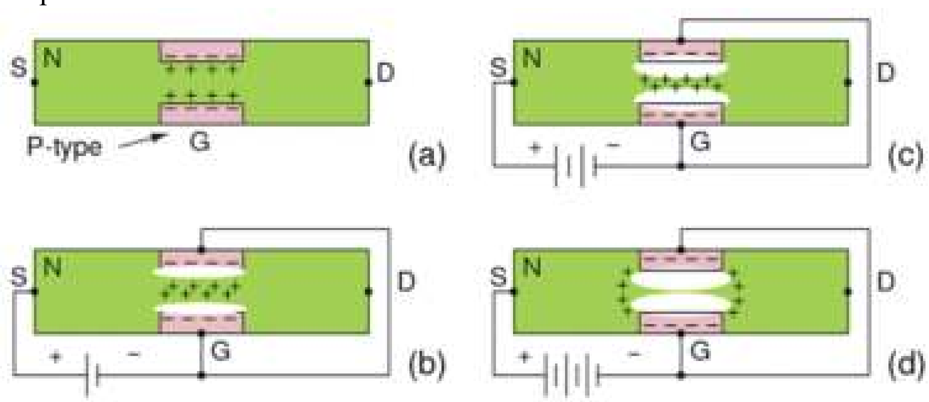
3.3 OPERATION OF JFET DEVICE

The operation of Field Effect Transistor is extremely simple. A voltage when applied to the gate, input element controls the resistance of the channel, which is the unipolar region between the gate regions.



Cross Section of Junction Field Effect Transistor

In an N-channel device, the channel is a lightly doped N-type slab of silicon with terminals located at each end. The source and drain terminals bear analogy to the emitter and collector, respectively, of a Bipolar Junction Transistor. In an N-channel device, a heavy P-type region located approximately midway on both sides of the slab serves as a control electrode, the gate. The gate is similarly analogous to the base terminal of a Bipolar Junction Transistor.



Biasing N-Channel JFET

In a properly biased N-channel Junction Field Effect Transistor (JFET) as illustrated above the gate appears as a diode junction to the source-drain semiconductor slab and is reverse biased. If a voltage were applied between the source and drain, the N-type bar would conduct in either direction because of the doping. Neither gate nor gate bias is required for conduction. If a gate junction is formed as illustrated above, conduction can be controlled by the degree of reverse bias.

Illustration (a) above shows the depletion region at the gate junction. This is due to diffusion of holes from the P-type gate region into the N-type channel, giving the charge separation about the junction, with a non-conductive depletion region at the junction. The depletion region extends more deeply into the channel side due to the heavy gate doping and light channel doping.

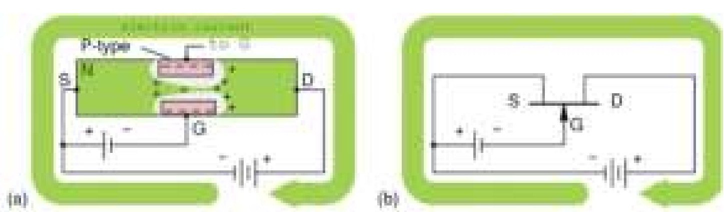
Take a look again at the illustration (a), (b), (c) and (d) above, (a) shows the depletion at gate diode under zero bias voltage. In (b) with reverse biased gate diode, the width of the depletion region increases while (c) shows the effect of increasing reverse bias which further enlarges the depletion region. Finally in (d) further increasing reverse bias pinches-off the Source-Drain channel and conduction through the semiconductor slab ceases altogether.

The thickness of the depletion region can be increased by applying moderate reverse bias as (b) illustrates. This increases the resistance of the source to drain channel by narrowing the channel. Increasing the reverse bias as shown in (c) increases the depletion region, decreases the channel width, and increases the channel resistance.

Increasing the reverse bias V_{GS} at (d) will pinch-off the channel current. The channel resistance will be very high. This V_{GS} at which pinch-off occurs is V_P, the pinch-off voltage. It is typically a few volts.

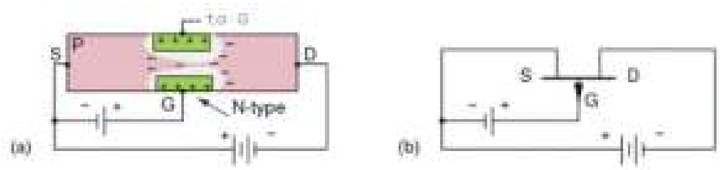
It should be quite clear to you by now that the channel resistance can be controlled by the degree of reverse biasing on the gate.

Remember that the source and drain are interchangeable, and the source to drain current may flow in either direction for low level drain battery voltage (< 0.6 V). That means, the drain battery can be replaced by a low voltage Alternating Current source.



N-Channel JFET

For a high drain power supply voltage however, the polarity must be as indicated in (a) above. This drain power supply which effect is not trivial distorts the depletion region by enlarging it on the drain side of the gate.



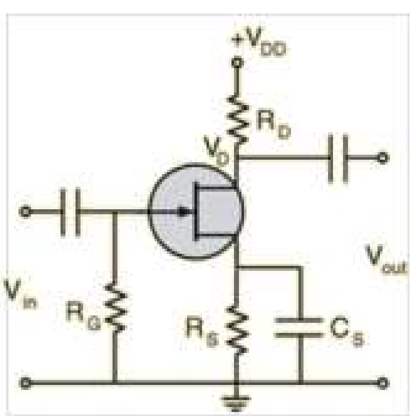
P-Channel JFET

This is a more correct representation for common DC drain supply voltages, from a few to tens of volts. As drain voltage V_{DS} is increased, the gate depletion region expands toward the drain. This increases the length of the narrow channel, increasing its resistance modestly. Larger resistance changes are due to changing gate bias.

Compare the two schematics in the preceding illustrations of N-Channel JFET and P-Channel JFET respectively and take particular note of the direction of the gate arrow in the schematics to the right of the illustrations; you will observe that the arrows point in the same direction as a junction diode. The directed arrow and non directed bar correspond to P and N-type semiconductors, respectively.

3.4 JFET AS AN AMPLIFIER

The most frequently encountered configuration in JFET amplifier design is the common source circuit where the source is common to the input as well as to the output. This is illustrated below.



N Channel JFET Common Source Amplifier

The source current flows through the resistor R_s to establish a voltage determined by the product of the two across the resistor. Noting that the gate is reversed biased with respect to the ground, it follows that effectively no current flows through the resistor R_g which infers that the voltage drop across it is zero; placing the gate effectively at ground potential. Drain current which flows through the resistor R_o creates a voltage drop across it being the product of the drain current and the output resistor R_o The difference between this voltage drop and the supply voltage represents the DC operating point of the drain.

The foregoing establishes the biasing of the transistor and the DC operating point. When a signal voltage is applied to the input through the capacitor, the signal sees R_g in parallel with the extremely high gate resistance of the JFET as the input impedance; this is essentially the same value as R_g which should be selected to be very high.

The voltage fluctuations at the input modulate the JFET's channel resistance which appears at the output as the lower arm of a voltage divider; the channel resistance being in series with the output resistance R_O the a rein turn are

4.0 CONCLUSION

In this unit we have learnt that Junction Field Effect transistors are device that operate with the input diode junction reversed biased which presents very high input impedance and derives its control from depletion of charge carriers from the channel.

5.0 SUMMARY

- Junction Field Effect Transistors derive control from depletion of charge carriers from the channel
- Very high input resistance is associated with the Junction Field Effect Transistor
- Junction Field Effect Transistor have a reversed biased gate junction diode
- Very clean manufacturing environment is necessary for Junction Field Effect Transistors

- Doping has a significant influence on channel depletion in Junction Field Effect Transistors

- Junction Field Effect Transistor are immune to damage through electrostatic discharge

- Modulating the Junction Field Effect Transistor's gate voltage modulates the current flow through the device

- Junction Field Effect Transistor is used as a switch or as an amplifier

6.0 TUTOR MARKED ASSIGNMENTS

1 Can you provide one good reason why bipolar junction transistors preceded field effect transistors?

2 The major drawback of the bipolar junction transistor is its very low input impedance when compared with the field effect transistor. Explain this as you would to a novice?

3 Describe in detail the operation of the junction field effect transistor?

4 Sketch the section of a junction P-channel field effect transistor and label its regions and parts?

5 Describe the control process for the junction field effect transistor stating why essentially all junction field effect transistors are depletion mode devices?

6 Why do junction field effect transistors not have a fourth terminal?

7 Sketch a JFET characteristic curve and label it?

8 The gate voltage at which the source current reaches zero is called the pinch voltage. Graphically illustrate this with a sketch and explain the process of pinch off in terms of channel resistance?

9 Using an N-channel JFET symbol and two voltage sources, draw a circuit illustrating how this JFET is biased"

10 Draw a sketch similar to that of question 9 above, but replacing one of the voltage sources with a bias resistor?

11 Sketch an N-channel common source JFET amplifier? Describe it operation?

12 Why are junction field effect transistors difficult to manufacture?

13 Are junction field effect transistors damaged by electrostatic discharge? Explain why?

14 List five advantages junction field effect transistors have over bipolar junction transistors? Can you list two that they have over MOSFETs?

7.0 REFERENCES/FURTHER READINGS

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By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

Semiconductor Device Fundamentals
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Electronic Devices and Circuit Theory 7th Edition
By Robert E. Boylestad and Louis Nashesky Published by Prentice Hall

UNIT 3 METAL OXIDE FIELD EFFECT TRANSISTOR

CONTENTS

1.0 INTRODUCTION

Most transistors in the market today are Metal Oxide Semiconductor Field Effect Transistors or MOS-FETs in short. MOS-FET technology was developed mainly by companies such as Bell Laboratories, Fairchild Semiconductor, and several of Silicon Valley and Japanese electronics firms amongst others.

Field-effect transistors are so named because a weak electrical signal applied to the coming in through one electrode creates an electrical field through the transistor which controls a current travelling through the transistor.

In 1945, Shockley toyed with the idea for making solid state devices out of semiconductors. He believed that a strong electrical field could cause the flow of electricity within a nearby semiconductor and tried to build such a device, He was unsuccessful. He later requested that Walter Brattain built it, also without success.

Barely three years had later Brattain and Bardeen built the first working germanium point-contact transistor which was later followed by the junction transistor. Junction Transistors were manufactured for several years afterwards. However, in 1960 Bell scientist John Atalla developed a new design based on Shockley's original field-effect theories and by the late 1960s, manufacturers converted from junction type integrated circuits to field effect devices.

Today, most transistors are field-effect transistors and your everyday world is shaped by the millions of them you encounter directly and indirectly every single day – through information technology, communication technology and every facet of life that depend on electronics.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. State why MOSFETS are the most commonly used transistors
2. Explain the role Shockley played in the development of the MOSFETs
3. Discuss what is meant by conductively modulated device
4. Contrast the process by which conduction is modulated in the MOSFET and JFET
5. Say why MOSFET gate insulation is usually silicon dioxide
6. Sketch a MOSFET output curve
7. Explain the meaning of inversion in MOSFETs
8. Sketch the different configuration of P and N channel MOSFETs
9. Distinguish between the enhancement and depletion modes of operation in MOSFETs
10. Draw transfer curves for all four MOSFET configurations
11. Appreciate the benefits of MOSFETS over JFETS
12. Recognise the transition from weak to strong inversion in MOSFETS

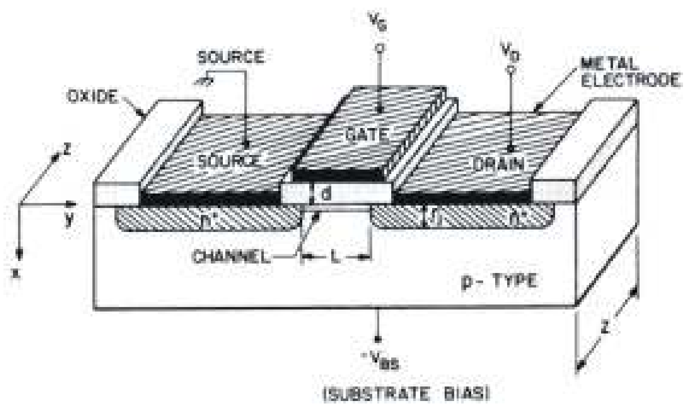
3.0 MAIN CONTENT

3.1 MOS-FET OPERATION

Both JFETs and MOSFETs are conductivity modulated devices, utilizing only one type of charge carrier which means they are unipolar devices as distinct from Bipolar Transistors which utilize both electrons and holes.

In a MOS-FET, the P-N junction is replaced with a metal-oxide layer, which is much easier to mass produce; particularly in microchips involving thousands integrated MOSFET devices.

Unlike a JFET in which a conducting channel is formed by doping and its geometry modulated by the applied voltages, MOSFETs change the carrier concentration in their channel which in turn changes the conductivity of the channel.



MOSFET structure

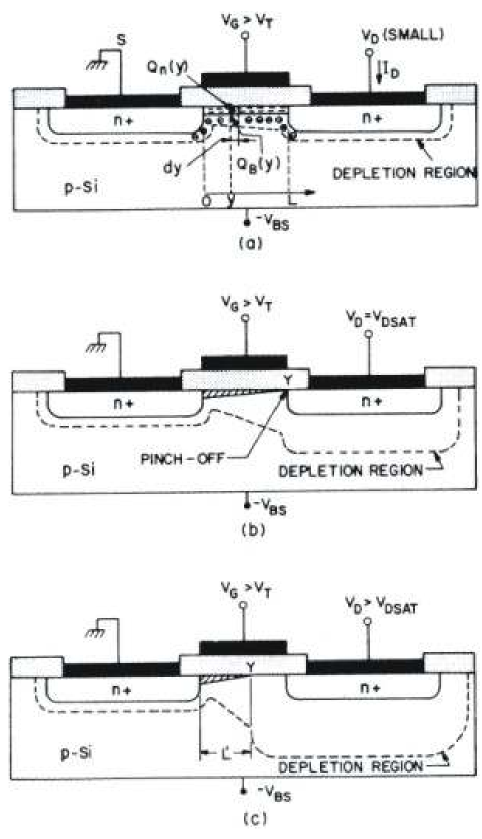
In the illustration of a p – type MOSFET above, the source and drain are *n*+ regions in a *p*-substrate while the gate is capacitive coupled to the channel region through an insulating layer; this insulating layer is usually a thin layer of Silicon dioxide (SiO_2).

When a positive voltage is applied to the gate, the electron concentration at the silicon surface beneath the gate increases and just as in the JFET the combination of the gate and drain voltages control the conductivity of the channel.

It s useful for you to remember that in the absence of any special surface preparation the surface of silicon is *n*-type, i.e. *p*-type silicon inverts at the surface. An *n*-channel MOSFET utilizes an *n*-channel in a *p*-substrate, so application of a positive potential to the gate forms the inversion layer needed for the channel.

As in the JFET, the combination of current flow in the channel and the applied potentials forms a depletion region that is greatest near the drain. At a sufficiently large drain potential the channel "pinches off".

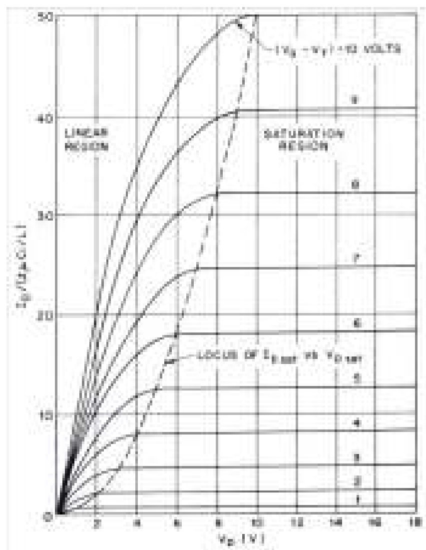
The illustrations (a), (b) and (c) below show the relationship between Drain voltage and saturation in a MOSFET. In the illustration (a), the drain voltage is less than the saturation voltage which can be expressed as V_D < Vsat. In this region the MOSFET presents a resistive channel. When V_D = Vsat as illustrated in (b) saturation begins to set in and when VD > Vsat as illustration (c) depicts, output current of the MOFET is saturated.



Relationship between Drain voltage and saturation in MOSFET

3.2 MOSFET OUTPUT CURVES

The output curves of a MOSFET are similar to a Junction Field Effect Transistor and similarly, the drain voltage required to attain saturation increases with the operating current.



MOFET Characteristic Curves

When the MOSFET is in the saturation region

$$I_D = \frac{W}{L}\frac{\mu\, C_i}{2}(V_G - V_T)^2$$

Where C_i is the gate capacitance per unit area e_{ox}/d_{ox} and V_T is the gate threshold voltage which corresponds to the commencement of strong inversion.

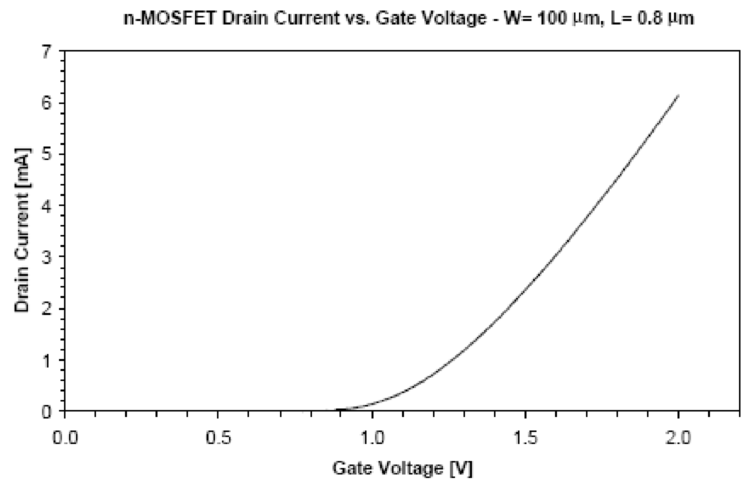
From the above, the transconductance is

$$g_m = \frac{W}{L}C_i\mu\,(V_G - V_T) = \frac{W}{L}\frac{\varepsilon_{ox}}{d_{ox}}\mu\,(V_G - V_T) = \sqrt{\frac{W}{L}\cdot\frac{\varepsilon_{ox}}{d_{ox}}\mu\cdot I_D}$$

and with a given width W and drain current I_D the transconductance is increased by decreasing the channel length L and the thickness of the gate oxide d_{ox}

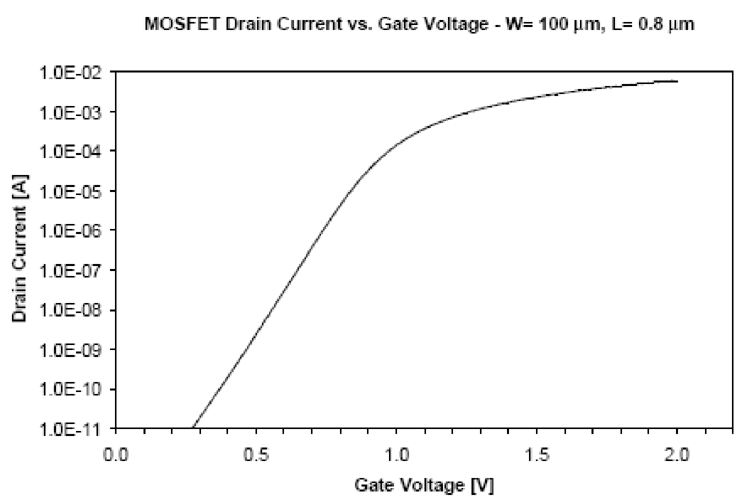
Once you understand the relationships between the variables which determine transconductance, you are well on your way towards understanding the physical parameters involved in the construction of MOFETs and how they are controlled to give specific device performance characteristics. Let's give this a try.

Let us consider a typical case with the measured characteristics of an *n*-channel MOSFET with 0.8 mm channel length and with 20 nm gate oxide thickness. The resultant plot is as shown below and you can see that for this device the threshold voltage V_T is about 1.2 V.



MOSFET with 0.8 mm channel length and 20 nm gate oxide thickness

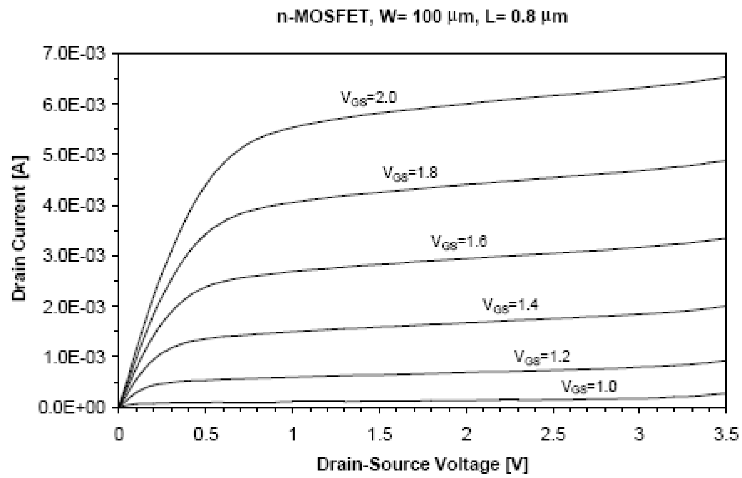
Further to this, when we plot the Drain Current against Gate Voltage on a logarithmic scale, the transition from weak to strong inversion becomes immediately apparent in the plot below.



Transition from Weak to Strong Inversion

Below the threshold region, the drain current is proportional to the inversion carrier concentration, and this increases exponentially with gate voltage.

Take a close look at the graphical display of this relationship below where you will see that clearly the increasing output saturation voltage with increasing gate voltage in the output curves.



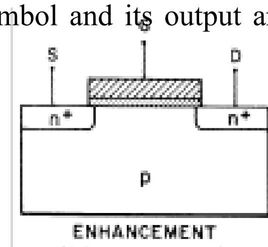
Increasing Output Saturation Voltage With Increasing Gate

3.3 MOSFET DEVICE TYPES

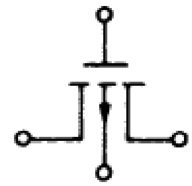
MOSFETs can be implemented with either *n* or *p*-channels depending on the substrate doping while a thin surface layer can be implanted to adjust the threshold voltage. This determines whether the device is normally on at zero gate voltage (the depletion mode device) or normally off at zero gate voltage whereby the gate requires increased voltage to form an inversion layer (the enhancement mode device)

3.3.1 P-Channel Enhancement Mode

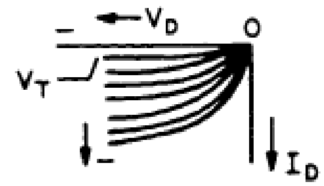
The P-Channel Enhancement mode MOSFET is normally off and applied gate voltage reduces channel resistance. The diagram below illustrates its construction, electrical symbol and its output and transfer characteristics respectively.



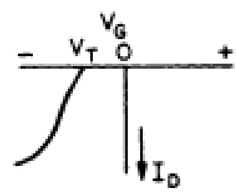
P-Channel Enhancement mode MOSFET



P-Channel Enhancement mode MOSFET electrical symbol



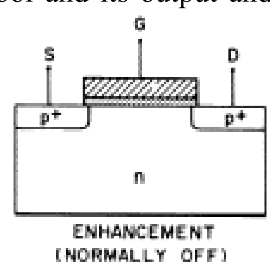
P-Channel Enhancement mode MOSFET output curve symbol



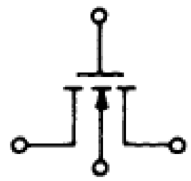
P-Channel Enhancement mode MOSFET transfer curve

3.3.2 N-Channel Enhancement Mode

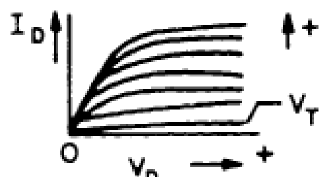
The N-Channel Enhancement mode MOSFET is normally off and applied gate voltage reduces channel resistance. The diagram below illustrates its construction, electrical symbol and its output and transfer characteristics respectively.



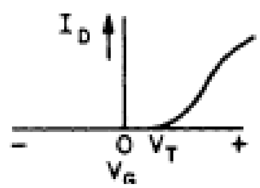
N-Channel Enhancement mode MOSFET



N-Channel Enhancement mode MOSFET electrical symbol



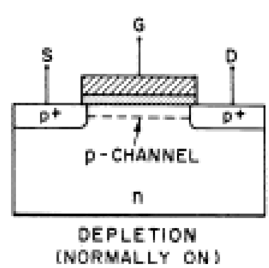
N-Channel Enhancement mode MOSFET output curve symbol



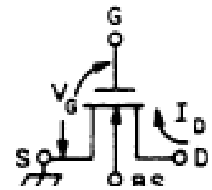
N-Channel Enhancement mode MOSFET transfer curve

3.3.3 P-Channel Depletion Mode

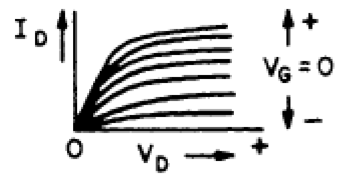
The P-Channel Depletion mode MOSFET is normally off and applied gate voltage reduces channel resistance. The diagram below illustrates its construction, electrical symbol and its output and transfer characteristics respectively.



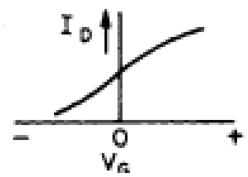
P-Channel Depletion mode MOSFET



P-Channel Depletion mode MOSFET electrical symbol



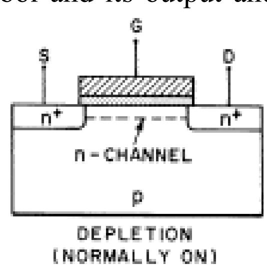
P-Channel Depletion mode MOSFET output curve symbol



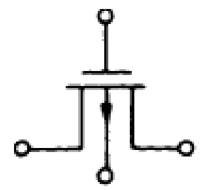
P-Channel Depletion mode MOSFET transfer curve

3.3.4 N-Channel Depletion Mode

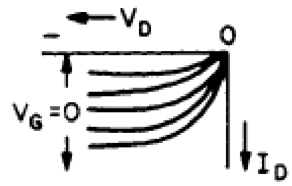
The N-Channel Depletion mode MOSFET is normally off and applied gate voltage reduces channel resistance. The diagram below illustrates its construction, electrical symbol and its output and transfer characteristics respectively.



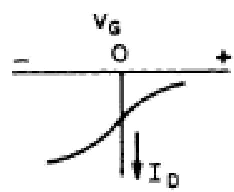
N-Channel Depletion mode MOSFET



N-Channel Depletion mode MOSFET electrical symbol



N-Channel Depletion mode MOSFET output curve symbol



N-Channel Depletion mode MOSFET transfer curve

4.0 CONCLUSION

In this unit we have learnt that the MOSFET operates by changing the carrier concentration in the device's channel which in turn changes the conductivity of the channel as distinguished from a JFET in which a conducting channel is formed by doping and its geometry is modulated by applied voltages,

5.0 SUMMARY

- MOSFETs action changes the conductivity the device's channel by changing carrier concentration
- The insulating layer at the gate is responsible for the high input impedance of the MOSFET
- MOSFETs are susceptible to electrostatic damage

- MOSFETS are the most commonly used transistors
- While both MOSFET and JFET devices are conductively modulated devices, the process of modulation are different
- MOSFET gate insulation is usually made of silicon dioxide
- There are four basic MOSFET modes of operation; P channel enhancement, N channel enhancement, P channel depletion and N channel depletion
- The three regions of operation associated with MOSFET transistors output curves are Pinch Off, Ohmic and Saturation regions
- On the logarithmic scale, transition from weak to strong inversion in MOSFETS is recognisable

6.0 TUTOR MARKED ASSIGNMENTS

1 Sketch a MOSFET, label its parts and describe MOSFET operation?

2 Why does the MOSFET not have a PN junction like the JFET?

3 In the MOSFET, how is the gate capacitive coupled to the channel region? Through what?

4 How many different types of MOSFETs are there? Sketch and label all of them?

5 Sketch a MOSFET output characteristic curve and label it highlighting the linear region and the saturation region?

6 Sketch the symbols of P-type enhancement mode and P-type depletion mode MOSFETs and state the observable differences in these sketches?

7 Why are MOSFETs susceptible to electrostatic damage?

8 To what potential is the substrate of MOSFET connected?

9 Describe the process of inversion in the MOSFET?

10 Using a sketch, illustrate the transition from weak to strong inversion?

7.0 REFERENCES/FURTHER READINGS

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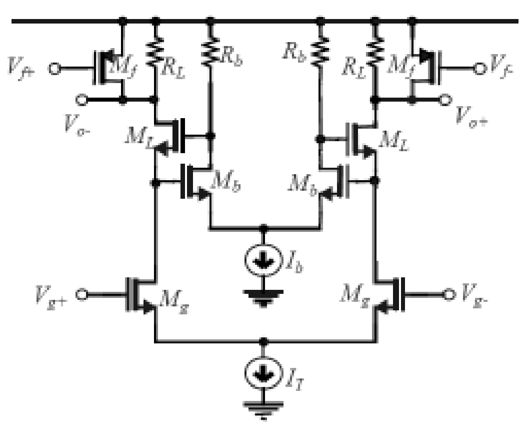
By Alexander and Sadiku Published by Mc Graw Hill

UNIT 4 TYPES AND CLASSIFICATION OF AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

An electronic amplifier is a device for increasing the power of an electrical signal which it does by taking energy from a power supply and controlling its output to match the input signal shape but with larger amplitude.



Circuit Diagram of An Amplifier

An amplifier can be classified according to input and output properties. All amplifiers have a multiplication factor which relates the magnitude of the output signal to the input signal. This multiplication factor is the Gain of the amplifier and may be specified as the ratio of output voltage to input voltage (in the case of voltage gain), output power to input power (in the case of power gain), or some combination of current, voltage and power.

Most times the input and output parameters of an amplifier are in the same units and in such cases, gain will be unit less quantity which may be expressed in decibels). Other cases might involve a mix of parametric units and this is the case with transconductance amplifier for example which has a gain with units of conductance (output current per input voltage).

The power gain of an amplifier depends on the source and load impedances used as well as its voltage gain and while a Radio Frequency amplifier may have its output and load impedances optimized for maximum power transfer, audio and instrumentation amplifiers are normally employed with amplifier input and output impedances optimized for least loading and highest quality.

It is often desirable that amplifiers possess a linear amplitude and frequency response for minimal distortion. This means that an amplifier with a linear amplitude response should have constant gain for any combination of input and output signal. If the gain is not constant, the output signal will be distorted.

By contrast with the preceding chapter, there exist cases where variable gain is desirable such as cases where automatic gain control is requires; particularly in the radio frequency receiver circuits where fluctuating radio signal strength has to be automatically compensated for.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. Recognise the different amplifier types
2. Be able to identify classes A, B, AB and C amplifiers
3. Discuss the attributes of power amplifiers
4. Explain the causes of nonlinearity in non class A amplifiers

5 Know why power amplifiers are often the last stage in a cascade

6 Determine the efficiency of amplifiers

7 Design simple amplifier circuits

8 State the properties of operational amplifiers

9 Apply common terminal classification to BJT, FET and triode amplifiers.

10 Explain current, voltage and power gain

11 Convert power, voltage and current ratio to decibel

12 Describe transconductance

13 Sketch the amplitude-frequency curve of an amplifier

14 Know which amplifiers employ variable gain

15 Enumerate the merits and demerits of BJT amplifiers

16 Explain why all operational amplifiers are not differential amplifiers

17 List why classes A, AB, B and C amplifiers are suitable for analogue applications

18 Appreciate the relationship between amplifier efficiency and nonlinearity

3.0 MAIN CONTENT

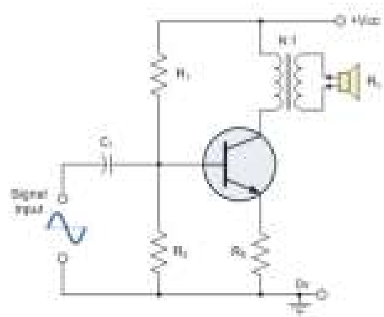
3.1 AMPLIFIER TYPES

Of the numerous amplifier types and applications, the following are highlighted so that you may have a grasp and become familiar with some of their properties and characteristics.

3.1.1 Power Amplifier

Power Amplifiers are often designated as the last amplifier in a transmission chain which usually is the output stage and is the amplifier stage that typically requires most attention to power efficiency.

This efficiency considerations result in various classes of power amplifiers and power amplification may loosely be related to the amount of power delivered to a load and/or sourced by the supply circuitry.



Audio Power Amplifier

Semiconductor amplifiers have to a large extent replaced valve amplifiers in low power applications however; they are little applied in high power applications where valve amplifiers are much more cost effective. These applications include radar, communications equipment and microwave amplifiers which utilise specially designed valves, such as the klystron, gyrotron, travelling wave tube, and crossed-field amplifier which provide much greater single-device power output at microwave frequencies than solid-state devices.

3.1.2 Transistor Amplifier

Transistor amplifiers represent a very rich variety of applications utilising transistors of aggregations of transistors as may be found on a microchip.

The primary role of the transistor irrespective of it being a Bipolar Junction Transistor of a Field Effect Transistor is to magnify an input signal to yield a significantly larger output signal. The amount of magnification known as the forward gain is determined by the external circuit design as well as the active device.

Many common active devices in transistor amplifiers are bipolar junction transistors (BJTs) and metal oxide semiconductor field-effect transistors (MOSFETs) in which amplification can be realized using various configurations. With Bipolar Junction Transistors, the common base, common collector or common emitter amplifier are realisable while by using a MOSFET you can realize common gate, common source or common drain amplifier; each of which has different characteristic gain, impedance and frequency bandwidth.

3.1.3 Operational Amplifier

An operational amplifier is characterised by very high open loop gain and differential inputs and employs external feedback for control of its transfer function.

You should note that Operational Amplifiers can be realised using valve as there is a general misconception that an "Op-Amp" implies a solid state Integrated Circuit.

A fully differential amplifier is a special case of operational amplifier which apart from having differential input terminals also has fully differential output terminals.

3.2 CLASSIFICATION OF AMPLIFIERS

Many alternative classifications address different aspects of amplifier designs, and all without exception express some particular perspective relating the design parameters to the objectives of the circuit.

Any amplifier design is always a compromise of numerous factors, such as cost, power consumption, real-world device imperfections, and a multitude of performance specifications which all provide several different approaches to classification of amplifiers.

3.2.1 Common Terminal Classification

Classifications for amplifiers may be based on which device terminal is common to both the input and the output circuit. This is convenient because most real world amplifier elements are primarily three terminal circuit elements.

In the case of bipolar junction transistors, the three classes are common emitter, common base, and common collector, and for field-effect transistors, the corresponding configurations are common source, common gate, and common drain

Can you guess the configurations when applied to the Triode vacuum devices? Yes, the common cathode, common grid, and common plate.

Since the output voltage of a common plate amplifier is the same as the input voltage in an arrangement used to present a high input impedance so as not to load the signal source, the common plate amplifier does not amplify the voltage – but provides a current boost. This configuration of the Triode Tube is referred to as cathode follower and by analogy the terms emitter follower and source follower are sometimes used for the same configuration in BJT and FET transistors circuits.

