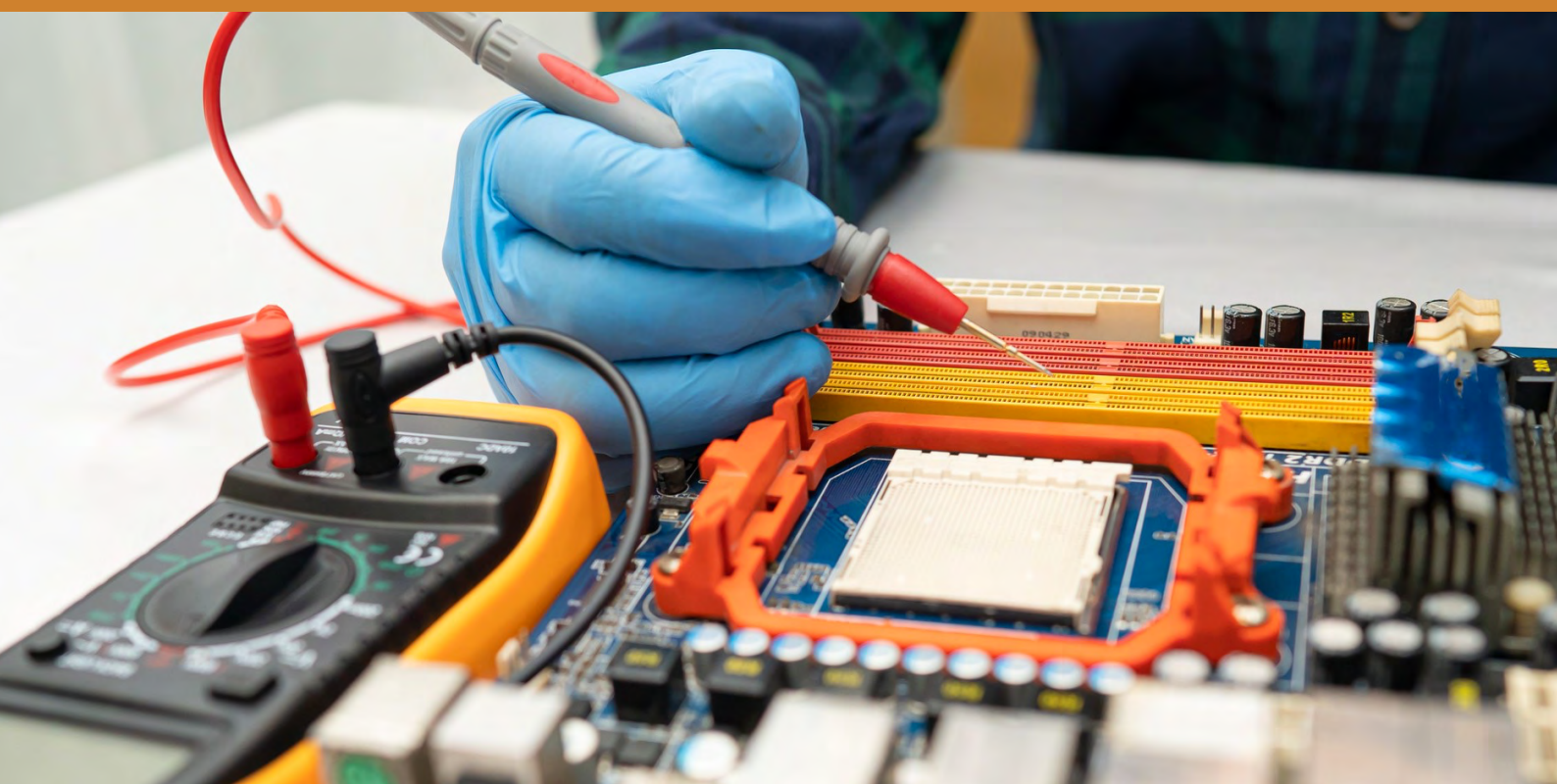


MINISTRY OF EDUCATION
TECHNICAL TEACHERS
ASSOCIATION OF GHANA



Electricals and Electronics Technology (Applied Technology) for Senior High Schools

Year 3



Evans Charles Sraha
Esther Pokuaa
Gilbert Second Odjamgba



**MINISTRY OF EDUCATION
GHANA ASSOCIATION OF
SCIENCE TEACHERS**

**Electricals and
Electronics Technology
(Applied Technology)
for Senior High Schools**

Year 3

Evans Charles Sraha

Esther Pokuaa

Gilbert Second Odjamgba



Ghana Education
Service (GES)





© Ministry of Education 2025

This publication is not for sale. All rights reserved. No part of this publication may be reproduced without prior written permission from the Ministry of Education, Ghana.

ISBN: 978-9988-9492-2-8

CONTENTS

FOREWORD	6
SECTION 1	
UNIT 1: AC, DC MOTORS AND AC, DC GENERATORS	8
INDUCTION MOTORS AND SYNCHRONOUS MOTORS.....	9
UNIT 2: AC, DC MOTORS AND AC, DC GENERATORS	23
DC MOTORS.....	24
UNIT 3 AC, DC MOTORS AND AC, DC GENERATORS	38
SINGLE-PHASE AC GENERATOR	39
UNIT 4 AC, DC MOTORS AND AC, DC GENERATORS	51
SECTION 2	
UNIT 5 TRANSFORMERS AND MAINTENANCE	63
SINGLE PHASE AND 3-PHASE TRANSFORMER	63
UNIT 6 LOSSES AND EFFICIENCY OF TRANSFORMERS	73
LOSSES IN TRANSFORMERS	74
UNIT 7 COOLING OF TRANSFORMERS VOLTAGE REGULATION	81
COOLING OF TRANSFORMERS.....	82
UNIT 8 COMMON FAULTS WITH HOME APPLIANCES	90
CLASSIFICATION OF ELECTRICAL APPLIANCES AND COMMON FAULTS AS- SOCIATED WITH THEM	91
SECTION 3	
UNIT 9 COMMON FAULTS WITH ELECTRICAL APPLIANCES	101
TROUBLESHOOTING AND SERVICING ELECTRICAL APPLIANCES.....	102
UNIT 10 MAINTENANCE, ELECTRICAL MACHINE FAULT AND CIRCUIT, AMPLIFIER, LOGIC GATES)	110
FAULT IN ELECTRICAL MACHINES.....	111
UNIT 11 INTEGRATED CIRCUITS	120
FEATURES AND PRINCIPLES OF OPERATION OF TIMERS.....	121
UNIT 12 MAINTENANCE, ELECTRICAL MACHINE FAULT AND CIRCUIT	136
FEATURES AND PRINCIPLES OF OPERATION OF OP-AMPS 741 & 4558 AND DESIGNING WITH OP-AMPS.....	137
SECTION 4	
UNIT 13 DIGITAL ELECTRONICS	154
TYPES OF LOGIC GATES AND THEIR PROPERTIES	154
UNIT 14 BOOLEAN ALGEBRA	169
BOOLEAN ALGEBRA.....	169

SECTION 5

UNIT 15 LOGIC EXPRESSIONS FROM CIRCUITS	180
LOGIC EXPRESSIONS FROM CIRCUITS	181
UNIT 16 ELECTRONIC CIRCUITS AND TRANSMITTERS IN ELECTRONIC COMMUNICATION	191
DESCRIPTION OF THE VARIOUS TYPES OF MODULATION IN COMMUNICA- TION	192
UNIT 17 COMMUNICATION	203
AM AND FM TRANSMITTER.....	204
UNIT 18 ELECTRONIC CIRCUITS AND TRANSMITTERS IN ELECTRONIC COMMUNICATION	220
AM RECEIVER AND FM RECEIVER.....	221
REFERENCES	239
GLOSSARY	243

FOREWORD

Ghana's new Senior High School Curriculum aims to ensure that all learners achieve their potential by equipping them with 21st Century skills, knowledge, character qualities and shared Ghanaian values. This will prepare learners to live a responsible adult life, progress to further studies and enter the world of work. This is the first time that Ghana has developed a Senior High School Curriculum which focuses on national values, attempting to educate a generation of Ghanaian youth who are proud of our country and can contribute effectively to its development.

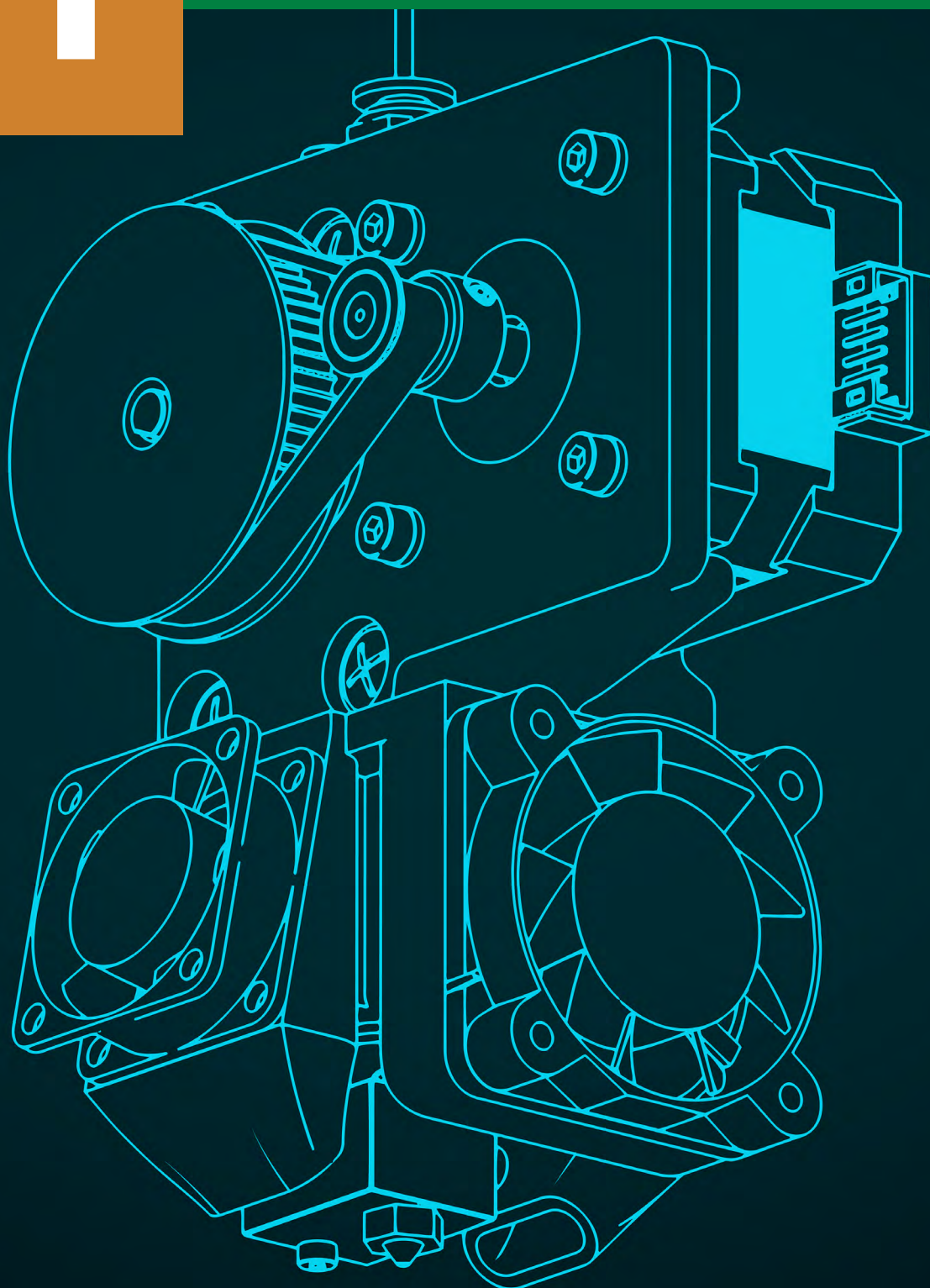
The Ministry of Education is proud to have overseen the production of these Learner Materials which can be used in class and for self-study and revision. These materials have been developed through a partnership between the Ghana Education Service, teacher unions (Ghana National Association of Teachers- GNAT, National Association of Graduate Teacher -NAGRAT and the Pre-Tertiary Teachers Association of Ghana- PRETAG) and National Subject Associations. These materials are informative and of high quality because they have been written by teachers for teachers with the expert backing of each subject association.

I believe that, if used appropriately, these materials will go a long way to transforming our Senior High Schools and developing Ghana so that we become a proud, prosperous and values-driven nation where our people are our greatest national asset.

Haruna Iddrisu MP
Minister for Education

SECTION

1



UNIT 1: AC, DC MOTORS AND AC, DC GENERATORS

INTRODUCTION

In year 2, you studied AC circuit theory, where you learned how alternating current behaves in resistive, inductive, and capacitive circuits, and how voltage, current, and power are related in AC systems. You also covered electromagnetism, understanding how magnetic fields are produced by electric currents, how coils and magnetic cores work, and how these principles are applied in transformers, generators and motors. In this unit, we build directly on that foundation by exploring single-phase and three-phase motors, which are practical applications of both AC circuit principles and electromagnetism. You will study the constructional features and operation of single-phase and three-phase induction motors, as well as synchronous motors. You will also learn the methods of starting these motors, such as direct-on-line, star-delta, and autotransformer starting and their applications in industry and everyday life.

KEY IDEAS

- Construction and Operation of Single-Phase Induction Motors. Understanding the main parts (stator, rotor, windings) and how they produce rotation using an AC supply.
- Starting Methods for Single-Phase Induction Motors. Learning the different ways to start these motors, such as split-phase, capacitor-start, and shaded-pole methods.
- Construction and Operation of Three-Phase Induction Motors. Studying the design and working principles of squirrel cage and wound rotor types.
- Types of Three-Phase Induction Motors and Starting Methods. Exploring variations of three-phase motors and starting techniques like direct-on-line, star-delta, and auto-transformer starting.
- Applications of Induction Motors. Identifying where and why single-phase and three-phase induction motors are used in homes, workshops, and industries.
- Construction, Operation, and Applications of Synchronous Motors. Understanding how synchronous motors differ from induction motors, how they run at constant speed, and where they are used.

INDUCTION MOTORS AND SYNCHRONOUS MOTORS

MOTORS

Before we talk about motors, just think about the things you use every day. When you switch on your ceiling fan, how does it start turning? When your mother uses the blender to make juice, what makes the blades spin? How does the washing machine drum rotate to clean clothes? The answer to all of these is the same: a motor.

A motor is a machine that changes electrical energy into mechanical energy. That means it takes in electricity and produces movement or rotation that can do useful work. This is why we find motors in so many appliances: fans to keep us cool, fridges to run the compressor and keep our food fresh, water pumps to lift water into storage tanks, and sewing machines to move the needle quickly.

Motors are also in many tools and machines in workshops and factories. In this topic, we will learn how these motors work, the different types, and why certain motors are chosen for specific jobs.” Motors are generally classified into *AC motors* (which run on alternating current) and *DC motors* (which run on direct current).

The choice between AC and DC motors depends on the type of power supply available and the job the motor needs to do. In Ghana, motors are used everywhere, ranging from small household devices like blenders, fans, and sewing machines to large industrial machines such as conveyor belts, milling machines, and water pumps. Their wide use is because they are efficient, reliable, and can be designed for many different applications.

AC MOTORS

An AC motor is an electric motor that runs on alternating current, converting electrical energy into mechanical energy using the principle of electromagnetism. When AC flows through its windings, it creates a rotating magnetic field that turns the rotor, producing motion to drive machines. There are two main types of AC motors, namely *synchronous* and *asynchronous*, also known as induction motors

Construction of Induction Motors

Induction motors, also known as asynchronous motors, are AC electric motors. The main parts are the Stator (the stationary part) and the Rotor (the rotating part).

There is no physical electrical connection between the stator and the rotor. The stator generates a rotating magnetic field when powered by alternating current (AC). The changing magnetic field induces a current in the rotor, and the rotor in turn generates its own magnetic field. The interaction between these two magnetic fields causes the rotor to spin; hence the name induction.

They are mainly classified into *single-phase induction motors*, used in household appliances like fans, fridges, and washing machines, and *three-phase induction motors*, used in industrial applications such as pumps, compressors, and milling machines. In operation, the rotor always turns at a speed slightly less than the speed of the rotating magnetic field. This difference is called a slip.

Single-phase induction motor

An induction motor works only if there is a rotating magnetic field. This rotating field is normally created when at least two phases are connected to the stationary poles of the motor. If the motor gets power from only one phase, the magnetic field will not rotate.

Instead, it will pulsate (move back and forth) in the same place. A pulsating field cannot start the motor; it is like trying to roll a ball by just shaking it. To make the motor start, engineers split the single-phase into two phases. This is done by adding a capacitor or inductor to another coil of wire. This second coil is called the starting winding, because the phase is “split” into two currents; the motor is called a split-phase induction motor.

How it works

The main winding (running winding) and the starting winding carry currents that are 90° apart in phase. This phase difference produces the rotating magnetic field needed to start the motor. Once the motor starts, the starting winding may be switched off, and the main winding keeps it running.

Construction

The single-phase induction motor has two main parts: the stator (the part that stays still) and the rotor (the part that turns). The stator has two sets of windings — the starting winding and the main winding. A capacitor or an inductor is connected in series with the starting winding, which also has a centrifugal switch. The main winding is connected directly to the power supply, as shown in **Figure 1.1.1a**.

Once the motor has been running for a short time, a centrifugal switch automatically disconnects the starting (auxiliary) winding, leaving only the main winding in the circuit. The rotor then continues to follow the magnetic field from the main winding, allowing the motor to continue running smoothly.

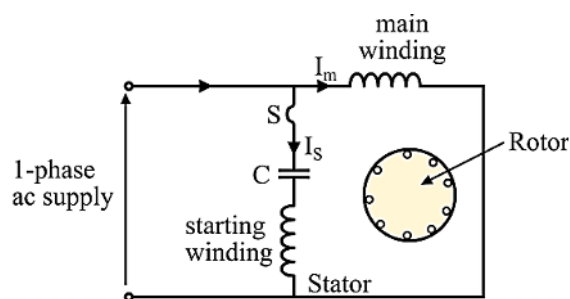


Figure 1.1.1a: Single-Phase Induction Motor

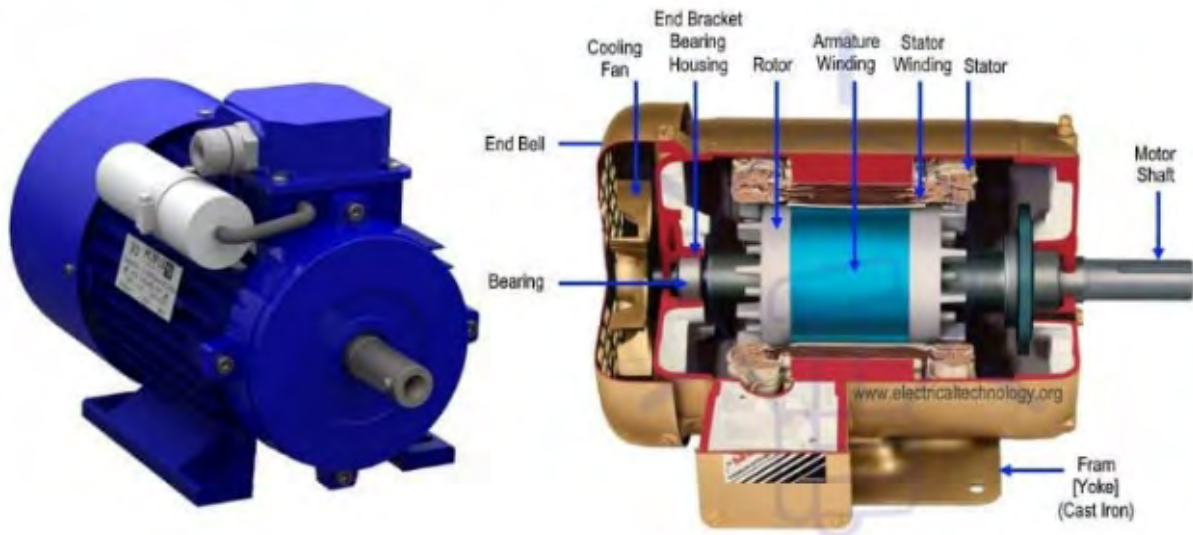


Figure 1.1.1b: Cross-sectional View

Figure 1.1.1a shows the circuit diagram of a capacitor start induction motor. The term *capacitor start* means that a phase difference of about 90° is created by adding a capacitor to the starting winding. This causes the current in the starting winding to lead the current in the main winding, making it seem like there are two separate phases. This helps the motor to start turning.

When the power supply is switched on, the two windings produce a rotating magnetic field inside the stator. This rotating field cuts across the rotor conductors and induces an electromotive force (emf) in them. The current produced in the rotor creates its own magnetic field, which, according to Lenz's law, opposes the stator's magnetic field, because opposite magnetic poles attract, the rotor starts to follow the rotating magnetic field. The rotor turns, but not at the same speed as the rotating magnetic field. If it turned at the same speed, the field would not cut the rotor conductors and no emf would be produced.

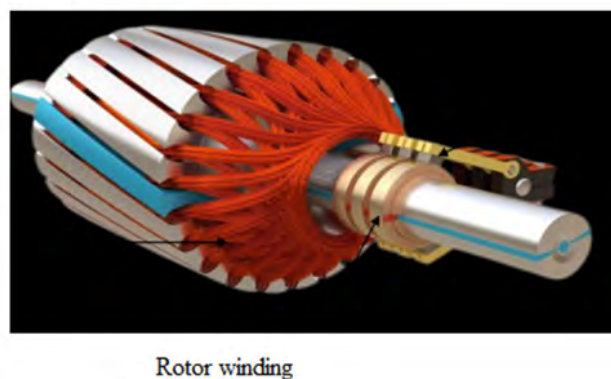
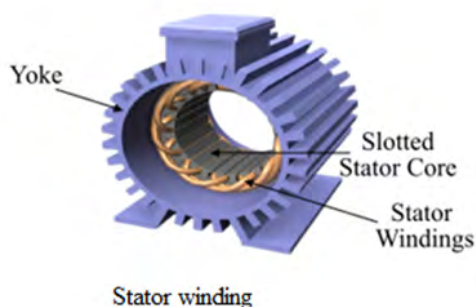


Figure 1.1.1c: The stator and rotor of an induction motor

The Three-Phase Induction Motor

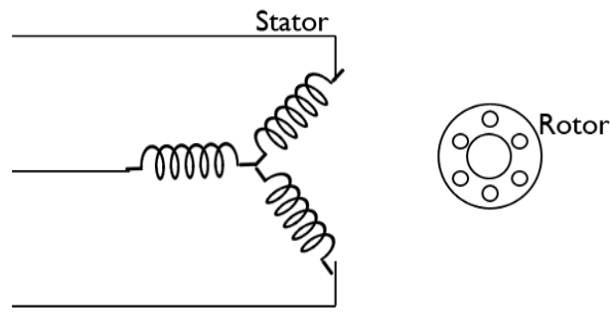


Figure 1.1.2 a: Three-phase induction motor

As we have already learned, induction motors work based on the principle of a rotating magnetic field. They have two main parts:

1. Stator, the stationary (non-moving) part
2. Rotor, the rotating part

In a three-phase induction motor, the stator is connected to a three-phase power supply. This supply produces the rotating magnetic field needed to make the motor work.

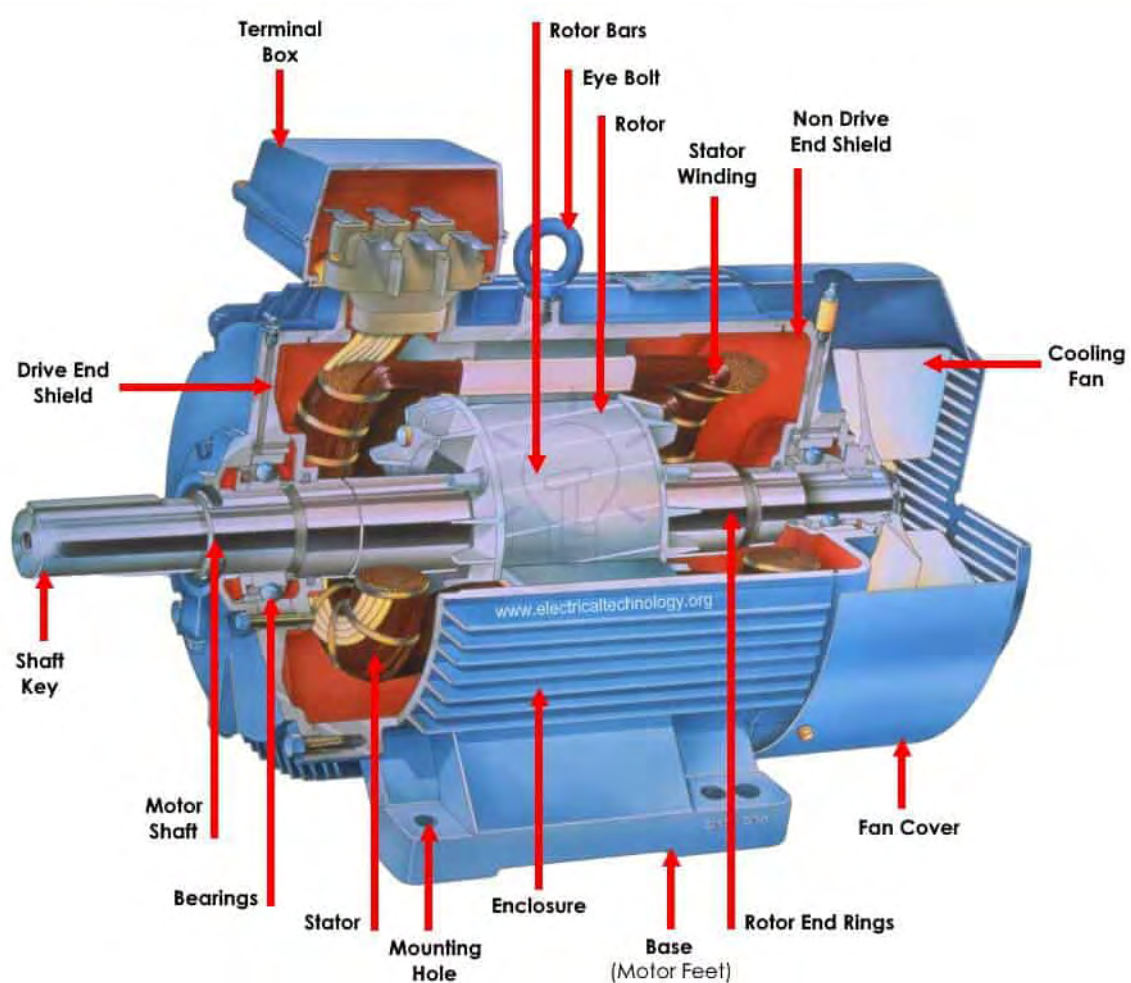


Figure 1.1.2b: Cross-Sectional View of 3-Phase Induction Motor

There are two main types of three-phase induction motors:

1. Squirrel cage type
2. Wound rotor type

Three-Phase Squirrel Cage Induction Motor

This type of motor is simple in design, small in size (for its power rating in kilowatts), needs very little maintenance, and is relatively cheap. It is widely used for many kinds of industrial work.

Construction

Like the single-phase motor, the three-phase induction motor has two main parts:

1. Stator – the stationary part
2. Rotor – the revolving (rotating) part

However, unlike the single-phase motor, the stator of the three-phase motor has three separate sets of windings made of fine wire. These windings are placed 120° apart from

Operation

1. When the three sets of stator coils are supplied with three-phase AC power, the stator windings produce a rotating magnetic field inside the stator.
2. This rotating field moves at a speed called the synchronous speed. As it moves, it cuts across the rotor conductors, inducing an electromotive force (emf) in them.
3. The induced emf causes currents to flow in the rotor bars. These currents create their own magnetic field in the cage rotor. The rotor's field interacts with the stator's rotating field, causing the rotor to turn.

The rotor always spins slower than the synchronous speed. If it ever reached the same speed, there would be no cutting of conductors, no induced emf, and no movement. The difference between the synchronous speed and the rotor's actual speed is called slip.

The turning of the rotor due to the interaction of the magnetic fields is called torque production.

If you swap (interchange) any two of the three power supply wires, the direction of the rotating magnetic field changes, and the rotor spins in the opposite direction each other. They can be connected in either star (Y) or delta (Δ) formation and are fixed inside the stator frame. The stator windings are connected to a three-phase power supply through a three-pole switch.

The rotor is made from a cylindrical core with copper or aluminium bars placed inside it. The ends of these bars are connected to metal rings, forming a shape that looks like a cage, which is why it is called a squirrel cage rotor.

Three-Phase Wound Rotor Induction Motor

In a squirrel cage induction motor, the speed cannot be easily changed—it runs at a nearly constant speed. For situations where the motor speed needs to be varied in industry, another type of induction motor is used: the wound rotor induction motor.

Construction

This motor is similar in construction to the squirrel cage type, but there is one key difference:

1. In the wound rotor motor, the rotor has windings (coils of wire) instead of solid bars.
2. These rotor windings are connected to a three-phase variable resistor through a slip ring and brush arrangement.
3. This connection allows for speed control and better starting performance.

Although its construction is slightly different, the principle of operation is the same as the squirrel cage induction motor.

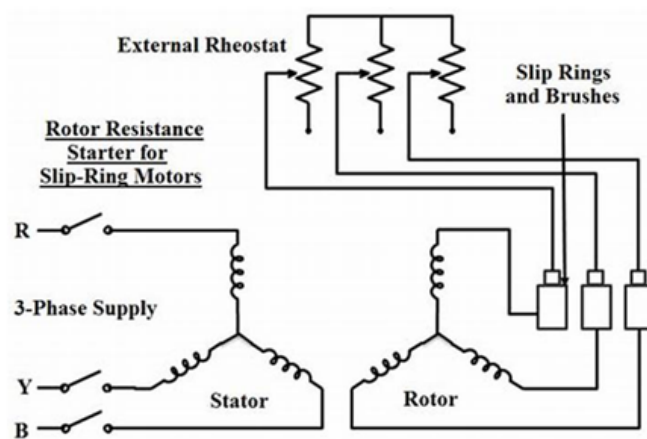


Figure 1.1.3: Wound rotor induction motor

Operation

Before switching on the motor, the variable resistor connected to the rotor winding is set so that maximum resistance is inserted into the circuit. This gives the motor very high starting torque (strong turning power at the start).

When the power is switched on, the motor begins to turn gradually. As the speed increases, the resistance is slowly reduced until it is completely removed from the rotor circuit. By adjusting the amount of resistance in the rotor circuit, the speed of the motor can also be controlled during operation.

Applications of Induction Motors

Induction motors are used in many areas because they are strong, reliable, and easy to maintain. Some common uses include:

1. Household appliances such as washing machines, refrigerators, and mixers use single-phase induction motors due to their compact size, low cost, and ability to operate efficiently on a standard domestic power supply.

2. Industrial machinery such as conveyor systems, pumps, and compressors. often uses three-phase squirrel cage motors due to their robust, simple construction and ability to provide the high starting torque required for heavy, continuous loads.
3. Fans and blowers in ventilation systems and HVAC (Heating, Ventilation, and Air Conditioning) commonly use shaded-pole or capacitor-run motors due to their smooth, quiet operation and ability to maintain steady airflow at relatively low torque demands.
4. Electric vehicles use three-phase AC induction or permanent magnet synchronous motors to provide propulsion (movement), as these motors offer high power density, precise speed control, and the ability to recover energy through regenerative braking.
5. Water pumps for agriculture, irrigation, and home water supply rely on single or three-phase induction motors due to their reliability in continuous operation, low maintenance requirements, and ability to deliver consistent torque for moving large volumes of water.

The Synchronous Motor

A synchronous motor uses two types of electricity to run—AC (alternating current) and DC (direct current).

Here is how it works

1. Stator (the outer part): This part gets a three-phase AC power supply. That means electricity flows in three different paths, creating a rotating magnetic field.
2. Rotor (the spinning part inside): This part receives DC power, which creates a steady magnetic field.

When the motor is switched on, the magnetic field from the stator rotates. The rotor's magnetic field locks onto this rotating field and starts spinning at the same speed. This is why it is called a synchronous motor (because both fields move in sync).

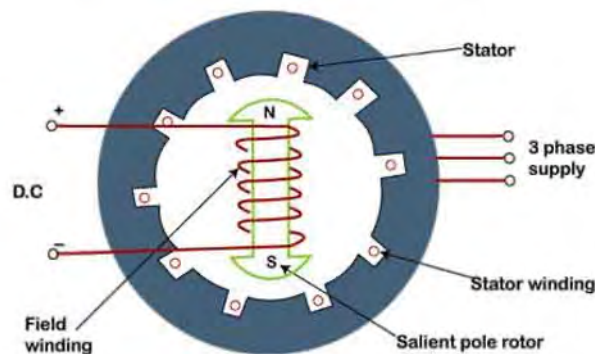


Figure 1.1.4: A three-phase synchronous motor

Starting and Speed Control of AC Motors

Sometimes, the rotor and stator poles in a synchronous motor can line up with the same magnetic side—like North facing North (N-N) or South facing South (S-S). This causes them to push away from each other (repulsion). Other times, they face opposite sides—North facing South (N-S). This pulls them together (attraction), because of this constant push and pull, the motor cannot start spinning on its own; to fix this, the rotor is first

turned by an external force (like another motor) in the same direction as the stator's rotating magnetic field. After a short time, the rotor "locks" with the magnetic field and starts spinning smoothly. This is called magnetic locking, and from then on, the motor runs on its own.

Direct-on-Line (DOL) Starter

A Direct-On-Line (DOL) starter is a simple way to start an electric motor. It works by connecting the motor directly to the power supply. This gives the motor full voltage right away, helping it start quickly with maximum torque (strong turning force).

Why use it?

1. It is great for small motors (less than 2 kW or about 2½ to 3 horsepower).
2. It is simple and cheap to install.
3. It, however, pulls a very high current when starting.

This can disturb other electrical devices connected to the same power source.

If the motor is powered by an isolated supply (like a stand-by generator), then even large motors (up to 100 kW) can use this method without causing problems.

Star-Delta Starter

A Star-Delta starter is used to start medium-sized motors in a way that reduces the starting current and avoids stressing the power supply.

How it works

The motor has six terminals connected to a special switch.

When starting, the motor windings are connected in a star shape. This reduces the voltage to each winding to about 58% of the full voltage.

Because of this, the motor starts with less current and less torque (about 33% of normal torque).

After the motor speeds up (almost full speed), the switch changes the connection to a delta shape. This gives the motor the full voltage so it can run at full power.

Best for: Medium-sized motors, Loads that are easy to accelerate, like fans or pumps

Auto-Transformer Starter

An Auto-Transformer Starter helps start motors smoothly by using a special transformer that controls the voltage.

How it works

It uses a variable auto-transformer with different voltage levels: 50%, 65%, and 80% of full voltage. The motor starts with reduced voltage, which means:

1. Lower current
2. Lower torque (starting force)

As the motor speeds up, the voltage is gradually increased by switching to higher taps. Once the motor reaches normal speed, the switch moves to the RUN position, giving the motor full voltage and cutting out the transformer.

Best for: motors that need a smooth start, situations where voltage control is important

Reversing Motor Rotation

In commercial and industrial settings, motors sometimes need to spin in the opposite direction. This is done by reversing any two of the three-phase power supply lines.

Works well for Heavy fans, Mixers, centrifugal machines, Motor-generator sets

Not suitable for starting motors under heavy load (because it does not provide enough torque)

AC Motor Speeds Explained

AC motors have three important types of speed:

Synchronous Speed (N_s)

This is the speed of the magnetic field inside the motor.

Formula:

$$N_s = \frac{120 \times f}{P}$$

Where:

N_s = Synchronous Speed (in RPM), f = Frequency of the AC supply (in Hertz) and P = Number of poles in the motor

Rotor Speed (N_r)

The rotor spins slightly slower than the synchronous speed due to slip.

Formula for slip:

$$\text{Slip, } s = \frac{N_s - N_r}{N_s}$$

Rearranging this formula to find the rotor speed: $N_r = N_s \times (1 - s)$

Rated Speed

This is the speed listed by the manufacturer. It is the motor's speed under full load and correct voltage/frequency.

Example

1. A 3 – phase induction motor runs at 1000 rev/min on no-load and 970r.p.m on full-load. Calculate the percentage slip at full-load.

Solution

$$\begin{aligned}
 \text{Percentage slip, } S &= \frac{N_s - N_r}{N_s} \times 100\% \\
 &= \frac{1000 - 970}{1000} \times 100 \\
 &= \frac{30}{1000} \times 100\% = 3\%
 \end{aligned}$$

2. A 3-phase induction motor is wound for 4 poles and is supplied from 50Hz System. Calculate the
 - a. Synchronous speed
 - b. rotor speed, when slip is 4%
 - c. Rotor frequency when rotor runs at 600rpm.

Solution

$$\begin{aligned}
 \text{a. Synchronous speed, } N_s &= \frac{120f}{P} \\
 &= \frac{120 \times 50}{4} \\
 &= 1500 \text{ rev/min (RPM)}
 \end{aligned}$$

$$\begin{aligned}
 \text{b. Rotor speed: } N_r &= N_s (1 - S) \\
 &= 1500 (1 - 0.04) = 1440 \text{ RPM}
 \end{aligned}$$

- c. The rotor frequency can be calculated using the formula: ω_m :
First, we need to calculate the slip at rotor speed of 600 rpm:

$$s = \frac{N_s - N_r}{N_s} = \frac{1500 - 600}{1500} = \frac{900}{1500} = 0.6 \text{ (or 60\% slip)}$$

Now, substituting in the formula for rotor frequency:

$$f_r = s \times f = 0.6 \times 50 = 30 \text{ Hz}$$

Applications of Synchronous Motors

Synchronous motors are unique because they run at a constant speed, exactly matching the frequency of the power supply. This makes them ideal for tasks where precision and stability are key. Common uses:

1. Power Factor Correction Systems

Synchronous motors can operate at leading power factor. They help improve the overall efficiency of electrical systems by reducing reactive power.

2. Precision Timing Devices

Used in synchronous clocks and other timing instruments. Their constant speed ensures accurate timekeeping.

3. Industrial Processes Requiring Constant Speed

Ideal for machines that must maintain a steady pace, such as: Conveyor belts, Rolling mills, and Textile machinery

4. Synchronous Generators in Power Plants

- a. Also known as alternators, they produce electricity at a fixed frequency.
- b. Widely used in hydroelectric, thermal, and nuclear power stations.

Activity 1.1.1 Exploring Single and Three-Phase Motors

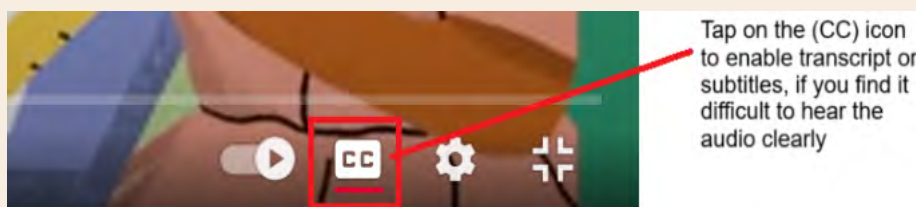
Scenario

As part of a youth innovation task force in your technical institute, your team will work with a nearby vocational centre to help improve small businesses in rural Ghana. You will research, explain, and demonstrate how single-phase and three-phase motors work, and show how they can be used in everyday businesses such as carpentry workshops, maize milling and water pumping.

Video Guide

Watch the simulation video on how a three-phase synchronous motor works:

Link: <https://share.google/sIFuUaZVbRjhzIx4J>



While watching, note down

1. how the rotating magnetic field is created in the stator.
2. the type of rotor shown
3. how the rotor speed is related to the speed of the magnetic field
4. what is meant by synchronous speed

Step 1 Single-Phase Induction Motor

1. Explain its construction (stator, rotor, starting winding, main winding, capacitor).
2. In small groups, use real components or a picture (**Figure 1.1.5**) to identify motor parts.
3. Explain at least one function of each part in **Figure 1.1.5**

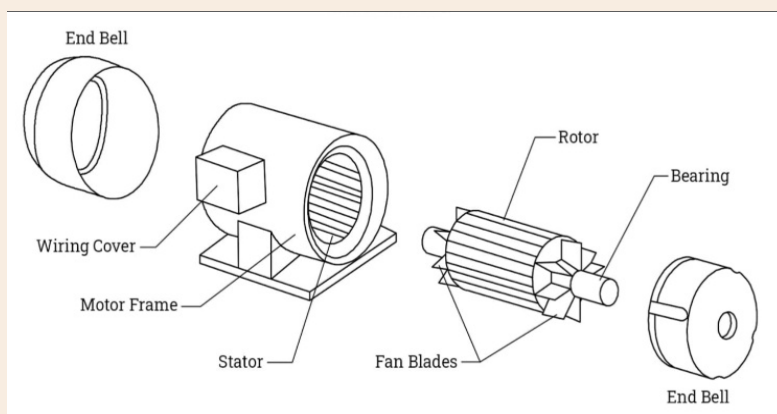


Figure 1.1.5: Main parts of a motor

Step 2 Wound Rotor Induction Motor

1. Describe how rotor windings and slip rings work.
2. Explain how varying rotor resistance changes speed and starting torque.
3. Show why it is used for variable speed control.
4. Research in groups using textbooks, notes or internet resources.
5. Draw a labelled diagram of the wound rotor motor.
6. Prepare a short explanation for presentation.

Step 3 Starting Methods for Three-Phase Motors

1. Research one assigned method (DOL, Star-Delta, or Auto-Transformer starter).
2. Complete the summary table below.

Summary Table

Starting Method	How it Works	Advantages	Disadvantages	Applications
Direct-On-Line				
Star-Delta				
Auto-Transformer				

Safety Tip

Before handling any motor, ensure it is disconnected from power. Use insulated tools and wear protective gear.

Step 4 Group Presentations

1. Use posters or flipcharts.
2. Include labelled diagrams.
3. Speak clearly and use analogies to help classmates understand.
4. After each presentation, other groups ask at least one question.

Step 5 Case Study Challenge

A maize milling workshop in a rural community needs a new motor. Given these conditions:

1. Power supply: 3-phase, 400 V
2. Need: High starting torque
3. Limited budget for maintenance

Recommend the motor type and starting method. Justify your answer.

Step 6 Application

1. Why might a single-phase motor be more suitable for a small carpentry workshop than a three-phase motor?
2. In which situation would a three-phase motor be preferred over a single-phase motor in your community?

Step 7 Reflection

In your notebook or tablet, write

1. What you learned about single-phase and three-phase motors.
2. One thing you found challenging and how you overcame it.
3. How you can apply this knowledge to solve a real-world community problem.

Extended Reading

1. Electrical 4U's guide on induction motors —Covers the basics, types, working principles, and self-starting characteristics of both single-phase and three-phase induction motors.
2. E-technophiles article on construction and working —Breaks down the motor's components like stator, rotor, and bearings, and explains how electromagnetic laws govern its operation.
3. Circuit Globe's explanation of electromagnetic induction — Focuses on how rotating magnetic fields interact with rotor conductors to produce torque.
4. Electrical Diary's overview — Offers definitions, classifications, and applications of induction motors in industrial and household settings.
5. Electrical Easy's beginner-friendly breakdown — Explains slip, synchronous speed, and why induction motors are called asynchronous motors.

REVIEW QUESTIONS

1. What is a motor?
2. Name the two main parts of an induction motor.
3. What type of current does an AC motor run on?
4. Explain why a single-phase induction motor needs a capacitor or inductor in its starting winding.
5. Describe how the rotor in a three-phase squirrel cage motor starts to turn.
6. Compare and contrast the construction and operation of the single-phase induction motor and the three-phase squirrel cage motor.
7. Analyse why a star-delta starter is preferred over a Direct-On-Line starter for medium-sized motors.

UNIT 2: AC, DC MOTORS AND AC, DC GENERATORS

INTRODUCTION

In Year 2, you learned that a current-carrying conductor placed in a magnetic field experiences a force, expressed as $F=BIL$ where F is force, B is magnetic field strength, I is current, and L is conductor length. This principle explains how DC motors work. A DC motor converts electrical energy into mechanical rotation by using the force on current-carrying conductors within a magnetic field. This force causes the motor's armature to rotate and perform useful work. In this unit, you will study the main parts of a DC motor such as the armature, commutator, brushes, and field windings and how they operate together. You will also learn about the types of DC motors (series, shunt, and compound), their starting methods, characteristics, and common applications in industries and everyday life. By the end, you will understand how DC motors operate and where they are used.

KEY IDEAS

- The rotating part of the DC motor that carries the armature windings. When current flows through these windings, they create a magnetic field that interacts with the stator's magnetic field to produce torque, causing the motor shaft to rotate.
- The commutator is a segmented copper ring connected to the armature windings, converting the induced alternating voltage into direct current to keep torque production steady. Brushes, usually made of carbon or graphite, press against the commutator to supply current from the power source to the rotating armature.
- The field system is composed of the yoke, stator, pole cores, pole shoes, interpoles, and field windings. It generates the magnetic flux needed for motor operation. Interpoles help reduce sparking and maintain smooth torque and performance by counteracting magnetic distortions.
- The operation principle is that, when DC voltage is supplied to the armature through brushes and commutator, current flows through armature windings, producing a magnetic field. This field interacts with the flux from the stator's field windings, generating a force that produces torque, turning the motor shaft.
- There are three main types of DC motors:
 - o Series Motor: Field winding connected in series with armature; provides high starting torque, speed varies widely with load.
 - o Shunt Motor: Field winding connected in parallel with armature; provides nearly constant speed and torque proportional to load.
 - o Compound Motor: Combines series and shunt windings for both good starting torque

and stable speed under varying loads.

- DC motors are widely used across industries due to their torque and speed control characteristics. Examples include cranes (series motors for high torque), conveyor belts (shunt motors for constant speed), electric vehicles, home appliances, medical equipment, and robotics.

DC MOTORS

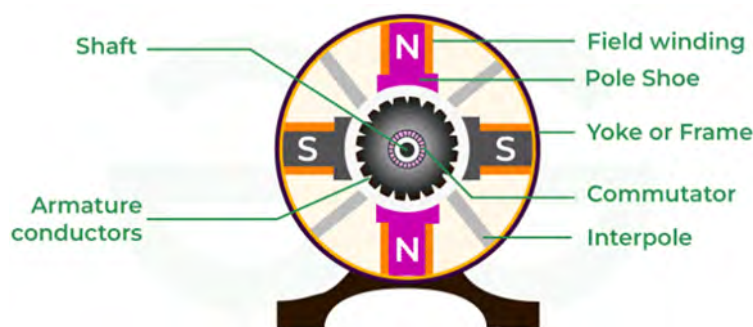


Figure 1.2.1: Diagram of a DC motor

Parts of a DC motor

The main parts of a DC motor are as follows:

1. Yoke

It protects the entire machine and carries the field windings that produce the flux during its operation. It also provides structural support and houses the magnetic poles and field windings. The field System that produces the flux includes the following parts:

- Stator: The stationary part that creates a magnetic field using field windings.
- Pole cores, Pole shoes: They hold the field windings that generate magnetic flux.
- Interpoles: They are placed between the main poles on the motor's yoke. Their polarity matches the main pole ahead of them in the direction of rotation (for motors). This reduces sparking and ensures smoother operation. Interpoles counteract distortion and help in maintaining consistent torque and performance.
- Field windings: The coils wrapped around the poles to produce a magnetic field when energised

2. Armature

The rotating part that interacts with the magnetic field of the stator to produce motion. Armature windings are coils on the armature that carry current and produce a magnetic field to interact with the magnetic field of the stator to produce torque.

3. **Commutator**

Its function is to rectify the alternating voltage induced in the armature conductors.

4. **Brushes**

They are mounted on an extension of the armature. The brushes are invariably made of carbon or graphite and housed in a brush holder. They transfer current from the power source to the rotating commutator.

5. **Shaft**

Transfers mechanical energy from the armature to the external load.

6. **Bearings**

Support the armature and reduce friction during rotation.

Operation

1. DC voltage is fed from an external source through the brushes into the conductors of the armature. This causes current to flow through the armature windings.
2. The current creates a magnetic field that interacts with the magnetic field produced by the field windings in the stator.
3. As a result, each conductor carrying current and placed in the magnetic field produced by the coil windings experiences a force.
4. The force of interaction causes the armature to turn or produce a torque.
5. The torque is transferred to the shaft of the armature and utilised to drive a mechanical load.

Types of DC Motors

There are three types of direct current motors, namely,

1. Series
2. Shunt
3. Compound motor

Series Motor

In the series motor, the field winding of the motor is connected in series with the armature. The series field resistance is small because of the small number of turns and also due to the much larger cross-section of the conductor in the series field. The field excitation is obtained by passing the armature current through the field winding, and the flux varies with the motor current. Because the field winding is in series with the armature, the magnetic field flux is directly proportional to the armature current. At startup, the armature current is at its highest, which means flux is also at its highest, producing very high starting torque. As the motor speeds up, back EMF increases, current drops, and torque decreases, making the series motor ideal for heavy starting loads such as cranes and traction systems.

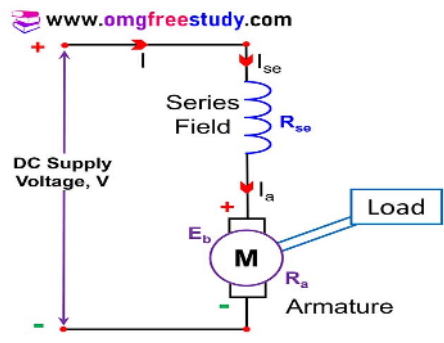


Figure 1.2.2: Circuit diagram of a Series DC motor

The equations deduced from the circuit are as follows:

1. $I_f = I_a = I_L = I$
2. $V = E_b + I_a(R_a + R_f)$

Example

1. A 400V d. c. series motor takes 100A from the supply when running at 750 rpm. The series field resistance is 0.15Ω , and armature winding resistance is 0.25Ω . Calculate the
 - a. generated e.m.f.
 - b. input power

Solution

- a. Generated e.m.f., $E_b = V - I_a(R_a + R_f)$

$$= 400 - 100(0.25 + 0.15)$$

$$= 400 - 40$$

$$= 360 \text{ V}$$
- b. Input Power, $P_i = VI$

$$= 400 \times 100$$

$$= 40,000 \text{ W}$$

Shunt DC Motor

In a shunt wound motor, the field winding is connected across the armature. A constant field current supplied at a constant voltage, results in a constant flux such that torque is proportional to armature current.

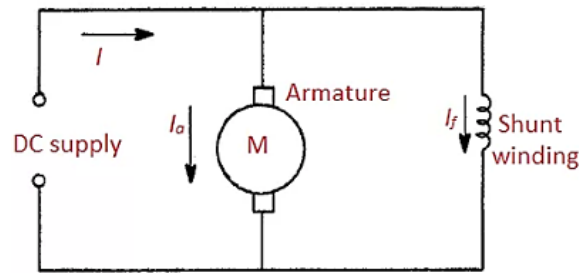


Figure 1.2.3: Circuit diagram of a Shunt DC motor

The current equation is $I_L - I_a - I_f = 0$, where $I = I_L$

The supply voltage is $V = E_b + I_a R_a$

Voltage across the exciting (shunt) windings, $V = I_f R_f$

Example

1. A 440V, shunt motor has armature resistance of 0.8Ω and the field resistance of 200Ω . When the motor is delivering an output of 7.46 KW at 85% efficiency. Determine the:
 - a. input power
 - b. load current,
 - c. armature current,
 - d. back e.m.f

Solution

$$a. \quad \text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}} \times 100\%$$

$$\begin{aligned} \text{Power input} &= \frac{\text{Power Output}}{\text{efficiency}} \\ &= \frac{7.46 \times 1000}{0.85} \\ &= 8776.5 \text{ W} \end{aligned}$$

$$b. \quad \text{Power input, } P_{in} = VI_L$$

$$\begin{aligned} I_L &= \frac{P_{in}}{V} \\ &= \frac{8776.5}{440} \\ &= 19.95 \text{ A} \end{aligned}$$

$$c. \quad \text{Potential difference across shunt field windings, } V_f = I_f R_f$$

$$I_f = \frac{V}{R_f} = \frac{440}{200} = 2.2 \text{ A}$$

$$\begin{aligned} \Rightarrow \text{Armature current, } I_a &= I_L - I_f \\ &= 19.95 - 2.2 \\ &= 17.75 \text{ A} \end{aligned}$$

$$\begin{aligned}
 \text{d. Generated (back) e.m.f., } E_b &= V - I_a R_a \\
 &= 440 - (17.75 \times 0.8) \\
 &= 440 - 14.2 \\
 &= 425.8 \text{ V}
 \end{aligned}$$

The Compound D. C. Motor

In the compound motor, the main field coil is connected in parallel to the commutator winding, and the other one is connected in series with the commutator winding. The shunt winding produces the main magnetic flux; it has a large number of turns made of small cross-sectional area of conductors, a high resistance and allows a small quantity of current to flow through it.

The series windings carry a large armature current, I_a and have a large cross-section of conductors made of a few turns and a small resistance so as not to reduce the emf of rotation. The series winding flux is designed to strengthen the main flux produced by the shunt winding. This arrangement is called cumulative compounding. If the series flux is reversed and weakens the main field, this arrangement is called differential compounding.

Because the compound motor combines both shunt and series windings, it inherits the benefits of both types. The shunt winding maintains a relatively stable base flux, providing consistent speed under varying loads, while the series winding boosts flux at startup when armature current is high, producing strong starting torque. This makes the cumulative compound motor well suited to applications that require both good starting torque and reasonably stable running speed, such as lifts, presses, and rolling mills.

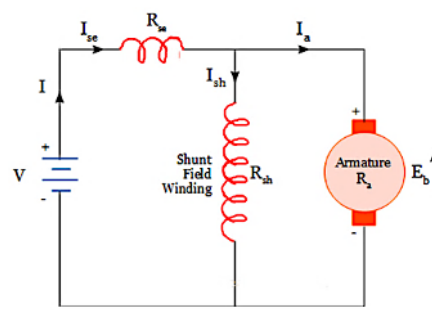


Figure 1.2.4: Diagram of a Compound DC motor

Example

1. A short shunt compound wound DC machine is connected to a 400 V DC supply and runs as a motor taking a current of 40 A. The particulars of the machine are as follows:

Armature resistance 0.21

Series field resistance 0.3 Ω

Shunt field resistance, 194 Ω

Speed of rotation 20 rev/sec.

Calculate

- a. shunt field current

- b. armature current
- c. Induced emf
- d. torque developed.

Solution

- a. Potential difference across the series series windings, $V_{se} = I_L R_{se}$
 $\Rightarrow 40 \times 0.3 = 12 \text{ V}$

Potential difference across the shunt winding $V_{sh} = V - I_L R_{se}$

$$\Rightarrow V_{sh} = 400 - 12 = 388 \text{ V}$$

Shunt field current $I_{sh} = \frac{V_{sh}}{R_{sh}} \Rightarrow \frac{388}{194} = 2 \text{ A}$

- b. $I_a = I_L - I_f \Rightarrow 40 - 2 = 38 \text{ A}$
 Voltage drop across armature $= I_a R_a = 38 \times 0.21 = 8 \text{ V}$
- c. Induced $emf E_b = V - I_a R_a \Rightarrow 400 - 8 = 380 \text{ V}$
- d. Torque, $T_a \omega = E_b I_a$

$$T_a = \frac{E_b I_a}{\omega} = \frac{E_b I_a}{\frac{2\pi N}{60}}$$

$$= \frac{380 \times 38}{2 \times 3.142 \times 20}$$

$$T_a = \frac{14,440}{125.68} = 114.9 \text{ Nm}$$

Characteristics of DC Motors

The characteristics of a DC motor show the behaviour of the motor under different load conditions. The performance of a DC motor is determined by the relation among the armature, torque and speed. These relations are depicted in the form of curves and are referred to as characteristics of DC motors.

Series Motor Characteristics

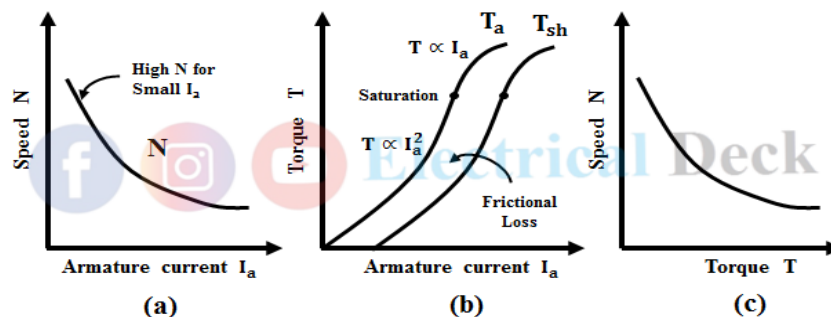


Figure 1.2.5: (a) Speed-armature current (b) Torque –Armature current (c) Speed-torque characteristics

It can be observed in **Figure 1.2.5**, in the speed-armature current characteristic (a), that the speed is inversely proportional to the flux and armature current. At very low values of

armature current (I_a), the speed becomes very high. The speed is low on heavy loads and dangerously high on light loads. For this reason, it is never run without some mechanical load on it. The series motor is essentially a variable-speed motor.

The torque-armature current characteristic in **Figure 1.2.5 (b)** depicts that the series motor has a high starting torque T , and the torque is proportional to the flux and armature current.

Shunt motor Characteristics

In a shunt motor, a constant field current supplied at a constant voltage results in a constant flux such that torque is proportional to armature current. The graph of speed-armature current is shown in **Figure 1.2.6**.

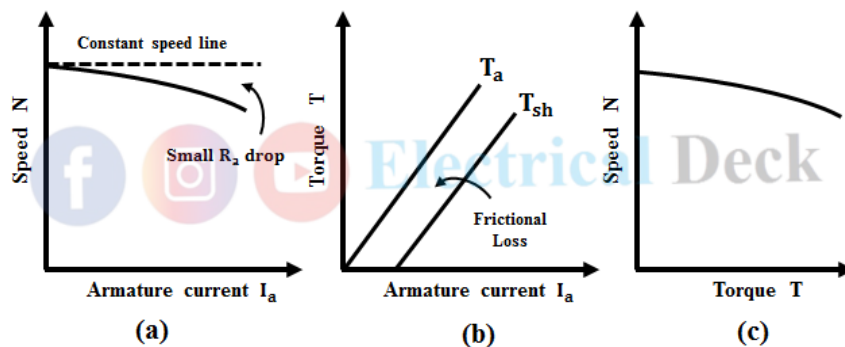


Figure 1.2.6: (a) Speed-armature current (b) Torque-Armature current (c) Speed-Torque characteristics

In the Speed-armature current characteristic, speed drops gently with an increase in torque, and if the load is extremely large, the armature current will drop practically to zero. Speed at no-load or light -load is fairly constant.

In the Torque-Armature current characteristics, T_a = Gross torque where T & I_a and T_{sh} = Net torque

Compound Motor

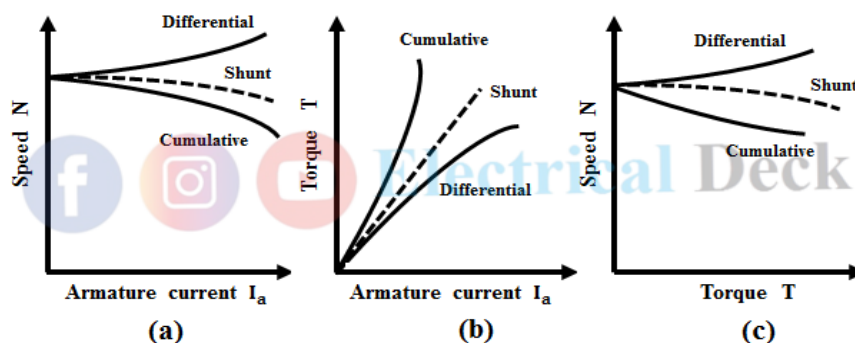


Figure 1.2.7: Speed-Armature Current Characteristics

The speed and armature current characteristics of DC cumulative and differential compound wound motors are shown in **Figure 1.2.7(a)**. Since the resultant flux is more in the cumulative

compound motor with respect to load, the curve will be slightly more dropping compared to the shunt motor.