3.2.2 Output and Input Variable Classification

Electronic amplifiers use two variables: current and voltage and either can be used as input or output leading to four types of amplifiers. In idealized form they are represented by each of the four types of dependent source used in linear analysis, namely: current amplifier, transresistance amplifier, transconductance amplifier and voltage amplifier.

In the real world the ideal impedances are only approximated. For any particular circuit, a small-signal analysis is often used to find the impedance actually achieved. A small-signal AC test current I_x is applied to the input or output node, all external sources are set to AC zero, and the corresponding alternating voltage V_x across the test current source determines the impedance seen at that node as $R = V_x / I_x$.

3.2.3 Unilateral or Bilateral Classification

By definition a unilateral amplifier has an output that exhibits no feedback to its input and as such the input impedance of a unilateral amplifier is independent of the load, and the output impedance is independent of the signal source impedance.

If feedback connects part of the output back to the input of the amplifier it is called a bilateral amplifier. The input impedance of a bilateral amplifier is dependent upon the load, and the output impedance is dependent upon the signal source impedance.

All amplifiers are bilateral to some degree; however they may often be modelled as unilateral under operating conditions where feedback is small enough to neglect for most purposes, simplifying analysis.

When negative feedback is applied deliberately, it is to tailor amplifier behaviour. Some feedback, which may be positive or negative, is unavoidable and often undesirable, introduced, for example, by parasitic elements such as the inherent capacitance between input and output of a device such as a transistor and capacitive coupling due to external wiring.

3.3 POWER AMPLIFIERS

Power amplifier circuits which are often output stages are classified as A, B, AB and C for analogue designs and applications. Additional classes D and E are for switching designs and are based upon the conduction angle of the input signal through the output amplifying device. This is the portion of the input signal cycle during which the amplifying device conducts.

The image of the conduction angle is derived from amplifying a sinusoidal signal. The angle of flow is closely related to the amplifier power efficiency. Apart from the classes mentioned above, there are several other amplifier classes, although they are mainly variations of the previous classes.

For example, class G and class H amplifiers are marked by variation of the supply rails either in discrete steps or continuous following the input signal and wasted heat on the output devices can be reduced as excess voltage is kept to a minimum. Amplifiers fed with these rails can be of any class.

These additional classes of amplifiers are more complex, and are mainly used for specialized applications, such as very high-power units. Also, class E and class F amplifiers are commonly described for radio frequencies applications where efficiency of the traditional classes are important. Other classes use harmonic tuning of their output networks to achieve higher efficiency and can be considered a subset of Class C due to their conduction angle characteristics

4.0 CONCLUSION

In this unit we have learnt that amplifiers are categorised according to any combination of a number of attributes which can be such as specific amplifier function, amplifier type, component material, active component type, operating range, operating power, operating frequency, voltage or current gain, relationship between input and output, and circuit layout or topology.

5.0 SUMMARY

- An electronic amplifier is a device for increasing the voltage, current or the power of an electrical signal

- Amplifiers function by taking energy from a power supply and controlling output to match input signal shape but with larger amplitude

- The different types of amplifiers include the Power Amplifier, the Transistor Amplifiers and the Operational Amplifier

- Several classes of amplifiers are defined according to their output signal waveform

- Three common terminal classifications of Bipolar Junction transistors are common emitter, common base and common collector

- Classes A, B, AB and C amplifiers have different operating efficiencies and different levels of distortion

- Power amplifiers are often the final stage of a cascade of amplifiers

- Operational amplifiers are idealised with infinitely high gain, infinitely high input impedance and zero output impedance

- Amplifier gain is often measured in Decibel

- Not all operational amplifiers are differential amplifiers

- Classes A, AB, B and C amplifiers are suitable for analogue applications while other classes are more suitable for switching purposes

6.0 TUTOR MARKED ASSIGNMENTS

1 In your own words, what is an amplifier? What qualifies an amplifier to be called a power amplifier?

2 If the power gain of an amplifier is 350, and the power output is 75 Watts, calculate its power input?

3 At what stage of an amplifier chain do you expect to find a power amplifier?

4 List five different categories of amplifiers?

5 If a circuit comprises transistor and valve amplification stages, can we qualify the circuit as a hybrid amplifier? Explain further?

6 List the idealised parametric quantities of an operational amplifier?

7 State four different classifications of amplifiers?

8 What do you understand by a transresistance amplifier? Can you give a practical example of one such amplifier?

9 Sketch a block diagram of a unilateral amplifier and a bilateral amplifier, and then use these to describe these properties of amplifiers? Why do you think that all real world amplifiers are more bilateral than unilateral?

10 Describe feedback? Describe negative feedback? Describe positive feedback? When are positive and negative feedbacks beneficial and when are they not? Draw sketches to buttress your answer?

11 State four types of amplifiers based on their classification by their input and output variables?

12 Compare and contrast a linear amplifier with a nonlinear one?

13 In what unit is power amplification measured?

14 A power amplifier has a power gain of 7.7 Decibels. Does this mean it has a voltage gain of 15.4 Decibels? Explain why?

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By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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UNIT 5 COMMON EMITTER, COMMON BASE & COMMON COLLECTOR AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

You will recall that in 3.2.1 of Unit 4 we treated Common Terminal Classification of amplifiers in which the device terminal common to both the input and the output circuit is adopted in the nomenclature of the amplifier class.

As quoted in that section "In the case of bipolar junction transistors, the three classes are common emitter, common base, and common collector, and for field-effect transistors, the corresponding configurations are common source, common gate, and common drain".

We shall take a closer look at the three Bipolar Junction Transistor configurations in this unit.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Sketch common emitter, common base and common collector amplifiers

2 Know the relationship between emitter, base and collector currents

3 Explain emitter degeneration and relate it to negative feedback

4 Understand why emitter degeneration increases bandwidth

5 Say why the emitter follower is best for high impedance input signal sources

6 Recognise that the common collector amplifier is also called the emitter follower

7 Know why the common base amplifier is best used as a voltage amplifier

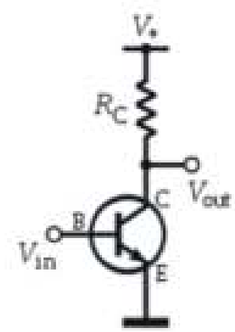
8 Calculate why the current gain of the common base amplifier is approximately unity

9 Discover why the voltage gain of the common collector amplifier is almost unity

10 Explain the meaning of current mirror

3.0 MAIN CONTENT

3.1 COMMON EMITTER AMPLIFIER

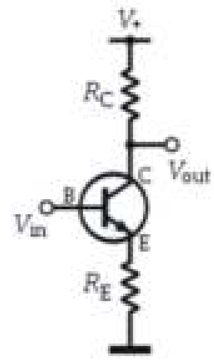


Common Emitter Amplifier

The Common-Emitter amplifier as illustrated above provides a high gain and an inverted output. The gain may vary from one device to the other and has a strong dependence on temperature and the bias current.

The gain is unpredictable and instability is a frequent problem resulting from unintentional positive feedback that may be present in the circuit. Some other problems associated with the Common Emitter circuit are the low input dynamic range imposed by the small-signal limit; there is high distortion if this limit is exceeded and the transistor ceases to behave like its small-signal model.

Negative feedback is applied through emitter degeneration. By this we mean that a small impedance is added in series with the common terminal which reduces the overall transconductance of the circuit as well as the voltage gain. This is illustrated below.



Negative Feedback applied through Emitter Degeneration

With the emitter degeneration resistor R_E in series with the emitter, transconductance becomes reduced by a factor of $g_m R_E + 1$, which makes the voltage gain

$$A_v \triangleq \frac{v_{out}}{v_{in}} = \frac{-g_m R_C}{g_m R_E + 1} \approx -\frac{R_C}{R_E} \qquad (\text{where} \quad g_m R_E \gg 1)$$

So the voltage gain depends almost exclusively on the ratio of the resistors R_C / R_E rather than the transistor's intrinsic and unpredictable characteristics. The distortion and stability characteristics of the circuit are thus improved at the expense of a reduction in gain.

At low frequencies the small-signal characteristics are:

Current Gain = $A_i \triangleq \frac{i_{out}}{i_{in}}$ denoted by β

Voltage Gain = $A_v \triangleq \frac{v_{out}}{v_{in}}$ denoted by $-\frac{\beta R_C}{r_\pi + (\beta+1) R_E}$

Input Impedance = $r_{in} \triangleq \frac{v_{in}}{i_{in}}$ denoted by $r_\pi + (\beta + 1) R_E$

Output Impedance = $r_{out} \triangleq \frac{v_{out}}{i_{out}}$ denoted by R_C

If the emitter degeneration resistor is not present, R_E = 0 ohms when R_E is increased, the input impedance is increased and the voltage gain A_V is reduced.

The bandwidth of the common-emitter amplifier tends to be low due to high internal capacitance This large capacitor greatly decreases the bandwidth of the amplifier and the problem can be eliminated in any one of the following ways.

- By reducing voltage gain through emitter degeneration
- By reducing signal source impedance
- By inserting a low input impedance current buffer
- Using an emitter follower to reduce the Miller effect is removed.

The common- emitter amplifier output is 180 degrees out of phase with the input signal. The input signal is applied across the ground and the base circuit of the transistor. The output signal appears across ground and the collector of the transistor. Since the emitter is connected to the ground, it is common to signals, input and output. The common- emitter circuit is the most widely used configuration in junction, transistor amplifiers.

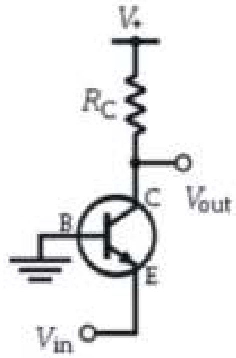
When compared with the common-base connection, the common emitter has higher input impedance and lower output impedance. A single power supply is easily used for biasing the circuit and in addition, higher voltage and power gains are obtainable from common-emitter amplifiers.

Current gain in the common emitter circuit is obtained from the base and the collector circuit currents. Because a very small change in base current produces a large change in collector current, the current gain (β) is always greater than unity for the common-emitter circuit; a typical value is about 50 and it is not unusual to obtain values of 300 from PNP transistors.

The applications of the Common Emitter Amplifier range from low frequency audio amplification through radio frequency tuners.

3.2 COMMON BASE AMPLIFIER

The common-base amplifier which is also known as grounded-base amplifier is one of high-frequency amplifiers in the Very High Frequency and Ultra High Frequency range because its input capacitance does not degrade bandwidth and because of the relatively high isolation between the input and output which translates into very little feedback from the output back to the input. This ensures high stability.



Common Base Amplifier

Common Base configuration finds application as current buffers since they have a current gain of approximately unity and very often, a common base amplifier is preceded by a common-emitter stage. The combination of these two forms the cascode configuration, which possesses several of the benefits of each configuration, such as high input impedance and isolation.

At low frequencies and under small-signal conditions, the Common Base Circuit has the following characteristics. First the definitions:

Open Circuit Voltage Gain = $A_v = \frac{v_o}{v_i}\Big|_{R_L=\infty}$

Short Circuit Current Gain = $A_i = \frac{i_o}{i_i}\Big|_{R_L=0}$

Input Impedance = $R_{\text{in}} = \frac{v_i}{i_i}$

Output Impedance = $R_{\text{out}} = \frac{v_o}{-i_o}\Big|_{v_s=0}$

With the complementing expressions:

Open Circuit Voltage Gain = $\frac{(g_m r_O + 1)R_C}{R_C + r_O}$

Short Circuit Current Gain = $\frac{r_\pi + \beta r_O}{r_\pi + (\beta+1)r_O}$

Input Impedance = $\frac{(r_O + R_C \| R_L) r_E}{r_O + r_E + \frac{R_C \| R_L}{\beta+1}}$

Output Impedance = $R_C \| \{[1 + g_m(r_\pi \| R_S)]r_O + (r_\pi \| R_S)\}$

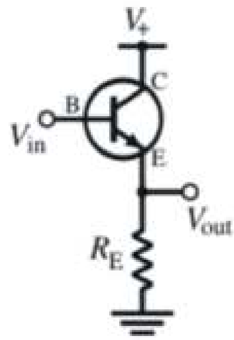
The range of allowed output voltage swing in this amplifier is tied to its voltage gain when a resistor load R_C is employed for voltage amplification, Large voltage gain requires large R_C, and that in turn implies a large DC voltage drop across R_C .and for a given supply voltage, the larger this drop, the smaller the transistor V_{CB} and the less output swing is allowed before saturation of the transistor occurs.

Saturation results in distortion of the output signal and to avoid this situation an active load can be used as in for example, a current mirror. If this choice is made, the value of R_C is replaced by the small-signal output resistance of the active load, which is generally at least as large as the output resistance of the active transistor.

On the other hand, the DC voltage drop across the active load is a fixed low value which is much less than the DC voltage drop incurred for comparable gain using a resistor R_C. An active load imposes less restriction on the output voltage swing.

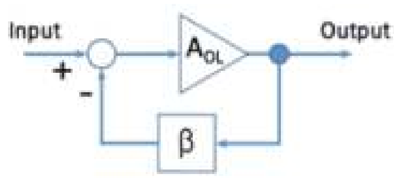
When used as a current buffer, gain is not affected by R_C, but output resistance is. Because of the current division at the output, it is desirable to have an output resistance for the buffer much larger than the load R_L being driven so that large signal currents can be delivered to a load. If a resistor R_C is used, a large output resistance is coupled to a large R_C, again limiting the signal swing at the output. An active load provides high AC output resistance with much less serious impact upon the amplitude of output signal swing.

3.3 COMMON COLLECTOR AMPLIFIER



Common Collector Amplifier

You can explain the circuit by viewing the transistor as being under the control of negative feedback as illustrated below and from this viewpoint, a common-collector stage as illustrated above is an amplifier with full series negative feedback. In this configuration with $\beta = 1$, the entire output voltage V_{OUT} is placed contrary and in series with the input voltage V_{IN}. Thus the two voltages are subtracted according to Kirchhoff's Voltage Law and their difference $V_{diff} = V_{IN} - V_{OUT}$ is applied to the base-emitter junction.



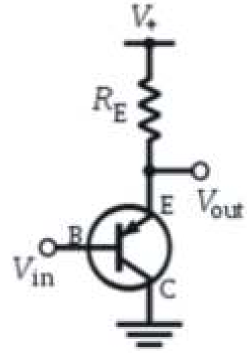
Negative Feedback Amplifier

The transistor monitors continuously V_{diff} and adjusts its emitter voltage almost equal (less V_{BEO}) to the input voltage by passing the according collector current through the emitter resistor R_E. As a result, the output voltage follows the input voltage variations from V_{BEO} up to V_+; which gives the amplifier the name, emitter follower.

Intuitively, this behaviour can be also understood by realizing that the base-emitter voltage in the bipolar transistor is very insensitive to bias changes, so any change in base voltage is more or less transmitted directly to the emitter. It depends slightly on various individual transistor circuit characteristics and environmental variables like tolerances, temperature variations, load resistance, collector resistor if it is added, etc. since the transistor reacts to these disturbances and restore the equilibrium. It never saturates even if the input voltage reaches the positive supply rail.

The common collector circuit can be shown mathematically to have a voltage gain of almost unity:

$$A_v = \frac{v_{out}}{v_{in}} \approx 1$$



All Polarities are reversed in PNP Emitter Follower Circuit

A small voltage change on the input terminal is replicated at the output. This circuit presents large input impedance, so it will not load down the previous circuit:

$$r_{in} \approx \beta_0 R_E$$

And it also presents low output impedance, so it can drive low-resistance loads:

$$r_{out} \approx R_E \| \frac{R_{source}}{\beta_0}$$

And typically, the emitter resistor is significantly larger and can be removed from the equation:

$$r_{out} \approx \frac{R_{source}}{\beta_0}$$

At low frequencies the following characteristics apply with parameters $\beta = g_m r_\pi$ and the parallel lines indicate components in parallel.

The following are parametric definitions:

Current Gain = $A_{\mathrm{i}} = \frac{i_{\mathrm{out}}}{i_{\mathrm{in}}}$

Voltage Gain = $A_{\mathrm{v}} = \frac{v_{\mathrm{out}}}{v_{\mathrm{in}}}$

Input Impedance = $r_{\mathrm{in}} = \frac{v_{in}}{i_{in}}$

Output Impedance = $r_{\mathrm{out}} = \frac{v_{out}}{i_{out}}$

Which have the following expressions:

Current Gain = $\beta_0 + 1$

Voltage Gain = $\frac{g_m R_{\mathrm{E}}}{g_m R_{\mathrm{E}} + 1}$

Input Impedance = $r_\pi + (\beta_0 + 1) R_{\mathrm{E}}$

Output Impedance = $R_{\mathrm{E}} || \left(\frac{r_\pi + R_{\mathrm{source}}}{\beta_0 + 1} \right)$

4.0 CONCLUSION

In this unit we have learnt that the common terminal classification of Bipolar Junction transistor amplifiers are the common emitter, common base, and common collector; in which the transistor's common terminal designated is common to both the input and the output.

5.0 SUMMARY

- The arithmetic sum of the base and the collector current of a transistor is equal to the emitter current
- Emitter degeneration t is a form of negative feedback
- Emitter degeneration, and indeed negative feedback in general increases signal bandwidth and linearity

- The common collector amplifier is also known as the emitter follower

- Common collector amplifiers are characterised by very high input impedance and relatively low output impedance when compared with the other two common terminal configurations

- The voltage gain of a common collector amplifier is essentially unity

- The common base amplifier is best used as a voltage amplifier

- The current gain of the common base amplifier is approximately unity

- Transistor current gain which is the ratio between the collector and base currents is designated with the symbol β

- Common base input capacitance does not degrade bandwidth and there is relatively high isolation between the input and output which makes it most suitable for very high radio frequency applications

6.0 TUTOR MARKED ASSIGNMENTS

1 By what are common emitter, common base and common collector amplifiers classified?

2 What type of amplifier suffers emitter degeneration? How are the effects of emitter degeneration neutralised at signal frequencies?

3 Can you explain if emitter degeneration is a form of negative feedback? If it is then how?

4 Which of the three common terminal amplifiers has the highest input impedance? And which has the highest voltage gain? Explain how?

5 What is the Miller effect, a capacitance or an inductance? Explain how it is reduced by using an emitter follower?

6 Sketch a common base amplifier stage and derive an expression for it voltage gain? Also derive an expression for its current gain?

7 Why is the common emitter amplifier's bandwidth the smallest out of the three common terminal transistor configurations? How can you increase this bandwidth?

8 Common base amplifiers are best suited for very high frequency work. Can you provide two good reasons why this is so?

9 Show that a common collector stage's voltage gain is less than but very close to unity? And explain why it's output DC voltage is always lower than its input DC voltage by approximately 0.7 volts?

10 Sketch a PNP common collector configuration indicating the emitter resistor? Label the parts?

11 What is the arithmetic relationship between the emitter, collector and base currents of a transistor?

12 List four parametric limitations of bipolar transistors in the design of common terminal amplifiers?

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By Robert E. Boylestad and Louis Nashesky Published by Prentice Hall

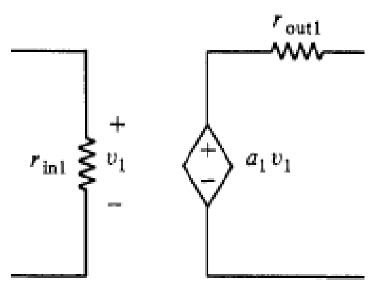
Fundamentals of Electric Circuits 4th Edition
By Alexander and Sadiku Published by Mc Graw Hill

UNIT 6 MULTISTAGE AMPLIFIERS

CONTENTS

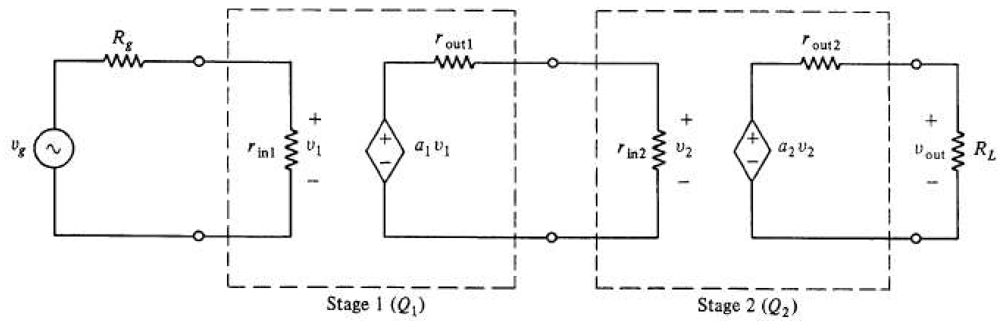
1.0 INTRODUCTION

Single stage amplifiers are characterized by finite and limited gain as well as finite and limited input and output impedances which are far from ideal irrespective of whether they are voltage amplifiers, current amplifiers or transconductance amplifiers.



Single Stage Amplifier

For the reasons above amongst others, multistage amplifiers, typified by the illustration below have evolved to provide desired gain, or just simply to buffer input or output performance of amplifiers. You can see examples of these in everyday appliances such as voltage probes, where a unity gain front end amplifier serves as a current boosting buffer, or in a current driver output buffer which establishes output voltage across a load and drives a desired current trough the load by acting as a high impedance output buffer.



Multistage Amplifier

As there is a limit to how much gain can be achieved from a single stage amplifier, multistage amplifiers find application and provide higher gain and better control of input and output impedances when desired. We can summarize by saying that the significant advantages multistage amplifiers have over single stage amplifiers are flexibility in input and output impedance and much higher gain.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. Explain the term multistage amplifier
2. List the merits demerits and of multistage amplifiers
3. Distinguish between open loop and closed loop multistage amplifiers
4. Associate instability with open loop multistage amplifiers
5. See how bandwidth and negative feedback are related
6. Find out why input and output impedances are better controlled in multistage amplifiers
7. Understand open loop and closed loop gain
8. Recognise operational amplifiers as multistage amplifiers
9. Describe the process of cascading amplifier stages

10 Sketch and name the four basic methods of applying negative feedback

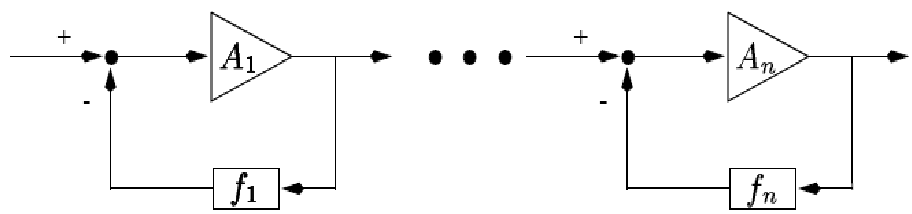
11 Understand that negative feedback reduces distortion

12 Know how amplifier gain is rendered independent of parameters and is defined by passive elements through negative feedback

3.0 MAIN CONTENT

3.1 CLASSIFICATION OF MULTISTAGE AMPLIFIERS

Multistage amplifiers are classified as open-loop, and negative feedback amplifiers. Open-loop amplifiers will be more straight forward and easier for you to understand and to design; however they have the drawback of being sensitive to environment and component variations.



Multistage Amplifier

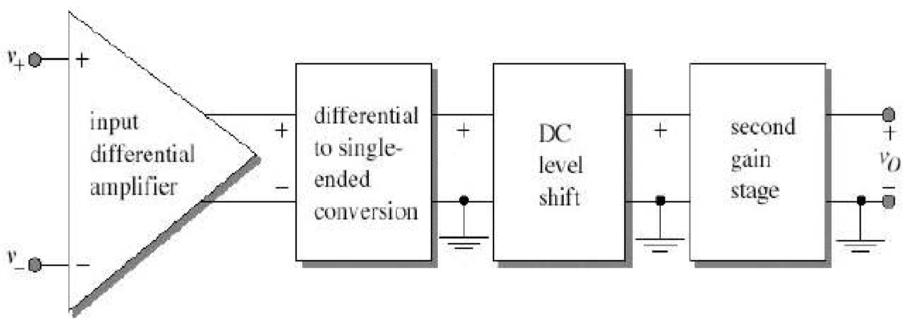
Negative feedback amplifiers on the other hand are more difficult to understand and more challenging to design. You may consider these difficulties trivial as they are more than compensated for by the advantage of being much less sensitive to environment and component variations.

Closed loop amplifiers are simply open loop amplifiers with a feedback loop and the design of a closed loop amplifier always begins with an open-loop amplifier. Subsequently, a good closed-loop amplifier begins with a good open-loop design.

For many transistor amplifier applications it is desirable for the input impedance to be very high. Thus, it is common for the first amplifier stage to be either a common-collector (emitter follower) bipolar junction transistor stage or a common-drain (source follower) or even common-source field effect transistor stage. Sometimes high input impedance is not important and the first stage may be a common-emitter. Field effect transistors are normally used only for the input stage and for the specific application of very high input impedance.

Where it is desirable for the output impedance of an amplifier to be low, a common-collector circuit is typically used. But in some cases there is no need for very low output impedance and the last stage may be a common-emitter. For the amplifier stages in-between it is common to employ common-emitter circuits because they achieve high voltage gain.

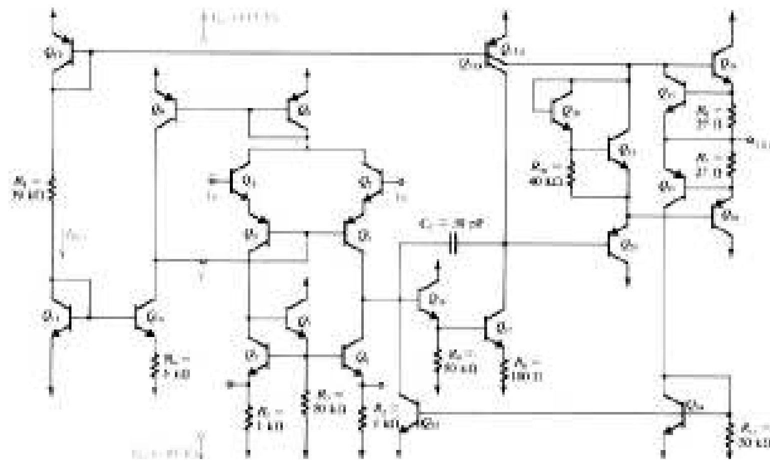
Multistage amplifiers are analysed a stage at a time starting with the input stage and progressing to the output stage. The analysis methods are identical to that of single stage amplifiers. One area of common contention, and which you should take serious note of in analyzing direct coupled amplifiers is the collector resistor of a preceding stage is the base resistor for the next stage to it.



Multistage Amplifiers Comprising Functionally Unique Stages

Stages involving common-collector amplifiers require modified approaches which may include simplification approximations because the characteristics of common collector stages depend on external impedances. You will routinely carry out these approximations and I therefore urge you to understand them and feel comfortable with using them as one main advantage of closed loop amplifiers is that errors resulting from approximation are greatly reduced.

When you design multistage amplifiers, you must start with the output stage and progresses towards the input stage and initially the number of stages might not be known to you. You must add stages incrementally until the desired requirements are met and it might entail a number of iteration in your design which number of stages you require might differ with each iteration.



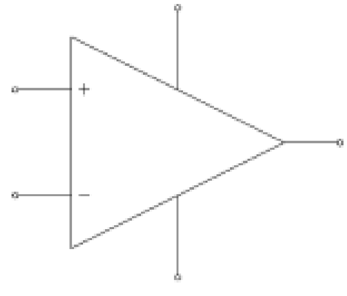
Operational Amplifiers as Multistage Amplifiers

Multistage amplifiers enable you to achieve greater input impedance and lower output impedance compared to single stage amplifier. There are also the benefits of higher gain and improved power handling capacity, particularly when implemented as integrated circuits which comprise large numbers of optimally matched transistors as illustrated above.

3.2 OPEN LOOP MULTISTAGE AMPLIFIERS

Because the performance obtainable from a single stage amplifier is usually inadequate, several stages may be combined to form a multistage amplifier in which the stages are connected in cascade. This means that the output of the first stage is connected to the input of the second stage, whose output becomes an input for the third stage. This is replicated until you get to the last stage; which very often is a power stage.

As you might have guessed, the open loop gain of an amplifier is its gain when no feedback is used in its circuit and the value of the open loop gain is usually very high indeed for such circuits as operational amplifiers because an ideal operational amplifier is assumed to have infinite open-loop gain.



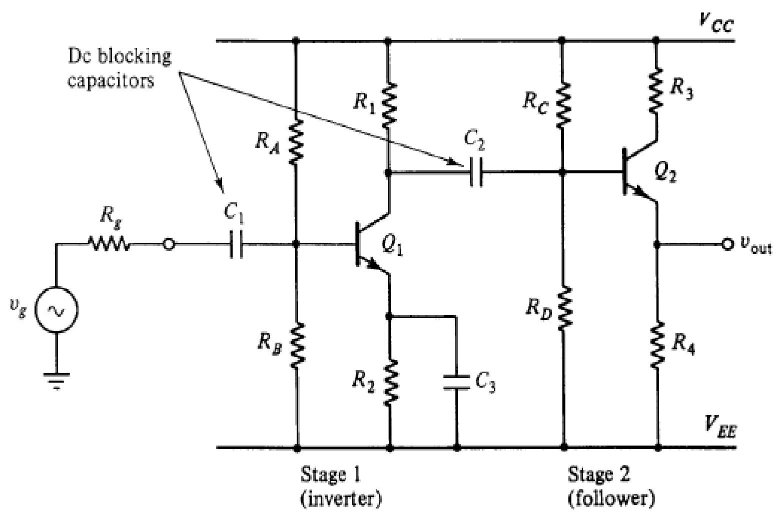
Basic Operational Amplifier as Open Loop Amplifier

The overall gain of a multistage amplifier is the product of the individual gains of the cascaded stages.

This can be expressed as follows where A_n is the gain associated with stage n :

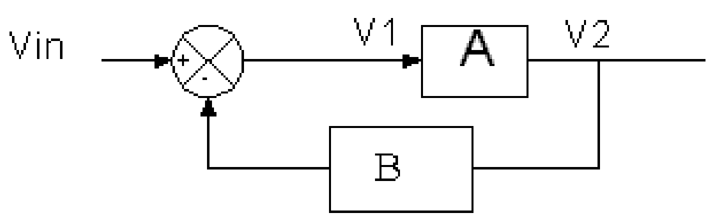
Gain (A) = $A_1 A_2 A_3 A_4 \dots A_n$.

As you can see; extremely high gain figures are possible with open loop amplifiers, however, a major drawback of open loop amplifiers is that the overall open-loop gain falls very rapidly with increasing frequency which grossly limits bandwidth.



Open Loop Multistage Amplifier

3.3 CLOSED LOOP MULTISTAGE AMPLIFIERS

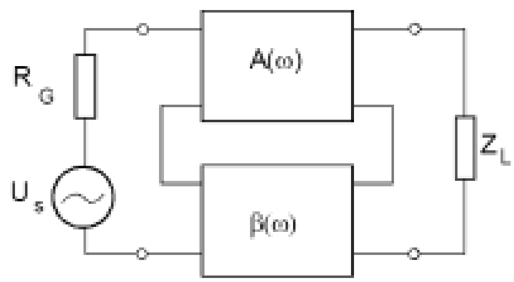


Closed Loop Amplifier

Increased stability in amplification reduces distortion, increased bandwidth and the more precise determination of input and output impedances are perhaps the most profound benefits derived from closed loop multistage amplifiers. These advantages are however achieved at the expense of overall gain which is less than that of an open loop multistage amplifier.

Stability, nonlinear distortion, bandwidth requirements and impedance matching are very important in amplifiers and form part of a long list of problems in telecommunications. They are controlled through application of negative feedback.

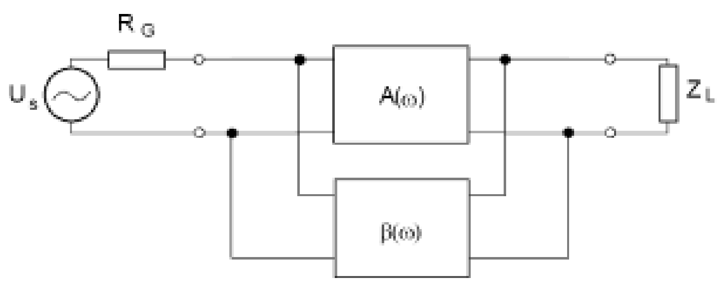
Negative feedback can be applied to an open loop amplifier through one of the four basic methods illustrated as follows;



Series-Series Feedback

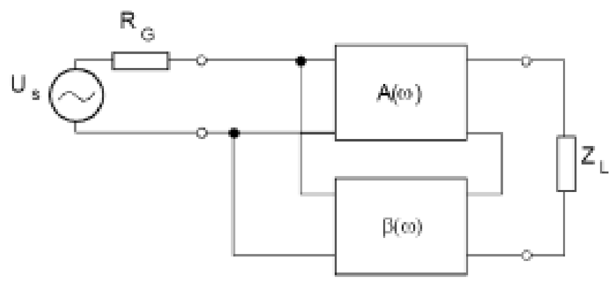
In the illustration above, part of the output current is applied as voltage to the input in series with the source signal. This is referred to as series-series negative feedback.

The illustration below shows negative feedback being applied to the input as a current in parallel to the input signal current. This method is called parallel-parallel negative feedback and results from a sampling of the output voltage to derive the feedback signal.



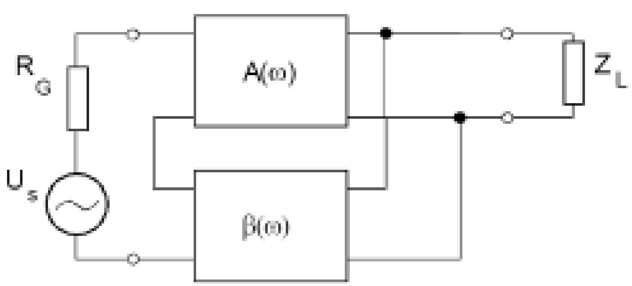
Parallel-Parallel Feedback

The third method illustrated below is parallel-series negative feedback and entails that a portion of the output current be fed through the input as a current.



Parallel-Series Feedback

When the output voltage is used to derive the negative feedback voltage at the input of the amplifier, then the amplifier is said to operate in series-parallel feedback mode.



Series-Parallel Feedback

You should study the four illustrations above, taking note that the input is named first and the output last, while the method of applying the feedback signal at the input, and that of deriving feedback signal at the output of the amplifier determines the nomenclature; series or parallel.

3.4 MERITS OF MULTISTAGE AMPLIFIERS

We earlier discussed the most obvious advantages of multistage amplifiers over single stage amplifiers. Here we add a few more advantages which at first glance might not appear so obvious.

- Compared to single stage amplifier, multistage amplifiers provide increased input resistance, reduced output resistance, increased gain and increased power handling capability

- Multistage amplifiers commonly implemented on integrated circuits where large numbers of transistors with common (matched) parameters are available

- Typical inverter (Common Emitter) has moderately large gain and has input and output resistances in the Kilohm range

- Follower configuration has much higher input resistance, lower output resistance but has only unity gain

- Amplifier requires the desirable features of both configurations

- There is increased stability in the amplification through application of negative feedback.