Torque-Armature Current

If the load on the cumulative compound motor increases, the torque developed also increases. But the torque decreases with an increase in load in the case of a differential compound motor as shown in **Figure 1.2.7(b)**.

Speed-Torque Characteristics

When there is a sudden application of heavy loads, the speed decreases, and the cumulative compound motors can develop a large torque similar to series motors. At no-load, they run at a definite speed due to shunt field flux, unlike a series motor attain dangerous speeds. The speed remains almost constant in differential compound motors with increases in load. Hence, shunt motors are more preferred compared to differential compound motors and are rarely used

Types of Excitations in DC Motors

1. Separate Excitation

- The field winding is powered by an independent external source.
- This setup allows precise control over field current, making it popular in industrial applications where speed and torque need fine-tuning.

2. Self-Excitation

The field winding is connected to the armature either directly or through a combination. Includes **shunt**, **series**, and **compound** motors.

- Shunt: Field winding is parallel to the armature.
- Series: Field winding is in series with the armature.
- Compound: Combines series and shunt features for a balanced performance.

The EMF Equation of a DC Motor

The induced/generated/back emf in a DC motor is determined by finding,

- the average emf per conductor,
- multiplying induced emf by the effective number of conductors acting in series between positive and negative brushes.

Emf generated per conductor

× total number of conductors connected in series per parallel path.

$$\text{Generated emf of a d.c motor, } E_b = \frac{P\Phi N}{60} \times \frac{Z}{A}$$

where P = number of poles, Φ = flux,

N = number of revolutions, $\frac{N}{60}$ = number of revolutions per second,

Total number of conductors connected in series per parallel path = $\frac{Z}{A}$

where $A = 2$ for wave winding

Torque equation of a DC motor

1. All conductors of the armature winding lie in the magnetic field of the air gap.
2. Each conductor experiences a force.
3. The resulting torque is exerted around the circumference of the armature.
4. As a motor, the torque is imparted to the mechanical load.
5. If speed is constant, the mechanical load is equal to the electrical torque developed.

Torque is deduced from $E_b I_a = T\omega$, where angular velocity, $\omega = \frac{2\pi N}{60} \text{ rev/sec}$.

$$\text{Torque on armature, } T_a = 0.159 P\Phi Z \frac{I_a}{A} \text{ Nm}$$

$$\text{Where Armature torque} = T_a \text{ and } \frac{1}{2\pi} = 0.159$$

The torque is directly proportional to the total flux per pole and the armature current.

Speed of a DC Motor

The expression for the speed of a DC motor is given as;

$$N = \frac{(60 A)}{PZ} \frac{E_b}{\Phi}, \text{ where } E_b = V - I_a R_a$$

$$\text{Let } \frac{60 A}{PZ} = k$$

$$\text{Then speed, } N = k \frac{E_b}{\Phi}$$

Where A, Z and P maintain their usual meaning.

The speed of a d.c. motor is proportional to the back emf and inversely proportional to the flux per pole

Example

1. A 4-pole, 250 V, DC series motor has a wave-connected armature with 200 conductors. The flux per pole is 25 mWb when the motor is drawing 60 A from the supply. Armature resistance is 0.15 Ω while the series field resistance is 0.2 Ω . Calculate the
 - a. induced emf
 - b. speed,
 - c. torque of the

Solution

$$\begin{aligned} \text{a. Generated/induced emf of a d.c motor, } E_b &= \frac{P\Phi N}{60} \times \frac{Z}{A} \\ E_b &= V - I_a(R_a + R_{se}) \\ E_b &= 250 - 60(0.15 + 0.2) \\ &= 250 - 21 \\ &= 229 \text{ V} \end{aligned}$$

- b. Speed, N is obtained from $E_b = \frac{P\Phi ZN}{60 A}$
- $$E_b \times 60 A = P\Phi ZN$$
- $$N = \frac{E_b}{P\Phi Z} \times 60$$
- $$\text{Speed, } N = \frac{229 \times 60 \times 2}{4 \times 0.025 \times 200} = \frac{27480}{20}$$
- $$N = 1,374 \text{ rev/min}$$
- c. Armature torque, $T_a = 0.159 P\Phi Z \frac{I_a}{A}$
- $$T_a = 0.159 \times 4 \times 0.025 \times 200 \times \frac{60}{2}$$
- $$T_a = 95.4 \text{ Nm}$$

Applications

Industrial Applications

1. Cranes and Hoists: Series DC motors provide high starting torque, ideal for lifting heavy loads.
2. Conveyor Belts: Shunt DC motors maintain constant speed, perfect for material handling systems.
3. Rolling Mills and Presses: Compound DC motors offer both torque and speed stability under varying loads.

Automotive Sector

1. Electric Vehicles (EVs): DC motors are used for propulsion due to their torque characteristics and ease of control.
2. Power Windows and Seats: Small permanent magnet DC motors provide precise movement.
3. Windshield Wipers and Fans: Compact and efficient, they are ideal for intermittent operation.

Home and Office Equipment

1. Printers and Scanners: Brushless DC motors offer quiet, precise control for moving components.
2. Fans and Blowers: Shunt motors deliver consistent airflow.
3. Electric Shavers **and** Toys: PMDC motors are compact and cost-effective.

Medical and Laboratory Equipment

1. Centrifuges: Require constant speed and torque, often powered by shunt DC motors.
2. Surgical Tools: Brushless DC motors provide smooth, reliable operation with minimal maintenance.

Computer Peripherals

Hard Drives and CD/DVD Drives: Use brushless DC motors for high-speed rotation and precision.

Aerospace and Robotics

Actuators and Positioning Systems: DC motors allow fine control over movement, essential for robotic arms and aircraft control surfaces.

Activity 1.2.1 DC Motors – Principles, Operation and Applications

Scenario

As part of an engineering team designing battery-powered devices for rural electrification in Ghana, your focus is on using DC motors to power tools and equipment in off-grid communities. You will research how DC motors work, test different types, and choose designs suitable for devices like water pumps, grain grinders, and sewing machines. The goal is to make these motors efficient, affordable, and durable for everyday use in rural areas.

Task

Explore how DC motors work, understand their parts and operation, and identify where they are used in everyday life and industries.

Materials needed

1. Small DC motor parts or diagrams
2. Worksheet with questions
3. Internet devices (if available)
4. Large paper, markers, pens
5. Devices using DC motors e.g. toys, etc.
6. Notebooks, pens/pencils

Step 1: Class Brainstorm

Think about what a motor is and where you have seen one. Discuss with your classmates:

1. What is a DC motor?
2. How do you think it works?
3. Where do you see DC motors being used?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 people.
2. Each group member takes a role: Researcher, Note-taker, Presenter or Artist.
3. Use books, internet, and other resources to complete the table below:

S/N	Main Part of a DC Motor	Description	Function	Why is it important?
1				
2				

4. Use these guiding questions

- What does each part do?
- How does the commutator help the motor run?
- Why are brushes important?
- How do the parts work together to make the motor spin?
- Can you name a device that uses this kind of motor? Why?

Step 3: Create Your Model and Poster

Make a poster or simple sketch showing:

- The main parts and what they do
- How the motor works in simple words

Step 4: Present Your Work

- Present your diagram and poster to the class.
- Explain:
 - what a DC motor is
 - how it works (using magnetic fields and current)
 - where DC motors are used in daily life and industries

Step 5: Ask and Answer Questions

- Listen carefully to questions from your classmates.
- Answer clearly to help others understand.
- Give helpful feedback on others' presentations, especially about their diagrams and applications.

Step 6: Reflect and Write

Answer these questions in your notebook:

- What did you learn about how DC motors are built and how they work?
- Which use of a DC motor surprised or inspired me the most? Why?
- How can you explain the importance of DC motors to someone else?

EXTENDED READING

1. [TutorialsPoint's detailed breakdown](#) — Offers a comprehensive guide to DC motor components like yoke, armature, commutator, and brushes, along with the physics behind torque generation and Fleming's Left-Hand Rule.
2. [Electrical4U's working principle article](#) — Explains how magnetic fields and current interact to produce motion, with step-by-step torque analysis and force equations.
3. [Etechnophiles' illustrated explanation](#) — Covers construction, working principle, and back EMF with clear diagrams and practical examples like elevators and rolling mills.
4. [Bright Hub Engineering's focus on DC series motors](#) — Dives into the specifics of series motor construction, torque behaviour, and speed control techniques.
5. [GeeksforGeeks overview](#) — Includes diagrams, formulas for torque and EMF, and comparisons between DC and AC motors, ideal for academic or exam prep.

REVIEW QUESTION

1. Name three main parts of a DC motor.
2. What is the function of brushes in a DC motor?
3. What type of field winding connection does a series DC motor have?
4. Explain the role of the commutator in a DC motor.
5. Why do interpoles reduce sparking in a DC motor?
6. Using the given formula, calculate the generated emf if the supply voltage is 400 V, armature current is 100 A, armature resistance is $0.25\ \Omega$, and series field resistance is $0.15\ \Omega$.
7. Discuss how the back emf in a DC motor influences its speed regulation.

UNIT 3 AC, DC MOTORS AND AC, DC GENERATORS

INTRODUCTION

In Year 2, you studied Faraday's Law of electromagnetic induction, which shows how moving a conductor in a magnetic field produces an electromotive force (emf). This principle explains how AC generators work. AC generators convert mechanical energy into electrical energy by rotating coils inside a magnetic field. A prime mover, such as a diesel engine or turbine, usually powers the rotation. As the coil moves through the magnetic field, voltage is induced, generating alternating current (AC). A single-phase generator produces one sinusoidal AC waveform. In contrast, a three-phase generator produces three waveforms, each 120° apart, resulting in smoother and more efficient power delivery. This makes three-phase power suitable for industrial use. In this unit, you will learn about the generation of sinusoidal waves in single-phase generators, the rotating magnetic field in three-phase generators, their main components, and how they operate.

KEY IDEAS

- The process of generating a sinusoidal voltage waveform involves a single-phase generator creating a smooth alternating voltage that oscillates in a sinusoidal pattern, facilitating effective energy transmission.
- A single-phase AC generator functions by rotating a coil within a magnetic field, inducing an electromotive force (EMF), and is typically employed for providing household electricity and in portable generators.
- Three-phase generators operate by utilising three coils arranged 120° apart to produce three alternating voltages, primarily used in industrial power systems to optimise energy distribution.
- A single-phase AC generator is constructed with essential components like a rotor and stator, designed to efficiently generate alternating current through the principle of electromagnetic induction.
- The three-phase AC generator features multiple coils along with critical structural components, enabling it to generate three alternating voltages that are phase-shifted, thus improving power delivery in industrial settings.

SINGLE-PHASE AC GENERATOR

A single-phase AC generator is also known as **alternator**. It converts mechanical energy into electrical energy using electromagnetic induction. The output is single-phase, meaning it has one sinusoidal voltage waveform. Single-phase generator is used in residential power backup, small appliances, and as portable a generator.

Construction

Parts of the single-phase generator are as follows:

Parts	Function
Yoke (Frame)	The outer casing that supports and protects the internal components.
Magnetic field(poles)	Provides the magnetic flux, either by means of permanent or electromagnet.
Armature	The rotating coil where emf is induced, it is mounted on the rotor
Slip rings	Conductive rings attached to the armature to transfer AC to the external circuit.
Brushes	Carbon rings that press against the slip rings to carry current out.
Prime-Mover	The external mechanical source that drives the rotor.

Operation of the Single-Phase AC Generator

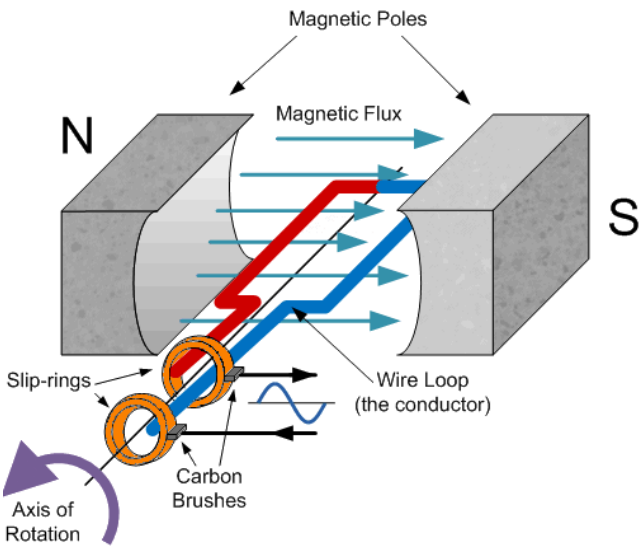


Figure 1.3.1: Diagram of a single-phase AC generator

1. **Magnetic Field Setup:** The generator has stationary magnetic poles (or a rotating magnetic field) that create a magnetic flux across the armature.
2. **Armature Rotation:** A rectangular coil (armature) is rotated by a prime mover (like a turbine or engine) within this magnetic field.

3. **Flux Cutting:** As the coil rotates, its conductors cut through magnetic lines of force, inducing an alternating EMF in the coil according to Faraday's Law.
4. **Current Collection:** The ends of the coil are connected to slip rings, which rotate with the armature.
5. **Carbon brushes:** press against the slip rings to transfer the generated AC to the external circuit.

The frequency of the AC output depends on the speed of rotation and the number of magnetic poles.

Cycle of A.C Waveform Generation

1. At **0° rotation**, the coil is parallel to the magnetic field $\Rightarrow$ **no EMF**.
2. At **90°**, the coil cuts through the field most effectively $\Rightarrow$ **maximum EMF**.
3. At **180°**, the coil is again parallel $\Rightarrow$ **zero EMF**.
4. At **270°**, maximum EMF is induced but in the opposite direction.
5. At **360°**, the conductors have returned to their starting point, $\Rightarrow$ no voltage induced. The coil has completed one revolution and produced a sinusoidal wave voltage.
6. This completes one full sine wave cycle of alternating current, as shown in **Figure 1.3.2**.

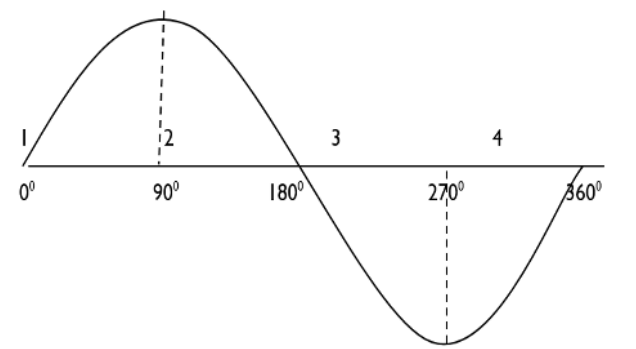


Figure 1.3.2: Single-phase sinusoidal voltage waveform

A cycle of alternating emf is generated as the armature passes through a set of north and south poles. The general equation of frequency is:

$$\text{Frequency, } f = \frac{\text{Number of poles}}{2} \times \frac{\text{Speed in rev/min}}{60}$$

$$f = \frac{P}{2} \times \frac{N}{60}$$

Relationship of Speed, Number of Poles and Frequency

Many sets of poles produce slower rotation, and engine-driven alternators are of the slow-speed type. The number of poles is much greater than that of turbo-generators, which run at very high speeds. For producing a frequency of 50Hz, the alternator will have to run at the following speeds in **Table 1.3.2** below.

Table 1.3.2: Relationship of speed and number of poles of alternators

Number of poles	2	4	6	12	24	36
Speed rev/min	3000	1500	1000	500	250	166

Example

1. A coil of 100 turns is rotated at 1500 rev/min in a magnetic field having a uniform density of 0.05T, the axis of rotation being at right angles to the direction of the flux. The area per unit turn is 4000mm², calculate the;
 - a. frequency
 - b. period
 - c. maximum value of the generated emf
 - d. value of the generated emf when the coil has rotated through 30° from the position of zero emf.

Solution

- a. *a. Frequency, $f = \frac{Nrev/min}{60} = \frac{1500}{60} = 25 \text{ rev/sec or } 25 \text{ Hz}$*
- b. *b. Period, $T = \frac{1}{f} = \frac{1}{25} = 0.04 \text{ s}$*
- c. *Maximum value of generated emf,*
 $E_{max} = N\Phi\omega \Rightarrow 2\pi f\Phi N \text{ volts}$
 $E_{max} = 2\pi fBAN \text{ volts (where } \Phi = BA)$
 $= 2 \times 3.14 \times 25 \times 0.05 \times 4000 \times 10^{-6} \times 100 = 3.14$
- d. *Emf at 30° = $N\Phi\omega \times \sin 30^\circ = 3.14 \times 0.5 = 1.57 \text{ V}$*

Three – Phase AC Generator

Construction

Component Parts of the three-phase AC generator are as follows:

Component	Function
Prime-Mover	The external mechanical source that drives the rotor (engine, turbine)
Stator	Stationary part with three sets of windings placed 120° and generates AC (the rotating magnetic field)
Rotor	Rotating magnetic field (an electromagnet or permanent magnet) driven by the prime-mover
Excitation system	Supplies DC to the rotor windings to create magnetic field
Voltage regulator	Maintains consistent output by adjusting excitation.
Bearings and shaft	Support rotor rotation and transfer mechanical energy
Cooling System	Prevents overheating during operation

Operation

A three-phase AC generator also known as an alternator is a power house of modern electrical systems. It converts mechanical energy into electrical energy using Faraday's law of electromagnetic induction.

In its design:

1. the stator windings are spaced 120° apart.
2. the rotor is turned by a prime-mover, and rotor's rotating magnetic field cuts across the stator windings.
3. electromotive force (EMF) is induced in each stator winding.
4. each voltage is **120° out of phase**, forming a balanced three-phase output.
5. the **voltage regulator** ensures stable output by controlling the excitation current.

The three-phase system:

1. delivers continuous power with minimal fluctuation.
2. is more efficient than single-phase systems.
3. is ideal for industrial loads, motors, and power transmission.

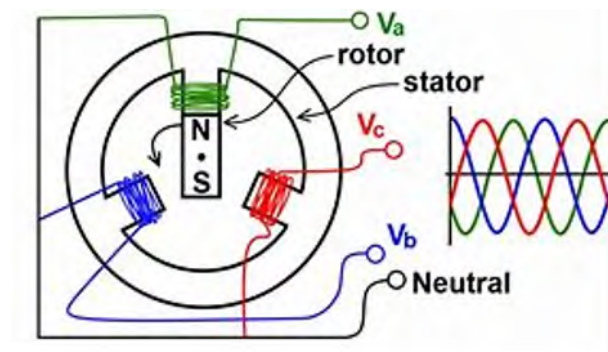


Figure 1.3.3: Three-phase AC generator (3 coils)

Output Characteristics

Three-phase voltage: Each phase reaches its peak at different times, ensuring smooth and continuous power.

Waveform: The output is sinusoidal and staggered, which improves efficiency and reduces vibration in motors.

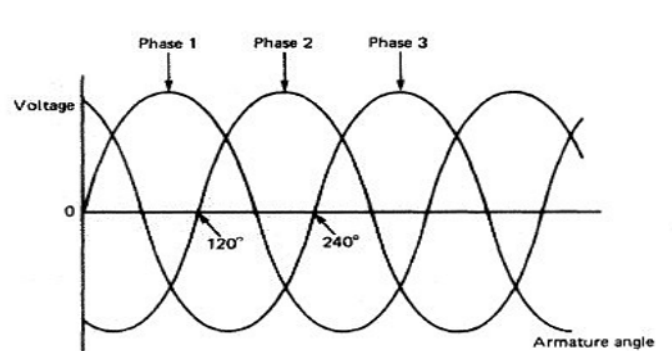


Figure 1.3.4: Output waveform of the three-phase AC generator

Example

1. A 12-pole -3- phase alternator driven at a speed of 500 rpm supplies power to an 8-pole 3-phase induction motor. If the slip of the motor, at full load is 3%, calculate the
 - a. frequency of alternator
 - b. synchronous speed of the motor
 - c. full-load (rotor speed) of the motor.

Solution

a. Synchronous speed of alternator, $N_s = \frac{60f}{P} \Rightarrow f = \frac{N_s P}{60}$

$$= \frac{500 \times 6}{60}$$

$$= \frac{3000}{60} = 50\text{Hz}$$

b. Synchronous speed of induction motor, $N_s = \frac{60f}{P}$

$$= \frac{60 \times 50}{4}$$

$$= \frac{3000}{2}$$

$$= 750 \text{ rev/min}$$

c. Percentage slip, $S = \frac{N_s - N_r}{N_s} \times 100\%$

$$\frac{3}{100} = \frac{N_s - N_r}{N_s}$$

$$3N_s = N_s - N_r \times 100$$

$$\frac{3N_s}{100} = N_s - N_r$$

$$N_r = N_s - \frac{3N_s}{100}$$

$$= 750 - \frac{3 \times 750}{100}$$

$$N_r = 750 - 22.5$$

Full load (rotor speed) of the motor $N_r = 727.5 \text{ rev/min}$

Phase Voltage and Line Voltage

The relation between the line voltage and phase voltage is $V_L = \sqrt{3}V_{ph}$

The voltage across each of the stator windings is the phase voltage, given by $V_{ph} = \frac{V_L}{\sqrt{3}}$

The voltage relation for the delta configuration is $V_L = V_{ph}$

where $V_L = \text{Line voltage} = 415 \text{ V}$ and $V_{ph} = \text{phase voltage} = 240 \text{ V}$ (in Ghana).

EMF Equation of the Alternator

The EMF equation of an AC generator is given by: $E = \frac{4.44 \cdot f \cdot \Phi \cdot P}{60}$

Where:

E = Induced EMF (volts)

P = Number of poles

Φ = Magnetic flux per pole (Weber)

f = Frequency of the induced EMF (Hertz)

Alternatively, the equation can be expressed in terms of conductors as: $E = \frac{Z \cdot \Phi \cdot N \cdot f}{60}$

Where:

Z = Number of conductors or coil sides in series per phase, with $Z = 2T$ (where **T** is the number of turns per phase)

N = Rotor speed (RPM)

Average emf per conductor, $E_{avg} = \frac{P\Phi N}{60} = \frac{P\Phi}{60} \times \frac{120f}{P} = 2f\Phi$ volts

where $f = \frac{PN}{120}$; making $N = \frac{120f}{P}$

Z = number of conductors per phase

Emf per phase = $2f\Phi \times Z = 2f\Phi Z$

T = Number of coils or turns per phase (where, one turn, has 2 sides) = $2T$

The emf equation per phase = $2f\Phi Z \times 2T = 4f\Phi T$

If the induced EMF is sinusoidal, form factor, $k_f = \frac{\text{Rms value}}{\text{average value}} = \frac{0.707}{0.637} = 1.11$

Also, from form factor, $k_f = \frac{\text{Rms value}}{\text{Average value}}$
 $\Rightarrow \text{Rms value} = \text{Form factor} \times \text{Average value}$

$\therefore$ Rms voltage per phase, $V_{rms} = 1.11 \times 4f\Phi T$ volts
 $V_{rms} = 4.44f\Phi T$ volts

Introducing coil span factor k_c , and distribution factor k_d

The actual rms voltage V_{rms} induced per phase, $V_{rms}/ph = 4.44k_c k_d f\Phi T$ volts

If the alternator is star-connected, the line voltage $V_L = \sqrt{3} \times V_{ph}$

Example

1. A 3-phase, 16 pole-alternator, has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole of 0.03 Wb, is sinusoidally distributed and the speed is 375 r.p.m.
 - a. frequency
 - b. emf per phase
 - c. Line emf

Take coil span factor $k_c = 1$ and distribution factor $k_d = 0.96$

Solution

a. Frequency, $f = \frac{PN}{120} = \frac{16 \times 375}{120} = 50 \text{ Hz}$

b. Number of conductors per phase, $Z = \frac{144 \times 10}{3} = 480$
 $T = \frac{Z}{2} = \frac{480}{2} = 240 \text{ per phase}$

$$V_{rms}/ph = 4.44 k_c k_d f \Phi T \text{ volts}$$

$$V_{ph} = 4.44 \times 1 \times 0.96 \times 50 \times 0.03 \times 240 = 1,534.46 \text{ volts}$$

c. Line voltage, $V_L = \sqrt{3} \times V_{ph} = \sqrt{3} \times 1534.46 = 2,557.69 \text{ V}$

2. A 4-pole, 3-phase, star-connected alternator armature has 12 slots with 24 conductors per slot and flux per pole 0.1 Wb sinusoidally distributed. Calculate the line emf generated at 50 Hz. Take coil span factor, $k_c = 1$ and distribution factor $k_d = 0.96$

Solution

Number of conductors per phase, $Z = \frac{12 \times 24}{3} = \frac{288}{3} = 96$

$$T = \frac{Z}{2} = \frac{96}{2} = 48 \text{ per phase}$$

$$V_{rms}/ph = 4.44 k_c k_d f \Phi T \text{ volts}$$

$$V_{ph} = 4.44 \times 1 \times 0.96 \times 50 \times 0.01 \times 48 = 1,022.98 \text{ volts}$$

Line voltage, $V_L = \sqrt{3} \times V_{ph} = \sqrt{3} \times 1022.98 = 1,771.80 \text{ V}$

Advantages of Alternators

1. **Efficient Energy Conversion:** Alternators are more efficient than DC generators because they only use the energy needed and conserve the rest.
2. **Lightweight & Compact:** Their design is generally more compact and lighter than traditional generators, making them ideal for automotive and portable applications.
3. **Low Maintenance:** With a stationary armature and fewer moving parts, alternators experience less wear and tear—especially in brushless designs.
4. **Stable Output Voltage:** Equipped with automatic voltage regulators (AVRs), alternators maintain consistent voltage even with load variations.
5. **High-Speed Operation:** Cylindrical rotor types are robust and suitable for high-speed applications like thermal power plants.

6. **Cost-Effective:** They are cheaper to manufacture and maintain compared to some other generator types.

Disadvantages of Alternators

1. **Requires Rectification:** Alternators produce AC, so a diode rectifier is needed to convert it to DC for devices that require direct current.
2. **Cannot Charge Dead Batteries:** Unlike some generators, alternators may fail to charge a completely dead battery and risk burnout if forced to do so.
3. **Overheating Risk:** If overloaded or poorly ventilated, alternators can overheat, affecting performance and lifespan.
4. **Dependent on External Excitation:** Some alternators need an external DC source to excite the rotor field, adding complexity.
5. **Limited Low-Speed Performance:** Salient pole rotors used in low-speed applications are bulkier and less efficient at high speeds.

Applications of Alternators

Automotive Applications

1. **Vehicle Charging Systems:** Alternators power the car's electrical system and recharge the battery while the engine runs.
2. **Electric Vehicles (EVs):** Used in hybrid systems to manage energy flow and auxiliary power.
3. **Emergency Vehicles:** High-output alternators support sirens, radios, and lighting.

Power Generation

1. **Power Plants:** Alternators in hydro, thermal, and nuclear stations convert turbine motion into grid-ready electricity.
2. **Standby Generators:** Provide backup power during outages in homes, hospitals, and data centres.
3. **Renewable Energy Systems:** Wind turbines and micro-hydro setups use alternators to generate clean energy.

Transportation & Marine

1. **Diesel-Electric Locomotives:** Alternators generate electricity to drive traction motors.
2. **Ships & Yachts:** Marine alternators are corrosion-resistant and explosion-proof, powering navigation, lighting, and communication systems.

Industrial & Commercial Use

1. **Factories:** Power heavy machinery and maintain stable voltage for sensitive equipment.
2. **Construction Sites:** Portable alternators supply electricity to tools and lighting in remote areas.
3. **Mining Operations:** Rugged alternators withstand harsh conditions to power drills and ventilation systems.

Specialised Applications

1. Radio Transmission: Historical use in generating low-frequency signals for long-distance communication.
2. Brushless Alternators: Used in high-reliability environments like aerospace and military systems due to reduced maintenance.

Activity 1.3.1 Alternators – Construction, Advantages and Applications

Scenario

You are part of a national service engineering team supporting a rural power station that uses alternators to supply electricity. Your task is to understand how alternators work, why they are preferred over DC generators, and how to use them safely to avoid overloading.

Materials You Will Use

1. Diagrams or animations of alternator parts and operation
2. A model or real alternator (if available)
3. Printed handouts comparing alternators and DC generators
4. Worksheet with guiding questions and a short quiz
5. Internet devices (optional)
6. Chart paper, coloured pens, and sketching tools
7. Sample appliances powered by alternators
8. Notebooks and pens

Step 1: Brainstorm and Discuss

1. What do you know about alternators? Use your ideas here to guide the parts-and-functions table you will complete in Step 2.
2. How do you think an alternator produces electricity? You will test and confirm your ideas during Step 2 and show the process clearly in your diagram in Step 3.
3. How is an alternator different from a DC generator? Keep your answers so you can expand them into a comparison chart in Step 3.
4. What might happen if an alternator is overloaded? Use your thoughts to help design the safety tips and warnings you will include in your Step 3 poster.

Step 2: Group Research and Table Completion

Form groups of 4 or 5. Assign roles: Researcher, Recorder, Presenter, Artist, and Facilitator. Use books, videos, and the internet to complete the table below by finding the parts of an alternator, their descriptions, functions, and why they are important:

Part of an Alternator	Description	Function	Importance
Rotor			
Stator			
Slip Rings			
Brushes			

Step 3: Create and Present

1. Draw and label a diagram or a model (shown in fig. 3) of an alternator showing parts like rotor, stator, slip rings, etc.

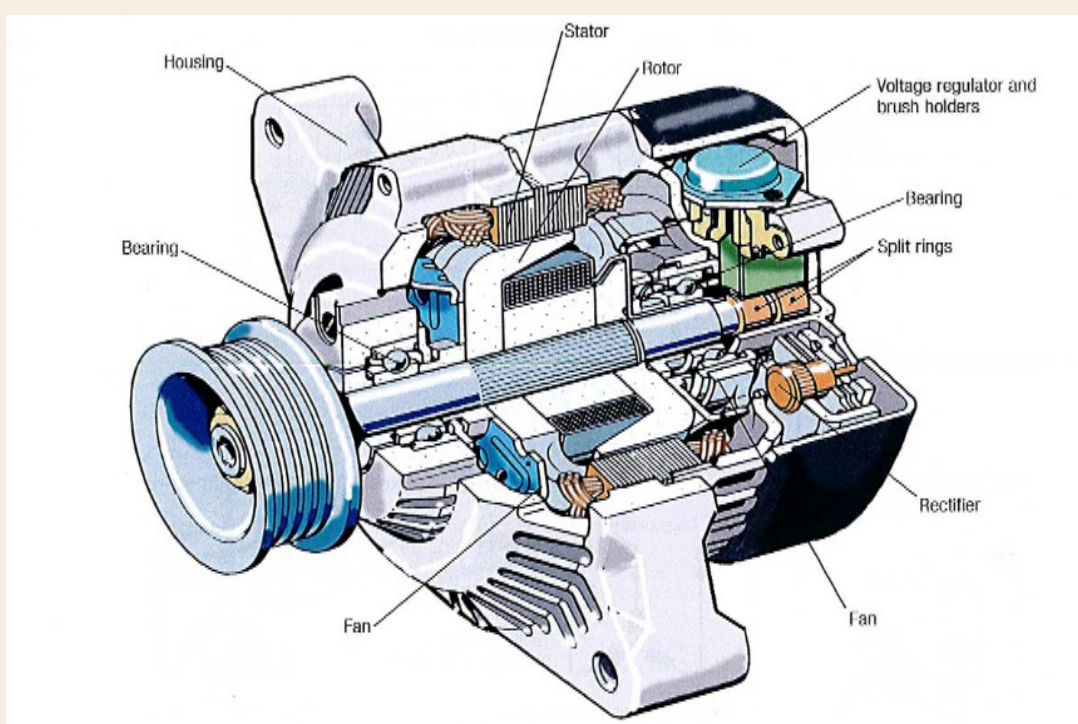


Fig 3 Parts of an alternator

2. Make a poster or infographic that includes:
 - a. How an alternator is built and how it works
 - b. At least 3 differences between alternators and DC generators
 - c. 3 common uses of alternators
 - d. What happens if an alternator is overloaded
 - e. How to avoid overloading
3. Present your diagram to your class.

Step 4: Ask and Answer Questions

1. Listen carefully to questions from your classmates.
2. Answer clearly to help others understand.

3. Give helpful feedback on others' presentations, especially about their diagrams and applications.

Step 5: Reflect

Write short answers in your notebook:

1. What new things did you learn about alternators?
2. Why are alternators used more than DC generators today?
3. What are the risks of overloading an alternator?
4. How can you help people in your community use alternators safely?

EXTENDED READING

1. Textbook: AC Generator – Diagram, Construction, Working, Types, and Uses Explain the roles of each part (armature, rotor, stator, slip rings), working principle using Faraday's Law, and compares AC vs DC generators.
2. BYJU'S: What Is an AC Generator? Covers the physics behind AC generation, component functions, and advantages over DC generators. Great for students and exam prep.
3. BrainKart: AC Generator – Principle, Construction, Working, Diagram Goes into detail on stator and rotor design, types of rotors, and includes schematic illustrations of single-phase and three-phase generators.
4. ALLEN: AC Generators – Working Principle, Theories, Equations & Applications Includes mathematical derivations for induced EMF, sinusoidal current behaviour, and sample problems for practice.

REVIEW QUESTIONS

1. Analyse how the design components of an alternating current (AC) generator contribute to its operational principle. Evaluate how changes in structural configuration, magnetic field orientation, or rotation speed impact voltage generation and overall performance.

Support your analysis with application-based examples.

2. A 3-phase, 10 pole alternator has 90 slots, each containing 12 conductors. If the speed is 600 r.p.m and the flux per pole is 0.1 Wb, calculate the line emf when the phases are star-connected. Take coil span factor, $k_c = 1$ and distribution factor $k_d = 0.96$

UNIT 4 AC, DC MOTORS AND AC, DC GENERATORS

INTRODUCTION

In Year 2, you studied Faraday's Law of electromagnetic induction, which explains that when a conductor moves through a magnetic field, an electromotive force (emf) is induced. A DC generator uses this principle to convert mechanical energy into direct current electricity. It has key parts such as the armature, commutator, brushes, and field windings. The magnetic field required for voltage generation is created by supplying current to the field windings, a process called excitation. Excitation can be done by different methods, including self-excitation and separate excitation. There are several types of DC generators—series, shunt, and compound—each with different winding arrangements and uses. DC generators are commonly used for battery charging, welding, and powering small devices because they provide steady and controllable DC output. In this unit, you will learn about excitation methods, types of DC generators, their operation, and practical applications.

KEY IDEAS

- A DC generator consists of key parts including the armature, commutator, brushes, field windings, and yoke, all designed to convert mechanical energy into electrical energy through electromagnetic induction.
- The generated electromotive force (EMF) depends on factors such as the number of poles, flux per pole, speed of rotation, and number of conductors, and is calculated using the EMF equation.
- Losses occur due to factors like copper winding resistance, iron core hysteresis and eddy currents, mechanical friction, and brush contact, affecting overall efficiency.
- Excitation involves supplying current to the field windings to create the magnetic field, achieved through methods like self-excitation (field winding connected to the armature) and separate excitation (independent external source).
- DC generators are classified as series, shunt, or compound depending on how their field windings are connected relative to the armature circuit.
- DC Generators: Excitation Methods, Types, Operation, and Practical Applications

Main Parts of a DC. Generator

1. **Yoke (Magnetic Frame)**
 - a. Made of cast iron or steel.

- b. Provides mechanical support and acts as the magnetic flux path.
- 2. **Pole Core & Pole Shoes**
 - a. Bolted to the yoke.
 - b. Enhance the distribution of magnetic flux.
- 3. **Field Windings (Exciter Windings)**
 - a. Coils wound around the pole cores.
 - b. When energised, they produce a magnetic field needed for induction.
- 4. **Armature Core**
 - a. Cylindrical core mounted on the shaft.
 - b. Laminated to reduce eddy current losses.
 - c. Houses armature windings where voltage is induced.
- 5. **Armature Windings**
 - a. Conductors placed in slots of the armature core.
 - b. Cut the magnetic flux when the armature rotates, generating electricity.
- 6. **Commutator**
 - a. A split ring made of copper segments insulated from each other.
 - b. Converts the alternating voltage (induced in armature) into direct current.
 - c. Ensures correct direction of current flow.
- 7. **Brushes**
 - a. Made of carbon or graphite.
 - b. Maintain contact with the commutator, transferring current to the external circuit.
- 8. **Shaft**
 - a. Central rotating component driven by mechanical input (e.g., turbine).
 - b. Supports the armature and the commutator.

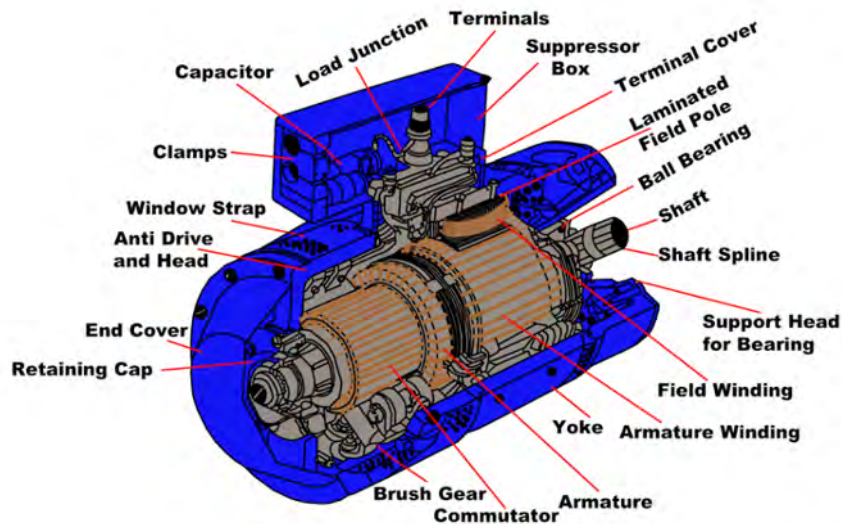


Figure 1.4.1: Yoke (Magnetic Frame)

Supporting Parts

1. Bearings – Enable smooth rotation of the shaft.
2. Cooling System – Prevents overheating during operation.
3. End Covers – Protect internal components from dust and damage.

Methods of Excitation for DC Generators

1. **Permanent Magnet Excitation**
 - a. Uses permanent magnets in the stator.
 - b. No external power source required.
 - c. Common in small DC generators and applications where simplicity is key.
 - d. Output voltage is fixed and not easily adjustable.
2. **Self-Excitation**
 - a. The generator uses a portion of its own output to power the field windings.
 - b. More common in medium to large generators.
3. **Separate Excitation**
 - a. Field winding is powered by an independent external DC source.
 - b. Allows for fine control of the output voltage.
 - c. Common in lab setups, testing systems, and precision applications.

Types of DC Generators Based on Excitation

DC (Direct Current) generators are classified based on how their field windings (the electromagnets that generate the magnetic field) are **excited**, or energised (i.e. how their field wings are connected to the armature)

1. **Separately Excited DC Generator**
 - a. Field winding is powered by an external DC source.

- b. The field and armature are electrically separate.
- c. Allows precise control of field current and voltage output.

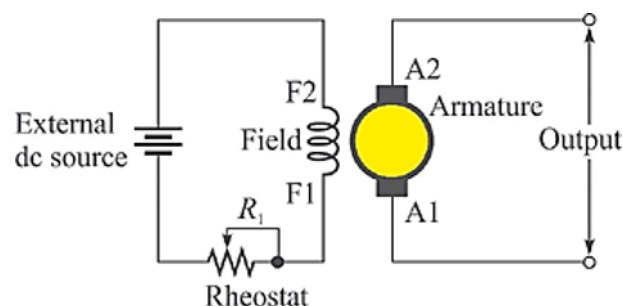


Figure 1.4.2: Separately – Excited DC Generator

2. Self-Excited DC Generators

These generators use their own generated voltage to power the field windings. They are as follows:

a. Series Wound Generator

- i. Field winding is in **series** with the armature.
- ii. Field current = armature current.
- iii. High starting torque, but voltage regulation is poor.

b. Shunt Wound Generator

- i. Field winding is connected in **parallel** (shunt) with the armature.
- ii. Constant voltage output.
- iii. Suitable for battery charging and lighting.

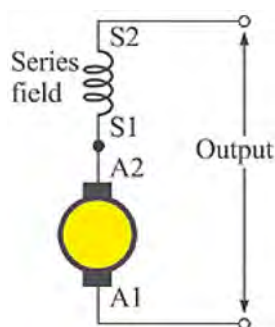


Figure 1.4.3: Series-wound Generator

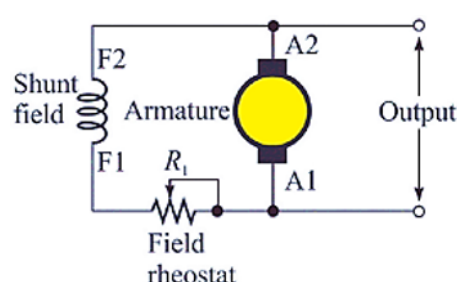


Figure 1.4.4: Shunt-wound Generator

Example

A load of 19.2kW is supplied from the terminals of a two-pole DC. shunt generator at 240V. The shunt winding of the generator has a resistance of 96Ω , and the resistance of the armature is 0.2Ω . Calculate:

- a. the current in the armature
- b. the emf generated
- c. the Copper losses in the machine.

Solution

Given Data: Load Power (P) = 19.2 kW

Voltage (V) = 240 V

Shunt winding resistance (R_{sh}) = 96 Ω

Armature resistance (R_a) = 0.2 Ω

- a. Calculate the load current (I_L):

$$I_L = \frac{P}{V} = \frac{19,200 \text{ W}}{240 \text{ V}} = 80 \text{ A}$$

Since it is a shunt generator, the armature current (I_a) is the sum of the load current and the shunt current (I_{sh}):

$$I_{sh} = \frac{V}{R_{sh}} = \frac{240 \text{ V}}{96 \Omega} = 2.5 \text{ A}$$

Thus, the armature current can be calculated as:

$$I_a = I_L + I_{sh} = 80 \text{ A} + 2.5 \text{ A} = 82.5 \text{ A}$$

- b. The EMF generated can be calculated using the armature current and the armature resistance: $Emf = Emf = V + I_a \cdot R_a$

Substituting the values: $Emf = 240 \text{ V} + (82.5 \text{ A} \cdot 0.2 \Omega)$

$$Emf = 240 \text{ V} + 16.5 \text{ V} = 256.5 \text{ V}$$

- c. Copper losses occur in the armature and shunt winding: $R_a + I_{sh}^2 \cdot R_{sh}$

$$\text{Copper Losses}_{\text{armature}} = (82.5 \text{ A})^2 \cdot 0.2 \Omega = 6,806.25 \cdot 0.2 = 1,361.25 \text{ W}$$

$$\text{Copper Losses}_{\text{shunt}} = (2.5 \text{ A})^2 \cdot 96 \Omega = 6.25 \cdot 96 = 600 \text{ W}$$

$$\text{Total copper losses} = 1,361.25 \text{ W} + 600 \text{ W} = 1,961.25 \text{ W} = 1.96 \text{ k W}$$

c. Compound Wound Generator

- i. Has both series and shunt field windings.
- ii. Combines the advantages of both series and shunt types.
- iii. Comes in two varieties
 - Long shunt: Shunt field winding in parallel with both armature and series field.
 - Short shunt: Shunt field winding in parallel only with the armature.

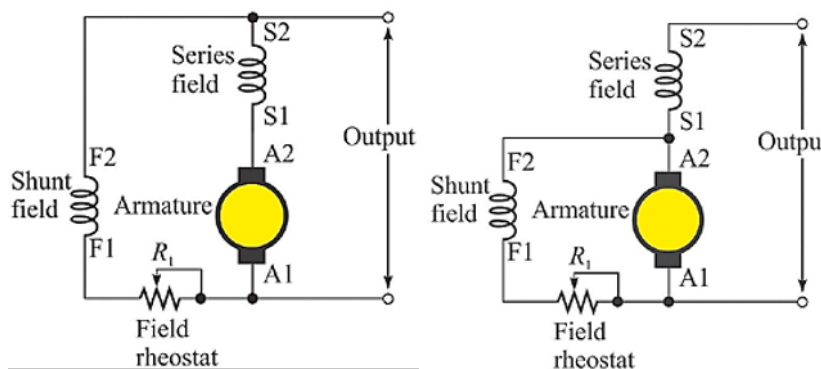


Figure 1.4.5: Compound wound generator – Long Shunt and Short Shunt

These different configurations influence how the generator behaves under varying loads—like how stable its voltage remains or how much torque it can deliver.

EMF Equation of a DC Generator

The generated EMF in a DC generator is given by: $E = \frac{P\Phi \times N \times Z}{60 \times A}$

Where:

E = Generated EMF across any parallel path

P = Total number of poles in the field

N = Rotational speed of armature revolutions per second (rpm)

Z = Total number of armature conductors in the field.

Ø = Magnetic flux produced per pole

A = number of parallel paths in the armature.

Losses in DC generators

In a DC generator, not all the input mechanical energy is converted into electrical energy.

Some of the energy is lost due to various factors.

The main types of losses include:

1. Electrical Losses (Copper Losses)

These arise due to the resistance in the electrical conductors. The two types are as follows:

- a. Armature copper loss: loss in the armature winding.
- b. Field copper loss: Occurs in the shunt or series field windings, depending on the generator type.
- c. Brush contact losses: This loss is due to the resistance at the interface between the brushes and the commutator and generates heat.

Note: EMF equation ($E=4.44f\Phi N$). The 4.44 factor comes from $4 \times \text{form factor}$ (where the form factor for a sine wave is 1.11, i.e., RMS/Average)

2. Core or Iron Losses

They are caused by alternating magnetic fields in the armature core:

- a. Hysteresis loss: Due to magnetisation and demagnetisation of the core material.
- b. Eddy current loss: Induced currents flowing in the core, producing heat.

3. Mechanical Losses

These occur due to physical friction and movement:

- a. Bearing friction: Resistance in the moving parts, like shafts and bearings.
- b. Brush friction: Friction between the carbon brushes and the commutator.
- c. Windage losses: Air resistance against rotating parts.

DC Generator Applications

Direct Current (DC) generators are used in a variety of niche and specialised settings where consistent, stable DC power is essential.

Here are some of the standout applications:

Industrial Uses

1. **Electroplating and Electrolysis:** These processes demand steady DC power to deposit metals or drive chemical reactions.
2. **Battery Charging Stations:** Especially for large batteries in backup power systems or electric vehicles.
3. **Welding Equipment:** Certain types of arc welders utilise DC generators for better control and penetration.

Transportation

1. **Diesel-electric locomotives:** DC generators help power the electric traction motors.
2. **Ships and Submarines:** For onboard lighting and communication systems where AC may be less stable.

Portable and Backup Power

1. **Emergency Backup Systems:** In hospitals, data centres, and telecommunications, DC generators may support or charge backup batteries.
2. **Remote Locations:** Useful in areas without access to grid electricity—think research outposts or rural telecom stations.

Scientific and Experimental Setups

Laboratories and R&D: Used where precise and controllable electrical output is key, especially in physics and electronics experiments. DC generators play roles in applications demanding reliable, smooth direct current.

Activity 1.4.1 Concept, Operation and Applications of DC Generators

Scenario

You are a trainee electrical technician working with a local technical team supporting communities facing frequent power cuts. Your team plans to introduce DC generators as backup power solutions. Before visiting these communities, you need to research, understand, and demonstrate how DC generators work, why they are important, and where they can be used effectively.

Task

Explore what a DC generator is, understand its parts and operation, and identify where DC generators are used, especially in Ghana.

Materials needed

1. Videos and animations about DC generators
2. Models or parts of a DC generator (if available)
3. Diagrams of DC generator structure
4. Large paper, markers, pens
5. Worksheets with guiding questions
6. Internet-enabled devices for research and simulations
7. Notebooks and pens

Step 1: Class Brainstorm

Think about what a DC generator is and where you have heard of or seen one. Discuss with your classmates:

1. What is a DC generator?
2. What are its main parts?
3. Where do you think DC generators are used?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 people.
2. Assign roles: Researcher, Note-taker, Presenter, Artist.
3. Use videos, books, internet, and other resources to complete the table below:

Link to video provided here: <https://youtu.be/mq2zjmS8UMI?si=Q7aTS5MfLpZr8kNM>



4. While watching the video, using books, internet resources, and the guiding questions to fill out the table below.

S/N	Part of DC Generator	Description	Function
1			
2			
3			
4			

Use these guiding questions

- a. What does each part do?
- b. How does the commutator help the generator produce DC?
- c. Why are brushes important?

- d. How do these parts work together to convert mechanical energy into electrical energy?
- e. Can you name a device or place that uses DC generators? Why is it suitable there?

Step 3: Create Your Diagram and Poster

1. Draw a labelled diagram or model of a (DC generator *Figure 1.4.6*) showing important parts such as the armature, field coils, commutator, and brushes.

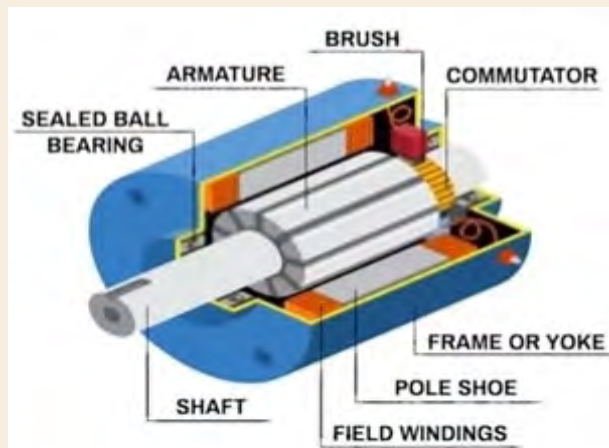


Figure 1.4.6: Model of DC generator

2. Make a poster showing:
 - a. A simple explanation of what a DC generator is and how it works (include Faraday's law of electromagnetic induction)
 - b. At least three practical uses of DC generators, including examples from Ghana or elsewhere
 - c. Benefits of using DC generators in places without stable electricity

Step 4: Present Your Work

Present your diagram and poster/model to the class. Explain clearly:

1. What a DC generator is
2. How it works to produce electricity
3. Examples of where DC generators are used and why they are useful there.

Step 5: Ask and Answer Questions

1. Listen carefully to questions from your classmates.
2. Answer clearly to help others understand.
3. Ask questions about other groups' presentations.
4. Give helpful feedback on their diagrams and applications.

Step 6: Reflect and Write

In your notebook or tablet, answer these questions:

1. What did you learn better about DC generators today?

2. How is a DC generator different from an alternator?
3. Which use of DC generators do you think is most important in Ghana and why?
4. How could you show others the value of DC generators in places with no reliable electricity?
5. What challenges did my group face during this activity, and how did we solve them?
6. What else do you want to learn about DC generators?

EXTENDED READING

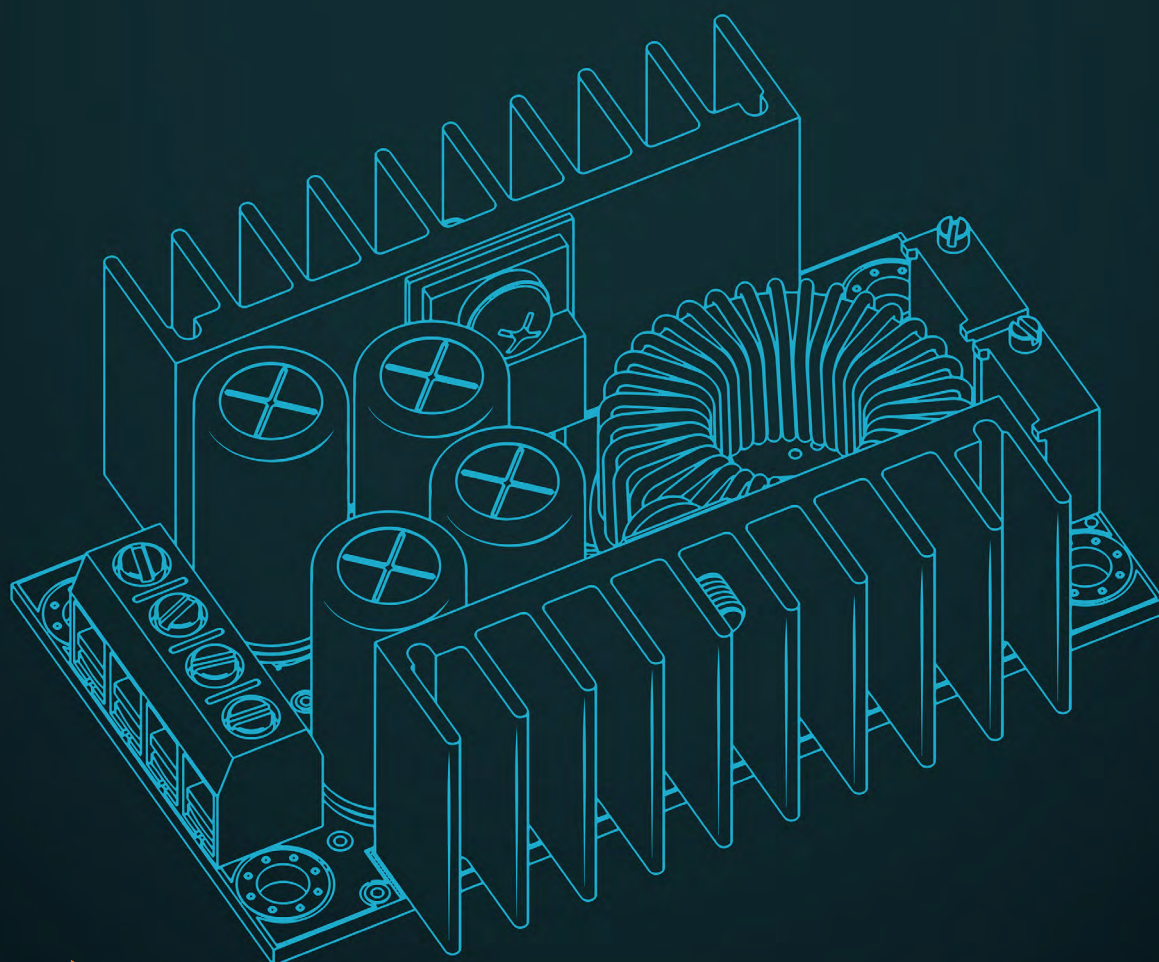
1. [TutorialsPoint: Construction and Working Principle of DC Motor](#) Offers a detailed breakdown of each component—yoke, armature, commutator, brushes—and explains how electromagnetic force drives rotation using Fleming’s Left-Hand Rule.
2. [Electrical4U: Working or Operating Principle of DC Motor](#) Covers the physics behind torque generation, Lorentz force, and how torque varies with armature position. Includes diagrams and torque equations.
3. [Etechnophiles: DC Motor Working Principle, Construction and Diagram Explanation](#). Explains stator and rotor parts, back EMF, and how commutation ensures unidirectional torque. Great visuals and real-world examples.
4. [Textbook: DC Motor – Definition, Construction, Working Principle, Diagram, Types & Applications](#). Provides a comprehensive guide for students, including formulas for torque and speed, types of DC motors, and a comparison with AC motors.
5. [GeeksforGeeks: DC Motor – Construction, Working, and Applications](#). Ideal for learners preparing for exams. Covers electromagnetic induction, motor characteristics, and practical uses in robotics and vehicles.

REVIEW QUESTIONS

1. State Faraday's law of electromagnetic induction
2. A conductor 300 mm long moves at a uniform speed of 4 m/s at right angles to a uniform magnetic field of flux density 1.25 T. Calculate the:
 - a. Induced EMF
 - b. Current in the conductor when its ends are open-circuited
 - c. Current through the conductor when a $20\ \Omega$ resistor is connected across its ends
3. Examine how the design and construction of a direct current (DC) generator facilitate its operational principles. Evaluate the influence of individual components—such as armature windings, commutator, and field system—on the generation of electromotive force (EMF), efficiency, and voltage regulation in various practical applications. Support your response with comparative analysis where appropriate.

SECTION

2



UNIT 5 TRANSFORMERS AND MAINTENANCE

INTRODUCTION

Transformers are key electrical devices that change voltage levels in power systems efficiently. They work on electromagnetic induction, where an alternating current in the primary coil creates a changing magnetic field that induces an electromotive force (EMF) in the secondary coil without direct contact. Transformers step up (increase) or step down (decrease) voltage, allowing safe and efficient power transmission and distribution. Single-phase transformers are used in household electrical systems and power supplies for electronic devices, while three-phase transformers serve large-scale power generation, substations, and factories, providing stable voltage for industrial use.

In this unit, you will learn about the construction and operating principles of single-phase and three-phase transformers. You will also study different methods of connecting three-phase transformers for various applications. Understanding these concepts is vital for managing and maintaining electrical power systems effectively.

KEY IDEAS

- A single-phase transformer has one primary and one secondary coil and is used for low-power applications like home appliances.
- Both types use laminated iron cores to reduce energy loss and improve magnetic efficiency.
- Copper wire is used for windings in coils to conduct electricity with low resistance.
- Different coil arrangements allow three-phase transformers to handle large electrical loads in industries and power distribution.
- Electromagnetic induction transfers energy from the primary to the secondary coil without physical contact.
- Flux change in the core creates voltage in the secondary coil when alternating current flows in the primary coil

SINGLE PHASE AND 3-PHASE TRANSFORMER

A transformer is made with copper coils wound around a laminated iron core. Both single-phase and three-phase transformers use this basic design. The number and arrangement of coils differ to match power needs, single-phase for homes and three-phase for factories. This strong construction ensures a safe voltage change from the primary winding to the secondary winding.

Construction of a transformer

A transformer changes Alternating Current (AC) from a low voltage to a high voltage or high voltage to a low voltage. It has two coils placed on a laminated iron core. The first coil is called the primary winding; it connects to the input voltage. The second coil is called the secondary winding; it connects to the load or device being powered. These two coils are not joined by wires. However, they are separated but share the same magnetic path. This magnetic link allows the transformer to work without direct electrical contact.

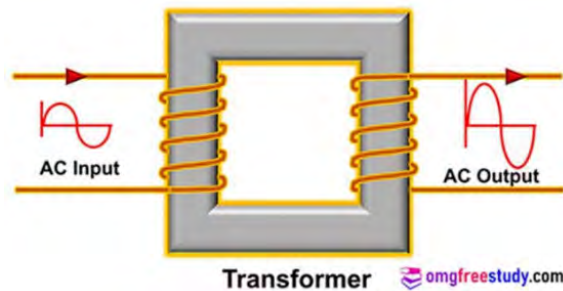


Figure 2.5.1: Simple Transformer construction

Figure 2.5.1 shows a simple diagram of a transformer. It is a single-phase transformer, which has two windings: one for input and one for output. In other types of transformers, especially three-phase ones, there can be more than two windings to handle bigger electrical loads.

Principle of Operation

Transformers work through mutual induction. This means the magnetic field from one coil affects a second coil and causes an emf (voltage) to be produced. For this to happen, the magnetic flux linking the coils must keep changing. This idea is based on Faraday's Law of Electromagnetic Induction.