- Overall gain is less dependent on the parameters of the amplifier elements when negative feedback is applied

- Ability to apply negative feedback greatly reduces waveform signal distortion

4.0 CONCLUSION

In this unit we have learnt that multistage amplifiers are classified as open-loop and closed loop amplifiers. Open-loop amplifiers are more straight forward to design and implement but suffer instability while closed loop amplifiers; which are essentially negative feedback amplifiers are more difficult to understand and more challenging to design, but offer several advantages including greater control over amplifier performance irrespective of component parametric characteristics.

5.0 SUMMARY

- Multistage amplifiers are comprised usually of a cascade of individual amplifiers in which the input of a stage is derived from the output of the stage before it

- Multistage amplifiers offer several advantages over single stage amplifiers

- Open loop and closed loop multistage amplifiers can de distinguished by their performance characteristics

- Closed loop multistage amplifiers offer higher stability and greater bandwidth but lower overall gain compared with open loop multistage amplifiers

- High input impedance input stage and low output impedance output stage can be used as the front end and back end of a multistage amplifier to optimise the input and output impedances

- Cascode amplifiers are multistage amplifiers

- Operational amplifiers are multistage amplifiers

- Four basic methods exist for applying negative feedback in multistage amplifiers

- Negative feedback reduces distortion and renders amplifier gain independent of parameters making it possible to define gain by passive elements only

- The overall gain of a multistage amplifier is the product of the individual gains of the cascaded stages and where A_n is the gain associated with stage n can be expressed as Gain (A) = A_1 A_2 A_3 A_4 ... A_n.

6.0 TUTOR MARKED ASSIGNMENTS

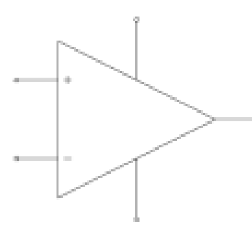
1. Sketch a block diagram of, and use it to describe multistage amplifiers?

2. State five advantages of multistage amplifiers over single stage amplifiers?

3. Is an operational amplifier a multistage amplifier? Why do you think this is so?

4. Does negative feedback affect input impedance of an amplifier? In what way?

5. What does this illustration represent?

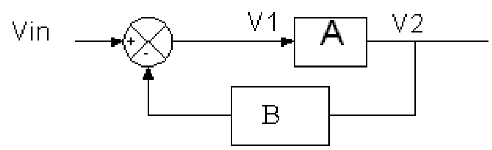


6 What is a closed loop amplifier?

7 Sketch, name and label the different methods of applying feedback in multistage amplifiers?

8 Increasing amplifier gain increases instability. Is this true? What measures can be used to increase stability?

9 The illustration below shows a closed loop amplifier. Which feedback method is being applied?



10 Why is it advisable to start the design of multistage amplifiers from the output stage? How do you determine the number of iterations required?

11 In a three stage multistage amplifier, the first stage is an emitter follower, the second stage common emitter and the final stage a common collector amplifier. Describe in detail the input and output characteristics of this multistage amplifier, and explain whether it is best suited for voltage or current amplification?

7.0 REFERENCES/FURTHER READINGS

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By Alexander and Sadiku Published by Mc Graw Hill

Module 2

UNIT 1 POWER AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

An amplifier is a device for increasing the power of a signal and in this context describes an electronic amplifier with an input signal which might be a voltage or a current.

High Power Amplifier

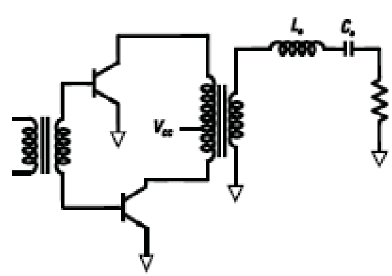
Amplifiers may be classified according to the input source which they are designed to amplify, the device they are intended to drive or by the frequency range which they amplify. You might therefore refer to an amplifier as an audio amplifier, a video amplifier, a guitar amplifier, a headphone amplifier, Intermediate Frequency, Radio Frequency and Very High Frequency amplifiers amongst many others. Classes A, B, AB and C are best suited for analogue applications while classes D and E/F are best for switching designs

They can also be classified based on whether they invert the signal; inverting amplifiers and non-inverting amplifiers, or by the type of device used in the amplification such as valve or tube amplifiers, Field Effect Transistor amplifiers and Bipolar Junction Transistor amplifiers.

You must learn to distinguish amplifiers from transducers which are devices for converting signals of one type to another. For instance; a photo-detector converts light signal in photons to a DC signal in amperes while thermocouples convert temperature to voltage or current. Transducers do not amplify power.

The main characteristics of an amplifier are Linearity, efficiency, output power, and signal gain; and a trade-off exists between these characteristics.

A higher amplifier efficiency leads to extended battery life for instance in battery operated equipment, which is important in the realization of small, portable products.



Transformer Coupled Power Amplifier

Power amplifiers dissipate power and generate heat, which has to be removed. Due to the small size of integrated circuits, this is often a challenging exercise in design and packaging and the problems with achieving high efficiency and linearity in fully integrated power amplifiers has always been a subject of interest to designers.

Power amplifier is used relatively to qualify an amplifier with respect to the amount of power delivered to the load or the power sourced by the power supply circuit and in general a power amplifier is designated as the last amplifier in a transmission chain – called the output stage. It is also the amplifier stage that requires that most attention be paid to power efficiency.

Efficiency considerations lead to various classes of power amplifiers which are grouped into classes which depend on their voltage and current waveforms. Major classes include class A, B, C, D, E, F, and G amplifiers with class-A amplifiers having the highest linearity over the other classes but with the lowest efficiency.

Note particularly that Class A, B, and C amplifiers can be configured either as a push–pull or a single ended amplifier. In Units 2, 3 and 4 of this Module, we shall discuss in detail the properties of the class A, B, AB and C amplifiers.

2.0 OBJECTIVES

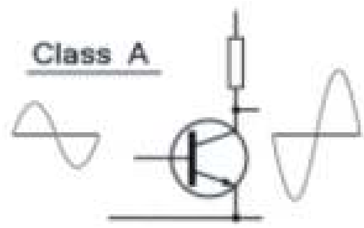
After reading through this unit, you will be able to

1. Describe the operation of power amplifiers
2. Classify power amplifiers
3. Know the important specifications of power amplifiers
4. State the practical limitations of power amplifiers
5. Discuss the characteristics of amplifier classes A, AB, B and C
6. Know which power amplifier classes are suitable for analogue applications
7. Classify power amplifiers by device type
8. Sketch power amplifier circuits
9. Sketch the signal waveforms for classes A, AB, B and C amplifiers
10. Discus the efficiency of classes A, AB, B and C amplifiers
11. Confidently correlate efficiency and distortion in the various classes of power amplifiers
12. Graphically discuss instability

3.0 MAIN CONTENT

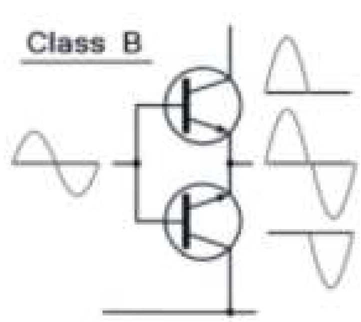
3.1 CLASSIFICATION OF POWER AMPLIFIERS

Classification of power amplifiers is usually by their output stage circuit configurations and method of operation. Thus they are either class A, B, C, and F. And the class an amplifier is categorised into is closely related to the amplifier's efficiency and linearity.



Class A Configuration

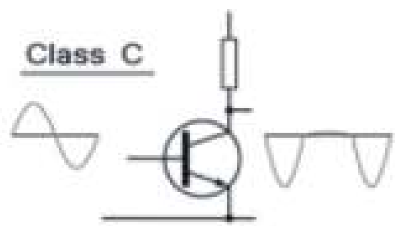
Class-A amplifiers have the highest linearity as they operate in a linear portion of their characteristic. To achieve high linearity and gain, the amplifier's active device biasing point should be carefully selected so that the amplifier operates in the linear region.



Class B and Class AB Configuration

Class B amplifiers operate ideally at zero quiescent current, so that the dc power is small and therefore, their efficiency is higher than that of the class-A amplifier. Linearity is sacrificed at the expense of efficiency.

Class-AB amplifiers are a compromise between class A and class B in terms of efficiency and linearity. The active device is biased as close to pinch-off as possible which means it will conduct for slightly more than half a cycle, but less than a full cycle of the input signal.



Class C Configuration

A Class C amplifier is biased so that the output current is zero for more than one half of an input sinusoidal signal cycle. A tuned circuit or filter is a necessary part of the class-C amplifier. It is more efficient than the preceding classes.

3.2 POWER AMPLIFIER SPECIFICATIONS

We will look at brief descriptions of some important power amplifier specifications which are a measure of amplifier performance. Study each of them carefully.

Power Gain: Power gain is the ratio of output to input power measured in decibels.

Bandwidth: A power amplifier’s bandwidth is the range of frequencies for which the amplifier gives satisfactory performance and which are determined by the half power points on the output vs. frequency curve.

Efficiency: This is a measure in percentage of the ratio of usefully power applied to the amplifier's output of an amplifier and the power delivered by the amplifier’s power source.

Linearity: Power amplifier linearity is an indication of the response of a power amplifier to increasing input signal until clipping and subsequent distortion commences.

Noise Figure: This is a comparison between the output signal to noise ratio and the thermal noise of the input signal of the power amplifier.

Output Dynamic Range: Given in decibels, Output Dynamic Range is the ratio between the smallest and largest useful output levels.

Slew Rate: The slew rate is the maximum rate of change of the output in volts per second

Rise Time: The time taken for the output to change from 10% to 90% of its final level when driven by a step input is called the Rise Time.

Setting Time: Setting time is time taken for the output to settle to within a given percentage of the final value.

Ringing: Ringing refers to an output variation that cycles above and below an amplifier's final value.

Overshoot: This is the amount by which the output exceeds its steady state value.

Stability: A major concern in power amplifiers is stability. It is closely related to feedback and can be quantified by the stability factor.

3.3 PRACTICAL LIMITATIONS IN POWER AMPLIFIERS

We have discussed power amplifiers in terms of ideal devices, however, practical power amplifiers utilise active components such as transistors which suffer from a number of limitations which in turn influence power amplifier operation and ultimately reduce their efficiency and output power.

Practical active devices have four fundamental effects that force their operation to deviate from the ideal case. These are their output resistance, Maximum output current, output breakdown voltage and the avalanche breakdown voltage.

Other limitations are high power dissipation and the need for forced cooling, signal distortion; particularly at high output power levels and dynamic impedance matching of output and load.

Class A power amplifiers are plagued by their inefficiency due to the high bias requirements which results in a high thermal dissipation requirement while class B suffer from a high level of distortion. Class AB power amplifiers are limited both by inefficiency when the output level is low compared with the maximum voltage swing. They also have thermal dissipation problems and have to be provided heat sink.

Additionally class AB power amplifiers require optimum characteristic curve matching of the output power transistors as well as identical biasing of the two.

Class C power amplifiers have intolerably high level of distortion which generates undesirable harmonics of the amplified frequencies. These harmonics can be coupled through the power cables and cause interference and are only reduced at the expense of additional noise suppression filters.

4.0 CONCLUSION

In this unit we have learnt that Power amplifiers dissipate power and generate heat, and are classified by their output stage circuit configurations and method of operation into many classes of which classes A, B and C have been discussed.

We have also learnt that the class of an amplifier is closely related to the amplifier's efficiency and linearity; and also to the level of distortion introduced by the amplifier.

5.0 SUMMARY

- Class A, AB, B an C amplifiers are capable of power amplification
- Power amplifiers are classified by their output stage circuit configurations and method of operation
- The practical limitations of power amplifiers are imposed by device parameters such as thermal, operating voltage and operating current limitations
- Different amplifier classes present different efficiencies
- Higher power amplifier efficiency reduces power waste and the need for large heat sinks
- Major amplifier classes include class A, B, C, D, E, F, and G
- Power amplifiers can either be directly coupled, capacitive coupled or transformer coupled
- Transformer coupled amplifiers provide output electrical isolation
- Amplifiers must be distinguish from transducers which are devices for converting signals of one type to another
- Power amplifiers are often the last stage of amplification which I expected to provide power to a load

6.0 TUTOR MARKED ASSIGNMENTS

1 Can you state four characteristics of power amplifiers"

2 Which state variables are amplified by power amplifiers?

3 How would you qualify a power amplifier which amplifies the frequency range 40 Hertz to 13.5 Kilo Hertz?

4 How would you distinguish amplifiers from transducers?

5 Can a transformer coupled output stage amplify direct current? Why?

6 What is a push-pull amplifier? And why do they require complementary or matched active circuit elements?

7 At what stage would you expect to see a phase splitter in a cascade of amplifiers?

8 List five practical limitations of power amplifiers?

9 Can you mention three kinds of power amplifiers classified by device type?

10 Discuss why instability is such a serious problem in power amplification stages?

11 Sketch four classes of power amplifiers and label their parts. Can you describe their operation?

12 State six specifications by which you can measure a power amplifier's performance?

13 Can you rank class A, AB, C and class C amplifiers in reverse order of efficiency?

14 Can negative feedback reduce the output impedance of a power amplification stage? If yes, how?

7.0 REFERENCES/FURTHER READINGS

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By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

Semiconductor Device Fundamentals
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Electronic Devices and Circuit Theory 7th Edition

By Robert E. Boylestad and Louis Nashesky Published by Prentice Hall

Fundamentals of Electric Circuits 4th Edition
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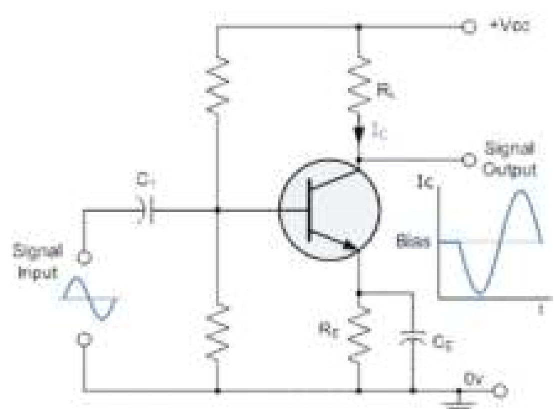
UNIT 2 CLASS A AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

Class A amplifiers amplify over the entire input cycle such that the output signal is an exact magnified copy of the input. Although class A amplifiers have a conduction angle of 360^o, they are not efficient being no more than 50% efficiency at most. This is because the device is always conducting whether or not input signal is applied.



Class A Amplifier

Class A amplifiers find application where efficiency is not the primary design criteria, but linearity. Most small signal linear amplifiers are designed as class A amplifiers. Class A amplifiers are typically more linear and less complex than other types, but are very inefficient. There exists a subclass designated A2 and which refers to vacuum tube class A stages where the grid is allowed to be driven slightly positive on signal peaks, resulting in slightly more power than in a normal class A.

2.0 OBJECTIVES

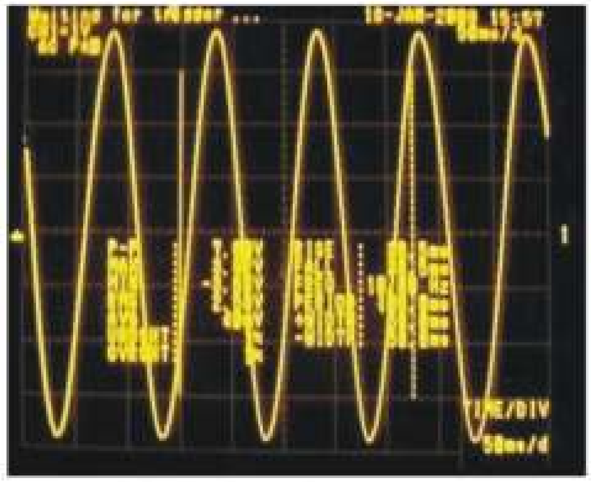
After reading through this unit, you will be able to

1. Describe the operation of class A amplifiers
2. Know why class A audio amplifiers provide the highest fidelity
3. See why class A amplifiers are the most energy inefficient class
4. Understand the reason why class A amplifiers are rarely used in power output stages
5. List the merits and demerits of class A amplifiers
6. Compare performance of class A amplifiers with classes AB, B and C amplifiers
7. Understand the term "single ended"
8. Qualify the high frequency performance of class A amplifier
9. Figure out why class A amplifiers have no crossover distortion
10. Explain why an overloaded class A amplifier can suffer from non linearity

3.0 MAIN CONTENT

3.1 CLASS A AMPLIFIER

Class A amplifiers provide the lowest distortion but are most expensive, and are the least practical to apply for high power applications. Class A amplifiers waste power but produce very clean signal output. Class AB amplifiers dominate the market and rival the best Class A amplifiers in sound quality. They use less power than Class A, and can be cheaper, smaller, cooler, and lighter. Class D amplifiers are even smaller than Class AB amplifiers and more efficient, because they use high-speed switching rather than linear control. Starting in the late 1990s, Class D amplifiers have become quite good, and in some cases rivalling high quality amplifiers in sound quality. Class B & Class C amplifiers aren't used in audio.



Class A Amplifier Sine Wave Response

In the following discussion, we will assume transistor output stages, with one transistor per function. In some amplifiers, the output devices are tubes. Most amplifiers use more than one transistor or tube per function in the output stage to increase the power. Class A refers to an output stage with bias current greater than the maximum output current, so that all output transistors are always conducting current. The biggest advantage of Class A is that it is most linear, it has the lowest distortion. The biggest disadvantage of Class A is that it is inefficient, it takes a very large Class A amplifier to deliver 50 watts, and that amplifier uses lots of electricity and gets very hot. Some high-end amplifiers are Class A, but true Class A only accounts for perhaps 10% of the small high-end market and none of the middle or lower-end market. Class B amplifiers have output stages which have zero idle bias current. Typically, a Class B audio amplifier has zero bias current in a very small part of the power cycle, to avoid nonlinearities. Class B amplifiers have a significant advantage over Class A in efficiency because they use almost no electricity with small signals.

3.2 MERITS AND DEMERITS OF CLASS A AMPLIFIERS

We can very quickly summarise the merits of the Class A amplifier as follows:

- Class A designs are easier to design and analyse than all other classes of amplifiers; primarily because it uses a single device to handle the 360^o conduction cycle of the waveform.

- Class A amplifiers are single ended amplifiers through using a single device

.

- The amplifying element in a class A amplifier is biased so the device is always conducting to some extent to ensure its operation is close to the most linear portion of its transconductance curve.
- There is no warm up or turn on time because the amplifying device is always on in a class A amplifier. This means no charge storage and better frequency performance.
- Class A amplifiers are immune to the problem of crossover distortion associated with class AB and B amplifiers.
- Class A amplifiers exhibit a total absence of crossover distortion, offer reduced odd-harmonic and high-order harmonic distortion and is ideally suited for high quality audio applications.

In addition to the foregoing, additional advantages are that in transformer coupled push-pull class A output stages

- The bias current for each of the active elements flow in opposite directions in the primary of the output transformer such that they effectively cancel each other out. This lack of static, offset direct current in the output transformer means that the core can be made smaller because it requires no air gap to prevent core saturation from the static offset current.
- Also, in single-ended transformer coupled class A amplifier output, the output transformer is huge compared to a push-pull class A amplifier of the same power level. The air gap required to prevent core saturation drastically reduces the primary inductance, so the transformer must have a larger core and more windings to achieve the same primary inductance.
- Again, a transformer coupled push-pull class A amplifier output stage will have inherent rejection of power supply ripple and noise. This is because the power supply signal is common-mode which means it is amplified by each side equally, but since each side is out of phase, the anti-phase ripple

Now let us take a look at some of a Class A amplifier's demerits. As stated earlier, class A amplifiers are the most inefficient class of amplifiers boasting a theoretical maximum efficiency of 50% with inductive output coupling and only 25% with capacitive coupling.

In a power amplifier this inefficiency not only wastes power but also limits battery operation in battery operated appliances. It place restrictions on the output devices that can be used and increases costs.

Inefficiency is not just a consequence of the device always conducting current to some extent as class A amplifiers are not unique in that respect, but that the standing current is at least half of the maximum output current if distortion through clipping is to be avoided on the one hand, and also that a large part of the power supply voltage is developed across the output device at low signal levels.

A major drawback with Class A amplifiers is that for every watt delivered to the load, the amplifier itself will, at best, dissipate another watt and where large power output delivery is to be achieved; very large and expensive power supplies and heat sinking must also be employed. It is wise to take special note of this.

When a class A amplifier is transformer coupled; additional disadvantages are:

- The need for a phase splitter stage to generate the oppositely-phased drive signals.

- Another disadvantage in transformer coupled push pull class A stages stems from the fact that even-order harmonics generated in the output stage are cancelled out in a push-pull output stage. This does not mean that the push-pull amplifier generates no even order harmonics, but because even-order harmonics generated in the preamplifier stages are amplified by the output stage and will pass right through to the output. Only those even-order harmonics generated in the output stage itself are cancelled out.

3.3 MISCONCEPTIONS OF THE CLASS A AMPLIFIER

Let us start be reviewing the property of a class A amplifier. Recall that a class A amplifier is biased to a point where load current in all output devices flows for the entire 360 degrees of an input cycle, at the full, unclipped output of the amplifier?

This is typically done by biasing the output stage halfway between cutoff and saturation, with the load impedance at a value that gives maximum undistorted output power.

Class A amplifier can be either single-ended or push-pull output. You have to avoid the common misconception of asking yourself how a push-pull amplifier can be class A amplifier where one half of the output amplifies half of the waveform while the other amplifies the other half.

You must also come to terms with the realisation that amplifier class has absolutely nothing to do with output stage topology since ff the output active elements on either side of a push-pull pair are biased in class A which means they are both biased halfway between cutoff and saturation, then the current in each side will still flow for the full 360 degrees of the input cycle, although in opposing directions.

As one active element's current increases from the midpoint, or idle, bias current, the other active element's current decreases by an equal amount and the output in the case of transformer coupling sums these oppositely-phased currents to produce the output waveform in the secondary winding. Therefore, as one side reaches saturation, the other side reaches cutoff, just as they would in a single-ended class A amplifier and neither side cuts off at the full, unclipped output power of the amplifier.

The output power of a push-pull class A amplifier is exactly twice the output power of a single-ended class A amplifier operating under the same conditions of load voltage, bias, and effective load impedance.

Another misconception which you have to overcome is that the class of operation does not depend on the method of biasing an amplifier therefore it is possible to have a fixed-bias class A amplifier or a cathode or emitter biased class AB amplifier, or vice-versa. The presence of the bias resistor and bypass capacitor is not an indication of class A operation in either case.

4.0 CONCLUSION

In this unit we learnt that Class A amplifiers amplify over the entire input cycle which is a 360 conduction angle. Class A amplifiers are the most inefficient class having a maximum efficiency of 50%, they are however the most linear and distortion free amplifier class.

We have also been taught that class A amplifiers are easier to design and analyse than all other classes of amplifiers; primarily because a single device may be used to handle the 360^o conduction cycle of the waveform.

5.0 SUMMARY

- One of the classifications of power amplifiers by their output stage circuit configurations and method of operation is the class A amplifier
- Class A amplifiers amplify over the entire input cycle
- Class A amplifiers are useful where efficiency can be sacrificed for linearity
- Class A amplifiers are inefficient
- A vacuum tube subclass is designated class A2 and refers to vacuum tube class A where the grid is allowed to be driven slightly positive on signal peaks, resulting in slightly more power than in a normal class A
- Class A amplifiers do not experience crossover distortion
- Biasing in class A amplifiers is such that the driven element is always conducting
- Push pull class A amplifiers utilise two driven elements
- Transformer coupled class A stages have inherent rejection of power supply ripple and noise
- The maximum efficiency achievable in a class A amplifier is 50% when the output inductively coupled to the load, but is only 25% if capacitive coupling is used
- High power class A amplifier stages require forced cooling
- Transformer coupled push-pull class A amplifiers require a phase splitter

6.0 TUTOR MARKED ASSIGNMENTS

1 Can you sketch a class A JFET amplifier circuit and label its parts?

2 What is the maximum efficiency attainable in class A amplifiers? Why is the class A2 an exception to this?

3 Can you discuss in qualitative terms the linearity of class A amplifiers?

4 Compare and contrast class A and class AB amplifiers? Which of the two has a greater conduction angle? State these conduction angles?

5 Would you consider using a class A power amplifier in the design of a battery powered circuit? Why or why not?

6 State four merits and four demerits of class A amplifiers?

7 Sketch a transformer coupled push-pull class A power output stage? What can you say about the transformer required when compared with a single ended circuit of the same power output?

8 Would you use a phase splitter for a single ended class A output stage? Explain in detail?

9 A class A amplifier generates 150 Watts output power. How many watts of power would this amplifier have to dissipate?

10 List five misconceptions of the class A amplifier?

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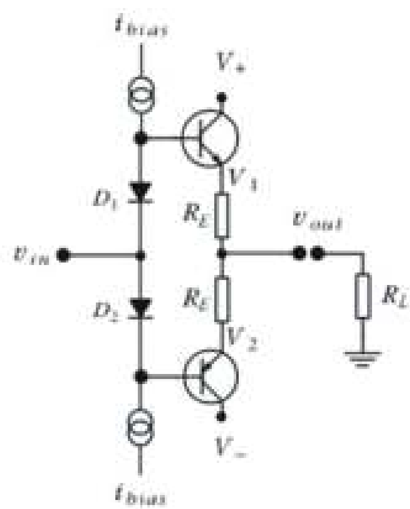
UNIT 3 CLASS B AND AB AMPLIFIERS

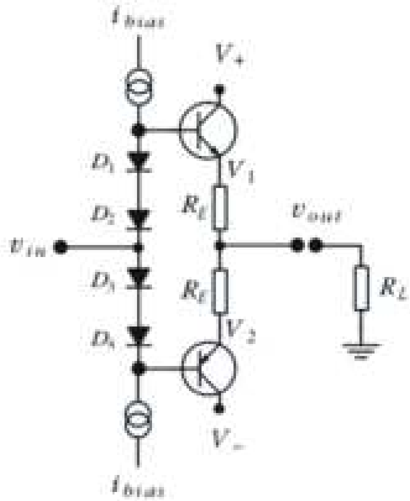
CONTENTS

1.0 INTRODUCTION



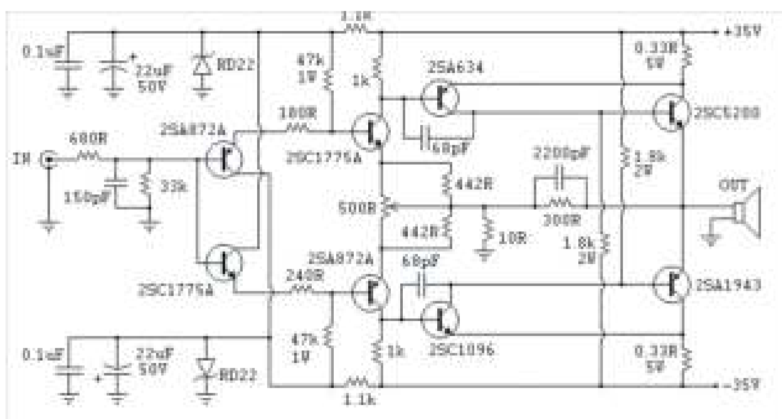
Class B Amplifier Output Stage

Class B amplifier is one whose operating point is at an extreme end of its characteristic, so that either the quiescent current or the quiescent voltage is almost zero and if a sinusoidal input voltage is used, the amplification of a Class B amplifier takes place only for 50% of the cycle. This means that the amplifying device is switched off half of the time.



Class AB Amplifier

Up to 78.5% efficiency can be attained by a Class B amplifier with the major drawback that a class B amplifier exhibits a higher distortion than an equivalent Class A amplifier.



Class AB Amplifier Output Stage

A Class AB amplifier is an amplifier that operates between the two extremes defined for Class A and class B amplifiers signal which means that it conducts more than 50% but less than 100% of the signal cycle.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Describe the operation of Class B and AB amplifiers

2 State the range of efficiencies of classes B and AB amplifiers

3 Sketch the output waveform of classes B and AB amplifiers

4 Compare and contrast distortion in classes B and AB amplifies

5 Describe biasing requirement for class AB amplifier

6 Sketch classes AB and B amplifiers circuit layout

7 Identify a class AB output stage in circuit diagram

8 See the need to match output active elements in class AB amplifier

9 Understand the meaning of push pull circuit

10 Explain the meaning of complementary paired elements

11 State the output phase relationship in classes B and AB amplifiers

12 Compare and contrast classes AB and B amplifier performance with class A and class C amplifiers performances

13 Appreciate the need for forced cooling in classes AB and B amplifiers

14 Sketch the output characteristics of classes AB and B amplifiers

15 Compare the low frequency responses of transformer coupled and transformerless class AB amplifiers

16 Understand why biasing diodes are used in bipolar junction transistor class AB amplifiers

3.0 MAIN CONTENT

3.1 CLASS B AMPLIFIER

Class B amplifiers only amplify half of the input wave cycle, thus creating a large amount of distortion, but their efficiency is greatly improved and is much better than class A. Class B has a maximum theoretical efficiency of 78.5% (i.e., $\pi/4$). This is because the amplifying element is switched off altogether half of the time, and so cannot dissipate power.

A single element class B amplifier is rarely found in practice but a good example of it is its application as a loudspeaker driver in the early IBM Personal Computers where it is used to produce the beeps.

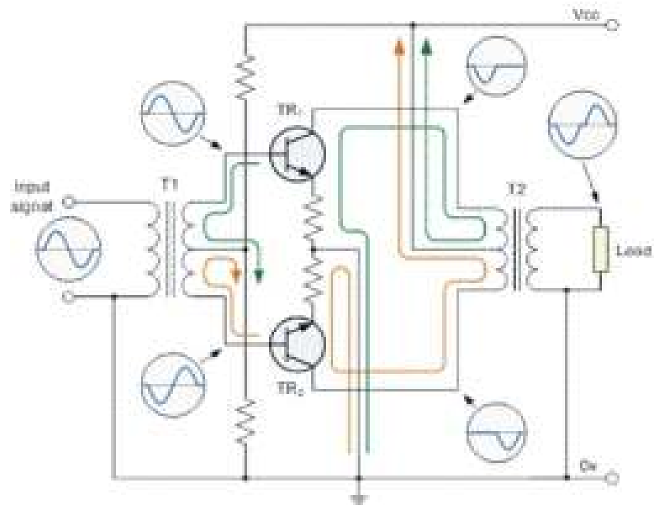
The active element of Class B amplifiers is active for 50% of the signal cycle within its linear range while it is more or less turned off for the other half. In most class B, there are two output devices each of which conducts alternately in a push–pull arrangement for exactly 180° of the input signal.

Class B amplifiers are subject to crossover distortion if the transition from one active element to the other is not perfect, as when two complementary transistors which may be a PNP and NPN pair in the case of Bipolar junction Transistor application; are connected as two emitter followers with their base and emitter terminals in common, requiring the base voltage to slew across the region where both devices are turned off.

More often than not a class B stage is preceded by a class a amplifier. Now, class A amplifiers are not very power efficient which explains the use of the class A amplifier to process the small signal while the class B amplifier stage with its higher power efficiency serves to boost the processed signal.

The Class B stage is therefore to improve the full power efficiency of the previous Class A amplifier by reducing the wasted power in the form of heat and, it is possible to design the power amplifier circuit with two transistors in its output stage producing what is commonly termed as a push-pull type amplifier configuration. Push-pull amplifiers use two complementary or matching transistors, one being an NPN-type and the other being a PNP-type with both power transistors receiving the same input signal together that is equal in magnitude, but in opposite phase to each other.

This results in one transistor only amplifying one half or 180^o of the input waveform cycle while the other transistor amplifies the other half or remaining 180^o of the input waveform cycle with the resulting two-halves being put back together again at the output terminal. Then the conduction angle for this type of amplifier circuit is only 180^o or 50% of the input signal. This pushing and pulling effect of the alternating half cycles by the transistors gives this type of circuit its name, but these types of audio amplifier circuit are more generally known as the Class B Amplifier as illustrated overleaf.

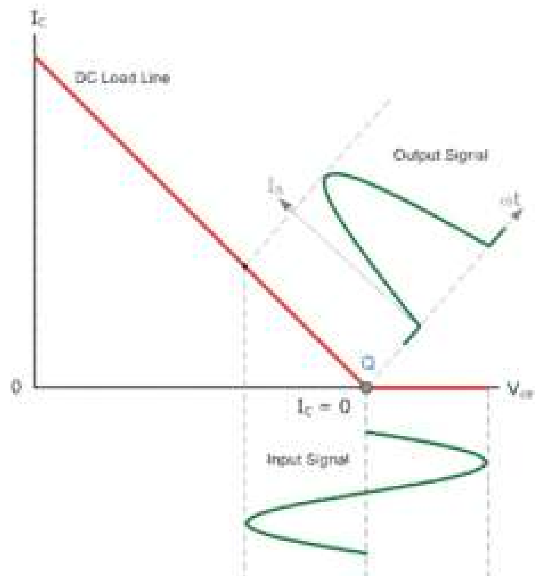


Class B Push-Pull Transformer Amplifier

The circuit above shows a Class B Amplifier circuit that uses a balanced centre-tapped input transformer, which splits the incoming waveform signal into two equal halves and which are 180^{o} out of phase with each other. Another centre-tapped transformer on the output is used to recombine the two signals providing the increased power to the load.

The transistors used for this type of transformer push-pull amplifier circuit are both NPN transistors with their emitter terminals connected together. Here, the load current is shared between the two power transistor devices as it decreases in one device and increases in the other throughout the signal cycle reducing the output voltage and current to zero. The result is that both halves of the output waveform now swing from zero to twice the quiescent current thereby reducing dissipation. This has the effect of almost doubling the efficiency of the amplifier to around 70%.

Assuming that no input signal is present, and then each transistor carries the normal quiescent collector current, the value of which is determined by the base bias which is at the cut-off point. If the transformer is accurately centre tapped, then the two collector currents will flow in opposite directions (ideal condition) and there will be no magnetization of the transformer core, thus minimizing the possibility of distortion. When a signal is present across the secondary of the driver transformer T1, the transistor base inputs are in "anti-phase" to each other as shown, thus if TR1 base goes positive driving the transistor into heavy conduction, its collector current will increase but at the same time the base current of TR2 will go negative further into cut-off and the collector current of this transistor decreases by an equal amount and vice versa. Hence negative halves are amplified by one transistor and positive halves by the other transistor giving this push-pull effect. Unlike the DC condition, these AC currents are additive resulting in the two output half-cycles being combined to reform the sine-wave in the output transformers primary winding which then appears across the load. The characteristic curve below displays the input and output signal excursions.