Since alternating current (AC) keeps changing direction, it creates a changing magnetic field, which is needed for mutual induction. Direct current (DC) stays constant and cannot cause induction.

When AC flows into the primary coil, it creates a changing magnetic flux. This flux connects both coils and causes a voltage (emf) to appear in the secondary coil. If a coil has (N) turns, the emf produced can be calculated using a special formula related to the rate of change of magnetic flux (i.e. Faraday's Law of electromagnetic induction):

$$E = N \frac{d\Phi}{dt}$$

Where:

E = Induced EMF (volts)

N = Number of turns (coils of wire)

$\frac{d\Phi}{dt}$ = Rate of change of magnetic flux (Webers per second)

Example 1

A coil of **150 turns** is linked by a magnetic flux of **7 mWb**. If the flux doubles in **10 ms**, calculate the induced emf.

Solution

Flux = 7 mWb = 0.007 Wb

Time = 10 ms = 0.01 s

Number of turns, $N = 150$

$$E = N \frac{d\Phi}{dt} = 150 \times 0.007 / 0.01 = 105 \text{ V}$$

Example 2

A coil of 300 turns is linked by a magnetic flux of 15 Wb. If the time is 12s, calculate the induced emf.

Solution

Number of turns, $N = 300$

flux, $\Phi_1 = 15 \text{ Wb}$

time, $t = 12 \text{ s}$

$$E = N \frac{d\Phi}{dt} = 300 \times 1.25 = 375 \text{ v}$$

Example 3

A coil of 500 turns, at an initial flux of 45 Wb and a final of 50Wb, if the flux takes 12s to 30s to ensure linkage, calculate the induced emf.

Solution

Number of turns, $N = 500$

Initial flux = 45 Wb

Final flux = 50 Wb

Initial time = 30 s

Flux change = 50 - 45 = 5 Wb

Time-change = 30 - 12 = 18 s

$$E = N \frac{d\Phi}{dt} = 500 \times 5/18 = 138.89 \text{ v}$$

In a transformer, we have two coils: the primary coil and the secondary coil. If the coils have N_p and N_s as the number of turns in the primary and secondary windings, respectively, and their respective RMS voltages induced in the windings are E_p and E_s , then:

1. The voltage in the primary coil (E_p) and the voltage in the secondary coil (E_s) are related by their number of turns:

$$E_p = E_s \text{ and } \frac{E_p}{E_s} = \frac{N_p}{N_s}$$

2. In a transformer, current is inversely proportional to voltage. Thus, if the voltage increases in one coil, the current will decrease in the other coil. This relationship can be summarised by:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p}$$

Here, I_p is the current in the primary coil and I_s is the current in the secondary coil.

3. An ideal transformer works without any energy loss. The voltage in the secondary coil (V_s) depends on the voltage in the primary coil (V_p) and the ratio of the number of turns:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

This means if you know how many turns are in each coil and the voltage in the primary, you can figure out the voltage in the secondary coil.

A transformer can either increase or decrease voltage:

1. A step-up transformer increases voltage by having more turns in the secondary coil than the primary.
2. A step-down transformer decreases voltage by having fewer turns in the secondary coil.

In heavy-duty power transformers, special care is taken to make sure all the magnetic flux from the primary coil links with the secondary. This helps the transformer work efficiently and reduces energy loss during voltage transfer.

Three-Phase Transformer Construction

A three-phase transformer is built by putting three sets of coils (windings) on a single laminated iron core. This design connects the three windings together to form one complete unit. Instead of using three separate single-phase transformers, all three are joined on one magnetic core. This setup saves space, costs less, and works more efficiently.



Figure 2.5.2: Three-phase transformer

A three-phase transformer uses three magnetic circuits that are combined to make the flow of energy between the high and low voltage coils smooth and balanced. The coils (windings) on the primary and secondary sides can be connected in different ways to fit different power needs. Common connection types include:

1. Delta–Star
2. Star–Delta
3. Star–Star
4. Delta–Delta

In a delta–star connection, the primary coil is arranged in a triangle shape (delta), and the secondary coil is arranged like a letter “Y” (star). This type is commonly used to step down voltage in power transmission systems.

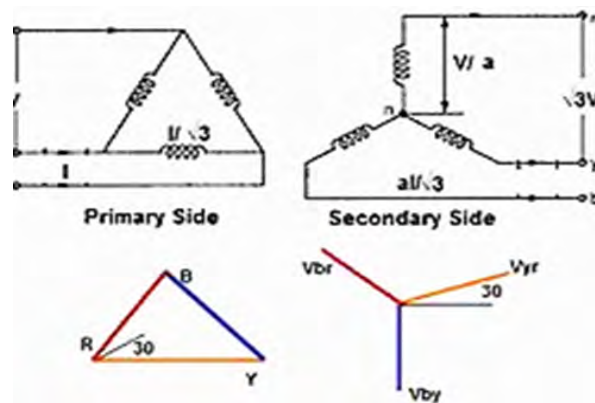


Figure 2.5.3: Delta-Star connection

EMF Equation of Transformer

Note the following symbols:

N_1 – Number of turns in the primary

N_2 – Number of turns in the secondary

Φ_m – Maximum flux in weber (Wb)

T – (period) Time taken to complete 1 cycle.

In a transformer, the magnetic flux produced is alternating, meaning it changes direction in the form of a sinusoidal wave. It first rises to a maximum value (Φ_m) in the positive direction, then falls to Φ_m in the negative direction. This wave repeats its pattern regularly.

Since a full wave cycle takes time T , the maximum flux is reached after a quarter of the cycle, which is $T/4$ seconds. This timing helps explain how transformers generate voltage continuously using changing magnetic fields.

In a transformer, the magnetic flux produced is alternating, meaning it changes direction in the form of a sinusoidal wave. It first rises to a maximum value (Φ_m) in the positive direction, then falls to Φ_m in the negative direction. This wave repeats its pattern regularly.

Since a full wave cycle takes time T , the maximum flux is reached after a quarter of the cycle, which is $T/4$ seconds. This timing helps explain how transformers generate voltage continuously using changing magnetic fields.

At no-load condition, an ideal transformer follows a special EMF equation that helps calculate the voltage in both coils. This equation helps show how energy moves from the input to the output when there is no electrical load connected.

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44f \Phi_m$$

Where:

E_1 is the voltage that enters the transformer through the primary coil.

E_2 is the voltage that comes out from the secondary coil—either measured or calculated in theory.

This helps explain how a transformer works to change the voltage level from input to output using coils and magnetic flux.

Advantages of a Three-Phase Transformer

1. Takes up less space and is easier to install.
2. Lightweight and compact in size.
3. Gives higher efficiency during operation.
4. Costs less to buy and maintain.
5. Easier and cheaper to transport.

Note: A single three-phase unit is more efficient and compact. However, a bank of three single-phase units allows for “N-1” redundancy, where the system can continue to operate at a reduced capacity if one unit fails.

Disadvantages of a Three-Phase Transformer

1. If one part fails, the whole transformer stops working.
2. Repairs cost more because it is a single unit.
3. Spare parts are expensive.

Applications of Transformers

1. Used in electricity transmission and distribution across the country.
2. Found in radio and TV receivers, where different voltages are needed.
3. Used as voltage regulators to control and maintain stable voltage levels.

Activity 2.5.1 Construction, Operation and Applications of a Transformer

Scenario

You are part of a technical team working to improve electrical power systems in your community. Your task is to understand how transformers work, why they are useful, and where they are applied. You will prepare and present your findings to help others appreciate the role of transformers in electricity supply.

Task

Explore the construction and principles of operation of transformers. Justify the advantages of using transformers, discuss typical applications, and explain the impact of overloading transformers.

Materials Needed

1. Diagrams or small parts/models of transformers (if available)
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens
5. Examples or images of transformers in real-life applications
6. Notebooks, pens

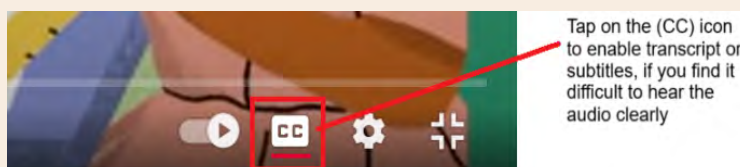
Step 1: Class Brainstorm

1. **What is a transformer?** Use your ideas to guide the parts-and-functions table you will complete in Step 2.
2. **How do you think it works?** You will test and confirm your ideas during Step 2 and show the process in your Step 3 diagram.
3. **Why do we need transformers in electrical systems?** Keep your answers so you can expand them into the advantages section in Step 3.
4. **Where are transformers commonly used?** Use your thoughts to help design the real-life application examples you will present in Step 3.

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners.
2. Assign roles: Researcher, Note-taker, Presenter, Artist.
3. Watch the video provided on transformers and the effects of loading on electrical devices.
4. Use books, internet and other resources to complete the table below:

Follow the link to watch video: https://youtu.be/UchitHGF4n8?si=3-WN-KV7_1RjrXlx



S/N	Transformer Aspect	Description/Explanation	Importance/Impact
1	Main parts of a transformer		
2	Principle of operation		
3	Advantages of transformers		
4	Typical applications		
5	Impact of overloading		

5. Use these guiding questions during your research to fill the table above.

- What are the key parts of a transformer and their functions?
- How does a transformer change voltage levels?
- Why is using a transformer advantageous in power systems?
- What happens when a transformer is overloaded?
- Can you name places or devices where transformers are used?

Step 3: Create Your Diagram and Poster

- Draw a labelled diagram (Figure A) or build a model of a transformer showing main parts (core, primary and secondary windings).

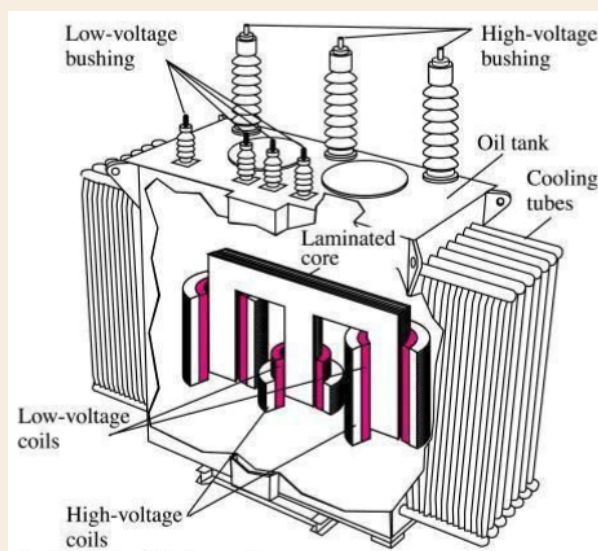


Figure A: Parts of a transformer

- Make a poster showing
 - The construction and principle of operation (mutual induction)
 - Advantages of using transformers
 - Examples of typical applications (e.g., power distribution, electronic devices)
 - Effects of overloading transformers

Step 4: Present Your Work

Present your diagram and poster/model to the class. Explain:

- What a transformer is
- How it works to change voltage
- Why transformers are important in power systems
- What happens if transformers are overloaded
- Examples of where transformers are used

Step 5: Ask and Answer Questions

- Listen carefully to questions from your classmates.

2. Answer clearly to help others understand.
3. Ask questions about other groups' work and give constructive feedback.

Step 6: Reflect and Write

In your notebook or tablet, answer these questions:

1. What did you learn about how transformers are built and how they work?
2. Why do you think using transformers is advantageous?
3. Which application of transformers do you like the most? Why?
4. How would you explain the importance of transformers to someone unfamiliar with them?
5. What did you learn about the effects of overloading transformers?

REVIEW QUESTIONS

Scenario 1

A technician reports that a three-phase transformer used in an industrial power system is showing voltage instability and slight vibration noise during operation, even though all input values seem normal.

1. Suggest 2 ways the situation can be rectified using low cost-effective measures.
2. Analyse how the construction and operation contribute to the reported issue.

Scenario 2

An engineering team is proposing to replace multiple single-phase transformers at a district power substation with one three-phase transformer. The district supplies electricity to schools, hospitals, and local businesses. The board seeks advice on whether this upgrade would be beneficial.

3. Evaluate the long-term advantages of the upgrade for the community.

UNIT 6 LOSSES AND EFFICIENCY OF TRANSFORMERS

INTRODUCTION

In Year 2, you learned about the principle of mutual induction, where a changing magnetic field produced by one coil induces an electromotive force (EMF) in a nearby coil. This principle forms the basis of how transformers work. A transformer is an electrical device used to increase (step up) or decrease (step down) voltage levels, which is vital for efficient power transmission and safe electricity distribution. However, transformers are not perfect; energy losses occur mainly in two forms: core losses and copper losses. Core losses happen due to hysteresis and eddy currents in the iron core, while copper losses arise from the resistance of the transformer windings. These losses reduce the efficiency of a transformer, wasting energy and increasing operational costs.

In this unit, you will study these losses in detail, explore methods to reduce them, and learn how to calculate the efficiency of a transformer.

KEY IDEAS

- Copper losses happen more when the transformer is carrying a heavy load (more current).
- Core losses happen all the time, even when the transformer is not supplying power.
- Efficiency means how well the transformer changes electrical energy without wasting too much. It is calculated using: $\text{Efficiency} = (\text{Output Power} / \text{Input Power}) \times 100$
- To make transformers work better, we must reduce these losses by using good materials (like silicon steel and thick copper wires) and proper cooling methods.
- Transformers lose some energy when they work. This means they are not 100% perfect or efficient.

LOSSES IN TRANSFORMERS

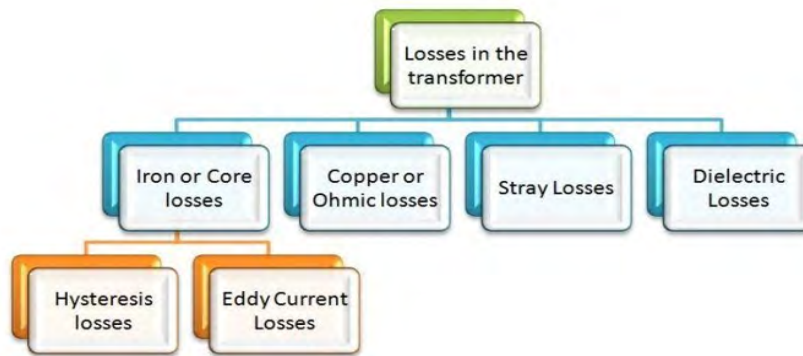


Figure 2.6.1: Types of transformer losses

Types of Losses in a Transformer

Transformers lose energy during their operation, and this affects how well they work. These losses are grouped into four main types: Iron Losses, Copper Losses, Stray Losses, and Dielectric Losses.

Iron Losses (Core Losses)

Iron losses happen inside the magnetic core of the transformer. When the transformer gets alternating voltage, it creates a changing magnetic field. This field causes energy loss in the core. Iron losses remain constant when the transformer works under normal conditions and are made up of two parts:

1. Hysteresis Loss

The transformer's core keeps getting magnetised and demagnetised as the current flows. Each time the magnetic particles (called domains) inside the core shift, they use up some energy. This energy loss depends on the type of core material and the frequency of the current.

2. Eddy Current Loss

As the magnetic field changes, it produces small electric currents called eddy currents in the core. These currents do not do any useful work—they just turn into heat and waste energy. To reduce eddy current loss, transformer cores are made using thin metal sheets called laminations. These laminations are insulated from each other, which limits how the eddy currents move and helps make the transformer more efficient. Also known as I^2R losses.

Copper Loss (Ohmic Loss)

Copper loss happens in the wires (called windings) of the transformer. These wires have resistance, and whenever current flows through them, part of the energy turns into heat. This type of loss depends on how much current is flowing, so it is called load-dependent. That is why it is called ohmic loss—because it follows Ohm's Law.

The total copper loss comes from both the primary winding and the secondary winding. The more current and resistance in each winding, the more loss you get. We calculate it using the formula:

1. For the primary: $\text{Copper Loss} = I_1^2 \times R_1$
2. For the secondary: $\text{Copper Loss} = I_2^2 \times R_2$

So, the total copper loss is the sum of both. These losses reduce efficiency and cause heating in the transformer.

Stray Loss

In theory, all the magnetic flux created by the transformer should link properly between the primary and secondary windings. But in real life, some of the flux escapes or leaks out. This is called leakage flux, and it causes unwanted currents in nearby parts of the transformer—like metal frames or support parts. These extra currents lead to heat and energy waste, which we call stray losses.

Stray losses are usually smaller than iron or copper losses but can still affect performance. To reduce them, engineers design the transformer carefully by:

1. Using strong insulation materials
2. Arranging windings precisely
3. Using high-resistivity metals in the structure
4. Improving the shape and layout of the magnetic core

Dielectric Loss

This type of loss happens in the insulating parts of the transformer when AC voltage is applied. The materials meant to block electric current actually allow a little to pass, causing:

1. Conduction loss — from the small conductivity in the insulating material
2. Polarisation loss — when the electric dipoles in the material react slowly to changes in voltage

How Losses Affect the Operation of a Transformer

If the transformer gets too hot, the heat can damage the insulation that protects its parts. This can make the transformer wear out faster and not last as long. Losses also reduce how efficiently the transformer works. More resistance means more energy turns into heat instead of being used. This can lead to poor voltage control, higher electricity bills, and less reliable performance. Other things like overloading the transformer, moisture getting into it, using the wrong type of insulation, or working in very hot areas can also reduce its insulating strength and efficiency.

How to Improve Transformer Efficiency

Reducing losses helps the transformer work better and last longer. Here are some ways to make it more efficient:

1. **Loop Area:** Keep the loop area in the magnetic core small to reduce heat loss from hysteresis (magnetic friction).
2. **Good Insulation:** Strong insulation materials help stop eddy currents and dielectric losses from forming.
3. **Coil Resistance:** Use coils with low resistance in both the primary and secondary windings to reduce energy loss.
4. **Flux Coupling:** Wind the coils properly so the magnetic flux transfers energy efficiently between them without leaking out.

Note: The Open Circuit Test is used to measure core/iron losses, and the Short Circuit Test is used to measure full-load copper losses.

Transformer Efficiency Calculation

Efficiency = (Output Power $\div$ Input Power) $\times$ 100

Basic Efficiency

Example 1

A transformer takes in 5,000 W of electrical power and delivers 4,600 W to the load. Calculate the efficiency.

Solution

$$\text{Efficiency} = (4,600 \div 5,000) \times 100 = 92\%$$

Find the Output Power Given Efficiency and Input

Example 2

A transformer is 96% efficient and receives 10,000 W of input power. Find the output power.

Solution

$$\text{Output Power} = (\text{Efficiency} \times \text{Input Power}) \div 100$$

$$= (96 \times 10,000) \div 100 = 9,600 \text{ W}$$

Find Input Power Given Output and Efficiency

Example 3

A transformer delivers 7,200 W to a machine and is operating at 90% efficiency. Calculate the input power.

Solution

$$\text{Input Power} = \text{Output Power} \div (\text{Efficiency} \div 100)$$

$$= 7,200 \div 0.90 = 8,000 \text{ W}$$

Activity 2.6.1: Understanding Transformer Losses, Effects and Efficiency

Scenario

A technical team is working to improve electrical power systems in a community. The team's objective is to understand transformer losses, their effects on transformer performance, and ways to enhance transformer efficiency.

Task

Explore the concept of transformer losses, analyse their effects on transformer performance, and illustrate how transformer efficiency can be increased.

Materials Needed

1. Diagrams or models of transformers (if available)
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens
5. Notebooks, pens

Step 1: Class Brainstorm

Think about what transformer losses are and why they might happen. Discuss with classmates:

1. What are transformer losses?
2. How do these losses affect a transformer's performance?
3. Why is it important to reduce losses?
4. What might happen if a transformer works inefficiently

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners. Assign roles: Researcher, Note-taker, Presenter, Artist.
2. Watch the video provided on transformer losses and efficiency.
3. Use books, internet, and other resources to complete the table below:
4. Follow the link to watch video: <https://youtu.be/422NqKXcctE?si=fre7Qgi4GekjGJGP>



Transformer Loss Aspect	Description	Effect on Performance	Ways to Reduce/ Improve Efficiency
Core losses (hysteresis, eddy currents)			
Copper losses (winding resistance)			
Total transformer losses			
Effects of overloading			

5. Guiding questions

- What causes core losses and copper losses?
- How do these losses reduce transformer efficiency?
- What design or operational changes can reduce losses?
- How does overloading affect transformer performance?

Step 3: Create a concept map

- Make a concept map showing various losses in transformers, an example in **Figure B**.

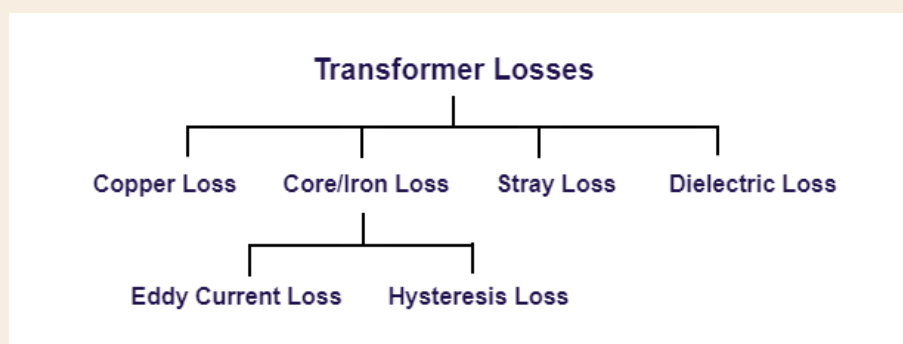


Figure B: A model of a concept map showing various transformer losses

- Make a poster showing
 - The main types of transformer losses and their causes
 - How losses affect performance and efficiency
 - Methods used to reduce losses and improve efficiency
 - Examples of what happens when transformers are overloaded

Step 4: Present Your Work

Present the concept mapping and poster to the class. Explain clearly:

- What transformer losses are
- How losses affect transformer performance
- Ways to increase efficiency

4. The impact of overloading transformers

Step 5: Ask and Answer Questions

1. Listen carefully to classmates' questions.
2. Answer clearly to help everyone understand.
3. Ask questions about other groups' presentations and give meaningful feedback.

Step 6: Reflect and Write

In notebooks or tablets reflect and answer these questions:

1. What was learned about transformer losses and efficiency?
2. Why is reducing losses important for power systems?
3. Which method to improve efficiency seems most effective? Why?
4. How would transformer losses be explained to someone new to the topic?

REVIEW QUESTIONS

A 10-kVA transformer operates with an input power of 10,500 W and an output power of 9,800 W. Based on this information:

1. Calculate the efficiency of the transformer.
2. Explain what type of losses might be causing drop in power.
3. Suggest two ways the transformer design could be improved to reduce these losses.

UNIT 7 COOLING OF TRANSFORMERS VOLTAGE REGULATION

INTRODUCTION

In Year 2, you learned about mutual induction, how a changing magnetic field in one coil induces an EMF in another. This principle is key to how transformers work. Previous discussions in Unit 6 introduced two main transformer losses: core losses in the iron core caused by magnetisation and copper losses due to resistance in the windings. Both produce heat, which lowers efficiency and can damage the transformer if not controlled. Today's lesson focuses on how these losses cause heating and the importance of keeping transformers cool. We will look at cooling methods in Dry Type and Oil-Filled Transformers to see how they improve performance and safety. We will also cover percentage voltage regulation, which shows how much the output voltage changes under load, helping us understand transformer reliability and efficiency. By the end, you will explain losses, cooling methods, and voltage regulation in transformers

KEY IDEAS

- Air Natural (AN) Cooling: Dry-type transformers use natural airflow to dissipate heat without mechanical fans, making them simple and low-maintenance.
- Air Forced (AF) Cooling: Fans or blowers are added to dry-type transformers to enhance cooling, improving efficiency in high-load conditions.
- Oil Natural Air Natural (ONAN) Cooling: Oil-filled transformers rely on natural oil circulation and air convection, suitable for small to medium power ratings.
- Oil Forced Air Forced (OFAF) Cooling: Pumps circulate oil while fans blow air, providing efficient cooling for large, high-capacity transformers.
- Oil Forced Water Forced (OFWF) Cooling: Both oil and water are pumped through heat exchangers, offering high-performance cooling for heavy-duty applications.
- Voltage Regulation: This measures a transformer's ability to maintain steady output voltage under varying loads, ensuring stable power supply.

COOLING OF TRANSFORMERS

When transformers are working and supplying power to homes, schools, factories, and other places, they heat up. This heat mostly comes from something called copper loss. This happens when electricity flows through the wires (called coils), and some energy is lost as heat. If a transformer becomes too hot, it can damage the insulation that is the protective covering around wires and cause the transformer to fail. That is why it must be cooled down just like how you fan yourself when you are feeling hot.

So, cooling a transformer means removing the heat it produces so that it can work safely and last longer. There are two main types of transformers based on how they are cooled:

1. Dry Type Transformers – cooled by air
2. Oil-Filled Transformers – cooled by oil and sometimes water or air

Dry Type Transformers (Air-Cooled)

These transformers do not use oil. Instead, they are cooled by air. There are two ways this is done:

1. Air Natural (AN) – Self-Cooling

This is the simple way of cooling using the natural air around the transformer. As the transformer gets hot, the warm air rises, and cool air comes in to replace it. This is called natural convection. It is used for small transformers (below 1.5 MVA). Think of it like sitting under a tree, when the wind blows, it cools your body naturally.

2. Air Forced (AF) – With Fans

With this, electric fans or blowers blow air forcefully over the hot parts. These fans turn on automatically when the temperature gets too high. This method cools the transformer faster and is used for larger transformers (up to 15 MVA). It is like using an electric fan or air conditioner when it is very hot.

Oil-Filled Transformers

These transformers use special oil to help carry away the heat. The oil cools the core and the windings (the wire coils inside the transformer). These oil-based cooling methods include:

2. Oil Natural, Air Natural (ONAN)

The oil absorbs heat from the transformer parts and rises to the top (because hot oil is lighter). Cool oil comes down to take its place. The hot oil at the top releases its heat to the air through metal radiators (like the way car radiators work). The oil then cools down and goes back to collect more heat. This cycle repeats automatically. This is used for transformers up to 30 MVA. Imagine cooking with palm oil: when you heat it, it rises and bubbles. Then it cools when removed from the fire. This is similar to how the oil moves and cools in the transformer. Fig 2.7.1 shows the type of transformer that utilises this method.

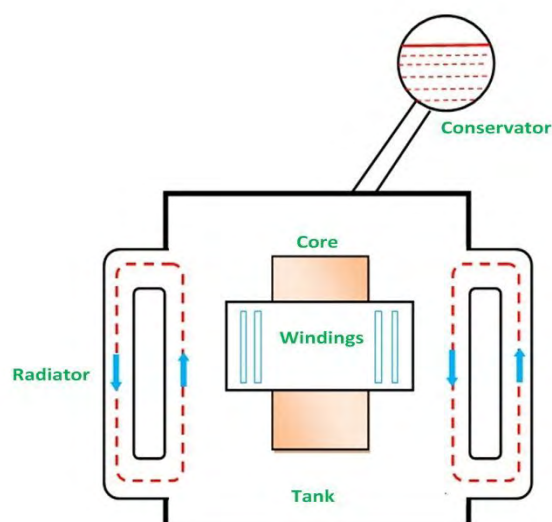


Figure 2.7.1: Oil Natural Air Natural cooling method

3. Oil Natural, Air Forced (ONAF)

Works like ONAN, but with fans to cool the radiators faster. The ONAF (Oil Natural, Air Forced) cooling method is used in oil-filled transformers to cool them more effectively than the basic ONAN method. In this system, the oil inside the transformer absorbs heat from the core and windings as they operate. The hot oil naturally rises to the top of the tank, while cooler oil from the bottom replaces it, creating a continuous natural circulation.

As the hot oil flows into the radiators on the sides of the transformer, electric fans blow cool air over the radiators to remove the heat more quickly. These fans automatically turn on when the transformer's temperature gets too high. Once cooled, the oil returns to the tank to repeat the process. This method allows the transformer to handle more load by improving its cooling efficiency. Fig 2.7.2 shows the type of transformer that utilises this method.

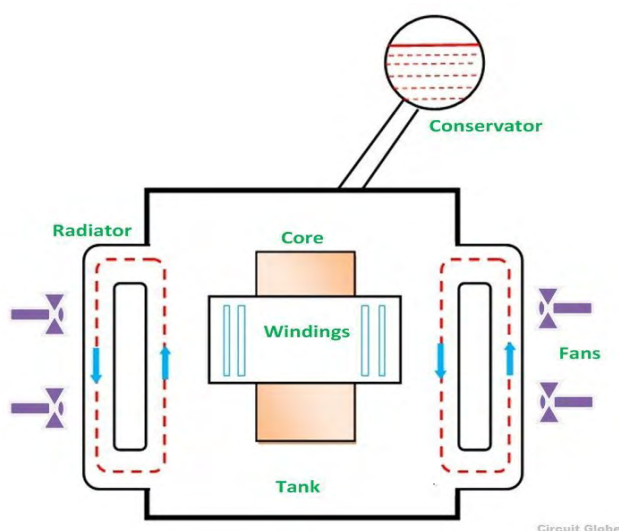


Figure 2.7.2: Oil Natural Air Forced method of cooling

4. Oil Forced, Air Forced (OFAF)

Oil is pumped around with a motor, and fans blow air. It is used in very large transformers. The OFAF (Oil Forced, Air Forced) cooling method is used for large transformers that generate a lot of heat. In this system, the oil inside the transformer absorbs heat from the core and windings. Unlike natural circulation, a pump is used to force the hot oil out of the transformer tank and into a heat exchanger.

In the heat exchanger, large fans blow air over the surface to quickly remove the heat from the oil. After cooling, the oil is pumped back into the transformer to absorb more heat, and this cycle continues. Because both the oil and air are moved using machines, this method provides fast and powerful cooling, making it suitable for high-capacity transformers. **Figure 2.7.3** shows the type of transformer that utilises this method.

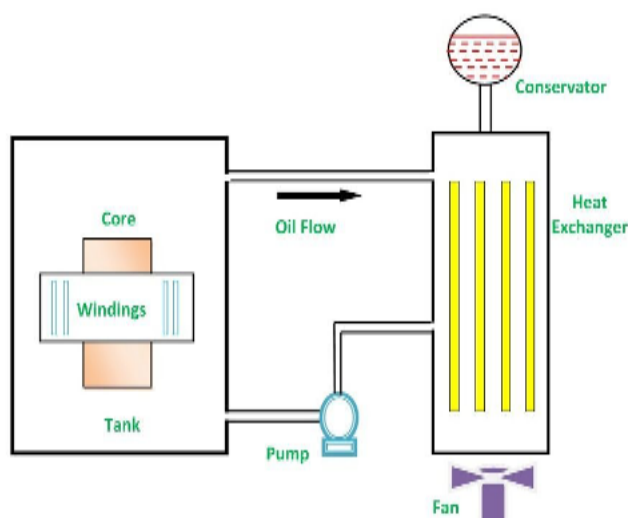


Figure 2.7.3: Oil Forced Air Forced Cooling of Transformer#

5. Oil Natural, Water Forced (ONWF)

Natural oil movement, but the cooling is done using water. The Oil Natural, Water Forced (ONWF) cooling method keeps large transformers operating efficiently by using a clever oil-and-water system. When electricity flows through the transformer, its copper coils and metal core generate heat, which is absorbed by the surrounding oil. This heated oil naturally rises to the top and flows into a heat exchanger, where it transfers its heat to circulating water without mixing. The cooled oil returns to the transformer, while the warmed water exits, maintaining a continuous cooling cycle. This process is highly effective in hot climates like Ghana's because water removes heat far better than air alone.

ONWF cooling offers key advantages for transformer performance and longevity. Maintaining stable temperatures, it prevents damage to the transformer's insulation and electrical components. The system's efficiency allows transformers to handle heavy power loads reliably while reducing energy waste. Like our body's sweat system, this natural water-assisted cooling ensures transformers can operate safely for years, providing the steady electricity supply we depend on daily. Its simplicity and effectiveness make it ideal for large transformers in power networks. **Figure 2.7.4** shows the type of transformer that utilises this method.

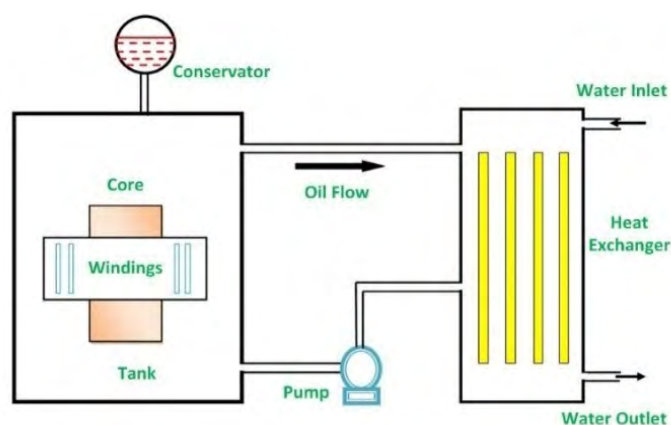


Figure 2.7.4: Oil Natural, Water Forced Cooling of Transformer

6. Oil Forced, Water Forced (OFWF)

Both the oil and water are moved by pumps. This is the most powerful cooling method. The Oil Forced, Water Forced (OFWF) cooling method is an advanced system designed to keep large transformers operating efficiently under heavy loads. In this system, specialised pumps actively circulate both oil and water to manage heat effectively. As the transformer operates, oil absorbs heat from the core and windings before being forcefully pumped to a heat exchanger. Simultaneously, cool water is pumped through separate channels in the exchanger, where it draws heat away from the oil without the two liquids ever mixing. This dual-pump system ensures rapid, consistent cooling regardless of external temperatures, making it particularly suitable for Ghana's warm climate and ideal for high-capacity transformers in power stations and industrial facilities.

This forced cooling method offers several key advantages over natural convection systems. The active pumping mechanism allows for more precise temperature control, preventing overheating even during peak demand periods. By maintaining optimal operating temperatures, the OFWF system protects the transformer's insulation and internal components, significantly extending its service life while improving energy efficiency. The design is especially valuable in our tropical climate where ambient air cooling alone may be insufficient. Much like how advanced cooling systems enable high-performance engines to work harder without overheating, OFWF cooling ensures transformers can reliably meet our growing electricity needs while minimizing maintenance requirements and power losses.

In summary, cooling is necessary to stop transformers from overheating and getting damaged. Small transformers use natural air or oil to cool down. Bigger transformers need fans or water to cool them faster. Just like humans use fans, breeze, or water to cool off, transformers also need their own ways to stay cool while working hard.

Voltage Regulation in Transformers

Voltage regulation is a measure of how well a transformer maintains steady output voltage when the electrical load changes. Think of it like a water pump's ability to maintain good

pressure, whether few or many taps are open. It is one of the most important characteristics of any transformer, especially here in Ghana, where we often experience voltage fluctuations.

Imagine you are using a garden hose to water plants. When you are the only one using the hose, the water comes out with strong pressure. But when three more people connect their hoses to the same tap, the water pressure drops significantly. This is exactly what happens in a transformer: as more electrical “load” (appliances) are connected, the output voltage tends to drop.

Technically speaking, voltage regulation measures how much the transformer’s output voltage decreases when going from no load (no appliances connected) to full load (maximum capacity being used). We calculate it using a simple formula that compares these two voltage readings:

$$\text{Voltage Regulation, V. R} = \frac{\text{No load voltage} - \text{full load voltage}}{\text{No load voltage}} \times 100\%,$$

$$\text{V. R} = \frac{E_2 - V_2}{E_2} \times 100\%,$$

Giving a practical example from our Ghanaian context, supposing we have a transformer powering part of your neighbourhood. When nobody is using electricity at night (no-load), we might measure 240 volts. But during peak hours when everyone is cooking, watching TV, and using lights (full-load), the voltage drops to 220 volts.

Plugging these numbers into our formula:

$$[(240\text{V} - 220\text{V}) \div 240\text{V}] \times 100\% = 8.33\% \text{ regulation}$$

This 8.33% shows how much the voltage “sags” under load. Ideally, we want this percentage to be as low as possible. Typically, V.R, less than 5%, is a good performance. When regulation is poor (above 10%), it results in problems such as:

1. Lights dimming when the refrigerator turns on
2. Phone chargers getting unusually hot
3. Appliances not working at full power

In power systems, engineers work hard to achieve good voltage regulation through using high-quality transformer materials, proper design of the windings, adequate cooling systems, among others.

Note: The voltage drop under load is caused by the voltage drop across the transformer’s internal impedance (winding resistance and leakage reactance). A higher impedance leads to a larger voltage drop and thus a higher (worse) voltage regulation.

Activity 2.7.1 Transformer – Cooling Methods and Voltage Regulation

Scenario

A local electrical company is designing transformers for different environments. You are part of the team that needs to understand transformer cooling methods and voltage regulation to ensure safe and efficient operation.

Task

Investigate two cooling methods used for dry-type transformers and recommend one suitable for transformers up to 15 MVA. Explain voltage regulation and discuss three cooling methods for oil-filled transformers.

Materials needed

1. Diagrams or models of dry-type and oil-filled transformers
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large sheets of paper, markers, pens
5. Notebooks, pens

Step 1: Class Discussion

Discuss with your classmates

1. What cooling methods are used in dry-type transformers?
2. Why is cooling important for transformers?
3. What does voltage regulation mean in transformers?
4. What are the cooling methods for oil-filled transformers?

Step 2: Group Research and Summary

1. Form groups of 3 to 5 members. Assign roles: Researcher, Note-taker, Presenter, Artist.
2. Watch the video on transformer cooling methods and voltage regulation.
3. Use this link to video: <https://youtu.be/OM2h6DoCVNA?si=69d95BMGLFiIvkSH>



4. While watching the video, find the answers to the questions below. Use other resources like the internet, books, etc.
 - a. List two cooling methods for dry-type transformers.
 - b. Choose one cooling method suitable for transformers up to 15 MVA and explain your choice.
 - c. Describe three cooling methods used for oil-filled transformers.
 - d. Explain what voltage regulation is and why it matters.

Step 3: Create Visual Aids

1. Draw labelled diagrams showing dry and oil-filled transformer types:

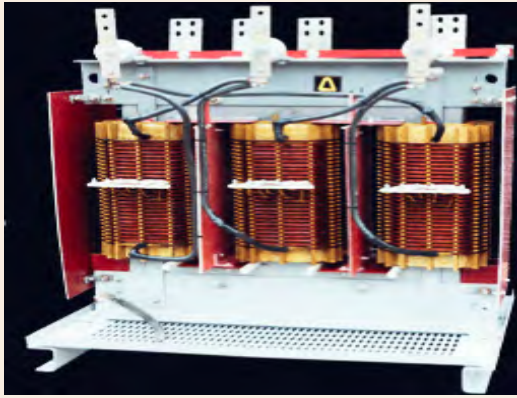


Figure C: Dry-type transformer



Figure D: Oil-filled transformer

2. Map two cooling methods to each
 - a. Dry-type transformers.
 - b. Oil-filled transformers.
3. Write a brief explanation of voltage regulation.

Step 4: Present Your Findings

1. Present your group's diagrams and explanations to the class.
2. Explain your recommendation for cooling dry-type transformers up to 15 MVA.
3. Be ready to answer questions.

Step 5: Class Questions and Feedback

Ask questions about other groups' presentations. Listen carefully and provide helpful feedback to your classmates.

Step 6: Individual Reflection

Reflect and write answers to these questions in your notebook, worksheet or tablet:

1. Which cooling method would you recommend for dry-type transformers up to 15 MVA, and why?
2. How does voltage regulation affect transformer performance?
3. Which oil-filled transformer cooling method seems most effective and why?

REVIEW QUESTIONS

1. A 20 MVA oil-filled transformer uses Oil Forced Air Forced (OFAF) cooling.

Given

Oil flow rate = 800 litters/min

Airflow rate = 1200 m³/min

Ambient temperature = 30°C

Maximum allowable oil temperature = 85°C

Calculate the cooling efficiency if the transformer dissipates 150 kW of heat losses.

2. A factory uses two transformers

Transformer A: Dry-type, Air Forced (AF) cooling, rated 10 MVA

Transformer B: Oil-filled, Oil Natural Air Natural (ONAN), rated 10 MVA

Which transformer is better suited for a hot climate like Ghana, and why?

3. A 11 kV/400 V distribution transformer has

No-load secondary voltage (E_2) = 410 V

Full-load secondary voltage (V_2) = 390 V

Calculate the voltage regulation. Is this within acceptable limits?

4. A 50 kVA transformer has

No-load voltage = 240 V

Voltage regulation = 6%

What is the full-load voltage? Would this cause issues for sensitive equipment?

UNIT 8 COMMON FAULTS WITH HOME APPLIANCES

INTRODUCTION

In Year 2, you learned that resistors and inductors are passive components—they do not supply power but respond to electrical energy. Resistors control current flow, while inductors store energy in a magnetic field when current passes through them. In homes, appliances mainly act as resistive or inductive loads. Electric kettles, toasters, and filament bulbs are resistive loads that convert electrical energy into heat or light. Refrigerators, washing machines, and ceiling fans contain motors and are inductive loads, operating through electromagnetic principles where magnetic fields create motion.

Today's lesson builds on this by focusing on the common failure symptoms of resistive and inductive loads, such as overheating and motor winding burnout. The fundamental differences in the operation of these appliances, classification of faults and the faults associated with resistive and inductive loads will be examined in this unit. Understanding these failures helps you diagnose appliance faults and maintain electrical safety in homes and communities.

KEY IDEAS

- Resistive loads like electric kettles and bulbs convert electricity directly into heat or light and often fail due to broken heating elements or burnt-out filaments.
- Inductive loads like refrigerators and fans use electric motors and commonly develop faults such as worn-out bearings or failed starting capacitors.
- You can identify a resistive appliance because it does not have moving parts and heats up quickly when powered.
- Inductive appliances make humming sounds when starting and may fail to work if their capacitors or motor windings get damaged.
- When servicing resistive appliances, always check for broken wires and test heating elements for continuity using a multimeter.
- For inductive appliances, inspect capacitors for bulging or leaks and listen for unusual noises that indicate motor problems before attempting repairs.

CLASSIFICATION OF ELECTRICAL APPLIANCES AND COMMON FAULTS ASSOCIATED WITH THEM

Electrical Appliance

An electrical appliance is any tool, device, or machine that uses electricity to do a specific job. These are things we use every day in our homes, schools, and workplaces. For example, a refrigerator uses electricity to keep food cold, a ceiling fan uses it to circulate air and cool down a room, and an air conditioner also uses electricity to make a room cooler and more comfortable. All of these are examples of electrical appliances because they rely on electrical power to function.

A Load

A load is anything that uses electricity when connected to a power source. So, when a fan is switched on at home, the fan becomes a load because it is now using up electrical energy to work. In simple terms, every electrical appliance is a load because it consumes electricity. However, not all loads are what we normally call appliances. Some loads are just small parts inside a machine or circuit, like resistors or coils, that still use electricity but do not perform a full function on their own like a TV or microwave would.

Loads can generally be divided into two main types and they are **resistive loads** and **inductive loads**. Resistive loads are devices that produce heat when electricity flows through them. Common examples include an electric iron, an electric heater, or a hot plate. These items get hot because they resist the flow of electricity, and that resistance produces heat.

Inductive loads, on the other hand, are devices that usually have moving parts inside them. These loads make use of coils and motors to work. When electricity flows through them, they create magnetic fields which help them move or spin. Good examples of inductive loads are fans, refrigerators, and water pumps, which rely on motors to perform their function.

In summary, an electrical appliance is something we use that runs on electricity to do a specific job. A load is anything that uses electricity, whether it is a full appliance or just a small part in a circuit. And these loads can either be resistive, which produce heat, or inductive, which involve movement or spinning with the help of motors. **Figure 2.8.1** shows a picture of a pressing Iron (An example of a resistive load).



Figure 2.8.1: A picture of a water heater (An example of a resistive load).



Figure 2.8.2: Water Heater (An example of a resistive load)

A resistive Load

A resistive load is a type of electrical load that uses electricity mainly to produce heat. It consumes only what is called active power, which is the real power that does useful work. This means that all the electrical energy it takes in is used directly, without wasting any in other forms like magnetism. You can find resistive loads in many of the things we use every day. For example, an electric iron, a hot plate, or an electric heater are all resistive loads.

When you switch them on, they begin to heat up right away because the electrical energy is being turned into heat. These devices do not have motors or moving parts. They simply get hot when electricity flows through them. One interesting thing about resistive loads is how the voltage and current behave. In simple terms, voltage is the force that pushes electricity through a wire, and current is the flow of electricity.

In a resistive load, the voltage and current rise and fall at the same time. They are said to be in phase, meaning they move together like two people dancing in perfect step. There is no delay between the voltage and the current. Because of this perfect timing, resistive loads use electrical power in a very efficient way. All the power that comes in is used for the intended purpose, usually to produce heat.

In summary, a resistive load is a device that uses electricity to produce heat, without any moving parts or magnetic effects. It uses only active power, and the voltage and current work together in perfect timing. **Figure 2.8.3** shows a phasor diagram of a Resistive load.

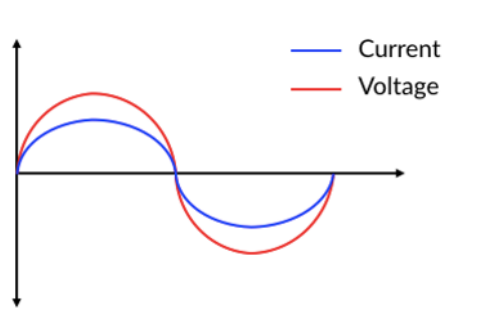


Figure 2.8.3: Resistive load

In a resistive AC circuit, the voltage and current maintain perfect synchronisation, rising and falling together in harmony. This alignment occurs because resistive elements like

heating coils or incandescent light bulbs convert electrical energy directly into heat or light without introducing any time delay between the voltage and current.

When represented on a phasor diagram, both the voltage and current vectors point in precisely the same direction, typically along the 0° reference axis. This perfect alignment results in a power factor of 1, indicating that all the power delivered to the load is being used effectively as real, usable power with no energy being temporarily stored and returned to the system as happens with reactive loads.

The straightforward relationship between voltage and current in resistive loads makes them the simplest type of electrical load to analyse and understand. This fundamental behaviour forms the basis for more complex circuit analysis involving capacitive or inductive elements.

Example of Resistive Load

1. Pressing Iron
2. Water Heater
3. Kettle
4. Electric stoves

Properties of Resistive Load

1. These loads consume only active power
2. Voltage and current waveforms of such loads are perfectly in phase with each other.
3. Power factor of such a load is unity
4. Power always flows from the source to the load.

Inductive Loads

An inductive load is a type of electrical load that mainly uses what is called reactive power. This kind of power does not do useful work like producing heat or light directly. Instead, it creates magnetic fields that help machines with moving parts to work; especially those that have motors or coils inside.

Examples of inductive loads are very common in homes and workplaces. They include devices like ceiling fans, refrigerators, blenders, water pumps, and air conditioners. All of these machines use motors that need magnetic fields to spin or move. These magnetic fields are made using reactive power. In simple terms, voltage is like the pressure that pushes electricity through wires, while current is the flow of electricity itself.

In inductive loads, the voltage and the current do not move together. Instead, there is a delay between them. The current “lags behind” the voltage. They are said to be out of phase with each other by about 90 degrees. You can think of it like this: imagine two people running a race, but one of them (the current) starts running a bit late every time. That small delay between the voltage and current is what we mean by “out of phase”.

In summary, an inductive load is any device that uses electricity to create magnetic fields, which are needed to run motors and moving parts. It mainly uses reactive power, and in this type of load, the current lags behind the voltage. They do not move together as they do in resistive loads. **Figure 2.8.4** shows a phasor diagram of an inductive load.

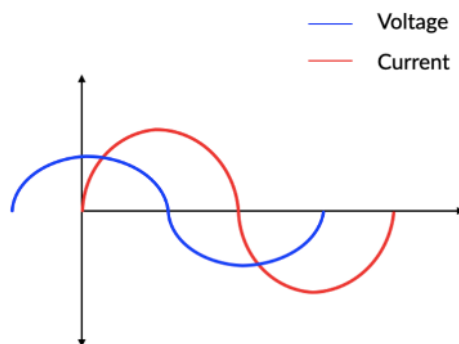


Figure 2.8.4: Inductive load

Let us explain this inductive load concept in a way that connects to your everyday experiences here in Ghana. Picture your ceiling fan when you turn it on, you press the switch (that is the voltage), but the fan blades take a second to start spinning (that is the current lagging behind). This delay happens because of something special inside these motor-powered appliances.

The magic and sometimes the headache come from coils of wire inside devices like the refrigerator, blender, or electric sewing machine. When electricity tries to flow through these coiled wires, they create an invisible magnetic field that fights against the incoming current at first. It is like when you're trying to push a heavy cart - you have to push hard to get it moving, but once it is going, it keeps moving more easily.

This explains several things you have probably noticed:

1. Why your fan makes that “hmm” sound for a second before the blades start turning
2. Why appliances with motors sometimes trip lights when starting up
3. Why they often have those little black cylinders (capacitors) attached to help them start

When these appliances stop working properly, common problems include:

1. A burned-out motor (you might smell something burnt)
2. A failed capacitor (the appliance hums but will not start)
3. Worn-out parts causing the motor to struggle

Examples of Inductive Load

1. Electric Motor
2. Fan
3. Washing machine
4. Drill machine
5. Blender

Figure 2.8.5a and 2.8.5b show pictures of a Blender and a washing machine (Examples of an Inductive load).



Figure 2.8.5a: Blender



Figure 2.8.5b: Washing Machine

Properties of Inductive Loads

1. This load consumes only reactive power
2. Voltage and current waveform of such loads are out of phase with each other by 90 degrees.
3. Power factor of such load is lagging
4. Power flows from source to load and load to source

Faults Associated with Electrical Appliances

An electrical fault is a problem in an electrical system that stops it from working the way it should. It can cause damage to machines like transformers, generators (alternators), power lines, and busbars (which are used to distribute electricity). When a fault happens, it can lead to equipment breakdown, interrupt electricity supply, and in some cases, it can even cause the death of people, birds, or animals who come into contact with the faulted part.

Classification of Faults

Electrical faults are mainly grouped into two main types

1. Open-Circuit Faults

This type of fault happens when there is a break in the wire or cable that carries electricity. When this break happens, electric current cannot flow, and the current in that part becomes zero. That is why these are also called series faults because the break happens in the same line or series path where the current is supposed to flow.

Causes of Open-Circuit Faults

- a. When a joint in a cable or overhead line fails (the connection becomes loose or broken).
- b. When one or more parts of a circuit breaker fails to close properly.
- c. When a fuse melts or blows in one or more phases, cutting off the current path.

2. Short-Circuit Faults

This type of fault happens when two parts of a circuit that should not touch each other accidentally become connected. This connection has very low resistance, so a large amount of current flows suddenly. These faults are also called shunt faults. Short-circuits are dangerous because the high current can cause fire or damage to appliances.

Causes of Short-Circuit Faults

- a. Lightning strikes or high-voltage switching can break through insulation and cause a fault.
- b. Dirt, dust, or other particles on electrical insulators can create a path for electricity to flow where it shouldn't, causing a flashover (an unwanted spark or arc).
- c. A broken power line might fall to the ground and touch trees, buildings, or people.
- d. Two or more wires (phases) might touch each other directly, causing a short circuit.

Note

There are other types of electrical faults too, such as ground faults, where a live wire touches the earth or metal parts.

Effects of Open-Circuit Faults

An open-circuit fault happens when a wire breaks or a connection is cut. This stops electricity from flowing in part of the circuit just like when one wire of your phone charger breaks and it stops working.

What happens when this fault occurs?

The machine that produces electricity, called the alternator, does not get enough load (demand for power). Because of this, the alternator starts spinning faster than normal. When it spins too fast, it causes an increase in frequency meaning the power supply is not stable. This can damage electrical appliances.

Effects of Short-Circuit Faults

1. The equipment can be damaged due to overheating caused by heavy current associated with short-circuit faults.
2. There may be fire hazards caused by arcing in the faulty element. There is a chance of spreading of the fire to other parts of the system.
3. There may be a reduction in the supply voltage of healthy feeders

Activity 2.8.1 Effects of Resistive and Inductive Loads Faults

Scenario

In many Ghanaian communities, maintaining household electrical appliances is important for safety and reliable use. Electrical devices work either as resistive loads,

which convert electricity directly to heat or light, or as inductive loads, which use electromagnetic principles to operate motors. Understanding the differences between these load types, recognising common faults, and knowing how faults affect appliance performance helps in improving maintenance and preventing accidents.

Task

Differentiate between resistive and inductive loads. Analyse the effects of common electrical faults on household appliances.

Materials needed

1. Diagrams or pictures of household appliances or the real objects e.g. kettles, fans, refrigerators.
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens
5. Notebooks, pens

Step 1: Class Brainstorm

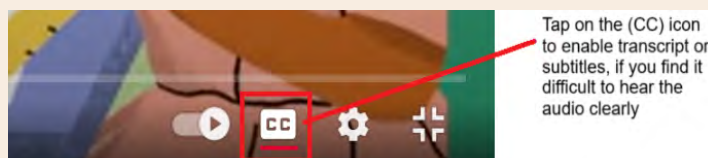
Work in pairs and discuss the following

1. What defines a resistive load? Use your ideas here to help you complete the definitions section in Step 2.
2. What defines an inductive load? You will confirm your thoughts in Step 2 and use them to create clear explanations in Step 3.
3. What are examples of appliances for each type? Keep your list so you can add pictures or sketches of these appliances in Step 3.
4. Why is it important to know these differences? Your answers will form the basis for the “importance” section of your Step 3 poster or presentation.

Step 2: Group Research and Table Completion

1. In groups of 3 to 5 learners research after watching a video on electrical faults and their effects.
2. Roles are assigned: Researcher, Note-taker, Presenter, Artist. Use resources to complete the table below:

Follow the video link: <https://youtu.be/98end5KEKPE?si=4HBXneJaBXYzITyJ>



S/N	Load Type	Example Appliance	Common Faults	Effects of Faults
1	Resistive			
2	Inductive			

3. These questions will guide you and your team
 - a. What faults commonly affect resistive appliances?
 - b. What faults occur in inductive appliances like motors?
 - c. How do faults influence appliance safety and function?

Step 3: Create Visual Aids

1. Prepare a circuit and phasor diagram of resistive and inductive load (**Figure E**):

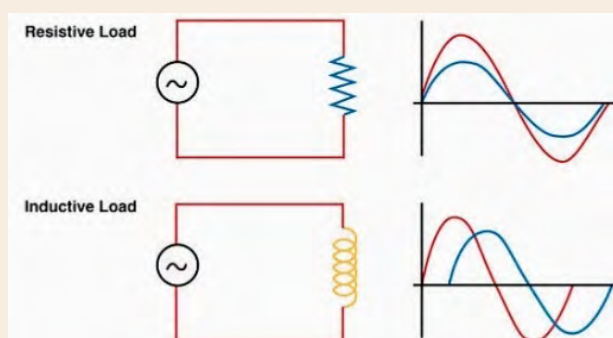


Figure E

2. Create a poster showing
 - a. Examples of resistive and inductive appliances
 - b. Typical faults for each load type
 - c. Effects of these faults

Step 4: Present Findings

Groups present posters or diagrams to the class, explaining

1. Differences between resistive and inductive loads
2. Common faults and their effects
3. How this knowledge supports appliance maintenance and safety

Step 5: Questions and Feedback

Engage with other groups' presentations through questions and meaningful feedback.

Step 6: Reflection and writing

Individually reflect and write answers to these questions

1. How do resistive and inductive loads differ?
2. What are common faults in each load type?
3. How do these faults affect appliance operation and safety?
4. Why is early fault detection important?

REVIEW QUESTIONS

1. What is the difference between resistive and inductive loads in home appliances? Give one example of each.
2. Why do inductive loads cause more wear and tear in switches compared to resistive loads? How can this be prevented?
3. A ceiling fan (inductive load) stops working suddenly but still makes a humming sound. What could be the fault, and how can it be fixed?
4. An electric iron (resistive load) is not heating up. What are three possible faults, and how can you troubleshoot them?

SECTION

3

UNIT 9 COMMON FAULTS WITH ELECTRICAL APPLIANCES

INTRODUCTION

Wiring accessories are devices used in electrical installations to connect, control, protect, or safely terminate electrical wiring. Common accessories like socket outlets, lamp holders, and ceiling roses help ensure electrical systems operate safely and efficiently. Household appliances such as lamps, electric irons, toasters, kettles, blenders, washing machines, and refrigerators, whether resistive or inductive loads are connected to the system through these accessories. You studied the classification of faults and faults related to resistive and inductive loads in previous unit. Building on that, this unit focuses on troubleshooting, the process of identifying, diagnosing, and fixing faults in electrical systems or appliances and servicing, which involves routine maintenance to keep equipment efficient and prevent problems. Understanding troubleshooting and servicing is important for maintaining safe and reliable electrical systems in homes and workplaces.

KEY IDEAS

- Accessories must suit the environment – Use weatherproof types for outdoor or damp areas to prevent faults.
- Correct accessories ensure safe installation – The right item helps avoid short circuits, shocks, and overheating.
- Domestic and industrial wiring need different accessories – Homes use standard types; factories need stronger, heavy-duty ones.
- Good installation helps the system work well – Loose or wrong connections can cause breakdowns or danger.
- Use strong, standard accessories only – Choose tested and approved brands for long life and safety.
- Wiring accessories have different uses – Switches control power, sockets provide connection, and lamp holders hold bulbs.

TROUBLESHOOTING AND SERVICING ELECTRICAL APPLIANCES

Troubleshooting Home Appliances

Fixing home appliances is not always easy, but with the right knowledge and tools, you can succeed. To begin, always use a **wiring diagram**. Think of it like a roadmap that shows how the parts are connected and how current flows through the system. Every wiring diagram has three key sections:

1. Line Side (Input): Where power enters the system—usually about 240V.
2. Control Side: Manages how the appliance works. The voltage here may be lower.
3. Load Side: Where the appliance does its work, like heating or spinning.

Breaking the circuit into these parts helps you find faults faster and easier.

Steps to Follow When Troubleshooting Appliances

1. Check the Socket Outlet

- a. Use a voltage tester to see if there's power.
- b. Plug another device into the socket to see if it works.
- c. If the socket is faulty, get an electrician to fix or replace it.

2. Inspect the Electrical Cord and Plug

- a. Look for signs like burn marks or torn wires.
- b. Check the plug for a blown fuse.
- c. If the cord or plug is damaged, replace it with one that matches your appliance's type.
- d. Always unplug the appliance before making any repairs.

3. Read the User Manual

- a. The manual gives useful tips on fixing common problems.
- b. It may also give step-by-step instructions for simple repairs you can do yourself.

4. Check for Warranty

- a. Before doing any repairs, see if the appliance is still under warranty.
- b. If it is, send it back to the supplier for free fixing.
- c. If you open it yourself, you might lose the warranty.

Common Appliance Problems and How to Fix Them

Electric Burner Not Working

Possible Causes

1. Heating element is damaged
2. Switch is faulty
3. Wiring is loose

Solution: Test each part with a continuity tester. Replace the faulty one.

Electric Iron Not Heating

Possible causes

1. Burnt heating element
2. Broken thermostat
3. Loose wiring

Solution: Use a continuity tester. Replace the part that is not working.

Iron Too Hot or Too Cold

Possible Cause

Faulty thermostat or disconnected wires

Solution: Replace the thermostat. For proper temperature control, let a professional handle the replacement and calibration.