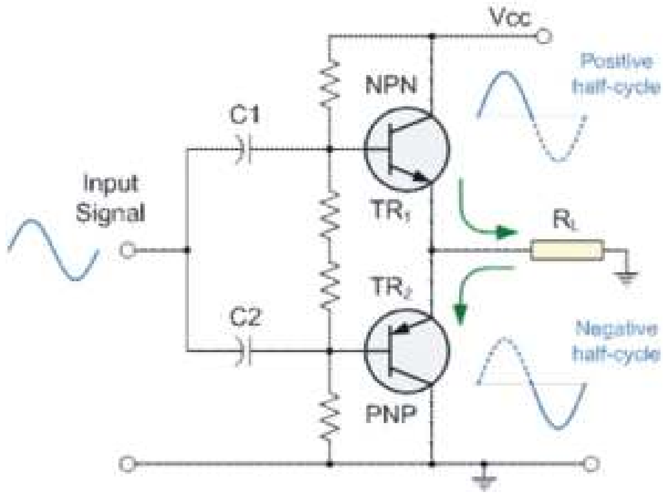


Class B output Characteristic Curve

Closely observe the characteristic curve above and you will see that Class B Amplifier operation has zero DC bias as the transistors are biased at the cut-off, therefore each transistor only conducts when the input signal is greater than the base-emitter voltage. At zero input there is zero output and no power is being consumed. This then means that the actual Q-point of a Class B amplifier is on the Vce part of the load line as shown in above.

One of the main disadvantages of the Class B amplifier circuit above is that it uses balanced centre-tapped transformers in its design, making it expensive to construct. However, there is another type of Class B amplifier called a Complementary-Symmetry Class B Amplifie**r** that does not use transformers in its design therefore; it is referred to as transformer-less using instead complementary or matching pairs of power transistors. As transformers are not needed this makes the amplifier circuit much smaller for the same amount of output, also there are no stray magnetic fields or non-linear transformer distortion to effect the quality of the output signal.

A Transformerless Class B Amplifier is illustrated below.



Transformerless Class B Amplifier

The Class B amplifier circuit above uses complimentary transistors for each half of the waveform and while Class B amplifiers have a much high gain than the Class A types, one of the main disadvantages of class B type push-pull amplifiers is that they suffer from crossover distortion.

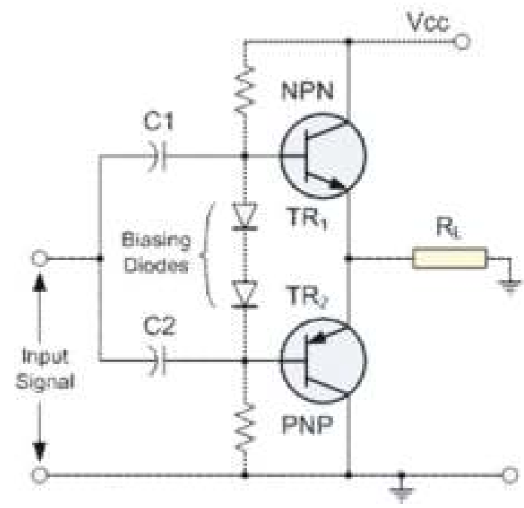
A simple way to eliminate crossover distortion in a Class B amplifier is to add two small voltage sources to the circuit to bias both the transistors at a point slightly above their cut-off point, As it is impractical to add additional voltage sources to the amplifier circuit PN-junctions are used to provide the additional bias in the form of silicon diodes.

Pre-biasing a class B amplifier in this way transforms it into a class AB amplifier which we shall be discussing next.

3.2 CLASS AB AMPLIFIER

Class AB amplifiers are almost the same as Class B amplifiers in that they have two driven transistors. However, Class AB amplifiers differ from Class B amplifiers in that they have a small idle current flowing from positive supply to negative supply even when there is no input signal. This idle current slightly increases power consumption. This idle current also corrects almost all of the nonlinearity associated with crossover distortion. These amplifiers are called Class AB rather than Class A because with large signals, they behave like Class B amplifiers, but with small signals, they behave like Class A amplifiers.

As you already know, you need the base-emitter voltage to be greater than 0.7v for a silicon bipolar transistor to start conducting, so if you 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.



Diode Biasing in Class AB Amplifier

We may say that 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 normally in their active region thereby eliminating any crossover distortion present in pure Class B amplifier designs. 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 giving a conduction angle of between 180 to 360^o or 50 to 100% of the input signal depending upon the amount of additional biasing used. The amount of diode biasing voltage present at the base terminal of the transistor can be increased in multiples by adding additional diodes in series.

4.0 CONCLUSION

In this unit we have learnt that class B amplifiers operate at an extreme end of its output characteristic curve such that either the quiescent current or the quiescent voltage is almost zero.

We also noted that for a sinusoidal input voltage, amplification takes place for only 50% of the signal cycle in class B amplifiers – implying that the active device is switched off for half of the time.

Finally, we now know that a class B amplifier stage can provide a maximum of 78.5% efficiency but exhibits higher distortion than a class A amplifier.

The class AB amplifier serves as a bridge between the performance of a class A amplifier and a class B amplifier in that it combines the advantages of the two; the higher efficiency of the class B amplifier and the linearity of the class A amplifier. This however comes at the price of reduced maximum efficiency to less than 78.5%

5.0 SUMMARY

- Class B amplifiers have a conduction cycle of 50% and a maximum efficiency of 78.5%.
- Class AB amplifiers always have some bias current flowing although small, and they function like partly biased class B amplifiers
- Class AB amplifiers are more efficient than class A but less efficient than class B amplifiers
- Transformer coupled class AB stages require a phase splitter
- Distortion is almost totally eliminated in class B amplifiers through proper biasing of the active elements which should present identical characteristic curve
- Class AB output stages use complementary pair devices
- High power class B and AB amplifiers require forced cooling
- The low frequency response of direct coupled class AB amplifiers extends to zero Hertz, or DC, compared the low frequency responses of an

identical transformer coupled stage which is limited by the low frequency response of the transformer

- Biasing diodes are used in bipolar junction transistor class AB amplifiers to bias the transistors and eliminate crossover distortion.

- Class B and class AB amplifiers are similar in that they both utilise two driven active elements

6.0 TUTOR MARKED ASSIGNMENTS

1 Can you sketch a class B amplifier and label its parts?

2 How many transistors would you require for a basic class B stage? And how many would you use for a complementary class B stage?

3 How would you transform a complementary class B amplifier into a complementary class AB amplifier?

4 You should sketch a class AB amplifier complete with biasing diodes. Under what condition would this amplifier perform as a complementary class A amplifier?

5 What is the conduction angle of a class B amplifier?

6 How would you qualify the distortion of class B and class AB amplifiers?

7 If an amplifier has a maximum efficiency of 78% would it be a class B amplifier or a class AB amplifier?

8 Why class AB amplifiers are often comprised of complementary output devices?

9 How is excessive heat dissipated in power amplifiers?

10 How would you transform a class B amplifier stage into a class A amplifier?

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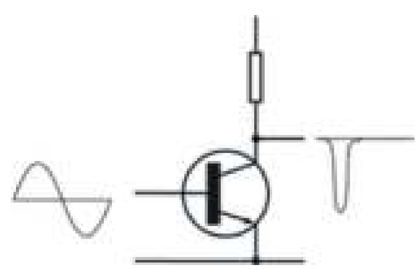
UNIT 4 CLASS C AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

Class C amplifiers conduct less than 50% of the input signal, allowing it to reach 90% efficiency but resulting in high distortion at the output. Thus, in a Class C amplifier, the output current (or voltage) is zero for more than 50% of the input waveform cycle. In some appliances such as megaphones, the high distortion of Class C amplifiers can be tolerated. Similarly, Class C amplifiers can be used in tuned Radio Frequency applications because the distortion of the class C amplifier can be significantly reduced by the tuned loads.



Class C Amplifier

In Radio Frequency and Tuned Load applications, the input signal is used to roughly switch the amplifying device on and off, which causes pulses of current to flow through a tuned circuit.

2.0 OBJECTIVES

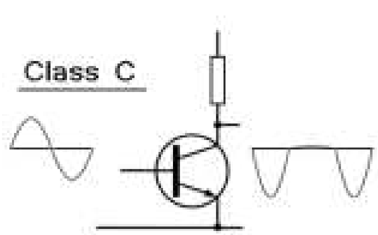
After reading through this unit, you will be able to

1 Describe the operation of the class C amplifier
2 Discuss the two modes of class C operation
3 State the maximum efficiency of class C amplifiers
4 Sketch the output waveform of class C amplifiers
5 Understand how tuned mode class C amplifiers clamp DC level
6 Explain why class C amplifiers are predominantly applied to radio frequency
7 Sketch a class C output stage
8 Say why class C stages do not require DC biasing

3.0 MAIN CONTENT

3.1 CLASS C AMPLIFIER

Class C amplifiers are similar to Class B in that the output stage has zero idle bias current. However, Class C amplifiers have a region of zero idle current which is more than 50% of the total supply voltage. The disadvantages of Class B amplifiers are even more evident in Class C amplifiers, so Class C is likewise not practical for audio applications. An NPN Class C Common Emitter Amplifier is illustrated below.



NPN Class C Common Emitter Amplifier

Class C applications are mostly radio frequency applications where the highly distorted output of the amplifier can be filtered out by a tuned circuit.
Applications such as FM transmission where linearity is not important frequently apply class C power output amplifiers stages.

3.2 MODES OF CLASS C AMPLIFIER

Class C amplifiers have two modes of operation and you should remember that they are the tuned mode and the untuned mode of operation. In untuned operation, waveform analysis will show massive distortion in the signal and when the proper load such as a pure inductive-capacitive filter is used, two things will happen.

The first is that the output's bias level is clamped, so that the output variation is centred at one-half of the supply voltage. This is why tuned operation is sometimes called a clamper operation. This action of elevating bias level allows the waveform to be restored to its proper shape, allowing a complete waveform to be re-established despite having only a one-polarity supply. You should read this paragraph again till you have a proper grasp of it as this is directly related to the second phenomenon.

The second thing to happen is that the waveform on the centre frequency becomes much less distorted and the distortion that is present is dependent upon the bandwidth of the tuned load, with the centre frequency experiencing very little distortion, but experiencing greater attenuation the farther from the tuned frequency that the signal gets.

A tuned circuit will only resonate at particular frequencies, and so the unwanted frequencies are dramatically suppressed, and the wanted full signal (sine wave) will be extracted by the tuned load provided a transmitter is not required to operate over a very wide band of frequencies.

The tuned mode Class C amplifier works extremely well and other residual harmonics can be removed using a filter.

4.0 CONCLUSION

In this unit we have learnt that with less than 50% conduction angle, class C amplifiers can attain as much as 90% efficiency but with a high level of distortion of the output signal

We now also know that there are two modes of operation of class C amplifiers which are most commonly employed for radio frequency work.
.

5.0 SUMMARY

- Class C amplifiers have less than 50% conduction angle
- Maximum efficiency of 90% is achievable in class C amplifiers
- Class C amplifier stages exhibit extremely high distortion
- The two modes of operation of class C amplifiers are tuned mode and the untuned mode
- The tuned mode of operation in class C amplifiers clamps the signal's DC level
- Class C amplifier stages do not require DC biasing
- Tuned mode class C stages are often employed in radio frequency work

6.0 TUTOR MARKED ASSIGNMENTS

1 Describe the operation of class C amplifiers?

2 What application would you recommend for class C amplifiers? Why?

3 Explain in detail the two modes of class C amplifiers?

4 Can you sketch a basic class C amplifier?

5 What is the maximum conduction angle of a class C amplifier?

6 Explain why class C amplifiers often have a tuned circuit load?

7 What class C phenomenon is referred to as clamper operation?

8 Compare the level of distortion introduced by class C amplifiers with that of class B amplifiers?

9 Do you require more forced cooling for a class C amplifier which delivers the same output power as a class B amplifier? Why?

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UNIT 5 LOW AND HIGH FREQUENCY POWER AMPLIFIERS

CONTENTS

1.0 INTRODUCTION

We must appreciate that low and high frequency amplifiers are classified by their frequency response and their relative operating frequency range.

While in audio frequency work, a 100 Hertz amplifier may be considered low frequency when compared to a 15 kilo Hertz amplifier classified as high frequency, a radio frequency intermediate frequency stage of 455 Kilo Hertz is definitely low frequency for radio frequency work.

Different techniques are required for processing electrical signals across the electromagnetic spectrum and components which we are familiar with at low frequencies; such as capacitors and inductors, might appear radically different at high frequencies. Also, at high frequencies, component leads and parasitic are non negligible – therefore, the inductance introduced by the leads of a capacitor, or the capacitance between two adjacent leads cannot be ignored.

At high frequencies, topology and circuit layout become critical considerations, and component layout must be carefully worked out. An interesting case is that of high frequency microchips where transit times within and between components may play havoc, while frequency response and bandwidth may be considerably limited by circuit topology.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Distinguish between low and high frequency power amplifiers

2 List the most common power amplifier specifications

3 Explain power amplifier signal bandwidth

4 Sketch an audio power amplifier output stage

5 Sketch a radio frequency power output stage

6 Compare the efficiencies of low frequency and high frequency power amplifiers

7 List the practical applications of low and high frequency power amplifiers

8 Appreciate the importance of impedance matching in power amplifiers

9 Express power gain in decibels

10 Understand the need for forced cooling in power amplifier designs

3.0 MAIN CONTENT

3.1 AMPLIFIER SPECIFICATIONS

We can characterise the quality of an amplifier by its specifications. Let us take a look at some of the important specifications which generally detail the quality of amplifiers.

Gain

The gain of an amplifier is the ratio of output to input power or output to input amplitude, and is often measured in decibels. When it is measured in decibels it is logarithmically related to the power ratio:

$$G(\text{dB})=10\ \log(P_{out}\ /(P_{in}))$$

Whereas Radio frequency amplifiers are often specified in terms of the maximum power gain obtainable, the voltage gain of audio amplifiers and instrumentation amplifiers is often specified since the amplifier's input impedance will be much higher than the source impedance, and the load impedance higher than the amplifier's output impedance.

Bandwidth

The bandwidth of an amplifier is the range of frequencies for which the amplifier provides satisfactory performance and the generally accepted metric is the half power points.

This is the frequency where power is reduced to half of its peak value on the output versus frequency curve. Bandwidth can be defined as the difference between the lower and upper half power points. This is therefore also known as the −3 dB bandwidth or the frequency response.

Efficiency

This is a measure of the amount of power from the power source which is usefully applied to the load at the amplifier's output. Class A amplifiers are very inefficient, being typically in the range of 10–20% with a max efficiency of 25% for direct coupling of output. Inductive coupling of the output can raise the efficiency of Class A amplifiers to a maximum of 50%.

Class B amplifiers have a very high efficiency but are impractical for linear applications because of high levels of distortion and in practical design, the result of a trade-off is the class AB design. Modern Class AB amplifiers commonly have peak efficiencies between 30–55% in high fidelity applications and 50-70% in radio frequency systems with a theoretical maximum of 78.5%.

More efficient amplifiers run cooler, and often do not need any cooling fans even in multi-kilowatt designs. The reason for this is that the loss of efficiency produces heat as a by-product of the energy lost during the conversion of power. In more efficient amplifiers there is less loss of energy so in turn less heat.

Linearity

An ideal amplifier would be a totally linear device but real amplifiers are only linear within limits.

When signal drive to the amplifier is increased, the output also increases until a point is reached where some part of the amplifier becomes saturated and cannot produce any more output; this is called clipping which results in distortion.

In most amplifiers gain reduction takes place before hard clipping occurs which results in compression and for amplifiers, the 1 dB compression point is defined as the input power or output the power where the gain is 1 dB less than the small signal gain. Negative feedback is used to reduce nonlinearity.

Noise

Noise is an undesirable but inevitable product of the electronic devices and components; and much noise results from intentional economies of manufacture and design time. The metric for noise performance of a circuit is noise figure or noise factor which is a comparison between the output signal to noise ratio and the thermal noise of the input signal.

Output Dynamic Range

This is the range between the smallest and largest useful output levels and is usually measured in dB. The lowest useful level is limited by output noise, while the largest is limited most often by distortion. The ratio of these two is referred to as an amplifier dynamic range.

Slew Rate

Slew rate is the maximum rate of change of the output and is usually stated in volts per second or microsecond. Most amplifiers are slew rate limited due to circuit capacitive and miller effect which limit the full power bandwidth to frequencies well below the amplifier's small-signal frequency response.

Rise Time

This is the time taken by an amplifier for its output to change from 10% to 90% of its final level when driven by a step input which for simple roll-off circuits such as RC circuits may be approximated by:

$t_r * BW = 0.35$, where t_r is rise time in seconds and BW is bandwidth in Hz.

Setting Time

The time taken for the output to settle to within a certain percentage of the final value is called the settling time, and is usually specified for oscilloscope vertical amplifiers and high accuracy measurement systems.

Ringing

Ringing refers to an output variation that cycle above and below an amplifier's final value and leads to a delay in reaching a stable output. Ringing is the result of overshoot caused by an under damped circuit.

Overshoot

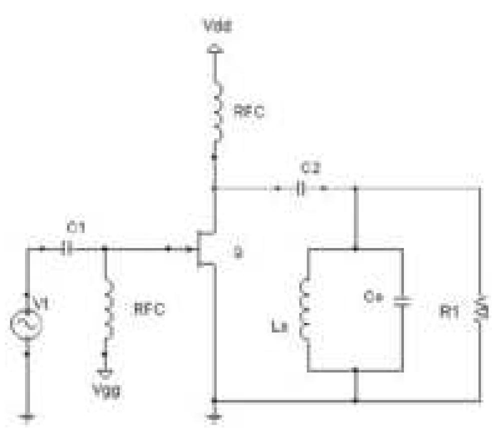
Overshoot is the amount by which the output exceeds its final, steady-state value in response to a step input.

Stability

Stability is a major concern in Radio Frequency and Microwave amplifiers. The degree of an amplifier's stability can be quantified by the stability factor which specifies a condition that must be met for the absolute stability of an amplifier in terms of its two-port parameters.

3.2 POWER ELECTRONIC AMPLIFIERS

Modern electronics as it is known today would not have been possible without active devices such as vacuum tubes, bipolar junction transistors and field effect transistors. Since active devices possess invariably are amplifiers, it goes to say that modern electronics would not have been possible without electronic amplifiers.



Single Ended Amplifier

The main characteristics of an amplifier are Linearity, efficiency, output power, and signal gain and in general, there is a trade off between these characteristics. Improving amplifier linearity will degrade its efficiency. It is therefore important to know the impact of each one of these characteristics as an important step towards designing an Amplifier.

Usually amplifier design is based on application as for instance, you will design a high output power non linear Class C Amplifier for use in the transmitter of a transceiver while you design a highly linear class A amplifier to be used in the receiver side.

Radio Frequency Power Amplifier

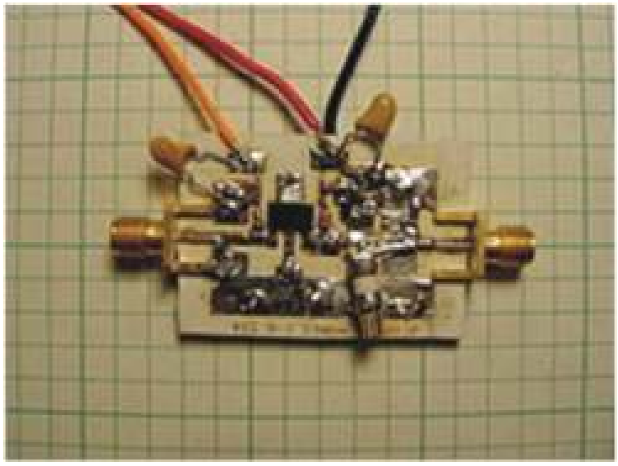
Electronic amplifiers serve as the basis for several technologies which have been spawned in recent times. Particular reference is made to Information Technology and Communications and their several applications through computers, transmitters, receivers, digital equipment, instrumentation which all utilise amplifiers through active devices.

You can remember that the introduction of this Unit qualifies amplifiers by input source, frequency range which they amplify, by whether they invert signal or by the type of device. Remember also to distinguish amplifiers from transducers.

3.3 HIGH FREQUENCY POWER AMPLIFIER

We shall discuss the radio frequency power amplifier as a member of high frequency power amplifiers; which can be described as an electronic amplifier used to convert a low-power radio-frequency signal into a larger signal of significant power which is typically for driving an antenna of a transmitter.

Radio Frequency Power Amplifiers are optimized to achieve high efficiency and deliver high output Power with minimal loss on the input and the output while providing impressive gain with optimized heat dissipation.



Radio Frequency Power Amplifier

Applications of the RF power amplifier include driving to another high power source, driving a transmitting antenna, microwave heating, and exciting resonant cavity structures. Among these applications, driving transmitter antennas is most well known. The transmitter–receivers are used not only for voice and data communication but also for weather sensing as in RADAR sensing.

Microwave or Radio Frequency heating is an industrial application which is also visible in homes in the form of microwave ovens while Subatomic Particles Accelerators utilize Radio Frequency sources extensively.

4.0 CONCLUSION

In this unit we now know that low and high frequency amplifiers are classified by their frequency response and their relative operating frequency range.

We also know that an amplifier operating at a given frequency range might be considered low frequency for some applications while it is considered high frequency for another application.

We have been made to appreciate that our day to day perception of components as we know them has to be radically revised at high frequencies because of parasitic influences..

5.0 SUMMARY

- Low and high frequency amplifiers are classified by their frequency range
- Audio frequency is considered low frequency and falls in the frequency range of a few tens of Hertz up to the region of 15 kilohertz
- The quality of an amplifier can be characterised by its specifications
- Low and high frequency power amplifiers can be identified through their specifications
- Gain, bandwidth, efficiency, linearity, noise, output dynamic range, slew rate, rise time, setting time, ringing, overshoot and stability are all parameters by which power amplifier performance are specified
- Active elements such as transistors, vacuum tubes and integrated circuitry play a pivotal role in amplifier design
- The main characteristics of an amplifier are Linearity, efficiency, output power, and signal gain
- Amplifier design is based on application and has served as the basis for several technologies in recent times
- Radio frequency power amplifier is electronic amplifiers used to convert low-power radio-frequency signal into signal of significantly higher power which typically drives the antenna of a transmitter
- Coupling in power amplifiers require impedance matching for maximum power transfer
- Power gain is the ratio of output power to input power usually expressed in Decibels
- Low frequency power amplifiers are usually less efficient than high frequency power amplifiers because of the class of amplifiers utilised
- Power amplifiers often require forced cooling
- High power high frequency amplifier applications are found in industrial microwave and Radio Frequency heating

6.0 TUTOR MARKED ASSIGNMENTS

1 How would you qualify a low frequency amplifier?

2 Explain why the leads of a capacitor cannot be neglected at very high frequencies?

3 Why are bandwidth, linearity and efficiency so important in amplifier design?

4 What causes signal clipping?

5 What is the consequence of impedance matching?

6 List four radio frequency high power applications?

7 What does RADAR stand for?

8 Explain the effects of parasitic in high frequency work and how they are nullified?

9 What class amplifier would you consider for an audio frequency output stage and which class for the antenna driver of a frequency modulated output stage?

10 What is an amplifier's slew rate? Describe it in detail?

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By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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Module 3

UNIT 1 POWER SYSTEMS

CONTENTS

1.0 INTRODUCTION

Do you remember that electrical energy is the occurrence and flow of electric charge and is observed in static electricity, electromagnetic fields and electrical discharges such as lightning? and do you know that ever since mankind learnt to harness electrical energy in its various forms, store the energy and convert it to other forms of energy, it has become necessary to describe this form of energy in a variety of ways; and that the most common of these descriptions are electric current, electric potential and electrical charge?

Electrical Energy in Lightning Discharge

Now, we also know that electric current is the movement of the electric charge and that electric current is qualified either as direct current or as alternating current. While direct current travels in one direction out of a power source, alternating current alternatively travels in both directions along a conductor within an electrical system. Alternating current form of electricity finds widespread application in electrical power systems because it is easily transmitted over long distances to provide electrical power to residences, cities and industries.

Electrical Power Grid

Electrical potential on the other hand is essential to the delivery of electric energy as its value determines range and power of electricity. When an electric charge exists within an object, a force is exerted from its electrical field which accelerates it in a direction either towards or away from the charge, depending on the electromagnetic polarization. Generally, we may say that positively-charged electricity pushes the object away, while negatively-charged electricity pulls the object towards the field

2.0 OBJECTIVES

After reading through this unit, you will be able to

11 Understand the true nature of electrical energy

12 Describe the various ways of generating electrical energy

13 Explain the principle behind electrical storage and storage devices

14 Describe electrical power transmission systems

15 Distinguish between direct current and alternating current

16 Sketch an electrical power distribution system

17 State the difficulties associated with electrical energy distribution system

18 Distinguish between electrical power generation, power transmission and power distribution systems

19 Know why electrical energy is transmitted at very high voltages

20 List the merits and demerits of direct current electrical transmission compared with alternating current transmission

21 Explain the skin effect and the measures employed to limit its negative impact

22 Explain why Aluminium conductors are preferred in electrical transmission systems

23 Enumerate the properties of alternating current and voltage

24 Sketch alternating current, direct current and pulsating direct current waveforms

25 State the roles that notable scientists like Nikola Tesla and Thomas Edison played in the practical application of electrical energy

26 List the domestic and industrial applications of direct current electrical energy

3.0 MAIN CONTENT

3.1 ELECTRICAL ENERGY

Ancient Egyptians are perhaps the earliest known civilization that understood electrical energy because they were able to define the shocks of electric fish; which knowledge and study of continued through the millennia with Greek, Roman and Arab scholars. Much later in history, Arab scientists were able to accurately determine that the same phenomena caused lightning.

Electric Eel

Very little was understood about electricity as a source of energy until the dawn of the 17^{th} century when an English physician, William Gilbert, studied electricity and magnetism. Several other researchers such as Otto von Guericke, Robert Boyle and Benjamin Franklin continued this study and by the 19^{th} century, scientists like Alessandro Volta had identified a way to harness electrical energy and store it into a battery. This was perfected with time by Nikola Tesla and Thomas Edison who were notable engineers of their time.

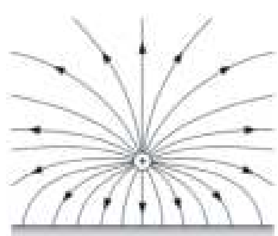
Electrical energy can be generated through a variety of means which include the burning of fossil fuels or the heat from nuclear reactions to produce steam that power generators which, in turn, generate electricity. Alternatively, kinetic energy extracted from either wind or water can power similar generators.

Generation of Electricity from Wind

In order that the generated electrical energy be available for use, it is often necessary to employ one method or the other to transform or modify the electrical energy such that the voltage is increased while the current is reduced; which makes it suitable for transmission over long distances. Alternative methods for storage of electrical energy involve the use of capacitors and accumulators or batteries.

Electrical Energy Storage Cells

As we have earlier discussed, electrical energy is the presence and flow of electric charge and energy in the form of electricity is found in a variety of phenomena which include static electricity, electromagnetic fields and lightning.



Electric Charge

Mankind has developed various ingenious methods of harnessing these phenomena and store the electrical charge for later use. Consequently, the concept of electrical energy is defined using a variety of different terminologies such as charge, current and potential.

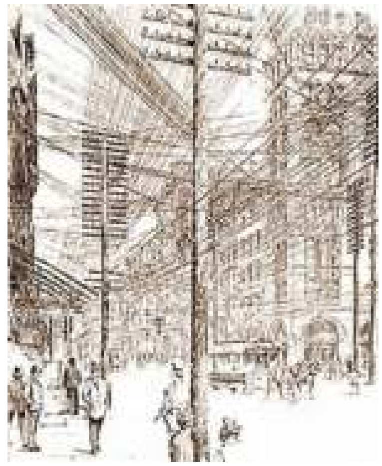
Electric Light Bulb

Electrical energy is the result of the interaction of subatomic particles with electromagnetic force. Within an atom, electrons and protons create electric charge which can be transferred between bodies through direct contact with conductive material such as copper or aluminium wire. When electric charge moves a current is said to flow which may be direct or alternating current.

Electricity stored in a battery and which travels in one direction out of the battery is direct current whereas alternating current occurs when the current changes direction repeatedly within an electrical system as in the public electricity supply where the current changes direction 50 times every second.

3.2 ELECTRICAL POWER SYSTEMS

In the early days of commercial electric power, transmission of electric power at the same voltage as used by lighting and mechanical loads restricted the distance between generating plant and consumers. Also, lighting, fixed motors, and traction railway systems required different voltages, and were forced to be powered by different generators and circuits

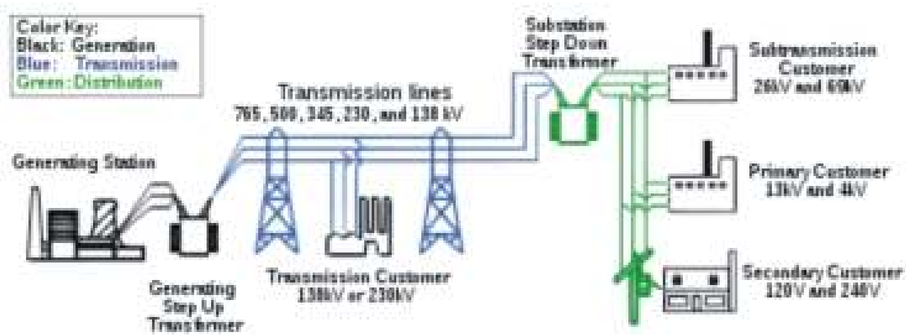


Early Electrical Power Transmission System

Compounding this was the fact that electricity generation was with direct current and this could not easily be increased in voltage for long-distance transmission.

Consequent on the limitations to electrical energy delivery and the specialization of power lines, and including the fact that transmission was so inefficient that generators needed to be near their loads, power industries developed into distributed generation systems with large numbers of small generators located near their loads.

The transformer, and Tesla's polyphase and single-phase induction motors, were essential for the first combined Alternating Current distribution system which served both lighting and machinery needs and which led to complete alternating current power system for both lighting and power.



Typical Electrical Power Distribution System

Modern power systems are configured around non insulated high-voltage overhead Aluminium alloy conductors, made into several strands and reinforced with steel strands. Aluminium alloy is preferred to Copper which is sometimes used for overhead transmission because of its lower weight and much lower cost for only marginally reduced performance.

Improved overhead transmission conductor material and shapes are regularly used to increased capacity and modernize transmission circuits. While conductor size, conductor resistance and conductor length all affect current-carrying capacity, thicker wires lead to relatively small increase in capacity due to the skin effect. Skin effect causes most of the current in power transmission systems to flow close to the surface of the wire which reduces transmission line current carrying capacity by increasing its resistance.

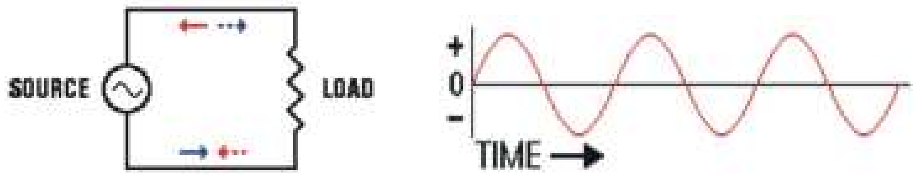
Because of this current limitation, multiple parallel cables called bundle conductors are used when high capacity is required. An additional advantage of bundle a conductor is that at high voltages, corona discharge is minimised which translates to energy loss reduction.

Transmission Substation

Transmitting electricity at high voltage reduces the current and thus the resistive losses in the conductor. If you raise the transmitted voltage by a factor of 10, you reduce the current by a corresponding factor of 10 and therefore the power loss due to conductor resistance which is the I^2R losses is reduced by a factor of 100, provided the same sized conductors are used in both cases.

If conductor cross-sectional area is reduced 10-fold to match the lower current the I^2R losses are still reduced 10-fold which is why long distance transmission is typically done with overhead lines at extremely high voltages. Transmission and distribution losses can be estimated from the discrepancy between energy produced as reported by power plants and energy sold to end customers. The difference between what is produced and what is consumed constitute transmission and distribution losses.

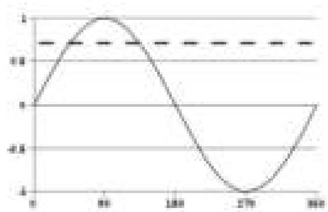
3.3 ALTERNATING CURRENT



Alternating Current Circuit

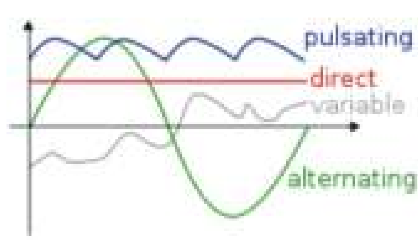
The earliest recorded practical application of alternating current was in electrotherapeutic triggering of muscle contractions by Guillaume Duchenne, inventor and developer of electrotherapy; in the middle of the 19^{th} century.

Ever since then, application of alternating current has rapidly progressed to the point where today, alternating current is the form in which electric power is delivered to businesses and residences worldwide.



Sinusoidal Alternating Current Waveform

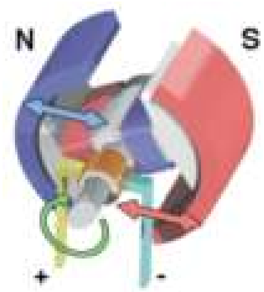
The usual waveform of an alternating current power circuit is a sinusoidal wave as is shown above. In certain applications, different waveforms such as triangular or square waves are used and in audio and radio signals applications in particular, the signals are conveyed by electrical wires where the objective often the recovery of information encoded or modulated onto the alternating current signal.



Alternating Current

In alternating current the movement of electric charge periodically reverses direction as opposed to direct current where the flow of electric charge is only in one direction.

Alternating current can be produced by a coil rotating in a magnetic field. This generates a current which regularly changes direction and where if the rotation is uniform creates a sinusoidal alternating voltage.



Rotating Coil in Magnetic Field

Because the changes in amplitude of alternating electrical systems are so regular, alternating voltage and current have a number of properties associated with any such waveform. Now shall we discuss a few of these properties?

Let us start with the frequency which is one of the most important properties of any regular waveform and which identifies the number of complete cycles the waveform cycles through in a fixed period of time. For standard measurements, the period of time is one second therefore the frequency of a voltage or current waveform is commonly measured in cycles per second or expressed in Hertz. Alternating current power systems operate at a frequency of 50 Hertz or 60 Hertz.

The Period is the amount of time required to complete one cycle of a waveform and is logically the reciprocal of frequency. Thus, period is the time duration of one cycle of the waveform, and is measured in seconds/cycle. An alternating current power system at 50 Hertz will have a period of 1/50 seconds/cycle or 0.02 seconds/cycle. At 60 Hertz, the power system has a period of 1/60 seconds/cycle = 0.016667 seconds/cycle.

Wavelength: Because an alternating current wave moves physically whilst changing its amplitude with time, sometimes we need to know how far it moves in one cycle of the waveform, rather than how long that cycle takes to complete. This is the wavelength of the wave and it depends on how fast the waveform travels through its medium of propagation which in the case of alternating current is electrical conductor.