TROUBLESHOOTING AND SERVICING ELECTRICAL WIRING CIRCUITS

Troubleshooting Electrical Circuits

Before you start working on any electrical circuit, make sure you have the right tools. All tools must be in good working condition because using broken ones can lead to accidents or electric shock.

Safety Precautions When Troubleshooting Circuits

Electricity is powerful and dangerous, so always follow safety rules to protect yourself and others:

1. Wear your safety gear like gloves and goggles (PPE).
2. Switch off the power before starting work.
3. Ground the circuit properly to avoid shocks.
4. Do not work alone—have someone nearby for support.
5. Keep your working area clean and organized.

Common Electrical Circuit Problems and Their Solutions

Problem	Solution
Blown Fuse	Change the fuse using one with the same amp rating.
Tripped Circuit Breaker	Switch it off, then on again to reset it.
Faulty Switch	Remove and replace the broken switch.
Loose Connection	Tighten the loose part or change it if damaged.
Ground Fault	Find and fix damaged insulation or replace faulty parts.

How to Troubleshoot Circuit Breakers

Circuit breakers help protect electric circuits from too much current or short circuits. But sometimes they stop working properly.

Here is how to check them:

1. Switch off the circuit breaker. If you are unsure which one, turn off the main power.
2. Carefully remove the cover of the breaker panel.
3. Look at the breaker—check for burns, cracks, or if it tripped.
4. If it tripped, reset it. If it trips again, there may be an overload or fault in the circuit.
5. Use a multimeter to test the voltage between the live and neutral wires.
6. If you are unsure about anything, call a trained electrician for help.

How to Troubleshoot Electrical Wiring

Wiring problems can be risky. Here are good ways to check and fix them safely:

Method	What it Means
Visual Inspection	Check with your eyes for broken, burnt, rusty or loose wires
Continuity Test	Use an ohmmeter to see if current can pass through the wire
Voltage Test	Use a voltmeter to check if electricity is present and if the voltage is correct

If the wires are damaged or loose, fix them or replace them. Sometimes rewiring is needed to make the circuit safe.

How to Maintain Electrical Wiring Circuits

To keep electrical circuits working well and safely:

1. **Inspect Regularly:** Check for damaged wires or loose connections.
2. **Clean Components:** Wipe dust off sockets, switches, and lamp holders.
3. **Tighten Connections:** Loose parts can cause faults. Make sure all parts are firmly connected.

Important note

Always switch off power before any repairs or maintenance. Wear safety gear like gloves and goggles. For big issues, get help from a licensed electrician.

Activity 3.9.1 Troubleshooting and Maintaining Electrical Appliances

Scenario

A community electrical maintenance team is working to keep household appliances and electrical systems safe and functional. The team needs to diagnose faults in appliances like electric irons and lighting circuits and develop a maintenance plan to prevent future problems.

Task

Explain how to troubleshoot an electric iron that is not heating and how to solve the problem. Explain how to troubleshoot a lighting circuit that is not working. Outline a maintenance plan to keep electrical systems safe and efficient.

Materials needed

1. Diagrams or images electric irons and lighting circuit
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens and notebooks

Step 1: Class Brainstorm

Work in pairs and discuss these with a classmate:

1. What types of household electrical appliances and circuits are commonly used? Use your list to guide the examples you will research and describe in Step 2.
2. What faults might develop in these appliances and circuits? You will confirm these in Step 2 and use them in your Step 3 fault-and-solution chart.
3. How can faults affect appliance or circuit performance? Keep your ideas so you can expand them into the “effects” section of your Step 3 poster.
4. Why is troubleshooting important? Your answers will help you prepare the “importance” and “safety” sections in Step 3.

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners.
2. Assign roles: Researcher, Note-taker, Presenter, Artist.
3. Watch the provided video on troubleshooting and maintenance of electrical appliances and circuits.

Follow the link here: <https://youtu.be/SnRXD-0oXZo?si=b7-RUcL3vgFRReX1>



4. Use textbooks, internet, and other resources to complete the table below:

Appliance/ Circuit	Operation & Function	Faults Identified	Testing Method	Solution to Fault
Electric Iron				
Lighting Circuit				

5. The following questions will guide you:
- How does each appliance or circuit work?
 - How can a faulty appliance/circuit be distinguished from a working one?
 - What tests can diagnose the fault?
 - How can the fault be repaired or solved?

Step 3: Create Your Poster and Diagram

1. Draw a labelled diagram (Figure F) or build a model of

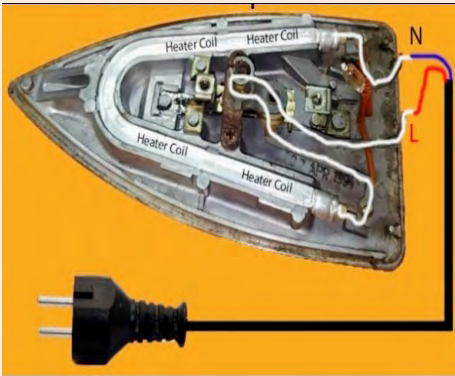


Figure G: Iron circuit

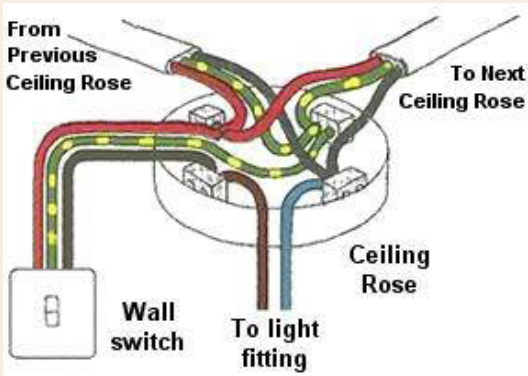


Figure H: Lighting circuit

- An electric iron and
 - a lighting circuit showing how they work
 - List common faults and how to detect them
2. Create a poster showing
- Troubleshooting steps for the electric iron and lighting circuit
 - A maintenance plan outline to keep electrical systems safe

Step 4: Present Your Work

Present your diagrams and poster to the class. Explain:

1. How to troubleshoot an electric iron that is not heating

2. How to troubleshoot a lighting circuit that is not functioning
3. How regular maintenance prevents faults and ensures safety

Step 5: Ask and Answer Questions

Listen carefully to questions from classmates and answer clearly. Give specific feedback to others.

Step 6: Reflect and Write

In your notebook or tablet, individually answer these reflective questions:

1. What have you learned about troubleshooting electrical appliances and circuits?
2. How can faults be identified and solved effectively?
3. What key steps should be included in a maintenance plan?
4. Why is regular maintenance important for electrical safety and efficiency?

EXTENDED READING

1. [Electrical Troubleshooting - Solve Circuit Issues](#)
2. [Troubleshooting Home Appliances: A Complete Step-by-Step Guide](#)
3. [Electric Iron Problems and Solutions](#)
4. [Troubleshooting Electrical Circuits: Expert Tips & Guidance](#)

REVIEW QUESTIONS

1. Identify the **BEST** step to confirm if a pressing iron's heating element is faulty during servicing.
 - A. Check wire continuity using a multimeter
 - B. Examine the iron's metal surface visually
 - C. Feel the heat with your bare hand
 - D. Switch the iron on for long hours
2. Select the **MOST** reliable method to diagnose why a ceiling fan spins slowly during operation.
 - A. Inspect the fan blades for balance
 - B. Measure voltage at the motor terminals
 - C. Oil the motor without testing it
 - D. Replace the capacitor immediately
3. Choose the **CORRECT** approach to solve a blender that powers on but does not rotate its blades.
 - A. Adjust speed control knob randomly
 - B. Open and clean the motor brushes
 - C. Replace the power cord directly
 - D. Test motor coil resistance with meter
4. Determine the **BEST** action to take when a lighting circuit trips immediately after switching on.
 - A. Check circuit breaker with a tester
 - B. Inspect the bulb for broken filament
 - C. Replace the switch with a new one
 - D. Tighten all terminals in the socket
5. Choose the **MOST EFFECTIVE** way to trace a short circuit in a two-way lighting system.
 - A. Disconnect all wires and restart circuit
 - B. Observe all switches during fan operation
 - C. Test wire insulation using a megger
 - D. Use a screwdriver to tap all joints
6. Identify the **SAFEST** method to verify power loss in a ring circuit of a workshop.
 - A. Connect a load to the socket outlet

- B. Measure current flow with a voltmeter
- C. Remove earth wire and observe result
- D. Test continuity with a multimeter

UNIT 10 MAINTENANCE, ELECTRICAL MACHINE FAULT AND CIRCUIT, AMPLIFIER, LOGIC GATES)

INTRODUCTION

In earlier units, faults were classified, and faults related to resistive and inductive loads were studied. Troubleshooting, the process of identifying, diagnosing, and fixing problems and servicing, which is routine maintenance to keep equipment working well, was also introduced. You will now focus on common types of faults that occur specifically in electrical machines. These include electrical faults such as open circuits and short circuits within components like windings, insulation, and connections. Mechanical faults are also covered, including issues like bearing wear, rotor misalignment, loose couplings, and excessive vibration. You will explore the causes and effects of these faults, how to detect and diagnose them, repair methods, and maintenance techniques.

KEY IDEAS

- Broken rotor bars cause the motor to vibrate, overheat, and lose power, leading to inefficient operation and possible motor failure.
- Early detection of bearing faults like unusual noises, vibrations, or overheating prevents costly motor failures and downtime by catching issues before they escalate.
- Electrical faults in machines can occur due to problems like damaged windings, insulation failure, broken connections, or poor power supply.
- Regular maintenance practices such as proper lubrication, alignment checks, and contamination control are essential to extend bearing life and ensure machine reliability.
- Stator winding faults, often caused by overheating or insulation breakdown, can burn the windings and completely stop the motor from working.
- Voltage surges, short circuits, and ground faults can seriously damage electrical machines, but using protective devices and regular maintenance can help prevent.

FAULT IN ELECTRICAL MACHINES

Electrical Faults and Their Effects

An electrical fault is a condition which can cause equipment failures (in transformers, transmission lines, alternators, busbars, etc.) and disturbs the normal working of the system failure and electric power supply interruption. It is a dangerous problem that can damage important equipment like transformers, power lines, generators, and switchboards. When these faults happen, they do not just break machines but can also cut off electricity supply and even cause serious harm or death to people, birds, and animals nearby.

Types of Faults in Electrical Machines

Faults in electrical machines can be grouped into two main types. They are mechanical faults and electrical faults. Most faults happen because of everyday wear and tear, poor manufacturing, harsh weather conditions, or mistakes in how the machine is used or maintained. Fixing these faults early save money, keeps machines running longer, and prevents bigger breakdowns.

Common Mechanical Faults & Their Causes

1. Bearing Failures

Bearings help the motor shaft spin smoothly. If they do not get enough grease, get dirty, or carry too much load, they wear out fast. You will notice loud noises, strong vibrations, and eventually, the motor may stop working.

2. Broken Rotor Bars

Inside motors, rotor bars can crack or break due to constant stress, poor-quality materials, or extreme heat. When this happens, the motor runs unevenly, loses power, and gets too hot.

3. Vibration Problems

If the motor's rotating parts are unbalanced or not aligned properly, they shake too much. These shaking wastes energy, damages other parts, and leads to costly repairs.

4. Misalignment

When the rotor (moving part) and stator (stationary part) are not lined up correctly, they rub against each other. This causes extra friction, overheating, and wears out bearings and wires faster.

5. Overheating

Motors can get too hot if they are overloaded or do not have enough cooling. High heat weakens insulation, damages bearings, and eventually burns out the motor. Having knowledge in these faults helps spot problems early before they destroy machines or cause accidents. Regular checks, proper lubrication, and correct installation can keep electrical machines running safely and efficiently.

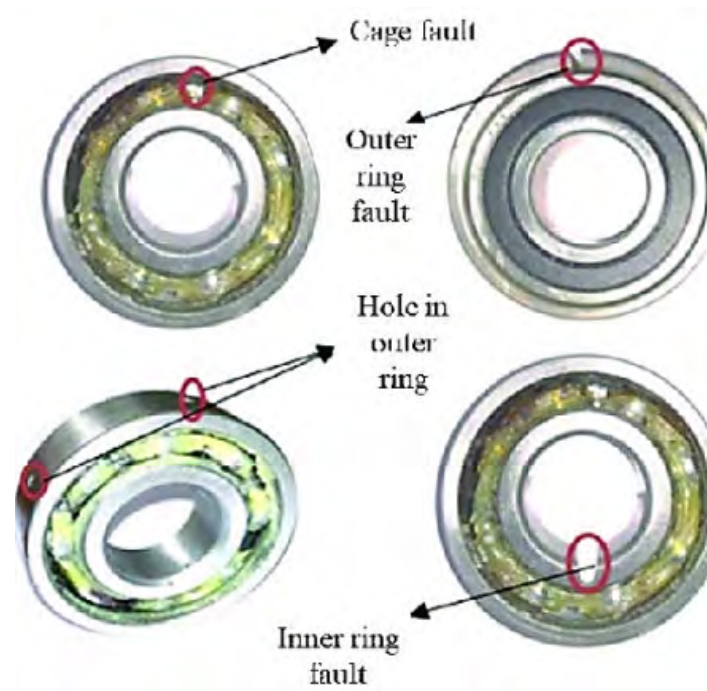


Figure 3.10.1: Types of bearing faults in electrical machines

Bearings are crucial components that allow motors and other electrical machines to run smoothly, but they can develop serious problems over time. Let us look at the four main types of bearing faults shown in your diagram.

First, there is the cage fault, where the part that keeps the bearing's rolling elements properly spaced gets damaged. This usually happens from lack of lubrication, too much force, or poor-quality materials. When the cage breaks, you will hear loud grinding noises as the bearing components crash into each other, and the machine might suddenly stop working.

Next is the outer ring fault, where cracks or pits form on the stationary outer part of the bearing. This often occurs due to misalignment, heavy loads, or corrosion. The machine will start vibrating badly, and you might feel the whole unit shaking during operation.

Then there is the hole in outer ring - a particularly serious problem where actual holes or deep wear marks appear. This happens when foreign objects like dirt or metal chips get inside, or from extreme pressure. When this occurs, parts can get completely stuck, creating dangerous screeching sounds and potentially causing the motor to burn out if not addressed immediately.

Finally, there is the inner ring fault, which affects the part that rotates with the motor shaft. Poor installation, rust, or misalignment can cause this. You will notice the shaft becoming loose and wobbly, leading to uneven operation and reduced power.

Spotting these problems early is crucial. Listen for unusual noises, watch for excessive vibration, and check for overheating. Regular maintenance, like proper lubrication and alignment checks, can prevent most of these issues and keep your machines running safely and efficiently for much longer.

Figure 3.10.2 shows a broken rotor bar, another fault in electrical motors



Figure 3.10.2: Broken rotor bar

The image shown above is a damaged part of an electric motor called the rotor. The rotor is the rotating part of the motor that works together with the stator (the stationary part) to produce motion. Inside the rotor are several metal bars, usually made of copper or aluminium, which help carry electrical current. These bars are very important because they help the motor spin and do useful work, like pumping water, turning a fan, or running a machine. Sometimes, one or more of these rotor bars can break. When this happens, we call it a broken rotor bar fault. This kind of fault can cause several problems with the motor.

First, the motor may begin to shake or make strange noises when it runs. This is because the spinning part is no longer balanced. Imagine riding a bicycle with one broken spoke in the wheel the ride would be rough and wobbly. Also, when a rotor bar breaks, the motor becomes weaker. It will not be able to perform its job properly. For example, a water pump motor might not be able to lift water as it should. The motor may also start to heat up too much, because the electricity is not flowing smoothly through the rotor. Just like how a phone gets hot when it has an internal fault, the motor too becomes hot.

Another effect of this fault is that the motor uses more electrical power than normal, trying to keep working. This wastes electricity and can increase your electricity bill. If the fault is not fixed, it can damage the motor completely. There are different causes of broken rotor bars. Sometimes, the motor gets damaged by rough use, like starting and stopping too quickly. Other times, it's because of poor-quality materials used during manufacturing.

Long-term overheating or constant vibration can also cause cracks in the rotor bars. To detect this fault, technicians use special tools. They can check the way the motor vibrates, measure how the electric current behaves, or use a thermal camera to look for hot spots inside the motor.

In summary, a broken rotor bar is a serious fault inside a motor. It causes the motor to be noisy, weak, hot, and less efficient. It should be fixed as soon as possible to prevent further damage and to keep the motor running smoothly. **Figure 3.10.3** shows a failure in a three-phase stator winding of an electrical motor, which is another fault in electrical motors



Figure 3.10.3: Failure in a three-phase stator winding of an electrical motor.

In an electric motor or generator, the stator is the part that does not move. It contains coils of copper wire called windings. These windings carry electric current and help to create a magnetic field that works with the rotor (the spinning part) to make the machine run.

In **Figure 3.10.3**, we are looking at a three-phase stator winding. That simply means there are three sets of wires working together, like a team, to carry electricity smoothly and powerfully. But something has gone wrong. You can clearly see a burnt section in the copper windings. Some of the wires are blackened and damaged. This is an example of a stator winding fault, which happens when there is too much heat or when the insulation (the covering on the wires) breaks down. The insulation is like the rubber on your phone charger. It keeps the wires from touching each other. If it fails, the wires can touch and create a short circuit, which can burn the wires. The following happens when this kind of fault occurs:

1. First, the part of the winding gets overheated, just like when a phone charger gets too hot and starts to melt.
2. This heat causes the wires to burn, leading to black marks and sometimes smoke or even a fire.
3. When this happens, the motor will stop working properly or may shut down completely.
4. The machine may also start to vibrate, make unusual noises, or trip the circuit breaker.

This kind of fault can happen for many reasons. For example, if the motor is overloaded (doing more work than it should), or if the cooling system fails and the motor gets too hot. It can also happen if the machine is not properly maintained, or if moisture gets inside and damages the insulation. To prevent this kind of damage, electricians and engineers check the motor regularly. They test the insulation, clean the windings, and make sure the machine is not overloaded.

In summary, the image shows a fault in the stator windings of a three-phase motor, where part of the copper wire has burned. This fault is dangerous because it can stop the motor, waste electricity, and even cause fires. That is why proper care, regular checks, and good wiring are very important in electrical machines.

Other Electrical Faults in Machines

1. Short Circuits

A short circuit happens when two wires that are not supposed to touch each other come into contact. This gives the electricity a shortcut, causing too much current to flow at once. Imagine two wires inside a fan touching each other. Sparks may fly, and the fan may stop working or even catch fire. This usually happens when the insulation (the covering around the wires) breaks down due to heat, damage, or wear and tear. As a result, the wires inside the machine overheat and may burn out quickly.

2. Open Circuits

An open circuit means there is a break or a cut in the electrical path. Electricity cannot flow through, just like how water cannot pass through a broken pipe. This could be caused by a cut wire, a loose connection, or a damaged switch. When this happens, the motor might not run at all, or it may run weakly because it is not getting the full power it needs.

3. Insulation Failures

The insulation is the, plastic or rubber covering around the copper wires. It keeps the wires from touching each other or metal parts. Over time, this insulation can wear out, especially if the machine gets too hot, is exposed to water or moisture, or is used for many years. When the insulation fails, wires can touch and cause short circuits or even ground faults, which may lead to the motor completely failing.

4. Overloading

Overloading happens when a machine is forced to work harder than it was designed for, like using a small blender to grind hard maize or stones. The motor tries to handle it, but it pulls too much current, making it overheat. This can damage the wires (windings), bearings, and other electrical parts inside the motor. The machine may suddenly stop working or give off a burning smell.

5. Voltage Surges

A voltage surge is a sudden increase in voltage, like when lightning strikes or when there is a problem with the electricity from ECG. It is like pushing too much water through a small pipe, something will burst. These surges can burn out sensitive parts of the machine. Using surge protectors or voltage regulators helps protect machines from this kind of damage.

6. Ground Faults

A ground fault occurs when electricity accidentally flows to the ground instead of staying in the wires. This can happen when wires touch metal parts that are connected to the earth (ground). Ground faults can cause electric shocks, machine damage, or even fire. That is why grounding (connecting the machine properly to the earth) is very important in all electrical setups.

In summary, electrical faults are serious problems that can damage machines, stop them from working, or even cause fire and injury. They are caused by things like damaged

wires, overheating, poor insulation, voltage problems, or bad connections. Taking care of machines, checking them regularly, and using protective devices can help prevent these faults and keep the machines running safely.

Activity 3.10.1 Faults in Electrical Machines and Diagnostics

Scenario

A technical team is working to maintain and improve the reliability of electrical machines in a community. The team's goal is to identify common faults, understand their effects on machine performance, and learn how to diagnose these faults effectively.

Task

State the two main categories of faults that occur in electrical machines. Analyse the effects of four common types of faults on electrical machines.

Materials needed

1. Diagrams or images of electrical machines and common faults (if available)
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens and notebooks

Step 1: Class Brainstorm

Think about faults that may occur in electrical machines. Discuss with classmates:

1. What are the two main categories of faults in electrical machines?
2. What types of faults can occur within each category?
3. How might these faults affect the performance of machines?
4. Why is it important to detect faults early?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners.
2. Assign roles: Researcher, Note-taker, Presenter, Artist.
3. Watch the video provided on electrical machine faults and diagnostics. Use textbooks and internet resources to complete the table below:

S/N	Fault Category	Fault Type	Description / Symptoms	Effects on Performance	Diagnostic Methods
1	Electrical				
2	Electrical				
3	Mechanical				
4	Mechanical				

4. Guiding questions

- What symptoms indicate each fault?
- How do faults impact machine safety and efficiency?
- What tools or methods are used to diagnose these faults?

Step 3: Create Your Poster and Diagram

- Draw a labelled diagram or create a poster or concept map (**Figure I**) that models an electrical machine showing areas where faults commonly occur.
- Poster should summarise:

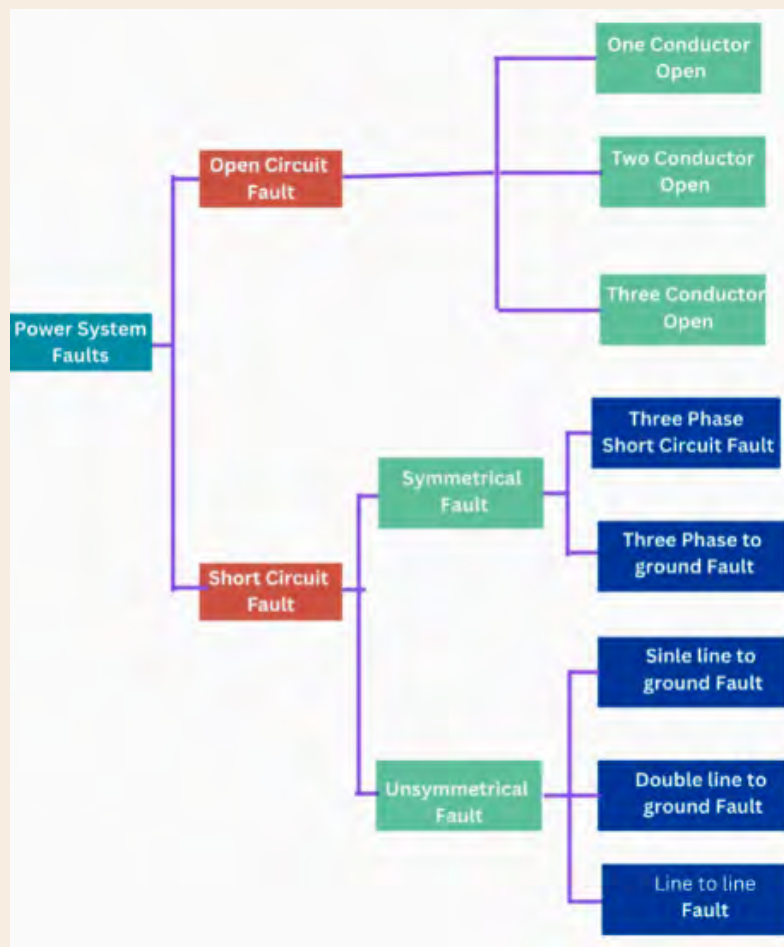


Figure I: Concept map of main faults

- The two main categories of faults and examples
- Effects of these faults on machines
- Diagnostic methods

Step 4: Present Your Work

Present your poster or diagram or concept map to the class. Explain:

- The two main categories of faults in electrical machines
- Four common fault types and their effects

3. Diagnostic methods used to identify faults

Step 5: Ask and Answer Questions

1. Listen carefully to questions from classmates. Answer clearly to help everyone understand.
2. Provide constructive feedback on others' presentations.

Step 6: Reflect and Write

In your notebooks, answer the following questions:

1. What are the two main categories of faults in electrical machines?
2. How do these faults affect machine performance?
3. Which diagnostic methods are most effective and why?
4. Why is early fault detection important for machine reliability?

EXTENDED READING

1. <https://electricalvoice.com/what-is-electrical-fault-types-causes-effects/#:~:text=An%20electrical%20fault,a%20power%20system.>
2. <https://ayanelectricians.co.uk/blog/common-electrical-faults-and-how-to-identify-them/#:~:text=September%2029%2C%202023-,In%20this%20article%2C%20you%20will%20learn%20about%20the%20most%20common%20electrical,Phone,-Your%20email>

REVIEW QUESTIONS

1. Your electric motor starts vibrating unusually and gives off a burning smell. On inspection, the rotor bars look discoloured and cracked. What type of fault is this, and what are the possible effects if it is not repaired?
2. A technician opens a motor and notices blackened, burnt windings in the stator section. What type of fault is this, what could have caused it, and how can it be prevented?
3. You are using a grinding machine at home, and suddenly the machine stops working completely. The socket is fine, but the machine is not receiving any power. What kind of fault could this be, and what might have caused it?
4. A lightning strike occurs during a storm, and afterwards, your water pump motor refuses to start. What type of fault may have occurred, and how can this be prevented in future?

UNIT 11 INTEGRATED CIRCUITS

INTRODUCTION

In Year 2, it will be recalled that Bipolar Junction Transistors (BJTs) and Field Effect Transistors (FETs), their construction, operation and applications were studied. An integrated circuit is one in which active components such as BJT and FET transistors, diodes and passive components such as resistors, capacitors and inductors are fabricated (formulated, put together) on a small single semiconductor chip (fragment). There is an extremely rapid growth in the number of transistors (as a measure of complexity) being integrated into circuits on a single silicon chip. Integration is characterised by reliability, low power consumption, extremely low weight and volume, low cost, coupled with an ability to cope easily with a high degree of sophistication and complexity.

Integrated circuits have made possible the design of powerful and flexible processors which provide highly intelligent and adaptable devices for the user. The most popular method of packaging digital logic ICs is Dual-in-Line (DIL), as exhibited in the various chip diagrams in the content. In this unit, digital logic integrated circuits, in which many transistors, diodes and resistors, together with all the interconnections, form a complete circuit and function as logic circuits such as timers and memories, will be examined.

KEY IDEAS

- 555 timers are used for time delays, oscillators, and pulse generation in electronics.
- 555 timers operate using comparators, a flip-flop, and transistors to control timing.
- The 556 timer combines two 555 timers in one IC for extended timing functions.
- 555 timers contain resistors, transistors, and a flip-flop that manage voltage levels.
- Pin Layout: Has 8 pins, each with a specific function like trigger, output, and reset.
- Versatility: Known for stability, ease of use, and wide use in electronic circuits.

FEATURES AND PRINCIPLES OF OPERATION OF TIMERS

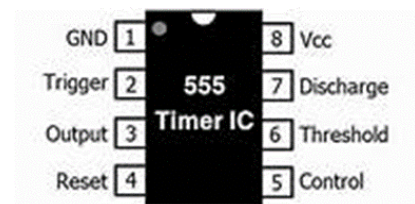
Features of the 555 Timer IC

The **555 timer** is a small electronic chip that is very popular in many electronic circuits. People like to use it because it is strong, reliable, and works well in different situations. This timer can do two main things:

1. Time Delay

It can be used in circuits where we need to wait for a short time before something happens. For example, it can delay when a light turns on.

2. **Oscillator:** It can also produce a wave signal (called a square wave) that turns on and off in a regular pattern. The timing of this pattern can be adjusted between **50% to 100%**, depending on how the circuit is designed.



The diagram (*Figure 3.11.1*) shows how the 555 timer looks and explains what each of its pins does in a circuit.

Figure 3.11.1: The 555 timer IC

The 555 Timer IC Package

The **555 timer** is packaged in a small chip called an **8-pin DIP**, which stands for **Dual In-line Package**. This means the chip has 8 pins—4 on each side, making it easy to plug into a circuit board. There is also a **double version** of the 555 timer called the **556 timer**. It combines **two full 555 timers** in one chip, and this version has **14 pins** instead of 8.

This makes the 556 timer useful in circuits that need two timers working together.

The diagram in *Figure 3.11.2* shows what the 555 and 556 timer chips look like, and where each pin is located and connected.

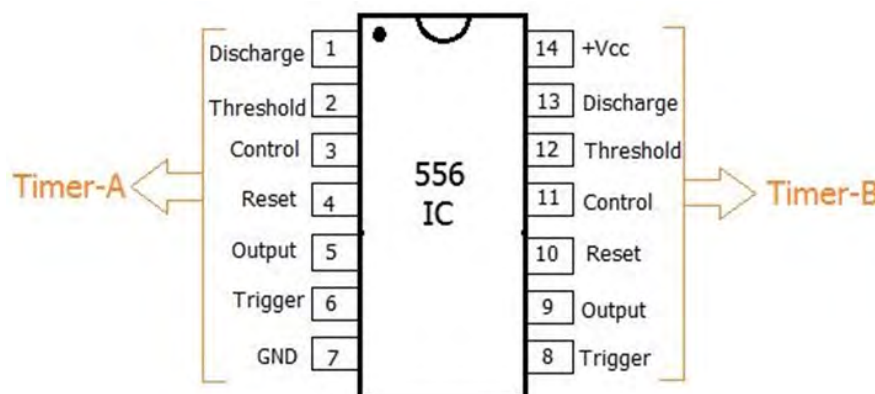


Figure 3.11.2: The 556 timer IC

Inside the 555 Timer IC

Figure 3.11.3 shows a simple diagram of how the inside of the 555 timer is connected. It helps us understand how the timer works without showing every tiny part. The real 555 timer is much more complex! It contains:

1. Over 16 resistors
2. Around 20 transistors
3. 2 diodes
4. A part called a flip-flop, which is used to switch between on and off states
5. Many other small components that help control time and voltage

Even though the actual circuit is complicated, the simplified diagram gives us a good idea of how the 555 timer functions as a timing device.