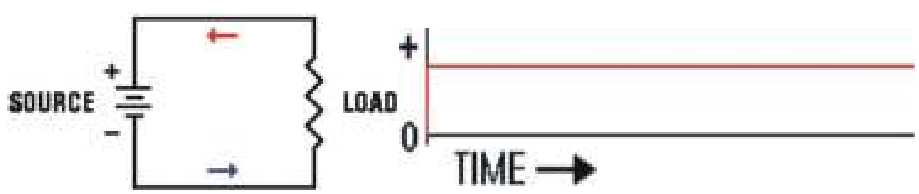
Electrical signals travel through wires at approximately the speed of light. If we know the frequency of the wave in Hertz, or cycles/second, we can determine the wavelength to be (speed of propagation through conducting medium)/(frequency of waveform).

Amplitude is a measure of how positive or negative voltage is with respect to a neutral reference. Direct current voltage is constant at a measurable value but alternating current is constantly changing, yet it still powers load and mathematically, the amplitude of a sine wave is the value of that sine wave at its peak. That is the maximum positive or negative value that it can attain.

When you deal with alternating current properties, frequency and amplitude are of great importance since some types of electrically powered equipment must be designed to match the frequency and voltage of the alternating current power supply. The period is also of some importance in electronic power supplies. While wavelength is not generally important at electrical power frequencies, it becomes much more important with signals at considerably higher frequencies.

3.4 DIRECT CURRENT

Direct current is the flow of electric charge is only in one direction as opposed to alternating where the movement of electric charge periodically reverses direction and direct current, as produced by, for example a battery and required by most electronic devices, is a unidirectional flow from the positive part of a circuit to the negative.



Direct Current Circuit

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When you look around you, you will notice that rarely is direct current used to power appliances.

3.4.1 Direct Current Power Systems

Modern high-voltage, direct-current electric power systems contrast with the more common alternating-current systems as a means for the efficient bulk transmission of electrical power over long distances. Over short distances, high voltage direct current transmission tends to be more expensive and less efficient than alternating current systems.

A major advantage of direct current transmission lies in the fact that direct current flows constantly and uniformly throughout the cross-section of a uniform wire which contrasts with alternating current of any frequency whatsoever, which is forced away from the centre of the conducting wires towards its outer surface.

This is because the acceleration of an electric charge in an alternating current produces waves of electromagnetic radiation that cancel the propagation of electricity toward the centre of materials with high conductivity in a phenomenon called skin effect.

High voltage direct current is often used to transmit large amounts of power over long distances or for interconnections between asynchronous grids. When electrical energy is required to be transmitted over very long distances, it is more economical to transmit it using direct current instead of alternating current. For long transmission lines, the lower losses and reduced construction cost of a Direct Current line can offset the additional cost of converter stations at each end of the line and special high voltage cables for DC are built. Many submarine cable connections of up to 600 km length are in use,

Whenever it is necessary to stabilize against control problems with alternating current electricity flow, high voltage direct current links are sometimes used. Alternating current power when transmitted through a line increases as the phase angle between source end voltage and destination ends increases. Because too great a phase angle will allow the generators at either end of the line to fall out of step as the power flow in a direct current link is controlled independently of the phases of the alternating current networks at either end of the link, system stability is compromised.

Direct current powered rail system

This does not apply to a direct current line, and it can transfer its full rating as stability related issues do not apply. A direct current link is used to stabilize alternating current and links the grids at either end where power flow and phase angle can be controlled independently.

Let us illustrate as follows. In order to transmit alternating current when needed in either direction between two distant locations, we would require highly challenging continuous real-time adjustment of the relative phase of the two electrical grids. If on the other hand we were to transmit high voltage direct current instead, the interconnection would convert alternating current into high voltage direct current which would be transmitted over long distance then converted to locally synchronized alternating current at the terminal end of transmission.

3.4.2 Disadvantages of Direct Current

When commercial use of electricity became wide-spread, certain disadvantages in using direct current in homes became apparent. If commercial direct-current system is used, voltage must be generated at the level required by the load. To properly light a 220 volt lamp, the direct current generator must deliver 220 volts.

If a 110 volt load is to be supplied power from the 220 volt generator, a resistance must be placed in series with the 110 volt load to create a voltage drop of 110 volts. When resistance is used to reduce voltage, an amount of power equal to that consumed by the load is wasted.

Another disadvantage of direct-current systems becomes evident when direct current from the generating station must be transmitted over a long distance through wires to the consumer. A large amount of power is lost due to the resistance of the wires and the power loss is equal to I^2R where I is the current through the wires and R the resistance of the wires.

This loss can be greatly reduced if the power is transmitted over the wires at a very high voltage and at low current. This is not a practical solution to power loss in a direct current system since the load would then have to be operated at a dangerously high voltage and because of the disadvantages related to transmitting and using direct current, practically all modern commercial electric power companies generate and distribute alternating current which can be stepped up or down by a transformer which permits efficient transmission of electrical power over long-distance lines.

At the electrical power generating station, the transformer output power is at high voltage and low current. At the consumer end of the transmission lines, the voltage is stepped down by a transformer to the value required by the load.

Due to its inherent advantages and versatility, alternating current has replaced direct current in all but a few commercial power distribution systems. Amongst commercial applications of direct current are electric railway systems and ore smelting plants.

4.0 CONCLUSION

In this unit we have learnt that electrical energy is the occurrence and flow of electric charge and is described in a variety of ways; the most common of which are electric current, electric potential and electrical charge.

We now know as well that electricity is generated through a variety of means which include burning of fossil fuels and utilising the heat from nuclear reactions to produce steam to power electricity generators. Similarly, kinetic energy extracted from either wind or water is used to power similar electricity generators.

This unit further teaches us that electrical power transmission systems employ non insulated high-voltage overhead conductors usually made of Aluminium to convey high voltage AC or DC over long distances.

And finally, this unit has made clear that AC and DC have both merits and demerits when compared and in general, that AC is better suited for local distribution systems and point of use where the line voltage is transformed to a suitable value for domestic or industrial use while high voltage DC can be transmitted over greater distances than AC because it is not plagued by skin effect and associated transmission losses.

5.0 SUMMARY

- Electrical energy is the occurrence and flow of electric charge
- Electrical energy is observed in static electricity, electromagnetic fields and electrical discharges
- Electric current can either be qualified as alternating current or as direct current

- Electrical energy can be stored and the energy convert to other forms of energy

- Alternating current is widely applied in electrical power systems because it is easily transmitted over long distances

- Electrical energy can be generated through a variety of means

- kinetic energy extracted from wind and water can power electricity generators

- Electricity transmission over long distance utilise high voltage transformers which increase the voltage and reduce current during transmission

- Electrical energy is stored in capacitors, inductors, accumulators and batteries

- Aluminium alloy is often used for high voltage overhead transmission due to its lower weight and lower cost at the expense of marginally reduced performance

- Alternating current can be produced by a coil rotating in a magnetic field

- Alternating voltage and current waveforms have properties associated with them which include amplitude, frequency, period and wavelength

- Direct current links are used to stabilize alternating current through linking grids at either end where power flow and phase angle are controlled independently

6.0 TUTOR MARKED ASSIGNMENTS

1 Briefly describe what an electrical power system is?

2 State two forms of naturally occurring electricity?

3 What are the most common parameters used in the description of electrical energy?

4 Define electric current and, sketch and describe direct and alternating currents?

5 How is electricity conveyed from the generating station to the consumer?

6 What methods are used to store electrical energy?

7 Compare direct current and alternating current power transmission

8 Can you describe the skin effect?

9 Compare direct current and alternating current power consumption?

10 What are the benefits of high voltage electricity transmission?

11 Sketch an alternating current waveform. Can you label it and mention three ways in which it can be produced?

12 Enumerate the properties of alternating current with labelled sketches. Can you recall the speed of propagation of electricity in conducting metal?

13 Mention five industrial appliances that use alternating current. Can you also identify five domestic appliances that use direct current?

14 Why are long distance high voltage direct current transmission systems superior in performance to alternating current systems?

15 What other purposes do high voltage direct current transmission systems serve in hybrid AC/DC transmission systems?

16 Discuss in detail the challenges that face electrical power generation, transmission and distribution in Nigeria?

17 Can you state two industrial consumer applications of direct current?

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By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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

Fundamentals of Electric Circuits 4th Edition
By Alexander and Sadiku Published by Mc Graw Hill

UNIT 2 POWER SUPPLIES

CONTENTS

1.0 INTRODUCTION

Electronic circuits require a wide variety of voltage levels to operate correctly. While some functions require alternating current, most need to be supplied direct current. DC to DC converters are used to either transform one voltage level to another or to provide isolation as in the case of a voltage bus. They are typically used in power distribution systems to provide local voltage conversion, point of load voltage regulation or power bus isolation.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Appreciate the reason why electrical power supplies are necessary

2 Distinguish between alternating current and direct current power supplies

3 Describe the functioning of the transformer

4 Sketch a half wave and a full wave rectifier

5 Sketch a half wave and a full wave rectifier output waveform

6 Explain the need for a filter capacitor in power supplies

7 Discuss methods for reduction of ripple in the output of power supplies

8 Distinguish between linear and non linear power supplies

9 Describe the operation of the switching power supply

10 List the merits and the demerits of the switching power supply when compared with the linear power supply

11 Compare the efficiencies of linear power supplies and switching power supplies

12 State the economic advantages of switching power supplies

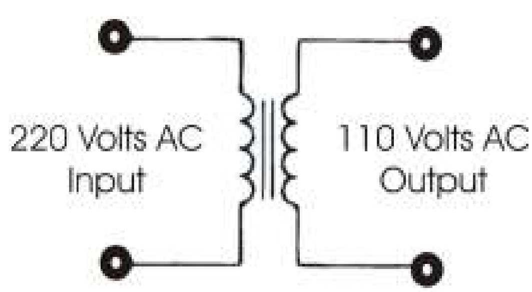
3.0 MAIN CONTENT

3.1 ALTERNATING CURRENT POWER SUPPLY

We are familiar with the mains electricity supply which is supplied at 220 volts AC, however in some parts of the world in the past, mains electricity was supplied as Direct Current while it was supplied as Alternating Current in others.

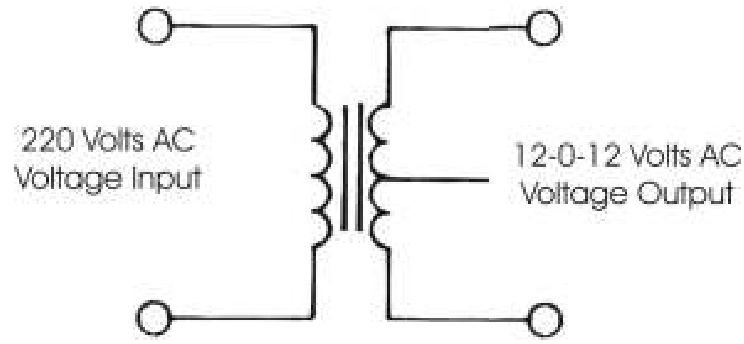
The major problem with direct current is that transformers cannot be used for voltage increment or reduction. With Alternating Current, long distance transmission at very high voltages makes it possible to transmit energy incurring minimal transmission losses.

In an Alternating Current Power Supply, mains voltage is supplied through electricity outlet at 220 volts 50 Hertz. If the equipment to be powered directly at 220 volts AC then it must pass through a transformer to either increase or decrease the voltage.



Step Down Transformer

Alternating Current from the [public utility company is usually not a pure sinusoidal waveform at 220 volts AC but suffers from a number of distortions to the pure waveform. The supply may contain impurities such as electrical noise which may occur within any band of the electromagnetic spectrum capable of being transmitted by the power grid. The frequency of the alternating current often deviates from 50 hertz because the power grid frequency is influenced by loading.



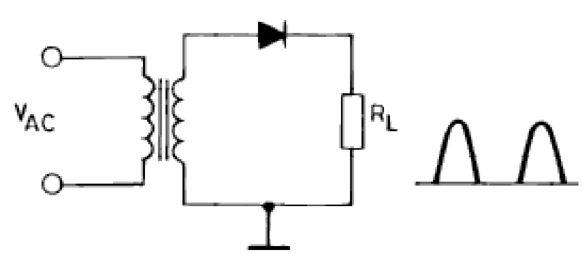
Centre Tapped Step down Transformer

A common occurrence is a situation where the voltage output is higher or lower than 220 volts; and occasionally there is a total absence of electricity supply or a power outage.

Other forms of electrical noise include spikes and other transients which may be during to inductive or capacitive (reactive) loading of the AC circuit.

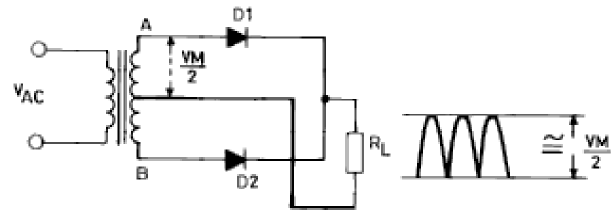
3.2 BASIC DIRECT CURRENT POWER SUPPLY

In mains-supplied electronic systems the AC input voltage must be converted into Direct Current voltage with the correct value and degree of stabilization. The simplest rectifier circuits are illustrated below and in these basic configurations the peak voltage across the load is equal to the peak value of the Alternating Current voltage supplied by a transformer's secondary winding.



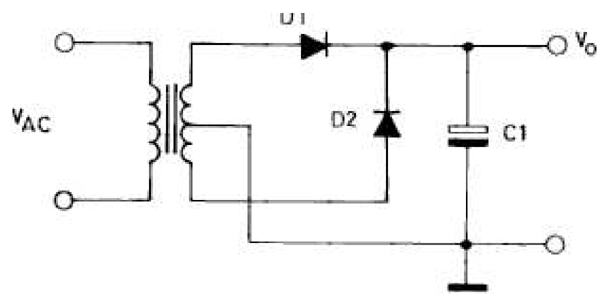
Half Wave Rectifier Circuit

Above is a basic half wave rectifier while the illustration below is a full wave rectifier circuit which uses a centre tapped transformer both for isolation and for voltage transformation.



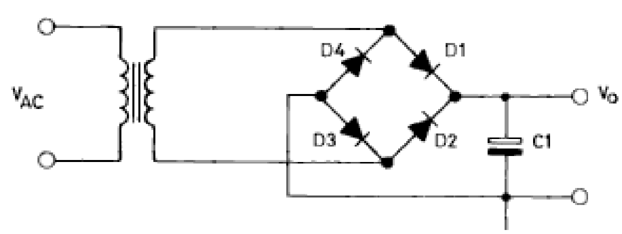
Full Wave Rectifier Circuit

The output ripple produced by these simple rectifier circuits is too high for most applications being only satisfactory for such applications as the driving small motors or lamps. The output waveform is greatly improved when a filter capacitor is added after the rectifier diodes as is illustrated below.



Full Wave Rectifier with Filter Capacitor

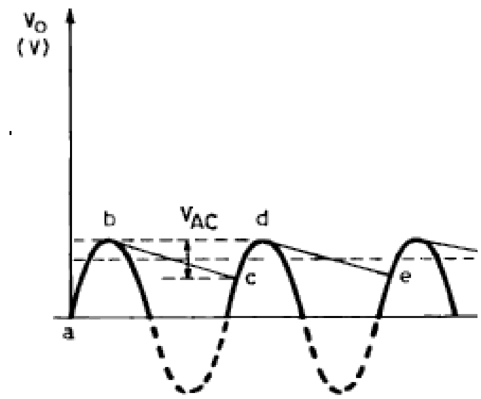
This circuit is a full wave rectifier and used only two rectifier diodes because it is designed around a centre tapped transformer. The functional equivalent of this circuit which does not employ a centre tapped transformer must use a bridge rectifier circuit comprising four rectifier diodes in order to achieve full wave rectification. This is illustrated below.



Full Wave Bridge Rectifier with Filter Capacitor

Output voltage waveform is improved considerably with full wave rectifier incorporating filter capacitor.

The addition of a filter capacitor generates the continuous voltage curve illustrated below where in the region defined by the line b-c, the filter capacitor exclusively supplies the load current as the rectifier diode is reverse biased in this region. The slope of this line increases as the load current increases bringing point c lower and increasing the ripple.



Half Wave Rectifier Filter Waveform

When no load current is drawn from the supply the DC output voltage is equal to the peak value of the rectified Alternating Current voltage.

It will be easy for you to understand that the value of the voltage ripple obtained is directly proportional to the load current and inversely proportional to the filter capacitor value.

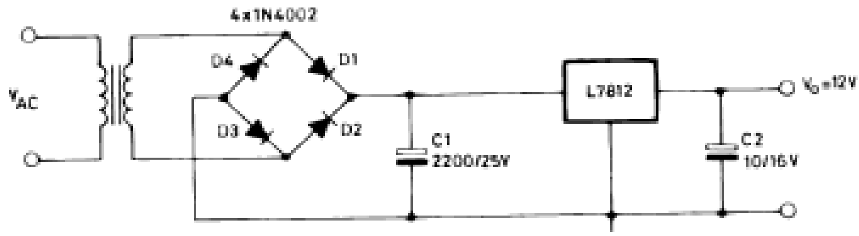
3.3 LINEAR POWER SUPPLY

The voltage output produced by an unregulated power supply is subject to loading load as well as variations in the supply voltage and for critical electronics applications, linear regulator are used to set the voltage to a precise value which is stabilized against fluctuations in input voltage and load.

Regulators reduce ripple and noise in the output while they often provide current limiting which protects the power supply and attached circuit from overload.

Linear Power Supply

The broad classification of power supplies which are used in electronic devices are Linear Power Supplies and Switching Power Supplies. Linear Power Supplies have a major advantage of simplicity of design while the major disadvantage is their size as their current handling capacity increases.



Simple Regulated linear Power Supply

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.

Adjustable Linear Power Supply

3.4 SWITCHING POWER SUPPLY

In case you do not realise that, on a daily basis, when you activate electronic devices by switching them on, the chances are that you actually do so by switching on a Switching power Supply better known as switched-mode power supply. So, next time you turn on your computer, charge your GSM handset, turn on your low energy environment friendly electric bulb, turn on your television or even when you switch over to your inverter – you more likely than not switch on a Switching Power Supply.

These power supplies do not work on the same principle as the Linear Power Supplies because usually, Alternating Current input at mains voltage, is rectified directly to obtain a Direct Current voltage without using a mains transformer,. The direct current voltage is then rapidly switched on and off by electronic switching circuitry at high high-frequency – resulting in a small, light weight, and inexpensive power supply.

Commercial switching power supplies are always regulated and when a properly insulated high-frequency transformer is used, the output will be electrically isolated from the mains voltage, which is crucial for operator safety.

Computer Switching Power Supply

One of the first wide scale commercial application of switching power supplies is the IBM computer power unit as depicted above;

It is a convenient modular device that converts the mains input AC voltage to the DC voltages needed by a personal computer and ever since the introduction of IBM PC/XT, several Personal Computer types have emerged which differ by their structure, form factors, connectors and volt/amp ratings. All invariably depend on Switching Power Supply Units for their operation.

A standard Personal Computer Power Supply Unit generates +5V, +3.3V, +12V1, +12V2, -12V and a standby 5V. Additional DC-DC converters step down 12V to the CPU core voltage and other low voltages needed for motherboard components, peripherals, floppy drive, and serial ATA connectors.

Power supplies for computers utilize switching mode technology and are ENERGY STAR compliant. This used to mean that computers consumed less than 10% of rated power in standby mode while in an active mode the efficiency of cheap models used to be 60-70%.

4.0 CONCLUSION

In this unit we found out that electronic circuits require a wide variety of voltage levels to operate correctly and that while some functions require alternating current, most need to be supplied direct current.

It has also been made clear by this unit that DC to DC converters are used to either transform voltage levels from a given level to another, or to provide isolation.

5.0 SUMMARY

- Electrical power supplies are requires to power electrical appliances
- Transformers cannot be used with direct current to increase supply voltage
- Alternating current from the public mains supply is impure as it contains electrical noise and many types of distortion
- Basic direct current power supplies produce pulsating half wave or full wave direct current
- Filter capacitors improve the waveform of basic direct current power supplies
- Voltage regulators reduce ripple and noise in the output
- Power supplies are classified into linear and switching power supplies
- Switching power supplies utilise an energy storing circuit element like a capacitor or an inductor
- Switching power supplies are more economical than linear power supplies of the same capacity

6.0 TUTOR MARKED ASSIGNMENTS

1 What is an electronic power supply?

2 Can you describe direct current power supply?

3 What role do transformers play in power supplies?

4 Can you sketch a centre tapped transformer with input of 220 Volts and output of 24 Volts? And label it?

5 Sketch a basic direct current power supply and label the parts and sketch its output waveform?

6 How can you reduce the ripple in a basic direct current power supply?

7 Can you state the two broad classifications of power supplies?

8 What role do regulators play in power supplies?

9 Mention ten devices which operate from switching power supplies?

10 Discuss the principle of operation of switched mode power supplies?

11 Discuss the function of filter capacitors in power supplies?

12 What do voltage regulators do?

13 Compare and contrast the benefits of linear and switching power supplies?

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UNIT 3 STABILISED POWER SUPPLIES

CONTENTS

1.0 INTRODUCTION

Voltage available from the public electricity supply through your wall outlet is poorly regulated Alternating Current in contrast with power requirements of electronic circuits which require stabilized Direct Current Power Supply.

Direct Current Power Supply

A power supply is a device that supplies electrical energy to one or more electric loads. The term is most commonly applied to devices that convert one form of electrical energy to another, though it may also refer to devices that convert another form of energy such as mechanical, chemical or solar energy to electrical energy.

Computer Power Supply

A regulated power supply is one that controls the output voltage or current to a specific value; the controlled value is held nearly constant despite variations in either load current or the voltage supplied by the power supply's energy source. Every power supply must obtain the energy it supplies to its load, as well as any energy it consumes while performing that task, from an energy source.

Power supplies for electronic devices can be broadly divided into linear and switching power supplies. The linear supply is usually a relatively simple design, but 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 regulators produce regulated output voltage by means of an active voltage divider that consumes energy, thus 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.

Power supplies may be implemented as a discrete, stand-alone device or as an integral device that is hardwired to its load. In the latter case, for example, low voltage DC power supplies are commonly integrated with their loads in devices such as computers and household electronics.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Understand how constant voltage power supplies operate

2 Describe the process of stabilisation in power supplies

3 Discuss voltage regulators

4 Distinguish between active and passive regulators

5 Explain the significance of feedback loop in stabilisation

6 Compare and contrast linear regulators and switching regulators

7 Appreciate the significance of hybrid regulation

8 Sketch the simplest regulator circuit

9 Discuss series and shunt regulators

10 Sketch an integrated circuit regulator

11 Associate the output voltage of the 78xx and 79xx solid state regulators with their product number

12 Explain drop-out voltage as applied to regulators

13 Compare the frequency response of switching and linear regulators

3.0 MAIN CONTENT

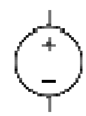
3.1 CONSTANT VOLTAGE POWER SUPPLIES

A voltage regulator is an electrical regulator which automatically maintains a constant voltage level. A voltage regulator may be a simple design or may include negative feedback control loops and may be electromechanical or electronic. It may, subject to design be used to regulate alternating or direct current voltages.

Electronic voltage regulators are found in various devices ranging from computer power supplies where they stabilize direct current voltages used by the processor and other elements, to automobile alternators and central power station generator plants where voltage regulators control the output of the plant.

They are also to be found in electric power distribution systems where voltage regulators are usually installed at substations or along distribution lines so that all customers receive steady voltage independent of how much power is drawn from the line.

Let us recall that in electric circuit theory, an ideal voltage source is a circuit element where the voltage across it is independent of the current through it and that a voltage source is the electrical dual of a current source. In analysis, a voltage source supplies a constant direct current or alternating current potential between its terminals for any current flow through it. Real-world sources of electrical energy, such as batteries, generators, or power systems, can be modelled for analysis purposes as a combination of an ideal voltage source and additional combinations of impedance elements.



Ideal Voltage Source

A simple voltage regulator can be made from a resistor in series with a diode or a tandem of diodes in series where due to the logarithmic shape of diode V-I curves, the voltage across the diode changes only slightly due to changes in current drawn. When precise voltage control is not important, this design is suitable.

Feedback voltage regulators operate by comparing the actual output voltage to some fixed reference voltage while any difference is amplified and used to control the regulation element in such a way as to reduce the voltage error. This arrangement forms a negative feedback control loop. If we increase the open-loop gain, it leads to an increase in regulation accuracy but reduces stability. It also results in a trade-off between stability and the speed of the response to changes.

If the output voltage is too low which may result from input voltage reduction or load current increase, the regulation element produces a higher output voltage and vice versa.

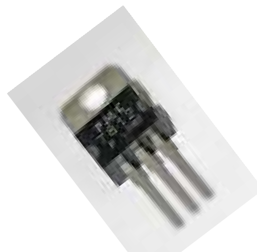
3.2 ACTIVE REGULATORS

An active regulator requires at least one active element such as a triode valve, a transistor or an operational amplifier. Known for being highly inefficient, shunt regulators are often composed of passive and simple components. They are inefficient because they shunt excess current not needed by the load and when more power must be supplied, more sophisticated circuits are used.

Active regulators are divided into classes; the two most important and universally used being the linear series regulators and switching regulators.

3.2.1 Linear Regulators

Linear regulators use devices that operate in the linear region of their characteristic curve with modern designs using one or more transistors or an Integrated Circuit, whereas in a switching regulator, a device is forced to act as an on/off switch.



Linear Solid State 12 Volt Regulator

The major advantage of linear regulators is the extremely low noise introduced into their direct current output but they are not as energy efficient as their switched counterparts. Because all linear regulators require a higher input voltage than their output voltage, if the input voltage approaches the desired output voltage, the regulator output will experience "drop out" and the input to output voltage differential at which this occurs is known as the regulator's drop-out voltage.

Integration has made it possible to implement entire linear regulators as integrated circuits such as the 78 and the 79 series; which are positive and negative voltage regulators respectively. Voltage regulator chips are either fixed or adjustable voltage regulators.

3.2.2 Switching Regulators

Switching regulators as the name implies operate by rapidly switching a series active device on and off while the duty cycle of the switched device determines how much electrical charge is transferred to the load. This function is controlled by a feedback mechanism that is similar to that in a linear regulator and because the series element is either fully conducting, or switched off, very little energy is dissipated in the switching device.

This result in very high efficiency associated with switching regulators. In contrast with linear regulators, Switching regulators are also able to generate output voltages which are higher than the input, or output voltages of reverse polarity.

Complete integrated circuit switching regulators are not available because the power reactive elements requires in switching regulators cannot be implemented on a chip, however nearly-complete switching regulators are available as integrated circuits which usually require one external component: an inductor that acts as the energy storage element.

In comparison with linear regulators; the two types of regulators have merits and demerits outlined as follows:

- Linear regulators introduce very little noise to their output voltage which in contrast with switching regulators which have very noisy output which produce a lot of radio frequency interference if additional circuitry is not used to suppress output noise. Linear regulators are therefore better when low output noise; particularly low radio frequency interference is required

- Linear regulators have quicker response to input and output variations of voltage and load respectively. Switching regulators on the other hand are much slower and suffer a more sluggish tracking of the reference voltage and as such are less suited for applications where fast response to input and output disturbances is required.

- In low power applications, Liner regulators are more economical; they cost less and require less space because complete and comprehensive designs can be implemented on a chip.

- Switching regulators are superior to linear regulators where power efficiency is critical.

- Where the only source of power is direct current at a lower voltage than a desired output voltage, Switching regulators are the only way that voltage can be produced.

In many power supplies there is the need to use more than one regulating method in series and therefore, the output from a switching regulator can be further regulated by a linear regulator. The switching regulator accepts a wide range of input voltages and efficiently generates a voltage slightly above the ultimately desired output. A linear regulator that generates exactly the desired voltage and eliminates nearly all the noise generated by the switching regulator follows the switching regulator. This combination of regulating methods is known as Hybrid regulator.

4.0 CONCLUSION

In this unit we learnt that electronic circuits which stabilized direct current power supplies which is achieved through regulation and that a regulated power supply is one that controls the output voltage or current to a specific value. Voltage regulator may be a simple design or may include negative feedback control loops.

5.0 SUMMARY

- Power supplies for electronic devices can be broadly divided into linear and switching power supplies
- Voltage sstabilisation in power sup[plies is attained through voltage regulators
- Regulators are classified as active and passive regulators
- Linear power supplies becomes increasingly bulky and heavy for high-current equipment because of the need for large mains-frequency transformers
- Hybrid regulators employ a combination of linear and switching regulators
- Power supplies may be implemented as discrete stand-alone devices or as integral devices hardwired to the appliance
- Electronic voltage regulators are found in devices ranging from computer power supplies to automobile alternators and central power station generator plants
- The simplest voltage regulator is made from a resistor in series with a diode
- Feedback voltage regulators operate by comparing actual output voltage to fixed reference voltage and the difference is amplified and used to control a regulation element to reduce voltage error
- Active regulator require at least one active element
- Complete integrated circuit switching regulators are not practicable because high power electrical energy storage elements cannot be implemented on a chip
- Linear regulators introduce very little noise to their output voltage
- Low power liner regulators are economical
- Switching regulators are the only way to produce voltage when the only source of power is direct current at a lower voltage than the desired output voltage

- Series regulators are connected in series with the load while shunt regulators are connected in parallel with the load

- The 78xx and 79xx are respectively integrated circuit positive and negative voltage regulators where for instance the 7805 is a 5 volt positive voltage regulator

- Linear regulators have a better frequency response than switching regulators

6.0 TUTOR MARKED ASSIGNMENTS

1 What is a stabilised power supply? Explain in detail with supporting illustration?

2 Why can you not use the mains voltage directly to power all of your electrical appliances?

3 Compare and contrast linear and switching regulators?

4 What is a common feature of switching regulators?

5 How would you describe an active regulator?

6 Which type of regulator is commonly found in computer power supplies? And what are the terminal voltages?

7 What voltages do the following solid state linear regulators provide at their output terminals?

7812 Regulator
7924 Regulator
7905 Regulator
7807 Regulator

8 Explain why it is not feasible to implement switching regulators on a microchip?

9 How does a switching regulator function? Explain in detail?

10 Can you sketch the voltage output of a linear regulator output?

11 Sketch the circuit diagram of a transistor buffered shunt regulator and label its parts?

12 Using the LM324 dual operational amplifier pair and a 7.4 Volt reference Zener diode, design a dual voltage regulated variable power supply with a voltage range from 0 Volt to 24 Volts?

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UNIT 4 USES OF TRANSISTORS IN STABILISED POWER SUPPLIES

CONTENTS

1.0 INTRODUCTION

The most effective way for you to appreciate the important role transistors play in power supplies is to understand the significance of transistors in regulators; we shall therefore revisit regulators; particularly those which employ negative feedback loop bearing in mind transistors form an integral part of the feedback loop and therefore cannot be divorced from stabilised power supplies.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. Recognise the importance of transistors in stabilised power supplies
2. Realise that regulator power stages consist of at least one transistor which serve as the active element in the regulation or negative feedback loop
3. See that the application of transistors in stabilised power supplies is almost always in association with negative feedback loop
4. Understand why regulators require a reference voltage which is derived from a potential divider arrangement

5 See how the current output of the basic regulator can be boosted with an active element such as a transistor

6 Amplify the error signal of the regulator output with a transistor through a negative feedback loop to correct the regulator output

7 Use the high open loop voltage gain of an operational amplifier along with its exceedingly high input impedance to buffer the output of an operational amplifier buffered regulator

3.0 MAIN CONTENT

3.1 SOLID STATE VOLTAGE REGULATORS

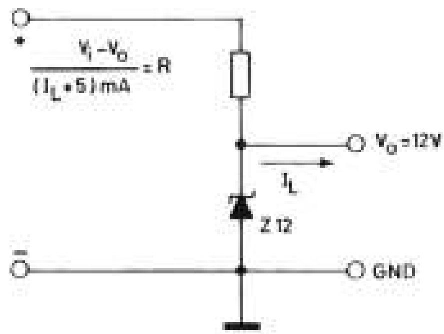
In solid state voltage regulation, a diode or an active element such as a transistor is used as one half of a potential divider to control the output voltage of the regulator.

Where an active circuit element is used, a feedback circuit can be made to compare the output voltage to a reference voltage in order to adjust the input to the active circuit element. This maintains a constant voltage at the output of the regulator.

We shall limit our discussion at this point to linear voltage regulators which are classified either as series regulators or shunt regulators. As we have earlier discussed, linear solid state voltage regulators are inefficient: since the active element acts like a resistor and as such dissipates electrical energy through conversion to heat.

Solid State Series Voltage Regulators

Series regulators are the more common form of linear regulators. Why do you think they are called series regulators? It is because the series regulator functions by providing a path from the supply voltage to the load through a variable resistance in series with the load. This way, it acts as a variable voltage divider and the power dissipated by the regulating device is equal to the product of the power supply output current and the voltage drop in the regulating device.



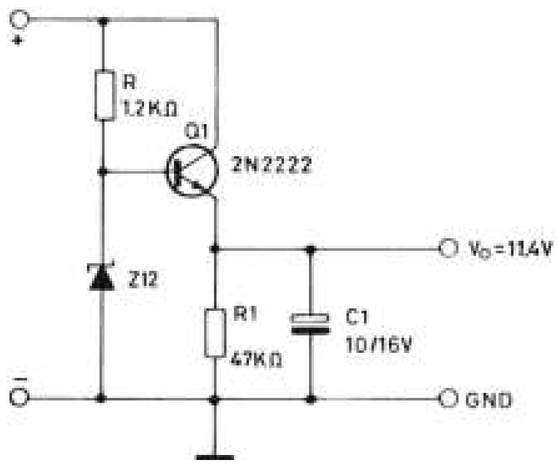
Simple Shunt Regulator

A shunt regulator on the other hand operates by providing a path from the supply voltage through a variable resistance which bypasses the load. The current through the shunt regulator is diverted away from the load and in effect is wasted. This renders this form of regulation even less efficient than the series regulator, however, it has a simpler topology and can be as simple as consisting of just a voltage-reference diode. This minimal form however is used in very low-powered circuits where the wasted current is considered negligible. It is common in voltage reference circuits.

All linear regulators require an input voltage which is higher than the desired output voltage. The minimum value that this voltage difference can have is called the dropout voltage. The output voltage for the common 7805 regulator is 5 Volts but the regulator will only maintain this output voltage if the input voltage remains above about 7 Volts as any value below 7V will result in an output below the rated 5V. The dropout voltage in this case is 2 Volts.

In an unregulated direct current power supply, a low ripple voltage can be obtained at the output by utilising an LC filter network but when inductors become costly and bulky or the degree of stability provided by the LC circuits described above is insufficient, a voltage stabilizer circuit is required.

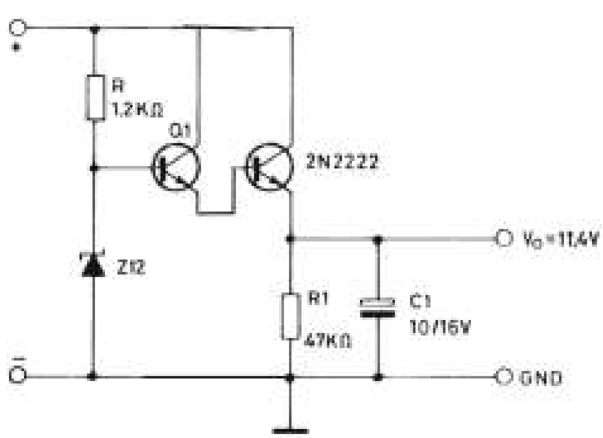
As illustrated above, the simplest regulator is the shunt regulator comprising a shunt Zener diode, and this circuit is often used as a reference voltage to apply to the base of an active device such as a transistor, or to the input of an operational amplifier to obtain higher output current.



Series Regulator

The simplest example of a series regulator is illustrated above and comprises a transistor which is connected as a voltage follower and where the output voltage is about 600 - 700mV lower than the zener voltage due to the emitter-base junction. The resistor R biases the Zener diode and base current is supplied to the base of Q_1.

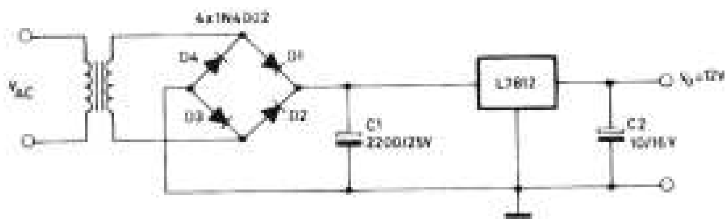
This regulator can be limited by the load requiring that the base current be higher than that which flows through the resistor R, in which case, the circuit illustrated below which is known as a Darlington may be used in place of the single transistor.



Darlington Buffered Series Voltage Regulator

When an even better regulation performance is required the operational amplifier is recommended. Because the open loop gain of an operational amplifier is extremely high, very good regulation is attainable and high output current is possible when output current buffer devices are included. We shall discuss the operational amplifier voltage regulator in detail in the next section.

Stabilized power supplies has been simplified dramatically by voltage regulator Integrated Circuits such as the L78xx and L79xx series which are three terminal regulators that provide a very stable output, include current limiter and has thermal protection functions.



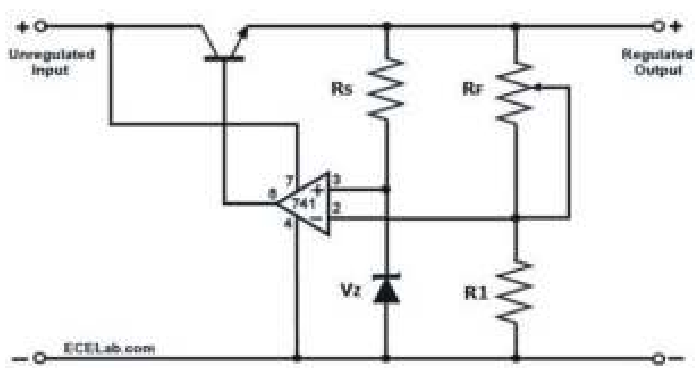
L78xx and L79xx Three Terminal Series Regulator Series

A complete positive 12 Volt stabilised power supply designed with such an integrated circuit is illustrated above.

3.2 OPERATIONAL AMPLIFIER VOLTAGE REGULATOR

The stability of the output voltage of an unregulated direct current supply can be significantly increased by using an operational amplifier.

The illustration below is an operational amplifier voltage regulator with a transistor output to boost the output current.



Operational Amplifier Voltage Regulator

Unregulated direct current input is applied to the circuit and at the output; regulated direct current with extremely low ripple content is available.

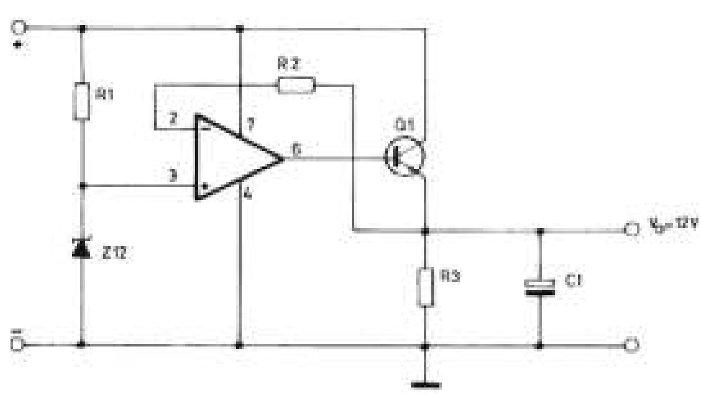
The input voltage must be higher than the desired output voltage level by a sufficient margin in order to achieve proper regulation at the output. The zener diode Vz acts as a voltage reference for the circuit, and is fed into the non-inverting input of the operational amplifier. The voltage divider formed by R_1 and R_F determines the voltage level of the inverting input of the operational amplifier while the NPN transistor is used to boost the output current of the circuit.

The voltage at the non-inverting input of the operational amplifier is set to the zener voltage while the voltage at the inverting input is always a fraction of the output voltage as defined by R_F and R_1.

When the output exceeds the set level, the inverting input voltage exceeds that of the non-inverting input, causing reduction of the output voltage of the operational amplifier. This in turn reduces the emitter current of the NPN transistor which causes a reduction in the output voltage.

Conversely, when the output voltage falls below the level set by the reference network, the operational amplifier's output increases and causes the NPN transistor to increase its emitter current. This results in an increase in the output voltage of the regulator.

The action describe above is a continuous process with the circuit reacting instantaneously to deviations in the output voltage while resistor R_F is used to set the desired output voltage of the circuit.



Operational Amplifier Voltage Regulator
With Output Voltage set to Zener Voltage

The circuit illustrated immediately above is similar in function to the one already described. You should study the two circuit topologies and reassure yourself that the output voltage is the same as the Zener Diode voltage.

4.0 CONCLUSION

In this unit we discover that transistors play a vital in power supplies; particularly regulated power supplies where they are used as current buffers to basic zener reference voltages and as the active element in negative feedback loops which amplify error voltage to be applied as a correctional feedback input voltage.

The role of transistors is also evident indirectly in regulator integrated circuits such as the 78xx and 79xx series regulator chips, as well as in operational amplifiers utilised for the purpose of regulation in power supplies.

5.0 SUMMARY

- Transistors directly and indirectly play an important role in stabilised power supplies
- Transistors are used as current buffer in basic regulators
- The negative feedback loop in regulated power supplies utilise transistors as the active element
- Transistors are used as the switching element in switched mode power supplies
- Integrated transistors in operational amplifiers and regulator chips play an important role in power supplies

6.0 TUTOR MARKED ASSIGNMENTS

1 In what kind of stabilised power supplies are transistors not used?

2 Can you state the electrical element that provides the reference voltage in stabilised power supplies and describe its operation?

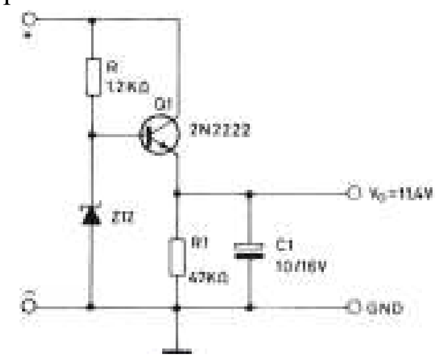
3 How would a 78xx/79xx solid state regulator be designated if it were to supply negative 15 Volts at its output?

4 Explain the method of operation of series and shunt regulators?

5 Sketch the circuit diagram of a transistor buffered series regulator?

6 Sketch the circuit diagram of a transistor buffered shunt regulator?

7 In the diagram below, can you state what kind of regulator this is? Describe the operation of this circuit in detail?



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Fundamentals of Electric Circuits 4th Edition
By Alexander and Sadiku Published by Mc Graw Hill

UNIT 5 SWITCHED MODE POWER SUPPLY

CONTENTS

1.0 INTRODUCTION

A switched-mode power supply incorporates a switching regulator for high efficiency in the conversion of electrical power and like other types of power supplies, a switched-mode power supply transfer's power from a source such as the electrical power grid to a load like a personal computer while converting voltage and current characteristics.

Inexpensive Switched Mode Telephone Handset Power Supply

Switched-mode power supplies efficiently provide a regulated output voltage at a voltage level that is different from the input voltage and unlike a linear power supply, the switching transistor of a switched mode supply switches very quickly at a frequency between 50 kHz and 1 MHz. This minimizes wasted energy while voltage regulation is provided by varying the ratio of on to off time.

In contrast linear power supplies must dissipate the excess voltage to regulate output which makes higher efficiency the chief advantage of a switched mode power supply.

Switching regulators are used to replace linear regulators when higher efficiency, smaller size or lighter weight is required. This advantage comes at the price of more complicated circuitry, generation of electrical noise and higher cost.

Switched-mode power supplies can be classified into four types according to the form of their input and output voltages: The first type is the AC to DC or off-line DC power supply. Another is the Voltage or Current Converter which is a DC to DC power supply. AC to AC converters are called frequency changers or cycloconverters while the fourth type is the well known inverter or DC to AC power supply.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. Appreciate why switched mode power supplies are in such widespread use
2. Visually recognise switched mode power supplies
3. See why switched mode power supply frequencies are supersonic
4. Explain how switched mode power supplies derive their high conversion efficiencies
5. Give reasons why it is impractical to have full implementation of a switched mode power supply as an integrated circuit
6. Describe the different types of switched mode power supplies
7. Sketch a switched mode power supply schematic diagram
8. List the functional blocks of switched mode power supplies
9. Understand why switched mode power supplies must include a reactive circuit element
10. Discuss the source of switched mode power supply noise
11. Appreciate why MOSFETs are preferred to bipolar devices in switched mode power supplies
12. List the merits and demerits of switched mode power supplies when compared with Linear power supplies

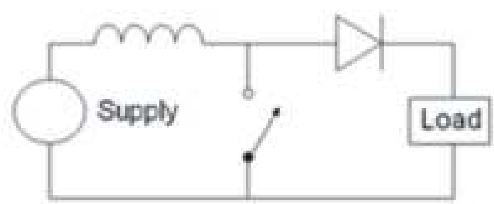
3.0 MAIN CONTENT

3.1 SWITCHED-MODE POWER SUPPLY OPERATION

The rapid switching of the pass transistor of a switched mode power supply is responsible for its operation.

A Switched mode power supply operates by regulating either output voltage or current by switching ideal storage elements such as inductors and capacitors, into and out of different electrical configurations. This is illustrated above with the ideal storage element being an inductor.

When visualized as an ideal circuit element, the pass transistor operates outside its active region and has no resistance when the switch is closed while it carries no current when the switch is open. Theoretically there is no energy dissipation in this ideal switch as the product of voltage across the switch and the current through the switch at any given time is zero. All the input power is delivered to the load and this converter operates at 100% efficiency.



Operation of Switched Mode Power Supply

In the schematic illustration above, the Direct Current source, an inductor, a switch, and the corresponding electrical ground are placed in series and the switch is driven by a square wave where the peak-to-peak voltage of the waveform measured across the switch can exceed the input voltage from the DC source.

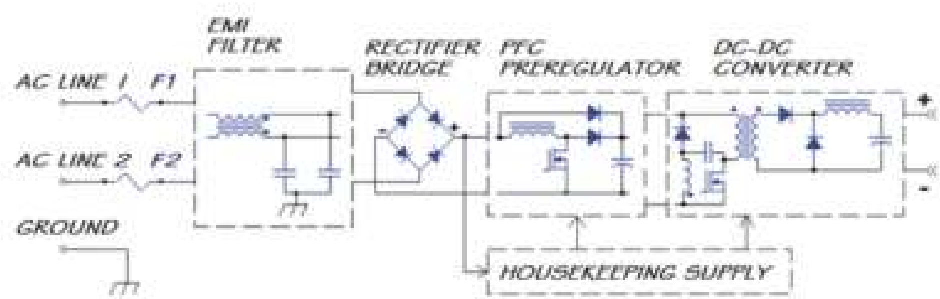
You must recognize that the inductor responds to changes in current by inducing its own voltage to counter the change in current which it adds to the source voltage while the switch is open. If a diode-and-capacitor combination is placed in parallel to the switch, the peak voltage can be stored in the capacitor, and the capacitor can be used as a DC source with an output voltage greater than the DC voltage driving the circuit.

Output current flow depends on the input power signal; the storage elements and circuit topologies used, and on waveform pattern in a switched mode power supply and quite often a pulse-width modulation with an adjustable duty cycle are used to drive the switching elements.

In general, an output parameter such as the output voltage can be controlled by varying duty cycle, frequency or phase shift of the switching of the active circuit element while output filters average the energy transfer rate and assure continuous power flow into the load.

The DC gain of a the converter is calculated based on the fact that in steady state, the net volt-seconds across an inductor over one switching cycle must be zero. The typical frequency range of an offline Switched Mode Power Supply is 50 kHz to 500 kHz while DC-DC converters with low-voltage input operate up to several MHz

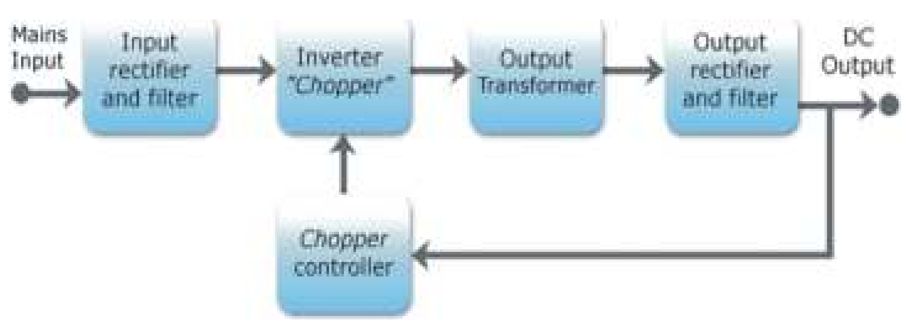
High operating frequency results in smaller size of switched mode power supplies since generally the size of power transformers, inductors and filter capacitors is inversely proportional to the frequency and Switched mode operation also reduces energy losses while it increases efficiency.



Schematic of Switched Mode Power Supply

In the next two Units of this Module we shall be discussing the building blocks which constitute the Switched Mode Power Supply then we take a look at the merits and demerits of this type of power supply.

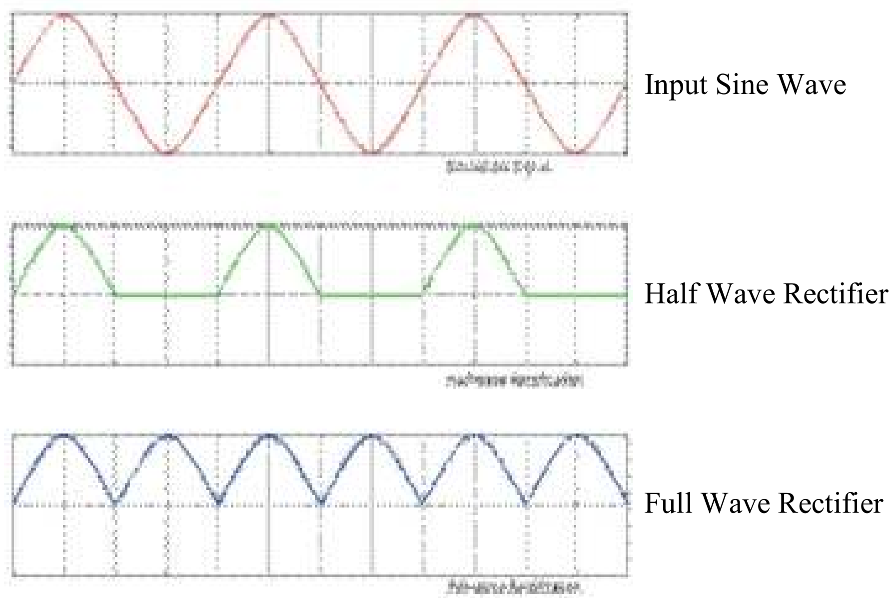
3.2 RECTIFIER, FILTER AND INVERTER



Functional Blocks of Switched Mode Power Supply

Now let us discuss the operation of a switched mode power supply operates by first taking a look at the block diagram illustration above with the alternating current input on the left side and the output on the right side of the block diagram.

The input rectifier and filter stage converts the input to AC to DC voltage through rectification which produces an unregulated DC voltage while the pulsating DC is applied across the terminals of a large filter capacitor.



Half-Wave and Full-Wave Rectified Input Signals

The current drawn from the input supply by the rectifier circuit occurs in short pulses around the AC voltage peaks. These pulses have significant high frequency energy which reduces the power factor and special control techniques can be employed by the chopper stage to force the average input current to follow the sinusoidal shape of the AC input voltage to correct the power factor.

Switched mode power supplies with DC input do not require input rectifier and filter stage and a switched mode power supply which is designed for AC input can be operated from a DC supply if it does not have an input transformer because the DC passes through the rectifier stage unchanged.

In the functional block diagram above, the output of the input rectifier and filter serves as input to the Inverter which functions as the chopper.

The inverter stage converts Direct Current to Alternating Current through a power oscillator, whose output transformer is very small and which operates at a frequency above 20 kHz to make it inaudible to humans but which may be as high as a few MHz In practical designs, the output voltage is optically coupled to the input and thus very tightly controlled and is electrically isolated from the mains potential.

Switching is practically implemented as a multistage high gain MOSFET amplifier because of the MOSFET's low on-resistance and high current-handling capacity.

3.3 CONVERTER AND OUTPUT RECTIFIER

In mains power supplies the output of a Switched Mode Power Supply is required to be isolated from the input and the inverted Alternating Current is used to drive the primary winding of a high-frequency transformer. This converts the voltage up or down to the required output level on its secondary winding. The output transformer in the block diagram serves this purpose.

Switched Mode Personal Computer Power Supply

If a DC output is subsequently required, the Alternating Current output from the transformer is rectified and whereas for output voltages above ten volts ordinary silicon diodes are commonly used; lower voltages however require Schottky diodes which have the advantages of faster recovery times than silicon diodes and lower voltage drop when conducting. A special case arises when even lower output voltages are required and when MOSFETs are used as synchronous rectifiers. MOSFETs compared to Schottky diodes have even lower conducting state voltage drops.

The rectified output is passed through a filter consisting of inductors and capacitors. When higher switching frequencies are used, components with lower capacitance and inductance can be used which reduces size.

A feedback circuit incorporating optical isolation monitors the output voltage and compares it with a reference voltage to achieve regulation.

There are two major types of regulation; on the one hand are Open-loop regulators which do not have a feedback circuit but instead rely on feeding a constant voltage to the input of a transformer or inductor with the assumption that the output will be correct. On the other hand are Closed Loop regulators which compensate for the impedance of the transformer or coil and for the magnetic hysteresis of the core in Monopolar designs. Because the feedback circuit requires power to operate before it can generate establish control, an additional non-switching power-supply is needed.

3.4 MERITS AND DEMERITS

In a switched-mode power supply, the switching transistor dissipates very little power outside its active region making the power supply very efficient; which is a major advantage This is so because the transistor acts like a switch and either has a negligible voltage drop across it or a negligible current through it resulting in very low power dissipation by the switching transistor.

Another advantage is the smaller size and lighter weight of switched mode power supplies which is a direct consequence of the elimination of low frequency transformers which have considerable size disadvantage, a weight disadvantage as well as a cost disadvantage. The switched mode power supply because of its high switching frequency utilises light weight high efficiency ferrite core or air core transformers. These generate less heat, have reduced hysteresis loss and are compact in size not to mention their comparatively low cost.

Disadvantages of switched mode power supplies include greater complexity, the generation of high-amplitude, high-frequency energy that the low-pass filter must block to avoid electromagnetic interference and a ripple voltage at the switching frequency and its higher harmonic frequencies.

Very low cost switched-mode power supplies may couple electrical switching noise back onto the mains power line, causing interference with Audio Visual equipment connected to the same phase while non-power factor corrected switched mode power supplies cause harmonic distortion of the output in the case of AC to AC or DC to AC supplies.

4.0 CONCLUSION

In this unit we have learnt that there are four basic types of switched mode power supplies; the AC to DC or off-line DC power supply, the Voltage or Current Converter which is a DC to DC power supply, the AC to AC converters also referred to as frequency changers or cycloconverters and the last type being the inverter or DC to AC power supply.

We understand why switched-mode power supplies are very efficient and how they provide regulated output voltage at a voltage level different from the input voltage.

We also know that they operate by switching a transistor very quickly at supersonic frequency while they regulate voltage by varying the ratio of on to off time.

5.0 SUMMARY

- Switched mode power supply which efficiency convert electrical power play an important role in stabilised power supplies
- Switched mode power supplies are very common and can be found in computers, televisions, amplifiers, telephone chargers and solar energy converters to mention a few
- There are four basic configurations of Switched mode power supplies
- Switched mode power supply operate at supersonic frequencies which are typically above 20 kilo Hertz and may range as high as several mega hertz
- Switching regulators are used to replace linear regulators when higher efficiency, smaller size or lighter weight is required
- Theoretically a switched mode power supply can operate at 100% efficiency
- An energy storage element; usually an inductor forms an integral part of all switched mode power supplies
- The output voltage of a switched mode power supply is controlled by varying duty cycle, frequency or phase shift of the switching element
- Switched mode power supplies are noisy and require output noise filters
- It is impractical to have full implementation of switched mode power supply as an integrated circuit because of bulky reactive components which cannot be microminiaturised

- MOSFETs perform better than bipolar devices in switched mode power supplies

6.0 TUTOR MARKED ASSIGNMENTS

1 Describe a switched mode power supply?

2 What is the operating frequency range of switched mode power supplies? What is the justification for this range?

3 Explain how switched mode power supplies derive their high conversion efficiency?

4 What are the four classifications of switched mode power supplies? State a practical application of each class?

5 What is a cycloconverter? Can you sketch a functional block diagram of one?

6 Switched mode power supplies are very noisy. Expand this comment?

7 Explicate how electrical isolation is achieved between the input and output in switched mode power supplies? Through which device is output to input feedback signal coupled to achieve regulation control?

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By Alexander and Sadiku Published by Mc Graw Hill

Module 4

UNIT 1 FILTER TOPOLOGY

CONTENTS

1.0 INTRODUCTION

A filter is an electrical network that alters the amplitude and/or phase characteristics of a signal with respect to frequency. Ideally, a filter will not add new frequencies to the input signal, nor will it change the component frequencies of that signal, but it will change the relative amplitudes of the various frequency components and/or their phase relationships.

All filters irrespective of type and response must have an electrical layout which is referred to as the topology of the filter. You will see as we proceed that certain filter types and frequency responses can only be accommodated by specific filter topologies. A good example of this is the bandpass filter which can never be accommodated by an L-filter topology.

Let us take a look at four of these topologies; Single element, L, T and the π Filter topologies which you will frequently interact with in the course of your career. While doing this remember that Inductors and capacitors are the reactive elements of a filter and the number of elements determines the order of the filter.

The exception to this rule in determining the number of elements is a parallel or series combination of an LC tuned circuit which is treated as a single element.

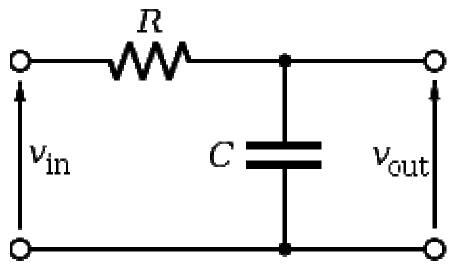
2.0 OBJECTIVES

After you have read this unit, you will confidently

1. Describe the electrical function of filters
2. Sketch the common filter topologies
3. Recognise a single element filter
4. Sketch single element filters
5. Explain why an LC pair is considered a single element in filter topology
6. Sketch simple low pass, bandpass and high pass filter topologies
7. Sketch L, T and π filter topologies
8. Discuss multiple element filters
9. Create multiple element filters from simple filter topologies
10. Explain why bandpass filters can never be implemented with an L-filter topology
11. Design simple practical filter circuits and provide component values to achieve desired and predictable results
12. Look inside appliances such as power supplies and other electrical and electronic circuits and without hesitation, identify low pass, high pass and band pass filters

3.0 MAIN CONTENT

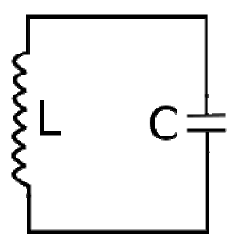
3.1 SINGLE ELEMENT FILTER



Single Element Filter Topology

The single inductor and single Capacitor filter is known as the Single Element Topology. This means it has a single reactance represented by the Inductor or the Capacitor in the topology. This is illustrated above in a Low Pass Filter. Can you say why this is a Low Pass Filter?

The Resonant circuit diagrammed below comprises an Inductor and a Capacitor in parallel. Placed across an input port it acts as a Band Pass Filter. Similarly a Capacitor in series with an Inductor placed in series with an input port also acts as a Band Pass Filter.

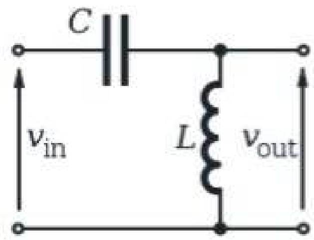


Single Element Filter Topology

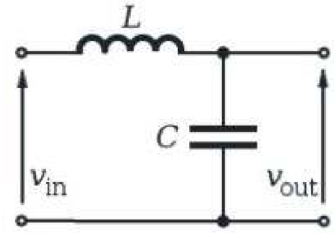
Now both of these L-C band Pass Filters described above are Single Element Filters; can you explain why? Remember the exception referred to in the Introduction of this unit

3.2 L-FILTER

An L filter consists of two reactive elements, one in series and one in parallel with the output port:



High Pass L-Filter



Low Pass L-Filter

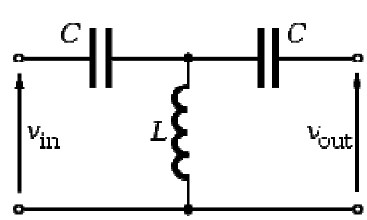
This makes it a two element filter. In the High Pass Filter illustrated above, the capacitor presents high impedance to lower frequencies while allowing higher frequencies to pass to the output port. Meanwhile you can see that the inductor which is connected across the output port shunts lower frequencies across the port at the same time presenting itself as high impedance to higher frequencies thereby complementing the capacitor in promoting the passage of high frequencies from the input port to the output port.

The converse is true of the Low pass Filter illustrated above where the roles of the capacitor and the inductor are reversed.

3.3 T FILTER AND π FILTER

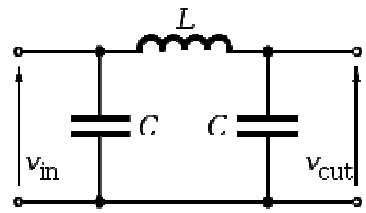
Three-element filters can have a T or **π** topology and in either of these topologies may be a low-pass, a high-pass, a band-pass or a band-stop filter. If the duplicated components in the filter are of the same value then it is said to be symmetrical otherwise it is asymmetrical. The symmetry of asymmetry of the T or **π** filter depends on the required frequency characteristics.

The high-pass T filter in the illustration below has very low impedance at high frequencies, and very high impedance at low frequencies. That means that it can be inserted in a transmission line, resulting in the high frequencies being passed and low frequencies being reflected.



T High Pass Filter

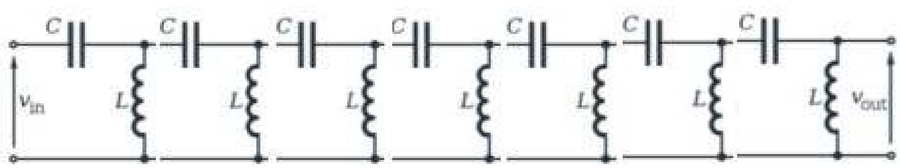
Similarly for the illustrated low-pass **π** filter below, the circuit may be connected to a transmission line to transmit low frequencies and reflect high frequencies.



π Low Pass Filter

3.4 Multiple Element Filters

Whenever you see a filter topology like a ladder, you are looking multiple element filters derived from replicated L filter sections, T filter sections or **π** filter sections as more elements are usually required to improve certain parameter of filters like stop-band rejection or slope of transition from pass-band to stop-band.



Multiple Element Filter comprising L-Topology Elements

4.0 CONCLUSION

In this unit we learnt that filters are electrical networks that alter amplitude and/or phase of electrical signals with respect to frequency and which should not add new frequencies or change the frequencies component of the input signal but change the relative amplitudes of the various frequency components and/or their phase relationships.

We discussed the single element, L, T and the π Filter topologies which are just four of the numerous topologies which all filters irrespective of type and response must have. This is the electrical layout of the filter which in some cases can only accommodate certain filter types and frequency responses.

5.0 SUMMARY

- Filters are electrical networks that alters the amplitude and/or phase characteristics of an electrical signal in the frequency domain
- All filters must have an electrical layout called topology of the filter
- Only certain filter types and frequency responses can be accommodated by specific filter topologies
- Bandpass filters can never be accommodated by an L-filter topology
- The order of a filter is determined by the number of reactive elements with the exception that a parallel or series combination of an LC tuned circuit is treated as a single element
- Capacitors present lower impedance at higher frequencies while inductors present higher impedance at higher frequencies
- Multiple element filters are derived from replicated L filter sections, T filter sections or **π** filter sections

6.0 TUTOR MARKED ASSIGNMENTS

1 How would you describe a filter to a layman? Would you also be able to explain to this layman what filters do?

2 What do you understand by filter topology? Can you sketch and label the ones you know?

3 Explain how you would determine the order of a filter?

4 If a passive filter is designed with seven reactive elements, and two pairs of these elements are tuned LC circuits, what then is the order of this filter?

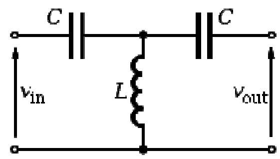
5 Describe the filter class known as single element filters ? sketch and label a single element low pass filter which uses a capacitive element?

6 What is a symmetrical filter?

7 Can you design a symmetrical low pass T filter and label it?

8 List five appliances around you which use filters?

9 Do you recognise this filter topology illustrated below? Which is it and what does it pass?



8 Describe in detail with illustrative sketches how multiple element filters can be derived?

9 Can you think of any filter topology that will not accommodate a filter type? Which is it or which are they?

7.0 REFERENCES/FURTHER READINGS

A Textbook of Electrical Technology 2010
By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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

Network Analysis with Applications 4th Edition
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Analog Filter Design
By M. E. Van Valkenburg Published by Holt, Rinehart and Winston

UNIT 2 BASIC FILTER TYPES

CONTENTS

1.0 INTRODUCTION

Filters are used to emphasize signals in certain frequency ranges and reject signals in other frequency ranges frequency dependent gain; often when useful signal at frequency range has been contaminated with unwanted signal of another frequency range.

Filters are classified in any of several ways. They may be classified by Technology, by topology or by design methodology. Each of these classifications defines group parametric characteristics which have merits and drawbacks. We shall discuss the three classifications described above to get a feel of them and then focus our attention on Passive Filters and Active Filters which are two important types of filters classified by technology.

2.0 OBJECTIVES

After you have read this unit, you will be able to

1 Discuss the classification of filters

2 Classify filters by topology, technology and methodology

3 Distinguish between passive and active filters

4 Explain how digital filters are implemented

5 Understand the Q factor of a filter

6 Sketch the frequency response of filters

7 Explain the transfer function

8 Work in the frequency domain

9 Sketch passive and active filters

10 Sketch twin T filters

11 Sketch the transfer function of Wien bridge filters

12 Explain active filter optimisation

13 Understand the order of a filter

14 Describe the effect of filter order on rolloff slope

15 Sketch ideal filter response curves

3.0 MAIN CONTENT

3.1 FILTERS CLASSIFICATION

As we have discussed earlier, filters can be classified in several ways; either by technology, topology or design methodology.

3.1.1 Passive Filters

The classification of filters by technology partitions them into passive filters, active filters and digital filters. Passive filters are linear networks which are constructed out of combinations of Inductors, Capacitors and Resistors. They do not have any active component such as transistors or valves; neither do they require an external power supply.

Passive filters are further classified by electrical topology into single element filters, L-filters, T-filters and π –filters. The number of circuit elements in each of these sub classifications of passive filters is easily determined by the number of inductors and capacitors which make up the filter except when an Inductor-Capacitor pair forms a resonant tank circuit in which case the pair is treated as a single circuit element. Multiple element Passive Filters usually have a ladder topology which can be viewed as a replication of L-filter, T-filter and π -filter sections.

3.1.2 Active Filters

A family of filters referred to as Active Filters are a combination of passive and active components. Active filters require a power source and often employ high gain Operational amplifiers in their designs to achieve very high Q factors. It becomes possible with Active filters to achieve specifically tailored response curves which are only limited by the bandwidth of the amplifiers used in the design.

3.1.3 Digital Filters

Advances in mathematics and digital techniques have progressed to the stage where routinely digital techniques are used to process both digital and analogue signals which have been converted to suitable digital form which computers programs can operate upon.

Powerful algorithms implemented in hardware for fast processing compute the output for specific filter response curves in the frequency domain. A practical application of this in audio is tone control through digital equalizer.

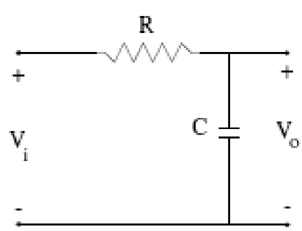
3.2 PASSIVE FILTERS

Let us take a closer look at Passive Analogue Linear Filters which are constructed with only resistors, capacitors and inductors, and are called RC and RL filters single-pole filters.

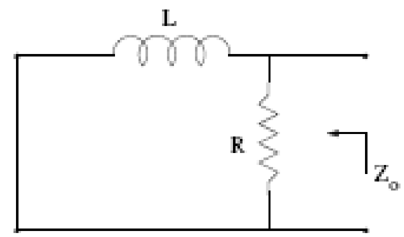
Realise that Multipole LC filters also exit with well documented and well understood characteristics; however this is not the subject of interest in this unit.

The Passive Filter is frequency-selective because it filters out undesirable frequencies and the circuit passes to the output only those input signals that fall within a desired frequency range. This is called the Pass band. The region outside the Pass band is referred to as the Stop Band and the amplitude of signals within the Stop band are greatly attenuated.

In analysing the Passive Filter, the signal source should possess extremely low internal impedance while the load should present very high impedance. This enables us to concentrate the Voltage transfer function while ignoring the Current Transfer Function because the current is kept to a minimum.

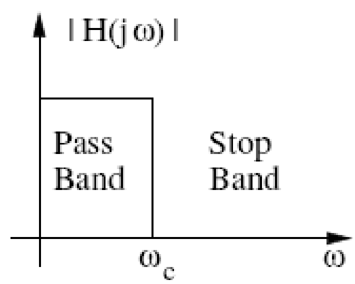


RC Low Pass Filter



RL Low Pass Filter

We focus attention on the Voltage Transfer Function in the frequency domain which for a Low Pass Filter should have the plot illustrated below.



Ideal Low Pass Filter Transfer Function

In practical filters, pass and stop bands are not clearly defined but varies continuously from its maximum toward zero and the cut-off frequency is defined as the frequency at which the amplitude is reduced to 0.7 of its maximum value. This corresponds to signal power being reduced by half. This is illustrated below.

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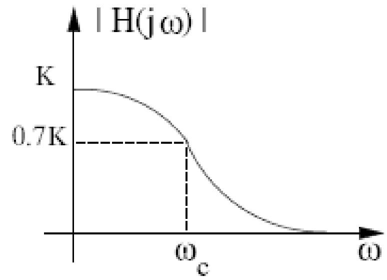
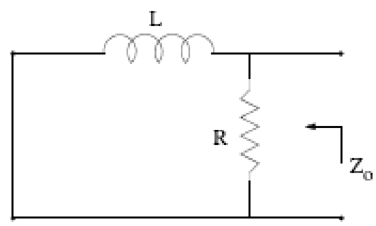


Practical Low Pass Filter Transfer Function

In the Low Pass Filter illustrated below;



LC Low Pass Filter

Voltage Transfer Function; the ratio of output to input voltage is

$$\frac{V_o}{V_i} = \frac{R}{R + j\omega L} = \frac{1}{1 + j(\omega L/R)}$$

Cutoff frequency at which the Transfer Function degenerates to 0.7 is

$$\omega_c = \frac{R}{L}$$

By substituting the above the Transfer Function is rewritten as

$$H(j\omega) = \frac{1}{1 + j\omega/\omega_c}$$

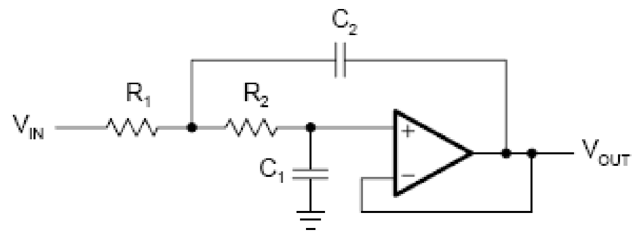
Input Impedance is

$$Z_i = \frac{V_i}{I_i} = j\omega L + R$$

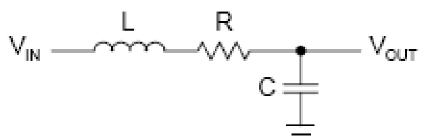
While the output impedance is stated as

$$Z_o = j\omega L \parallel R$$

3.3 ACTIVE FILTER



Operational Amplifier based Low Pass Active Filter

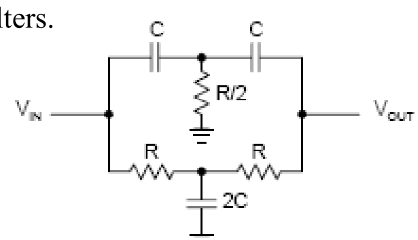


Passive filter equivalent of Low Pass Active Filter above

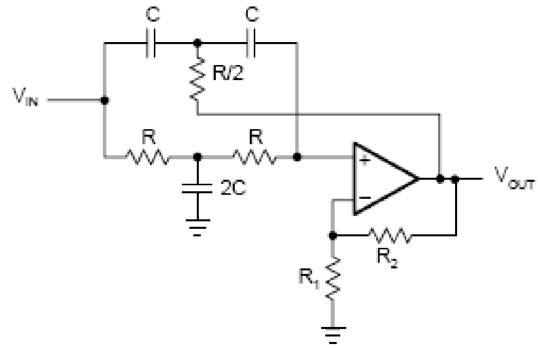
According to Webster "*A filter is a device that passes electric signals at certain frequencies or frequency ranges while preventing the passage of other"*

Filters of all kinds find application over a broad spectrum of frequencies ranging from sub-audio applications through microwave frequencies. At frequencies higher than 1 Megahertz, filters consist almost entirely of passive components such as Inductors, Capacitors and resistors. In certain cases are hybridisations where parasitic effects of real world component imperfections are capitalised upon such as the parasitic inductance of the leads of a capacitor; to achieve these filters.

At the sub-one-megahertz frequency range however, the physical values of some passive filter components become prohibitively high and the components themselves become bulky and expensive rendering production of filters difficult and uneconomical. All these conditions which plague Passive Filter implementation at lower frequencies promote the use of Active Filters.



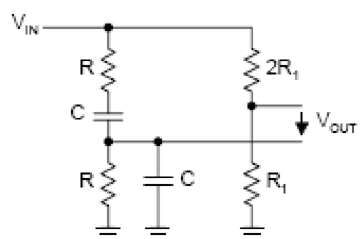
Passive Twin-T Filter



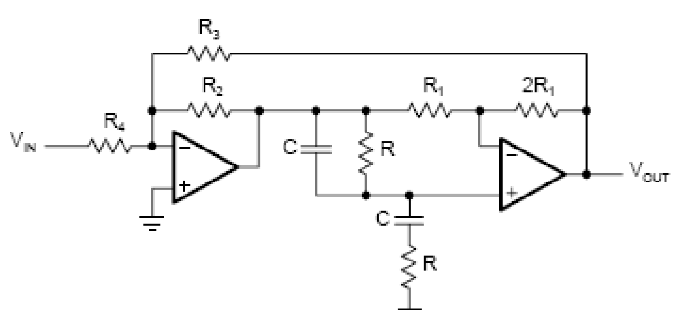
Active Twin-T Filter

Active Filters are circuits that use operational amplifier as an active device in combination with resistors and capacitors to provide LRC-like filter performance as illustrated above; and can generally be referred to as Network Synthesis Filters.

The family of network Synthesis Filters include Butterworth filter, Tschebyscheff filter, Elliptic filter which is also called the Cauer filter, Bessel filter, Gaussian filter, Linkwitz-Riley filter and the Optimum "L" filter derived from the Legendre filter.



Passive Wien-Robinson Bridge Filter



Active Wien-Robinson Bridge Filter

The three main optimizations of Active filters are the Butterworth, Tschebyscheff and the Bessel filters. All active filters find application in low-pass, high-pass, band-pass, band-rejection, and all-pass filters.

3.4 OTHER FILTER METHODS - HUM INJECTOR FILTER

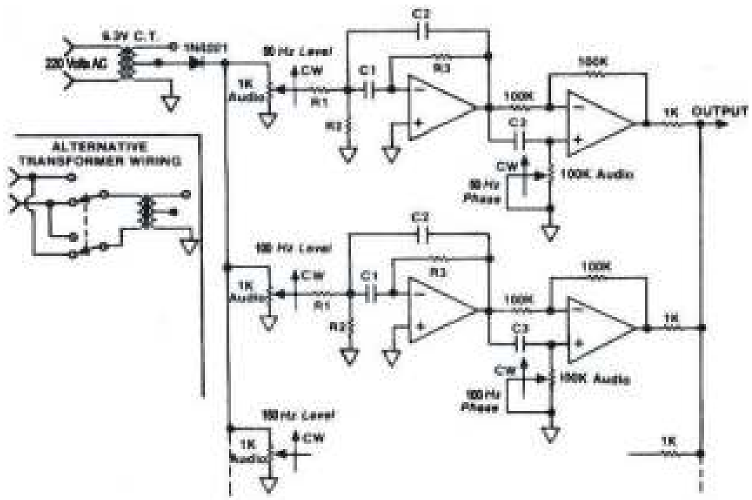
By discussing the operation of the Hum Injector Filter, we shall now look at a practical filter application which solves the common and difficult problem of filtering out power line hum, especially in the presence of audio frequencies such as music.

Very often, more than one offending frequency is present which requires several notch filters to be cascaded and if a desirable frequency lies near one of the offensive frequencies, the useful frequency will be removed as well as the offensive one. Such an impossible situation arises when it is desirable to filter out 50 Hertz. Hum without affecting a signal at exactly the same frequency.

The obvious solution would be to employ a conventional notch filter in which the input signal undergoes a phase shift of 180 degrees at some specified frequency, relative to the input and when the input and output signals are combined; a null in the response is created at that frequency. The phase-shifted signal is used to oppose the original input, and if the two signal levels are exactly equal the result is complete cancellation.

In cancelling 50 Hertz hum, the opposing frequency need not be derived from the original signal, but instead is derived from a sample of the actual power line, and it can be used to exactly balance any hum in the output without affecting the desired range of useful signal frequencies. This however must be done in real time, so that the hum source and the cancellation signals will be synchronized.

The illustration overleaf is the circuit diagram of an actual hum injector filter which employs the technique discussed above. Because most devices depend on power supplies derived from the mains and use full-wave rectification in these power supplies, apart from the 100 Hertz hum being predominantly present, there is also the fundamental, third, and fifth harmonics in significant quantities. The higher the frequency, the more diminished in amplitude the harmonic amplitude and in this particular circuit, it was not necessary to have more than four stages.



Hum Injector Filter

You should recognise this method of filtering out an undesirable frequency through cancellation as a very effective method which precisely cancels out the offending signal frequency while leaving desirable signal at that same frequency untouched.

4.0 CONCLUSION

In this unit we have discovered that filters may be classified by technology, topology or design methodology which defines the group parametric characteristics.

We then discussed three of the classifications concluding by laying emphasis on passive filters and active filters which are two filter types classified by technology.

5.0 SUMMARY

- Passive filters are linear electrical networks comprising combinations of inductors, capacitors and resistors that alter amplitude and/or phase characteristics of electrical signals in the frequency domain
- Single element filters, L-filters, T-filters and π –filters are all passive filter topologies

- Active filters combine passive and high gain active components, and require a power source. They are capable of achieving very high Q values and very steep cutoff slopes

- Mathematical and digital techniques have made it possible for digital techniques to be used to process both digital and analogue signals by powerful algorithms implemented in hardware

- The amplitude response of filters in the frequency domain is also the transfer function

6.0 TUTOR MARKED ASSIGNMENTS

1 Can you list three basic classifications of filters?

2 If we were to classify filters into active and passive filters, by what are we classifying them?

3 Why do you thing that filter transfer curves are plotted in the frequency domain and not in the time domain?

4 If a filter response to a step input is plotted in the time domain, do you think you would be able to convey this response into the time domain to create an amplitude/frequency plot? If you do, how would you do it?

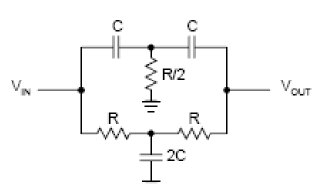
5 Explain in the simplest terms what passive filters are? And mention some of their merits and demerits?

6 State a major economic advantage of active filters?

7 How are the high Q values achieved in active filters?

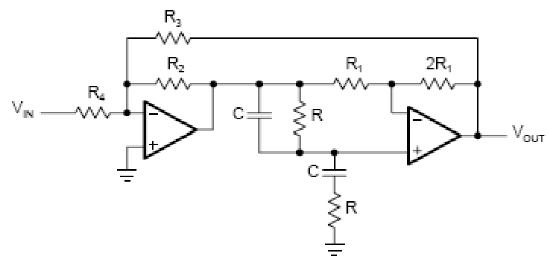
8 Explain the process of creating a digital filter using block diagrams for illustrations?

9 Take a look at this diagram. What is the name given to this type of filter?



10 Explain the operation of a hum injector filter and state its major advantage in its specialised application?

11 What is this circuit called? And what does it do? Can you explain its action?



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Analog Filter Design
By M. E. Van Valkenburg Published by Holt, Rinehart and Winston

UNIT 3 PASSIVE FILTERS

CONTENTS

1.0 INTRODUCTION

Passive filters comprise combinations of resistors, inductors and capacitors. They do not contain active components nor do they depend on external power supplies. Series Inductors block high-frequency signals and conduct low-frequency signals, while series capacitors conduct high frequency signals and block low frequency signals.

A filter in which the signal passes through an inductor, or in which a capacitor provides a path to ground, presents less attenuation to low-frequency signals than high-frequency signals and is a low-pass filter. If the signal passes through a capacitor, or has a path to ground through an inductor, then the filter presents less attenuation to high-frequency signals than low-frequency signals and is a high-pass filter. Resistors on their own have no frequency-selective properties, but are added to inductors and capacitors to determine the time-constants of the circuit, and therefore the frequencies to which it responds.

The order of a filter is determined by the number of reactive elements of the filter however you should note that while inductors and capacitors are the reactive elements of the filter, an LC tuned circuit used in a band-pass or band-stop filter is considered a single element even though it consists of two components.

2.0 OBJECTIVES

After you have read this unit, you will know

1. State the definition for passive filters
2. Learn more about passive filters
3. The five basic filter types
4. That phase shift filters pass all frequencies without attenuation
5. How to recognise filters which impact on your life very day
6. The transfer function sketches of low pass, high pass, band pass, and reject and phase shift filters
7. The relationship between phase and frequency for the five types of filters
8. How to use inductors, capacitors and resistors to design the five types of filters
9. The distinction between passband and stopband
10. Many practical applications of passive filters

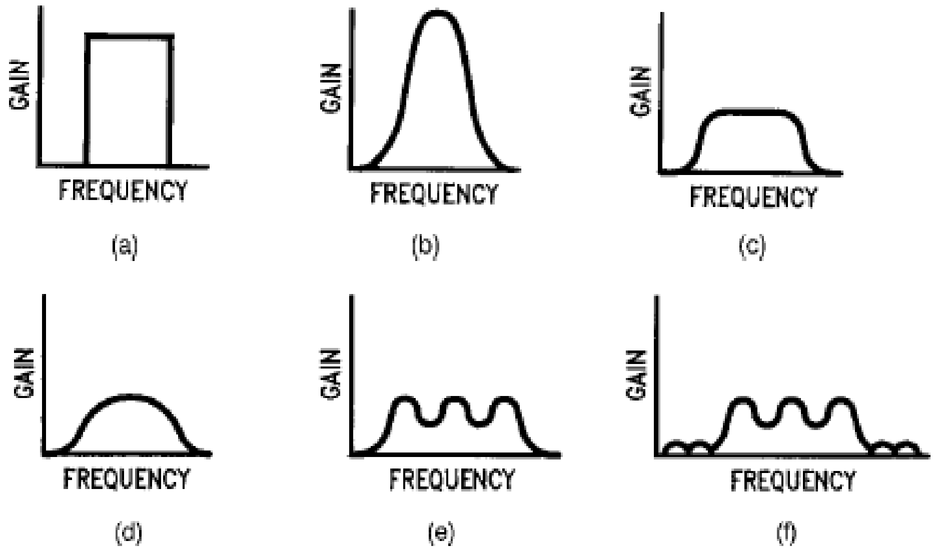
3.0 MAIN CONTENT

3.1 BAND-PASS FILTER

There are five basic types of filter and these are the bandpass, notch, low-pass, high-pass, and all-pass filters. Have you come across any of them before? I am sure you must have as filter applications abound in our everyday experiences.

If you take the Bandpass filter as a typical illustration, the number of possible bandpass response characteristics is infinite, but all share the same basic form.

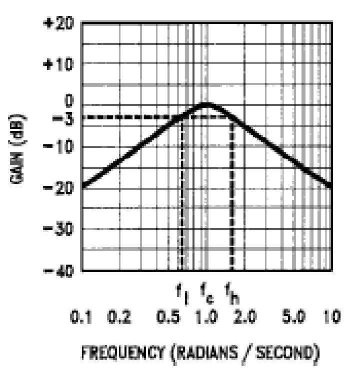
The sketches below illustrate several bandpass amplitude response curves and only the first curve (a) can be referred to as the “ideal” bandpass response, Can you imagine why? Yes. The curve has absolutely constant gain within the pass band, zero gain outside the pass band, and an abrupt boundary between the two.

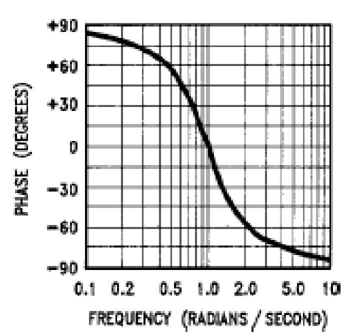


Bandpass Filters

You can not realize this response characteristic in practice, but you can approximate to varying degrees of accuracy by real filters. The Curves (b) through (f) represent examples of a few bandpass amplitude response curves that approximate the ideal curves with varying degrees of accuracy and you should note that while some bandpass responses are very smooth, other have wavy ripple which is actually gain variations in their passband and others have ripple in their stopband as well.

Bandpass filters have two stopband; one above and one below the passband. The stopband is the range of frequencies over which unwanted signals are attenuated.





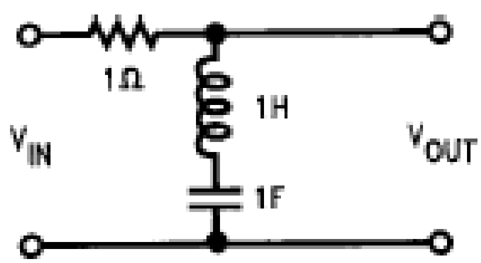
Amplitude Curve ***Phase Curve***

It is difficult to determine through observation alone exactly where the boundaries of the passband and the stopband lie as they are seldom obvious and consequently, the frequency at which a stopband begins is usually determined by system specific requirements of a given attenuation at a given frequency which defines the beginning of a stopband. The rate of change of attenuation between the passband and the stopband also differs from one filter to the next and the slope of the curve in this region depends strongly on the order of the filter. Higher order filters present steeper cut-off slopes.

Bandpass filters are used in electronic systems to separate a signal at one frequency or within a band of frequencies from signals at other frequencies. As example, a filter whose purpose was to pass a desired signal at frequency f1, while attenuating as much as possible an unwanted signal at frequency f2. This function could be performed by an appropriate bandpass filter with centre frequency f1. Such a filter could also reject unwanted signals at other frequencies outside of the passband, so it could be useful in situations where the signal of interest has been contaminated by signals at a number of different frequencies.

3.2 BAND-REJECT FILTER

The band-reject filter has effectively the opposite function of the bandpass filter and a typical illustration of the filter elements is diagrammed below.



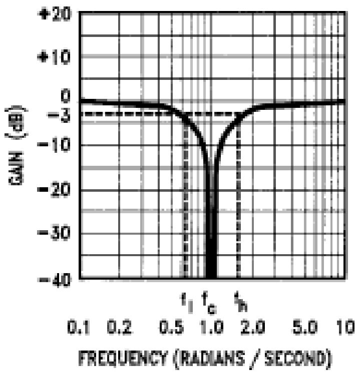
Band Reject Filter

This filter also known as the Notch Filter has the transfer function:

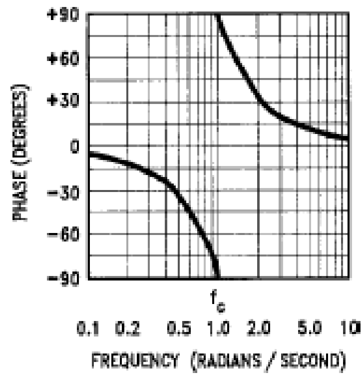
$$H_N(s) = \frac{V_{OUT}}{V_{IN}} = \frac{s^2 + 1}{s^2 + s + 1}$$

Notch filters are used to remove an unwanted frequency from a signal with as little effect as possible on all other frequencies.

The amplitude and phase curves for this Band Reject filter circuit are as follows:



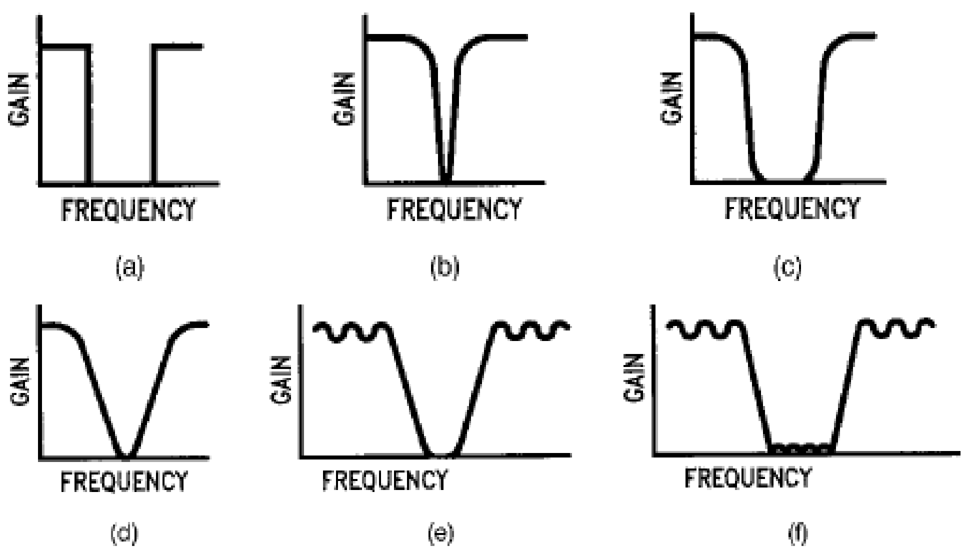
Amplitude Curve



Phase Curve

And it is evident that from the curves, the quantities used to describe the behaviour of the band-pass filter are also applicable for the notch filter.

You should study the Band Pass filter’s amplitude response curves below and note that curve (a) shows an “ideal” notch response, while the other curves show various approximations to the ideal characteristic.

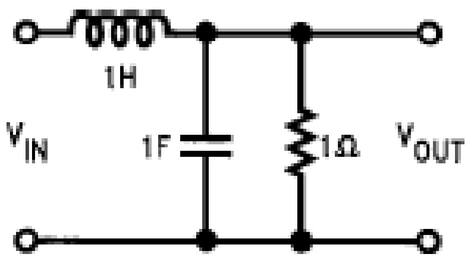


Band Reject Filter

3.3 LOW-PASS FILTER

The third filter type is the low-pass filter. A low-pass filter passes low frequency signals, and rejects signals at frequencies above the filter's cut-off frequency.

The circuit diagram below shows the circuit elements connected to realize a low pass filter.



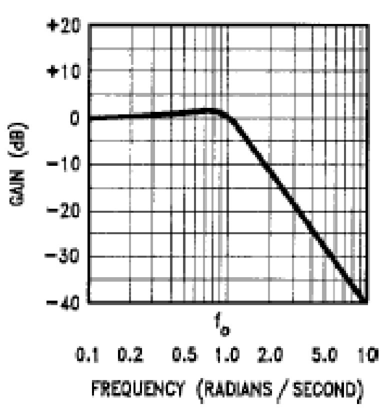
Low Pass Filter

The transfer function is:

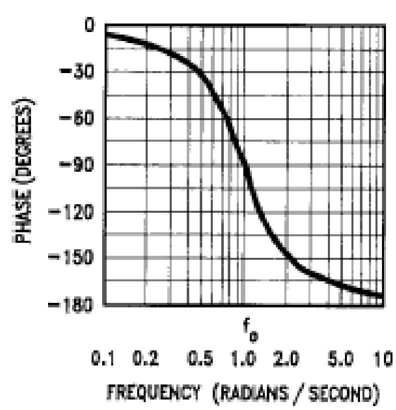
$$H_{LP}(s) = \frac{V_{OUT}}{V_{IN}} = \frac{1}{s^2 + s + 1}$$

You can see by inspection that this transfer function has more gain at low frequencies than at high frequencies because as ω approaches 0, H_{LP} approaches 1; as ω approaches infinity, H_{LP} approaches 0.

The amplitude and phase response curves are shown with possible amplitude response curves and you should note that the various approximations to the unrealizable ideal low-pass amplitude characteristics take different forms, some are monotonic by always having a negative slope while others have ripple in the passband and/or in the stopband.

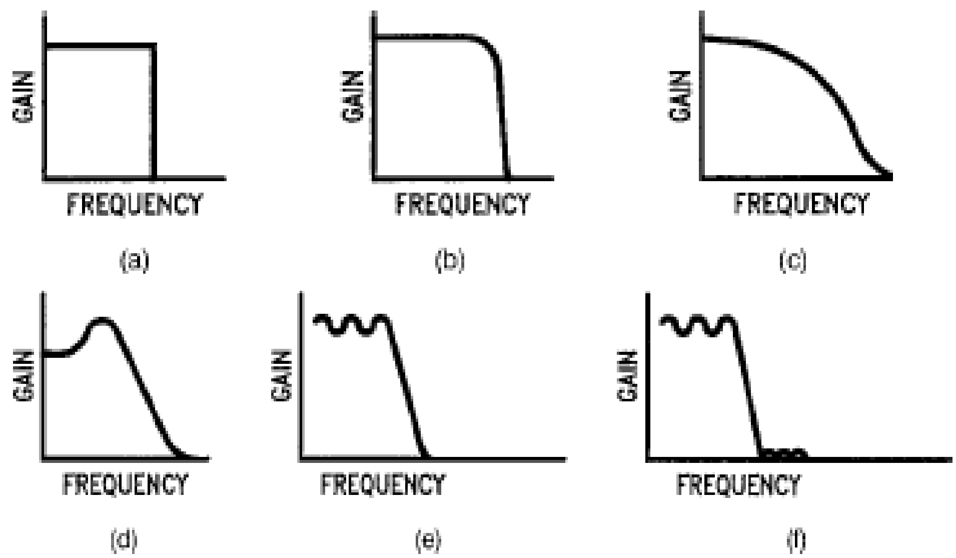


Amplitude Curve



Phase Curve

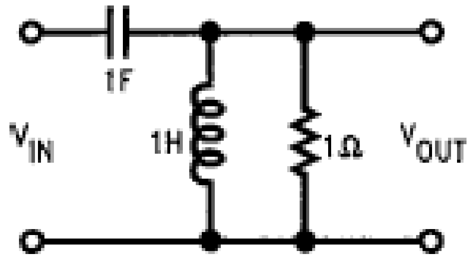
Low-pass filters are used whenever high frequency components must be removed from a signal. This can be illustrated with light-sensing photodiode. If light levels are low, the output of the photodiode could be very small, allowing it to be partially obscured by the noise of the sensor and its amplifier, whose spectrum can extend to very high frequencies. If a low-pass filter is placed at the output of the amplifier, and if its cutoff frequency is high enough to allow the desired signal frequencies to pass, the overall noise level can be reduced.



Low Pass Filter

3.4 HIGH-PASS FILTER

The opposite of the low-pass is the high-pass filter. The high pas filter rejects signals below its cut-off frequency and a high-pass filter can be realized with the circuit diagram below.

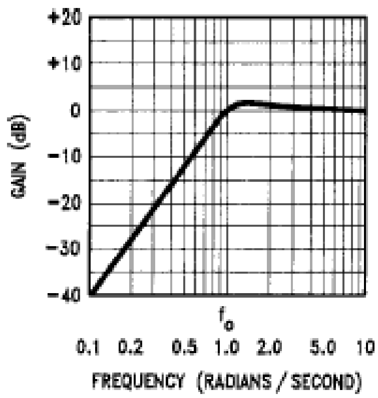


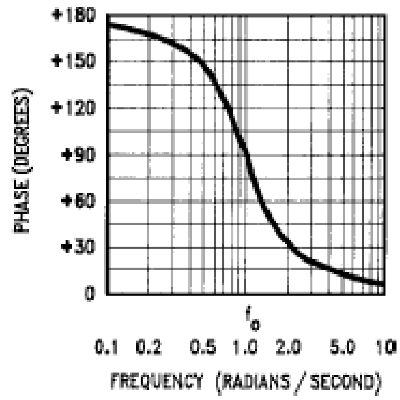
High Pass Filter

The transfer function for this filter is:

$$H_{HP}(s) = \frac{V_{OUT}}{V_{IN}} = \frac{s^2}{s^2 + s + 1}$$

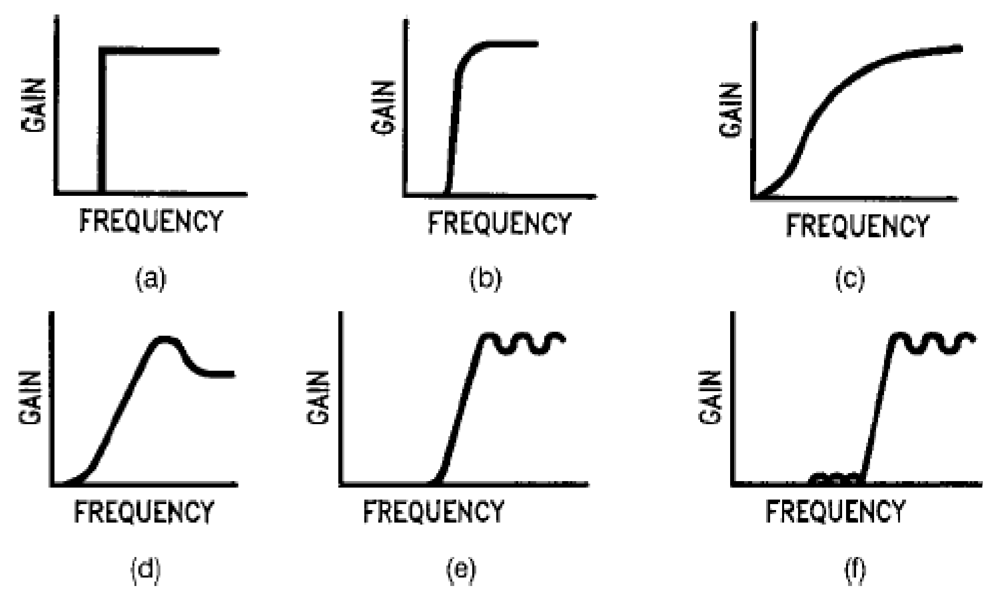
and the amplitude and phase curves are shown below.





Amplitude Curve ***Phase Curve***

The amplitude response of the high-pass is a “mirror image” of the low-pass filter response and examples of high pass filter responses are shown below with the “ideal” response in (a) and various approximations to the ideal shown in (b) through (f).



High Pass Filter

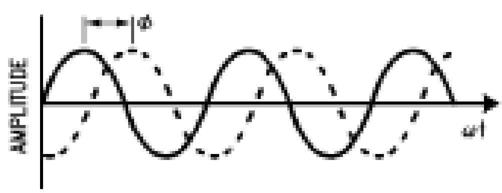
High-pass filters important and find application when the rejection of low-frequency signals is desirable An application of high pass filters is in high fidelity loudspeaker systems where high-frequency audio drivers known as tweeters can be damaged by low frequency audio signals of sufficient energy.

A high-pass filter between the broadband audio signal and the tweeter input terminals will prevent low frequency program material from reaching the tweeter. In conjunction with a low-pass filter for the low-frequency driver and possibly other filters for other drivers, the high-pass filter is part of what is known as a "crossover network".

3.5 PHASE-SHIFT FILTER

Take cognizance of the fact that the response of the final filter type has no effect whatsoever on the amplitude of an input signal over a broad band of frequencies but instead changes the phase of the signal without affecting amplitude. This type of filter is called an all-pass or phase shift filter.

The effect of a shift in phase is illustrated below by the two sinusoidal waveforms where the curves are identical except that they are out of phase. You can conclude by saying that the output of the bandpass filter has undergone a time delay relative to the input signal.



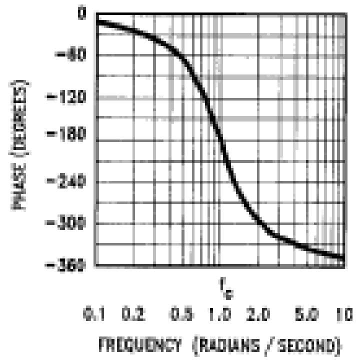
Phase Shift Filter

Since we are dealing with periodic waveforms, time and phase can be interchanged—the time delay can also be interpreted as a phase shift of the output signal relative to the input signal.

The relation between time delay and phase shift is $T_D = \theta/2\pi\omega$, so if phase shift is constant with frequency, time delay will decrease as frequency increases. All-pass filters are typically used to introduce phase shifts into signals in order to cancel or partially cancel any unwanted phase shifts previously imposed upon the signals by other circuitry or transmission media The illustration below shows a curve of phase vs frequency for an all-pass filter with the transfer function

$$H_{AP}(s) = \frac{s^2 - s + 1}{s^2 + s + 1}$$

The absolute value of the gain is equal to unity at all frequencies, but the phase changes as a function of frequency



Phase Curve

Let's take another look at the transfer function equations and response curves presented so far. First note that all of the transfer functions share the same denominator. Also note that all of the numerators are made up of terms found in the denominator: the high-pass numerator is the first term (s2) in the denominator, the bandpass numerator is the second term (s), the low-pass numerator is the third term (1), and the notch numerator is the sum of the denominator's first and third terms (s2 + 1). The numerator for the all-pass transfer function is a little different in that it includes all of the denominator terms, but one of the terms has a negative sign.

4.0 CONCLUSION

In this unit we gave learnt that passive filters do not contain active components or depend on external power supplies as they are composed entirely of combinations of resistors, inductors and capacitors which are purely passive components.

5.0 SUMMARY

- The five basic passive filters types; bandpass, notch, low-pass, high-pass, and all-pass filters, each have a specific amplitude response in the frequency domain

- Passive filters are solely resistive, inductive and capacitive electrical networks

- Low pass and high pass filters have only one cutoff frequency, band pass and band reject filters have two cutoff frequencies while all pass filters have none
- Phase shift filters pass all frequencies without attenuation but introduce phase shift
- The five filter types have nei\merous everyday applications

6.0 TUTOR MARKED ASSIGNMENTS

1 State in explicit terms what passive filters are and how they operate?

2 What is an idealised filter response transfer curve? Sketch the idealised transfer curves for the five basic filter types?

3 How would you describe the transfer curve of an all pass filter?

4 By what other name is a phase shift filter known?

5 Sketch a second order passive band pass filter and label it?

7.0 REFERENCES/FURTHER READINGS

A Textbook of Electrical Technology 2010
By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

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

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By William D. Stanley Published by Prentice Hall

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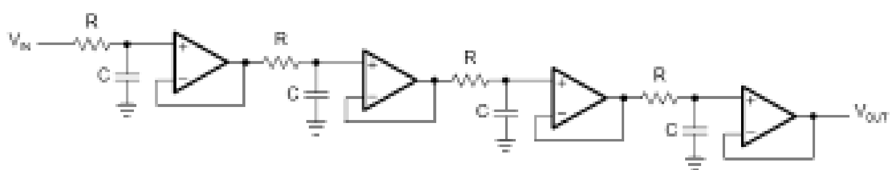
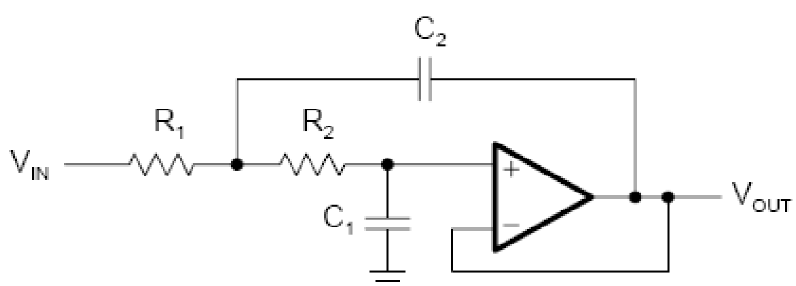
UNIT 4 ACTIVE FILTERS

CONTENTS

1.0 INTRODUCTION



Four Element Low Pass Active Filter



Two Element Low Pass Active Filter

Active Filters such as those illustrated above might include one or more active components such as thermionic valves, transistors or integrated circuits used as voltage buffer amplifiers boast three major advantages over passive filters:

- Large and expensive Inductors can be avoided; particularly at low frequencies where they might present significant internal resistance and are susceptible to induced electromagnetic noise.

- Filter response envelope, the Q factor and tuned frequency can be easily and independently varied with adjustable resistors. Variable inductances for low frequency filters are not practical.

- The filter amplifier can serve the secondary purpose of buffering the filter's output thereby isolating the filter from the effects of a variable load which could affect the filter's response envelope.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1 Describe the characteristics of active filters.

2 Sketch active filters

3 Identify the role that active circuit elements play in active filters

4 Identify practical applications of active filters

5 List the advantages of active filters over passive filters

6 Design active filters based on design criteria

7 Remember the characteristic traits of Butterworth, Tschebyscheff and Bessel filters

8 Compare the transfer functions of Butterworth, Tschebyscheff and Bessel filters

9 Explain ideal filter approximation

10 Recognise audio tone controls as filter implementation.

3.0 MAIN CONTENT

As we have discovered in unit 2 of this module, the family of filters generally referred to as active filters are composed of passive filter components as well as at least one active component.

They require a power source and usually designed around high gain operational amplifiers in order to achieve very high Q factors which result in very steep transition slopes at their cutoff frequencies.

3.1.1 ACTIVE FILTER DESIGN CRITERIA

In designing an Active Filter, you must establish specifications to meet the desired performance criteria. The following filter circuit configurations will serve as a template to guide your design.

Sallen and Key, and VCVS filters offer low dependency on accuracy of the components which mean low tolerance components can be used to construct the filter. State variable and biquadratic filters, Twin T Active filter, Dual Amplifier Bandpass, Wien notch, Multiple Feedback Filter, Fliege which offers the lowest component count for 2 operational amplifiers but with good controllability over frequency and type and the Akerberg Mossberg filter that permits you completely and independently control gain, frequency, and filter envelope.

For the design proper, first you must ascertain the passband or desired range of frequencies which the filter is expected to filter through. Then you have to decide on the shape of the frequency response which indicates the variety of filter and the centre or the corner frequencies.

Also is the need for you to specify the input and output impedances as these will limit the circuit topologies available for the design. To buttress this fact you should note that not all active filter topologies allow you to buffer output to give low output impedance which is desirable for driving most loads. You must also take special note of the frequency dependence and frequency limitations of the active devices you intend to use; particularly for high Pass Filter design.

You should additionally have to bear in mind the following when deciding the level of attenuation in the stopband;

- If the design is for narrow-band bandpass filters, the Q value determines the -3dB bandwidth and the degree of rejection of frequencies far removed from the centre frequency; if these two requirements are in conflict then a staggered-tuning bandpass filter may be needed.

- If the design is for notch filters, the degree to which unwanted signals at the notch frequency must be rejected determines the accuracy of the components, but not the Q value, which is governed by desired steepness of the notch. This means that the bandwidth around the notch before attenuation will be small.

- If the design is for high-pass, low-pass as well as band-pass filters far from the centre frequency, the required rejection may determine the slope of attenuation needed, and thus the order of the filter.

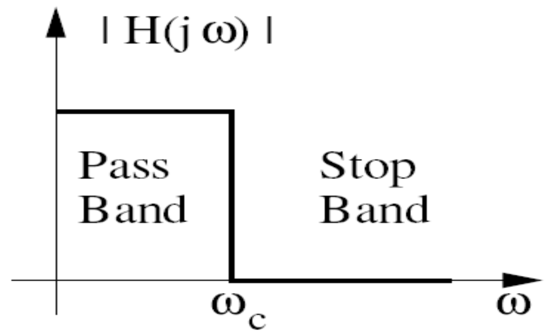
- The permissible ripple within the passband of high-pass and low-pass filters, as well as the shape of the frequency response curve near the corner frequency, determines the damping factor and the phase/time response to a square-wave input.

Damping factors to which you might refer have well established responses. The Tschebyscheff Filter is characterised by a slight peaking with ripple in the passband before the corner frequency while Butterworth filters provide the flattest amplitude response. Linkwitz–Riley filter are best suited for audio crossover applications when critically damped and Paynter filter which is alternatively known as the transitional Thompson-Butterworth and the compromise filter has a faster fall-off than Bessel filters. Bessel filter offer the best time-delay as well as the best overshoot response while Elliptic filter or Cauer filters add a notch just outside the passband, to give a much greater slope in this region than the combination of order and damping factor without the notch.

In the next section we shall concern ourselves with ideal filter response approximations and then take a brief look at the Butterworth Filter, Tschebyscheff Filter and the Bessel Filter optimisations, each with its unique response characteristics which will place the content of preceding sections in proper application perspective.

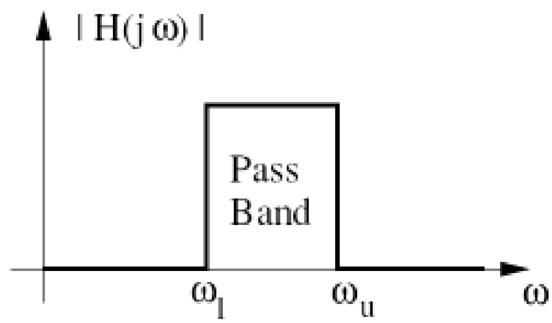
3.2 IDEAL FILTER APPROXIMATIONS

The ideal filter response curve is a rectangular shape, indicating an abrupt boundary between the passband and the stopband with an infinitely steep rolloff slope. The ideal response curve, were it achievable would allow us to completely separate signals at different frequencies from one another.



Low Pass Filter

Such amplitude response curves are not physically realizable and the best approximation that will still meet requirements for a given application is often applied out of several options and deciding on the best approximation involves making a compromise between various properties of the filter's transfer function.



Band Pass Filter

Let us take a look at these properties of a filter's transfer function which we will later relate to required performance characteristics of different filters in different areas of application.

Order

The order of a filter is directly related the steepness of its rolloff slope, the number of components in the filter, its cost, physical size and its complexity.

Ultimate Rolloff Rate

The amount of attenuation for a given ratio of frequencies is be 20 dB/decade for every low and pass filter pole and 20 dB/decade for every bandpass filter pole pair is known as the ultimate rolloff rate.

Attenuation Rate near the Cutoff Frequency

A sharp cutoff characteristic is required when a frequency to be rejected lies adjacent to a frequency to be passed by a filter necessitating high attenuation rate.

Transient Response

The response of a filter to a step function and filters will sharper cutoff characteristics or higher Q will have more pronounced ringing as contrasted with the smooth reaction to a step input signal of filters with lower rolloff.

Monotonicity

A monotonic filter's amplitude response never changes sign and its gain always increases with increasing frequency or always decreases with increasing frequency in high and low pass filters, but bandpass or notch filters can be monotonic on either side of their centre frequency.

Passband Ripple

For non monotonic filters, the transfer function within the passband will exhibit one or more undulations known as ripple.

Amax

Amax Is the maximum allowable change in gain within the passband.

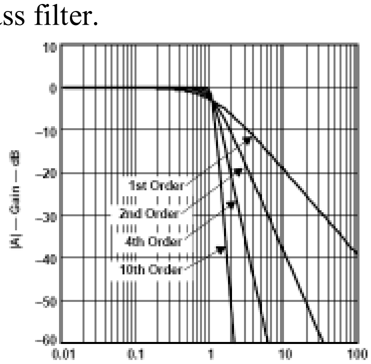
Amin

Amin is the minimum allowable attenuation within the stopband.

3.3 BUTTERWORTH FILTER

The best known ideal filter approximation is the Butterworth low-pass filter; otherwise called the maximally flat filter and which is unique in its ability to provide maximum passband flatness and they offer superior performance as anti-aliasing filter in data converter applications where precise signal levels are required across an entire passband. It exhibits a nearly flat passband with no ripple. The rolloff is smooth and monotonic, with a low-pass or high-pass rolloff rate.

This characteristic is seen in the illustration below which shows the plots the gain response of different orders of Butterworth low-pass filters against normalized frequency. As you can see, the higher the filter order, the longer the passband flatness, and the closer the filter characteristics to the idealised low pass filter.



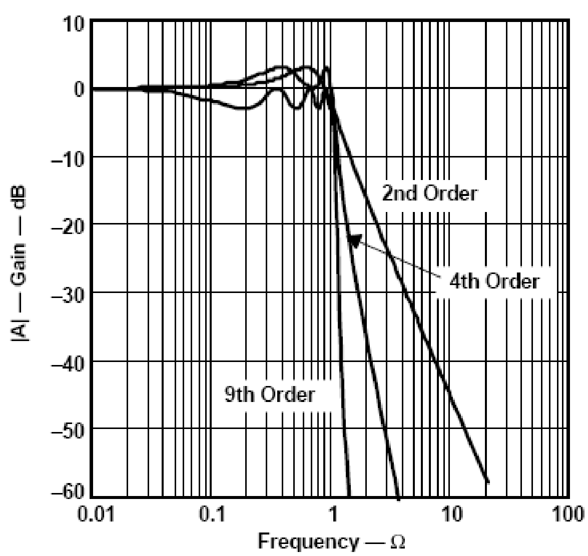
Butterworth low Pass Filter Optimisation

3.3 TSCHEBYSCHEFF FILTER

Alternatively known as the equal ripple filter, Tschebyscheff low-pass filter which we shall discuss as our second ideal filter approximation provides impressively high gain roll-off above the cutoff frequency, the major drawback being that passband gain is not monotonic but comprises ripples of constant magnitude and for a given filter order, higher passband ripples result in higher filter rolloff.

You should observe that the influence of the magnitude of the ripples on filter rolloff diminishes with increasing filter order and that each ripple accounts for one second-order filter stage. Tschebyscheff filter of order n will have n−1 peaks or dips in its passband response. Tschebyscheff low-pass Filters with even order numbers generate ripples above the 0-dB line, while filters with odd order numbers create ripples below 0 dB. You should also remember to take note that the nominal gain of the Tschebyscheff filter is equal to the filter's maximum passband

The Tschebyscheff filter Optimisation find useful application in filter banks, where frequency content of a signal is of more importance than constant amplification. All these properties of the Tschebyscheff low-pass filter optimisation are illustrated below.

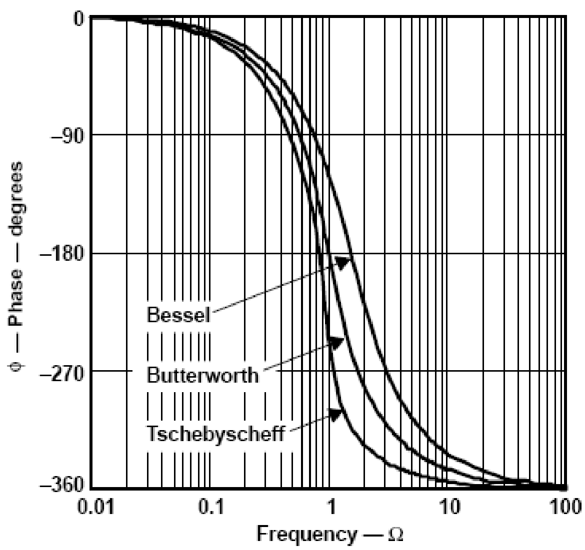


Tschebyscheff Low-Pass Filter Optimisation

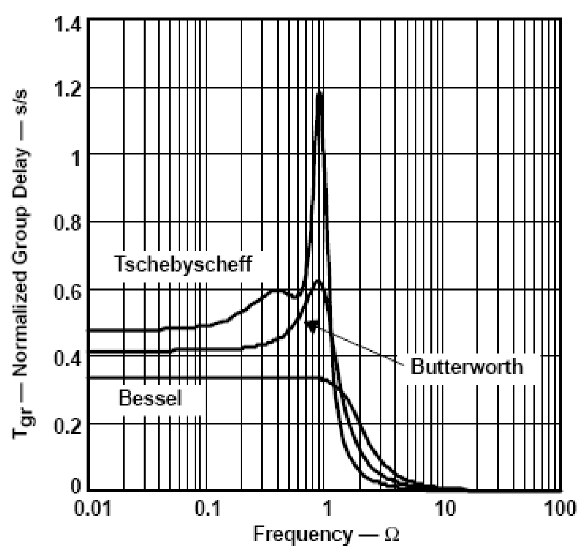
3.4 BESSEL FILTER

Frequency dependent phase shift is an expected characteristic of filters and can present problems in certain situations. Linear phase increase with frequency has the effect of delaying output signal by constant time period but if the phase shift is not directly proportional to frequency, components of the input signal at one frequency will appear at the output shifted in phase with respect to other frequencies and distorts non-sinusoidal waveforms.

Where linear phase response is of uttermost importance, the Bessel low-pass filter which is alternatively called the Thompson filter has a clear advantage over the Butterworth and the Tschebyscheff filters. This linear phase response exhibited over a wide frequency range which results in constant group delay is illustrated in the two plots below in comparison with those of the filters we previously discussed for fourth order filters.



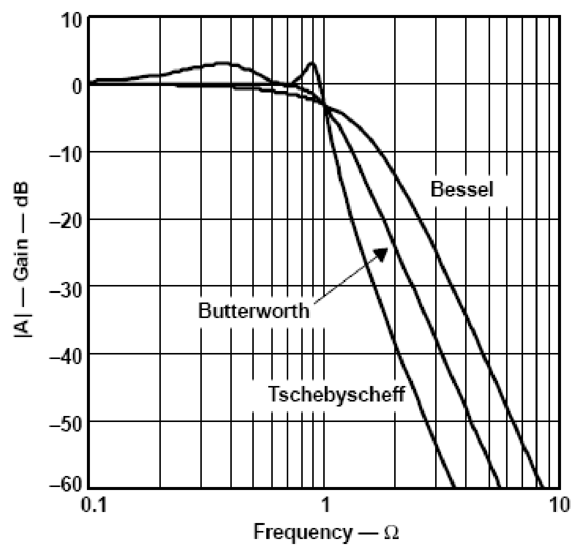
Comparative Phase Responses of Discussed Low-Pass Filters



Relative Group Delay

Because of its wideband linear phase response, Bessel filters exhibit optimum square-wave transmission behaviour.

In comparison, the passband gain of the Bessel low-pass filter is not as flat as that of the Butterworth low-pass filter and transition from passband to stopband is not as sharp as that of a Tschebyscheff low-pass filter. See this fact illustrated below for fourth order filters and learn to recognise it.



Relative Gain Responses

4.0 CONCLUSION

This unit has taught us that active filters which may include one or more active components in addition to inductors, capacitors and resistors have three major advantages over passive filters; large and expensive inductors are eliminated at low frequencies, the filter response envelope, the Q factor and tuned frequency are independently tuneable with adjustable resistors, and filter amplifiers can also function as output buffers.

5.0 SUMMARY

- The design of active filters entails the establishing of specifications to meet desired performance criteria

- The ideal filter response curve is a rectangular shape, indicating an abrupt boundary between the passband and the stopband

- The useful properties of a filter's transfer function are the order, ultimate rolloff rate, attenuation rate near the cutoff frequency, transient response, monotonicity, passband ripple, amax and amin

- The best known ideal filter approximation is the ideal filter approximation is the Butterworth filter which is alternatively known as the maximally flat filter because of the flatness of its response curve

- Tschebyscheff filter is an ideal filter approximation which is alternatively known as the equal ripple filter because of the ripple in its transfer curve

- The Bessel filter as an ideal filter approximation provides linear phase response. It is also known as the Thompson filter and has a clear advantage over Butterworth and the Tschebyscheff filters where linear phase response is required

6.0 TUTOR MARKED ASSIGNMENTS

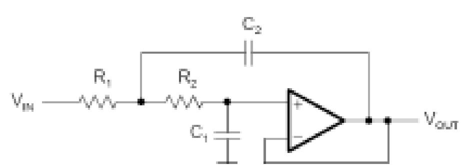
1 Sketch any active filter you know and describe its operation? Also state the properties of the transfer function?

2 List tree common ideal filter approximations and highlight the virtues of the transfer function of each, through illustrative diagrams?

3 Which of the ideal filter approximations is referred to as the maximally flat response filter?

4 If you want a very steep cut off frequency gradient, which ideal filter approximation would you use?

5 Is this a two or a four element filter? How did you arrive at your answer?



6 List the three major advantages and one major disadvantage active filters have over passive filters?

7 Can you describe the steps you would take in designing an active filter? Also mention the filter circuit configuration you know which you would use as your design template?

7.0 REFERENCES/FURTHER READINGS

A Textbook of Electrical Technology 2010
By B. L. Theraja and A. K. Theraja. Published By S. C. Chand,

Electrical Circuit Analysis
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Electronic Devices and Circuit Theory 7th Edition
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UNIT 5 APPLICATION OF FILTERS

CONTENTS

1.0 INTRODUCTION

Basically filters can be categorized in the time domain as sampled data filters or continuous time filters and the choice to employ which of these two categories is more often than not determined by application.

Sampled data filters are generally preferable for applications where accurate centre frequencies and small board space requirements are desirable. These applications involving accurate tone detection for instance are prevalent in Communications, FAXs, Modems, Biomedical Instrumentation and Acoustical Instrumentation where Switched Capacitor Filters play a predominant role.

It is often necessary to eliminate noise trough Line-Frequency Notches for Biomedical Instrumentation which process signals within the frequency range of the line frequency, or to implement Low-Pass Noise Filtering for General Instrumentation and to design Anti-Alias Filtering for Data Acquisition Systems.

While conventional active filters and sampled data filters perform relatively well in these applications, exceptions arise when signal bandwidths are high enough relative to the centre or cutoff frequencies such as to cause aliasing, or if the system requires dc precision. When such cases arise; particularly where dc precision is needed, conventional active filter built with precision op amps are recommended over sampled data filters. If dc precision is not an issue then sampled data filters can be used so long as a resistor and a capacitor are used to eliminate the aliasing problem.

Where it is desirable to have controllable, variable frequency filtering such as in Spectrum Analysis, Multiple-Function Filters and Software-Controlled Signal Processors, sampled data filters play a dominant role; particularly in applications that require multiple centre frequencies which centre frequencies are clock-controlled. In such applications, a single filter can cover a centre frequency range up to 5 decades.

Sampled signal filters like the switched capacitor filter are usually too nosy for the high fidelity required in tone controls, Equalization and other audio signal processing, all-pass filtering and active crossover networks. This is partially because audio filters often need to handle three decades of signal frequencies simultaneously, so continuous filters are preferred for general audio use.

2.0 OBJECTIVES

After reading through this unit, you will be able to

1. List several applications of filters
2. Categorise filters into continuous time and sampled data filters
3. Recognise the role of filters in communications technology
4. Appreciate that digital filters are implemented through computer software algorithms
5. Discuss the negative effects of transients and radio frequency interference on electronic equipment
6. Sketch a simple capacitive electrical noise suppressor
7. Explain the function of snubber resistor in noise suppressors
8. Understand the principle of operation of the spectrum analyser
9. Appreciate the broad application of spectrum analysis
10. Realise the difficulty entailed in totally eliminating mains frequency hum from audio equipment

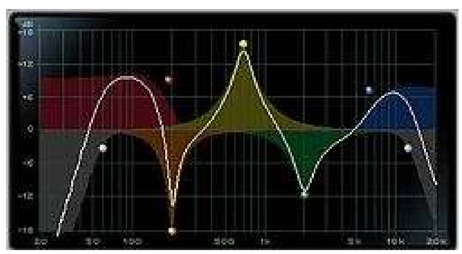
11 See typical applications of bandpass filters in radio frequency signal processing

12 Understand how load impedance affects the response characteristics of filters

3.0 MAIN CONTENT

3.1 AUDIO FREQUENCY USES OF FILTERS

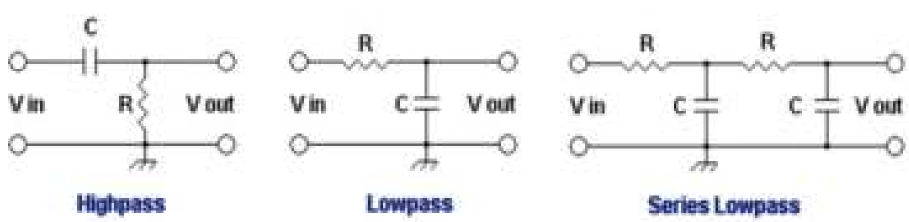
Audio filters are implemented both in analogue circuitry as analogue filters, and as computer software in digital filters. Their function primarily involves changing of the harmonic content of audio signals. In audio terms; the harmonic content of audio signals is the timbre and is a measure of the subjective quality of sound.



Digital Parametric Equalisation Display

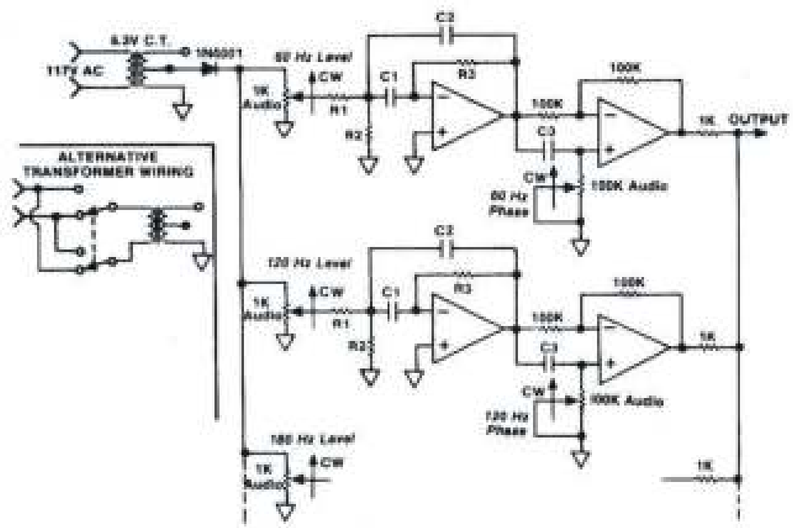
Audio frequency filters are applied to frequencies commencing from direct current; 0 Hz to beyond 20 kilo Hertz and many types of filters exist and are used for audio frequency applications. These include graphic equalizers, synthesizers, sound effects, Compact Disk players and virtual reality systems.

Audio filters are designed to amplify, pass or attenuate some frequency ranges and common types include low-pass filters, which pass through frequencies below their cutoff frequencies, and progressively attenuate frequencies above the cutoff frequency, high-pass filters which do the opposite by passing high frequencies above the cutoff frequency, and progressively attenuating frequencies below the cutoff frequency.



Audio Filter Networks

Audio bandpass filters pass frequencies between their two cutoff frequencies while attenuating those outside the range while band-reject filters attenuate frequencies between their two cutoff frequencies, while passing those outside the 'reject' range. Finally, the audio all-pass filter passes all frequencies, but affects the phase of any given sinusoidal component according to its frequency.



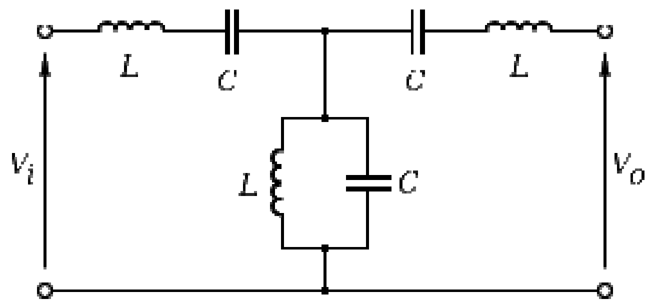
Audio Filter Application

The design of graphic equalizers and Compact Disk players depend on a set of objective criteria. These criteria include pass band, pass band attenuation, stop band, and stop band attenuation and they determine where the pass bands are the frequency ranges for which audio is attenuated less than a specified maximum, and the stop bands which are the frequency ranges for which the audio must be attenuated by a specified minimum.

Audio filter often provide a feedback loop, which introduces resonance as well as attenuation. Some audio filters are designed to provide gain as well as attenuation while in synthesizers and sound effects applications, filter audio aesthetic is of uttermost importance and must be evaluated critically as well as subjectively.

3.2 BANDPASS FILTERS AT RADIO FREQUENCIES

Signals at radio frequencies frequently require that a range of frequencies within a band be filtering through a circuit. This is a very common occurrence in high frequency applications such as the 20 metre band.

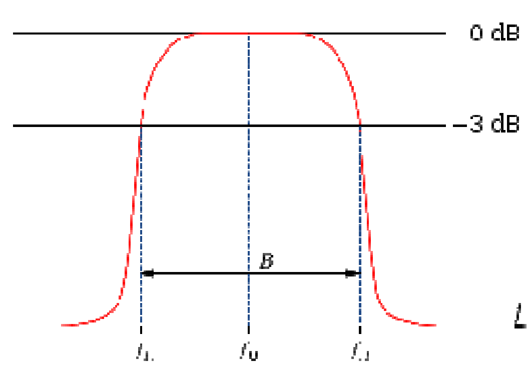


Radio Frequency bandpass Filter

Above is a typical configuration of a radio frequency bandpass filter and below, its frequency response curve. The topology above is that of a T filter. The pair of series LC elements on the upper arm of the T are stagger tuned; which means one set is made to resonate slightly above while the other slightly below the centre frequency which results in a double peaked response with a trough in between.

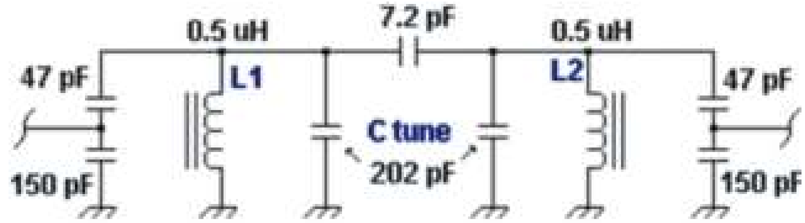
Being series resonant circuits, they allow desired frequencies within the passband to pass suppressing slightly the centre frequency. The parallel LC resonant circuit presents a high impedance to the centre frequency while allowing other frequencies around to bypass the output of the filter.

With very careful selection of the component values, the combined effect of the parallel tuned circuit will result in the filling in of the trough in the response curve to create a flatter passband with steep rolloff slope as illustrated below.



Bandpass Filter Response Curve

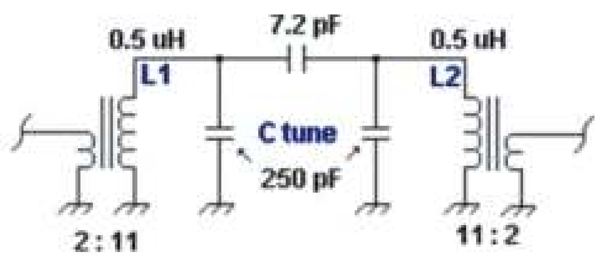
The illustration below is a practical application of a 20 metre bandpass filter with a centre frequency of 14.2 Megahertz and a passband bandwidth of 575 Kilohertz.



20 Metre Radio Frequency Bandpass Filter

The filter illustrated above must be terminated with 50 ohm impedance in order to achieve the designed band pass response and associated stop band attenuation.

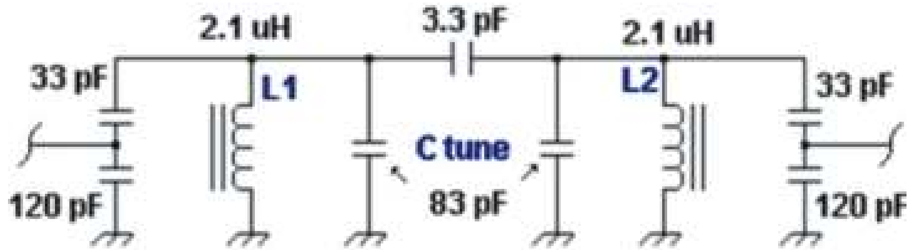
Now let us remember all we have discussed about filters in the preceding modules and sections and apply to the circuit above: On the right of the illustration is a second order Butterworth band pass filter. Do you recognise it? It is designed for the 20 meter band and has a centre frequency is 14.2 MHz, a bandwidth is 0.575 Megahertz.



Equivalent of 20 Metre Radio Frequency Bandpass Filter

The illustration above is an equivalent filter which uses transformers to match the filter to a 50 ohm load impedance as opposed to output capacitor used in the illustration above it.

Look at the values of the components used in the 20 metre band pass filter and compare them with values for a 30 Meter Band design with the same circuit layouts illustrated below. This is a second order Butterworth band-pass filter for the 30 meter band. It has a center frequency is 10.125 Megahertz and a bandwidth is 400 Kilohertz.



20 Metre Radio Frequency Bandpass Filter

See if you can figure out the relationship between the values and the centre frequencies.

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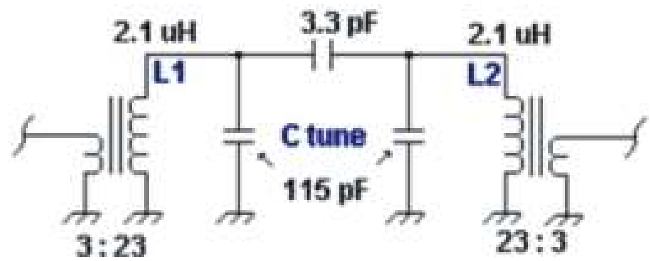


Equivalent of 30 Metre Radio Frequency Bandpass Filter

3.3 EMI AND TRANSIENT SUPPRESSOR FILTERS

Electrical transient is rich in radio frequencies which are responsible for electromagnetic interference. Electromagnetic disturbances affect electrical circuits through electromagnetic induction or electromagnetic radiation and the disturbance may interrupt, obstruct, degrade or limit the effective performance of a circuit. They can range from simple degradation of data to a total loss of data in computers.

The two major categories of transient and Electromagnetic Interference suppressors are suppressors that attenuate transients and thereby prevent their propagation into sensitive circuit on the one hand; and those that divert transients away from sensitive loads and so limit the residual voltages on the other.

Attenuating a transient means keeping it from propagating away from its source or keeping it from impinging on a sensitive load. It can be accomplished with filters inserted within a circuit.

If placed in series with a circuit, these filters are generally low-pass type and they attenuate high frequency transients while allowing signal or power frequencies to continue undisturbed.

The frequency components of a transient are several orders of magnitude above the power frequency of an AC circuit and the obvious solution is radio frequency interference is to install a low-pass filter between the source of transients and the load. This is usually made up of a capacitor placed across the line. The impedance of the capacitor forms a voltage divider with the source impedance, resulting in attenuation of the transient at high frequencies.

Inductive components in the circuit may create unwanted resonances with this capacitance and a series resistor is usually added to the capacitor to create an RC snubber circuit.

More elaborate schemes have been developed for the suppression of radio frequency and transient induced interference as they degrade the performance of certain communication systems. Amplitude modulated radio transmission is particularly susceptible to interference and various methods which improve selectivity are used in radio receiver.

Wi-Fi digital radio systems employ sophisticated error-correction techniques while spread-spectrum and frequency-hopping are used with both analogue and digital signalling to reduce sensitivity to radio frequency and transient induced interferences.

3.4 SPECTRUM SWEEPING

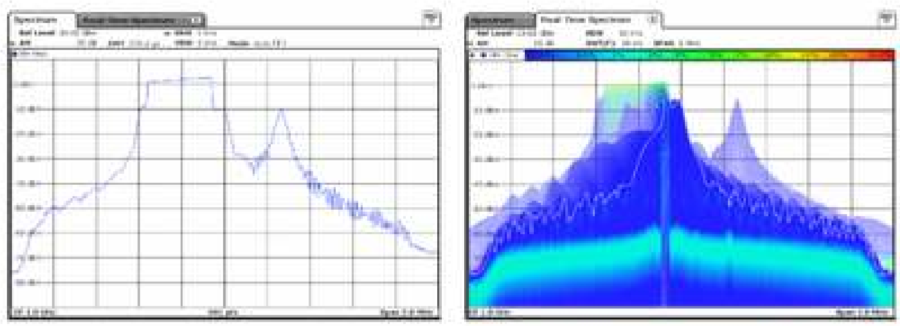
Swept-tuned spectrum analyzers sweep a voltage-controlled oscillator through a range of frequencies which are mixed with, and which down-converts a portion of the input signal spectrum to the centre frequency of a band-pass filter.

Spectrum Analyser

To understand this you must remember that the output of an oscillator can be mixed with a signal frequency to generate the sum and the difference of the oscillator and the signal frequency.

If the difference of the frequencies is passed through high Q value, narrow band bandpass filter, then, the output of the filter will respond to the difference frequency produced which falls within its passband. As the oscillator frequency is swept across a range, the filter responds to those frequencies in the input signal which difference with the oscillator's frequency fall within its passband.

Proper calibration with an oscilloscope will display a curve in the frequency domain when the swept frequency is generated with a voltage controlled oscillator.



Frequency Spectrum Display of Spectrum Analyser

In commercial spectrum sweeping devices, bandwidth of the band-pass filter determines the spectral resolution bandwidth and this is related to the minimum bandwidth that can be detected by the instrument.

Spectrum analyzers are universally applied in the measurement of frequency response, noise and distortion characteristics of several types of Radio Frequency equipment circuitry. This is done easily and effectively by comparing the input and output spectra of the circuitry.

Telecommunications spectrum analysis entails the use of spectrum analyzers to determine occupied bandwidths and to track interference sources; this is very important in GSM cell planning. They are applied in determining wireless transmitters' compliance with defined standards for purity of emissions.

Output signals at frequencies other than the intended communications frequency appear as vertical lines (pips) on the display. A spectrum analyzer is also used to determine, by direct observation, the bandwidth of a digital or analogue signal.

4.0 CONCLUSION

We learnt in this unit that filters applications abound everywhere and we directly and indirectly come into contact with filters every single day.

We now know that Filters are divided into sampled data and continuous time filters, and the choice of filter type for a particular application depends on its merits when applied.

5.0 SUMMARY

- Electronic filters are extensively applied to modify the frequency domain response of electronic systems from audio frequency and across the entire frequency range through to radio frequencies.
- Filters are categorized as either sampled data filters or continuous time filters
- Choice of filter is determined by application and performance criteria
- Audio frequency application of filters include graphic equalizers, synthesizers, sound effects, Compact Disk players and virtual reality systems
- In radio frequency work, most filter applications are bandpass filters of which intermediate frequency stages are a good example. So are tuners.
- Electrical transients which is responsible for electromagnetic interference is rich in radio frequencies and is suppressed using low pass filters
- Snubber resistor suppress unwanted resonances in noise suppressors
- The two types of electromagnetic interference suppressors are those that attenuate transients and those that divert transients away from loads
- Swept-tuned spectrum analyzers operate by sweeping a frequency range of the radio spectrum through a narrow bandpass filter
- Filter response characteristics is affected by loading
- It is very difficult to totally eliminate mains frequency hum from audio equipment

6.0 TUTOR MARKED ASSIGNMENTS

1 State two industrial applications of filters?

2 Can you imagine a filter application in the aviation and maritime sectors? What is this application and how does it function?

3 Where would you expect to find transient suppressors?

4 What possibly could be the consequence of electromagnetic interference emanating from a passenger's personal computer aboard a plane on the plane's electronic navigational system? Discuss in detail?

7.0 REFERENCES/FURTHER READINGS

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By M. E. Van Valkenburg Published by Holt, Rinehart and Winston