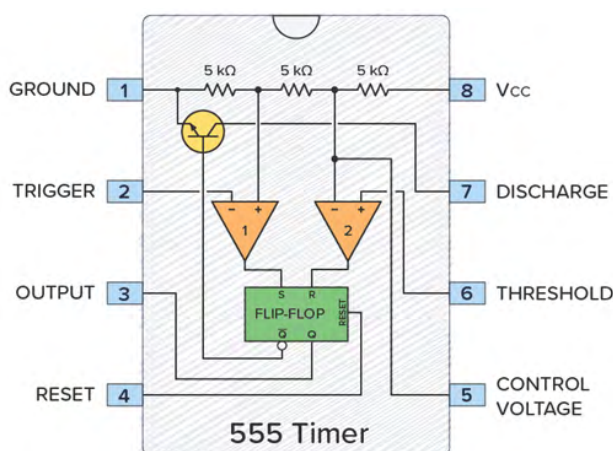


Figure 3.11.3 Internal circuit connection of the 555 timer

Functions of the 555 Timer Pins

The **555 timer IC** has 8 pins, each with a special function. Here is what each pin does:

Pin 1 – Ground

1. Connects the chip to zero volts (the ground).
2. It helps share the supply voltage (V_{cc}) evenly across the resistors inside the chip.
3. Each of the 3 resistors gets about $\frac{1}{3}$ of the supply voltage.

Pin 2 – Trigger

1. This pin starts the timer by sending a signal.
2. If the input voltage is less than $\frac{1}{3}$ of V_{cc} , it switches the output on (high).
3. It works by comparing voltages using a part called a comparator.

Pin 3 – Output

1. Sends out the final signal to whatever device is connected.
2. It connects to the load like a buzzer, LED, or motor.

Pin 4 – Reset

1. Used to stop the timer or reset the output.
2. It is an active low pin, which means it works when given a low signal (0V).
3. To avoid problems from noise, it is usually tied to Vcc (high) unless reset is needed.

Pin 5 – Control Voltage

1. Adjusts the signal inside the chip.
2. Normally at $\frac{2}{3}$ Vcc.
3. It can change how long the output stays on, no matter the resistor-capacitor timing setup.

Pin 6 – Threshold

1. Checks if the capacitor's voltage is more than $\frac{2}{3}$ Vcc.
2. If it is, the output is switched off (low).
3. Works with another comparator to manage timing.

Pin 7 – Discharge

1. Empties the charge from the timing capacitor.
2. Helps the timer restart its cycle and generate a square wave signal.

Pin 8 – Supply Voltage (Vcc)

1. Connects to the power supply (usually +5V or +9V).
2. Powers the entire IC so it can work properly.

Designing Circuits With the 555 Timer IC

The 555 timer IC is used in many electronics projects. It can act like a *stopwatch*, *light blinker*, or *sound maker*, depending on how it is connected. It works in *three main modes*:

1. **Monostable:** Produces a short signal when triggered (one-shot pulse)
2. **Bistable:** Works like a flip-flop — stays on or off until triggered
3. **Astable:** Keeps switching on and off to create a regular signal (like a wave)

Common Applications of the 555 Timer

1. **Timing Applications**
 - a. Delay Timer: waits a short time before starting something — like a light turning on after a few seconds.
 - b. Pulse Width Modulation (PWM): controls speed of motors, brightness of lights, and dimming of LEDs.
2. **Oscillator Applications**
 - a. Frequency Generator: produces regular signals (square waves) for sounds, clocks, or signal patterns.
 - b. Tone Generator: makes sounds in buzzers, alarms, or music gadgets.

3. Flashing Lights

- a. LED Flasher: makes lights blink for decoration or signalling.
- b. Light Chasers: lights turn on in a pattern — often used in displays or Christmas decorations.

4. Timer Circuits

- a. One-Shot Timer: creates a single signal pulse — good for things like appliance timers.
- b. Interval Timer: waits a set amount of time between two actions.

5. Pulse Generation

- a. Square Wave Generator: produces wave signals used to test circuits or process signals.
- b. Random Pulse Generator: creates random signals for games or testing devices.

6. Bistable Applications

- a. Flip-Flop: keeps a circuit in one state until something changes it — used in memory or control systems.
- b. Switch Debouncing: keeps buttons or switches from accidentally sending multiple signals.

7. Control Systems

- a. Motor Control: adjusts how fast a DC motor runs or changes its direction.
- b. Temperature Control: regulates heaters or coolers based on temperature levels.

8. Sound Generation

- a. Alarm Systems: makes warning sounds for safety or alerts.
- b. Music Synthesisers: creates sounds for musical effects and instruments.

Connecting the 555 Timer in Different Modes

Monostable Mode

A monostable mode has one stable state, usually the *off* state (low voltage).

How it behaves

When it is triggered, it temporarily switches to the *on* state (high voltage) for a set amount of time. After that time, it automatically returns to its normal *off* state. This timing action is controlled by a resistor–capacitor (RC) setup. The resistor and capacitor decide how long the output stays on before switching back to off.

Think of it like pressing a doorbell:

1. When you press (trigger) it, the bell rings for a few seconds.
2. Then it stops ringing, even if you do not press it again.

Example Circuit

Figure 3.11.4 shows a monostable 555 timer circuit:

1. The trigger pin (Pin 2) receives a signal to start the timing.
2. The output pin (Pin 3) turns on for the set time.
3. After the capacitor charges, the timer resets itself.

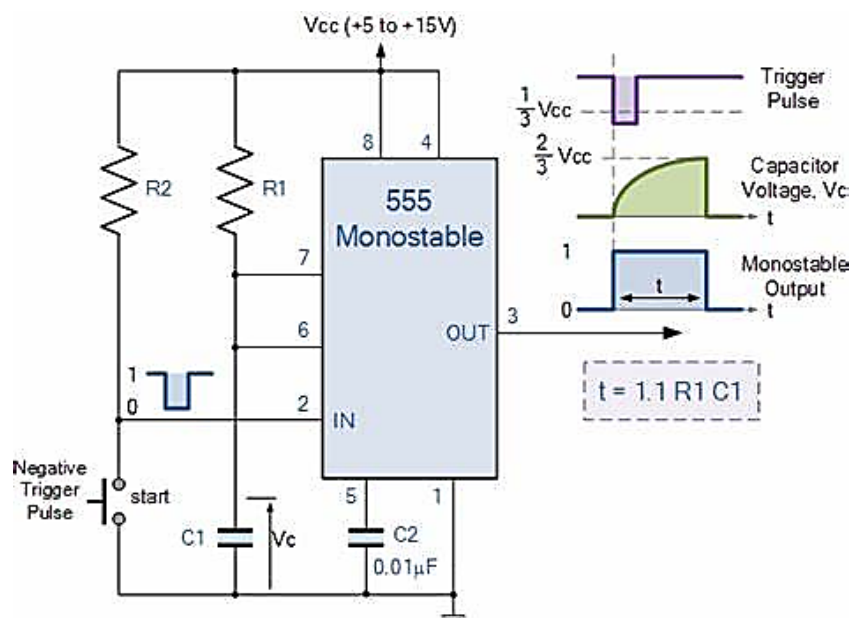


Figure 3.11.4: Monostable mode of a 555 timer

This setup has **one stable state**—usually OFF. When a signal is sent to **Pin 2 (Trigger)**, the timer switches ON for a short time and then automatically switches back OFF.

How it works

1. Pin 2 is kept HIGH by resistor R_2 . When Pin 2 receives a LOW signal, timing begins.
2. Pin 3 (Output) goes HIGH for a short period, then returns LOW. The length of time the output stays HIGH depends on:
 - a. Resistor R_1
 - b. Capacitor C_1

Time Equation

$$t = 1.1 \times R_1 \times C_1$$

Practical Uses

Turns a short or messy input signal into a clean pulse. Used in:

1. burglar alarms (vibration sensors)
2. button press delays
3. pulse stretchers

Bistable Mode

This mode has **two stable states**—ON and OFF. The circuit **stays in one state** until it receives a signal to switch to the other.

How it behaves

It does not change automatically like monostable mode. You control it with *two different signals*: one triggers it ON and the other triggers it OFF.

Real-life Applications

1. Memory cells (storing bits of data)
2. Flip-flop circuits
3. Switch debouncers (removes noise from buttons or switches)

Figure 3.11.5 shows the basic setup of a bistable 555 timer circuit.

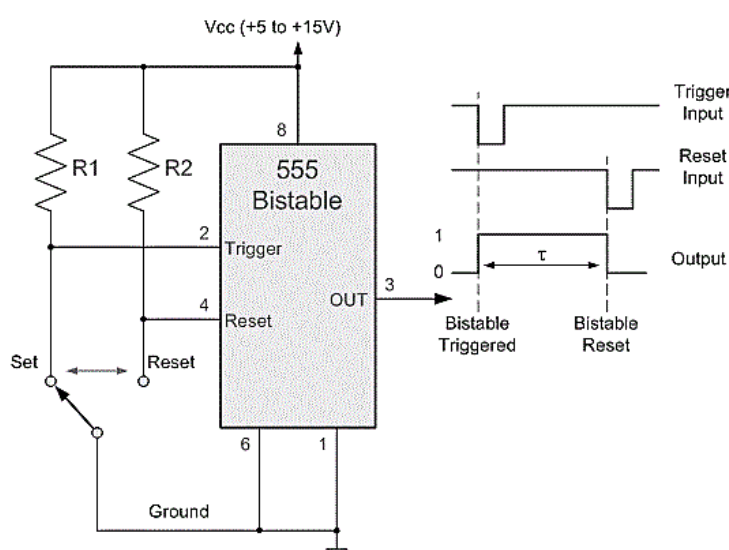


Figure 3.11.5: Bistable mode with change-over switch trigger

In **bistable mode**, the 555 timer works like a flip switch — it has **two stable states**: ON or OFF. Unlike the monostable mode, this setup doesn't need timing capacitors since the timer does not change state on its own. It only changes when triggered.

How It Works

Set state

A LOW signal (0V) is sent to Pin 2. This turns the output ON — so Pin 3 becomes HIGH (sends out voltage).

Reset state

A LOW signal is sent to Pin 4. This turns the output OFF — so Pin 3 becomes LOW.

Start-up Note

When the timer is first powered on (boot up), if Pin 2 is LOW, Pin 3 starts HIGH.

Switches

The switching between set and reset can be done using a double-throw switch. You can also use two separate push buttons — one to set and one to reset, shown in *Figure 3.11.6*.

Real-Life Uses

1. Memory circuits (storing ON/OFF states)
2. Button debouncing (making button signals clean and reliable)
3. Flip-flop designs in digital electronics

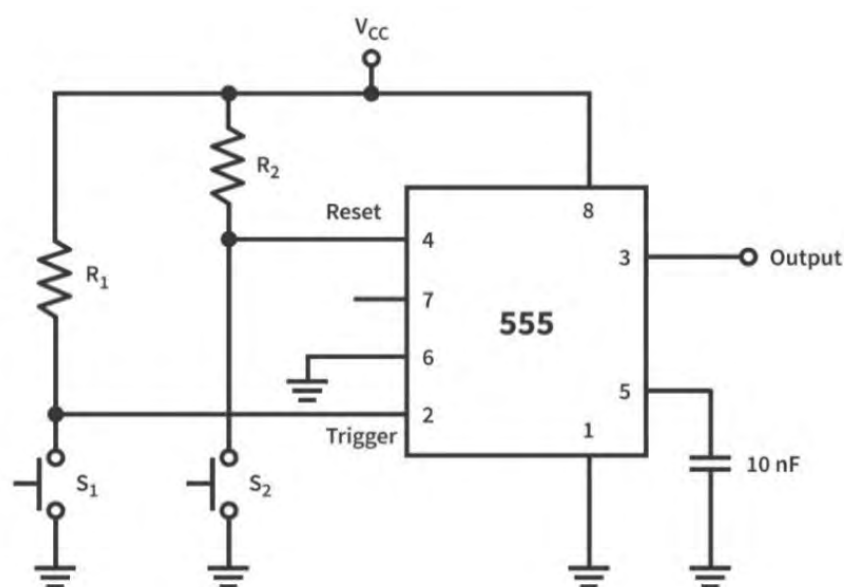


Figure 3.11.6: Bistable mode with two push-button triggers

Astable Mode of the 555 Timer

In a stable mode, the 555 timer does not wait for any input; it works continuously, switching between ON and OFF all by itself. This creates a repeating pattern, called a square wave.

Square wave means the output stays HIGH for a short time, then LOW, then HIGH again, and so on — like blinking.

How it Works

There is no stable state — the timer keeps cycling. The timing is controlled by:

1. 2 resistors (usually labelled R_1 and R_2)
2. 1 capacitor (C_1)

These components decide:

1. The frequency — how fast the signal repeats
2. The duty cycle — how long the signal stays ON vs OFF
3. You can adjust the resistors and the capacitor to get different speeds or patterns.

Figure 3.11.7 shows a typical astable circuit using a 555 timer, including the resistor-capacitor arrangement.

Real-Life Uses

1. Flashing lights (e.g. LED blinkers)
2. Tone generators (buzzers or music)
3. Digital clocks and timers
4. Signal and pulse generators

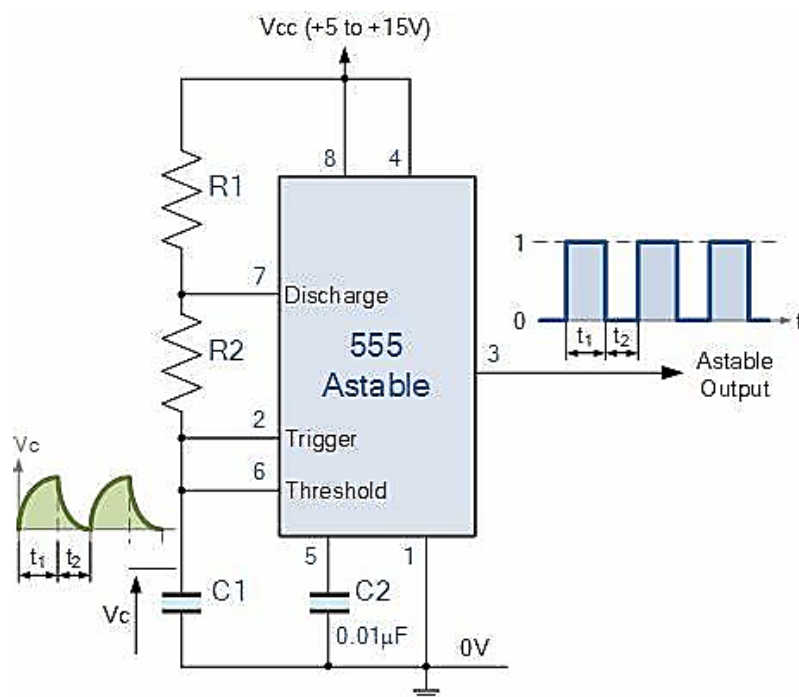


Figure 3.11.7: Astable mode of a 555 timer

Frequency & Duty Cycle in Astable Mode

In the astable mode of the 555 timers, the circuit creates a repeating signal that switches ON and OFF—like a heartbeat or blinking light. This pattern is called a square wave.

How Frequency is Controlled

The timing of ON and OFF periods depends on these three parts:

1. R_1 (Resistor 1)
2. R_2 (Resistor 2)
3. C_1 (Capacitor 1)

Together, they set how fast the signal repeats — this is called the frequency.

You can change the frequency by:

1. replacing R_1 with a variable resistor (like a knob you can turn)
2. adjusting C_1 to be bigger or smaller

What is Duty Cycle?

The duty cycle tells us how much of the total time the output stays ON (HIGH).

$$\text{Duty Cycle (\%)} = T_{\text{ON}} / (T_{\text{ON}} + T_{\text{OFF}})$$

Where: T_{ON} is how long the signal stays HIGH, and T_{OFF} is how long it stays LOW

Example

If the duty cycle is 50%, it means the output is ON half the time and OFF the other half.

That is typical for many square wave applications, like flashing lights or tones.

Figure 3.11.8 shows the output waveform — you will see the regular up-and-down shape of the square wave, with equal ON and OFF times when the duty cycle is 50%.

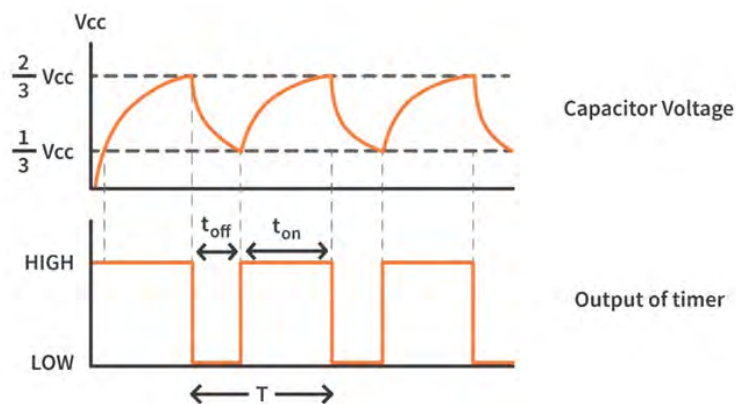


Figure 3.11.8: Output wave of an astable mode of a 555 timer

Calculating Frequency and Duty Cycle in Astable Mode given:

$$T_{\text{ON}} = 17 \text{ milliseconds (ms)}$$

$$T_{\text{OFF}} = 12 \text{ milliseconds (ms)}$$

Total Time Period (T)

The period is the total time for one full cycle of ON + OFF: $T = T_{\text{ON}} + T_{\text{OFF}} = 17\text{ms} + 12\text{ms} = 29\text{ms}$

Frequency (f): Frequency is how many cycles occur in one second:

$$f = 1 / T = 1 / 29\text{ms} = 34.48\text{Hz}$$

Figure 3.11.8 shows a clap switch circuit involving a timer. So, the output signal repeats about 34.5 times per second.

Duty cycle tells us how long the signal stays ON during each cycle:

$$\text{Duty Cycle} = T_{\text{ON}} / (T_{\text{ON}} + T_{\text{OFF}}) = 17 / 29 = 0.586 = 58.6\%$$

Equation for Pulse Timing

To set the frequency and duty cycle yourself, use these key equations.

Period (T): $T = 0.7 \times (R_1 + 2R_2) \times C_1$

Frequency: $f = 1 / T$

By changing R1, R2, or C1, you can fine-tune how fast and how long each pulse lasts.

1. Use a variable resistor to adjust values easily.
2. Larger capacitors make longer delays.

Practical Application of Timers

Figure 3.11.8 is a clap switch circuit. It is a typical example of the application of the 555 timers.

Clap Switch Circuit – Components List

The clap switch circuit is a simple electronic project that uses sound (like a clap) to turn an LED ON or OFF. It uses a condenser microphone to detect the clap and the 555 timer IC to control the output.

Here are the required parts:

S/N	Component	Quantity
1	NE 555 Timer IC	1
2	NPN Transistor (BC 547)	1
3	10μF Capacitor	1
4	Condenser Microphone	1
5	LED (5mm)	1

Building the Clap Switch Circuit

Here is a simple step-by-step guide for connecting the components on the breadboard:

1. Place the 555 timer IC on the breadboard.
2. Connect Pin 4 and Pin 8 to positive (Vcc).
3. Connect Pin 1 to ground (GND).
4. Connect 100KΩ resistor (R₁) between Pin 7 and Vcc.
5. Connect 10μF capacitor (C1) between Pin 7 and GND.
6. Link Pin 6 to Pin 7 using a jumper wire.
7. Connect the LED between Pin 3 and GND through a 220Ω resistor (R₂).
8. Connect positive of the microphone to Vcc through a 47KΩ resistor (R₄), and negative to GND.
9. Connect the base of BC547 transistor to the microphone’s positive line.
10. Connect the collector to Vcc through a 1KΩ resistor (R₃) and the emitter to GND.
11. Connect Pin 2 of the IC to the collector of the transistor.
12. Power the circuit with a 9V battery — positive to Vcc, negative to GND.

How the Clap Switch Works

1. The condenser mic detects sound (like a clap) and turns it into electrical energy.
2. This activates the transistor, which amplifies the signal and sends it to Pin 2 of the timer.
3. The 555 timer is in monostable mode, so Pin 3 (output) goes HIGH for a short time — turning on the LED.
4. After that time, the LED turns off automatically. To change how long the LED stays on, you can adjust R_1 or C_1 .

This circuit can also be used to turn on lamps, fans, or other devices using a relay, keeping users safe from electric shock since no touch is required — just a clap!

Troubleshooting Tips

1. **Incorrect Timing**
 - a. Check values of resistors and capacitors.
 - b. Make sure components are connected to the correct pins.
 - c. Use the right formula when calculating timing.
2. **Unstable Output**
 - a. Make sure the power supply is clean and steady.
 - b. Use decoupling capacitors near the timer IC.
 - c. Check for any loose wires or faulty parts.
3. **No Output**
 - a. Confirm the trigger signal is reaching Pin 2 properly.
 - b. Make sure Pin 4 (reset) isn't accidentally pulled low.

Activity 3.11.1 555 & 556 Timer ICs – Monostable and Astable Multivibrators

Scenario

An engineering design team is developing electronic control circuits for household devices. The team needs to understand the operation of 555 and 556 timer ICs and apply their principles to design circuits such as a fan controller.

Task

Compare the monostable and astable multivibrators in terms of construction and operation. Explain how the principle of a monostable multivibrator can be adapted to design a circuit to control a standing fan.

Materials needed

1. Diagrams of 555 and 556 timer ICs
2. Worksheet with guiding questions

3. Internet-enabled devices for research and videos
4. Large paper, markers, pens
5. Circuit simulation software (e.g., Multisim), if available
6. Notebooks, pens

Step 1: Class Brainstorm

Think about timers and oscillators used in electronic devices. Discuss with classmates:

1. What are 555 and 556 timer ICs?
2. What is a monostable multivibrator?
3. What is an astable multivibrator?
4. How might these circuits be used in everyday electronics?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners. Assign roles: Researcher, Note-taker, Presenter, Artist.
2. Use books, internet, and videos e.g. YouTube to research the 555 and 556 timer ICs.
3. Complete the table below:

Video link to 555 IC: <https://youtu.be/Y9rJF0PRXEY?si=h-rloPc7z-eduQUv>
 video link to 556 IC: <https://youtu.be/MFpPsKa-hx0?si=1amUHMue8hECUsGA>

Aspect	Monostable Multivibrator	Astable Multivibrator
Construction		
Operation		
Pin connections of IC		
Typical voltage supply		

4. Guiding questions
 - a. What are the main differences in construction and function?
 - b. How does each circuit generate output signals?
 - c. How are the pins connected in each configuration?

Step 3: Create Your Diagrams and Poster

1. Draw diagrams of the 555 and 556 timer ICs indicating name and function of all pins.

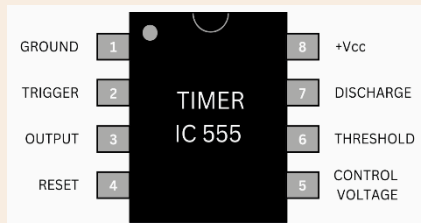


Figure J: IC 555

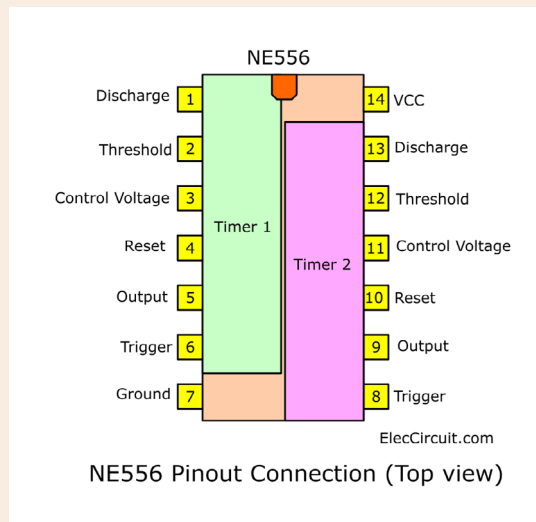


Figure K: IC 556

2. Make a poster that shows
 - a. Construction and operation of monostable and astable multivibrators
 - b. Typical circuit connections
 - c. Example application: How a monostable circuit can control a standing fan

Step 4: Present Your Work

Present your diagrams and poster to the class. Explain:

1. Differences between monostable and astable multivibrators
2. How the 555/556 timer IC works in each mode
3. How a monostable circuit can be adapted to control a standing fan

Step 5: Ask and Answer Questions

1. Listen carefully to classmates' questions.
2. Answer clearly to help understanding.
3. Provide helpful feedback on others' presentations.

Step 6: Reflect and Write

In your notebook, answer reflective questions:

1. What are the main differences between monostable and astable multivibrators?
2. How can the monostable principle be used to control a fan?
3. What did you learn about the 555 and 556 timer ICs?
4. How would you explain these concepts to someone new?

EXTENDED READING

1. [Introduction to the 555 Timer - Circuit Basics](#)
2. [555 Timer IC: Introduction, Basics & Working with Different Operating Modes](#)
3. [556 Circuits: Ultimate Guide for its Operation - CompileIoT](#)

4. <https://www.eeeguide.com/astable-multivibrator-using-555-timer-ic/>
5. [Astable Multivibrator using 555 Timer IC | Working | Duty Cycle](#)
6. <https://www.electricaltechnology.org/2014/12/555-timer.html>
7. <https://arshon.com/blog/applications-of-a-555-timer-exploring-its-versatility-in-electronics/>
8. <https://www.eeweb.com/typical-555-ic-circuit-applications/>
9. <https://www.circuits-diy.com/simple-clap-switch-circuit-using-555-timer/>

REVIEW QUESTIONS

1. Analyse how resistor and capacitor values affect 555 timer's delay.
2. Why would you choose monostable mode when designing a circuit that turns an LED for 10 seconds after a button press?
3. How can a 555 timer be used to control the automatic shut-off of a device after a set time?

UNIT 12 MAINTENANCE, ELECTRICAL MACHINE FAULT AND CIRCUIT

INTRODUCTION

In Year 2, you studied the single-stage amplifier, which uses one transistor (BJT) to amplify signals. Building on this, today's lesson introduces operational amplifiers (Op-amps), more advanced and versatile components widely used in analogue electronics. Op-amps were originally designed for mathematical operations such as addition, subtraction, and integration in analogue computers, which is why they are called operational amplifiers. They work with feedback to control gain and behaviour. There are two common Op-amp configurations: the inverting amplifier, where the input is applied to the inverting terminal and the output is 180° out of phase; and the non-inverting amplifier, where the input is applied to the non-inverting terminal and the output is in phase with the input. This lesson covers the Op-amp chip pin diagram, ideal characteristics, operation in open-loop and closed-loop modes, and their applications in amplification, switching, radio consoles, and instrumentation.

KEY IDEAS

- An operational amplifier (op-amp) is an electronic device used to amplify voltage signals in many analogue circuits.
- An op-amp typically has two input terminals; the inverting (-) and non-inverting (+) and one output terminal.
- Key features of op-amps include very high voltage gain, high input impedance, and low output impedance, which make them ideal for signal processing.
- The function of each pin is to either receive input, deliver output, or supply the op-amp with power for it to operate correctly.
- The pins of an op-amp include input pins, output pin, power supply pins ($V+$ and $V-$), and sometimes offset or compensation pins, depending on the model.
- The principle of operation of an op-amp is to amplify the voltage difference between its two input terminals, often controlled by negative feedback for stability and accuracy.

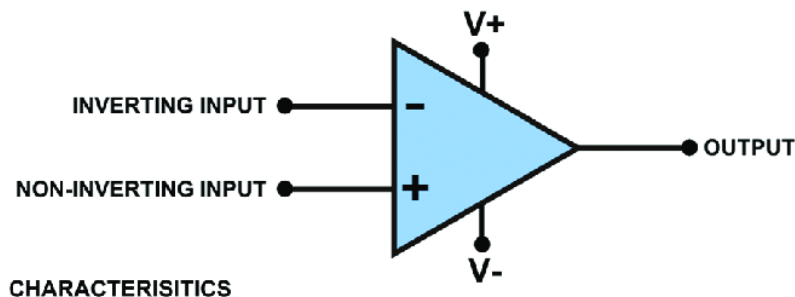
FEATURES AND PRINCIPLES OF OPERATION OF OP-AMPS 741 & 4558 AND DESIGNING WITH OP-AMPS

Operational Amplifier

An operational amplifier, also called an op-amp, is a small electronic chip found in many devices. It is used to increase (amplify) weak electrical signals to make them stronger. This means if you put in a small voltage, the op-amp gives you a much bigger voltage at the output. It has two input points; one called the inverting input (-) and the other called the non-inverting input (+) and one output point. The op-amp compares the voltages at the two inputs and gives an output based on the difference.

The reason it is called “operational” is that, before digital computers, op-amps were used to perform mathematical operations like adding, subtracting, multiplying, and even solving equations using electrical signals.

Today, op-amps are used in many electronic circuits such as radios, speakers, alarms, and measuring tools because they are very powerful and reliable. **Figure 3.12.1** shows a schematic representation of an Op-Amp.



- Two very high resistance voltage inputs $> 10^{12} \Omega$
- One very low resistance voltage output $< 100 \Omega$
- Very high amplification gain – typically 10^6

Figure 3.12.:1 Schematic Representation of an Op-Amp

Imagine you have a magical box with two ears and one powerful voice. This is your operational amplifier (op-amp), one of the most useful tools in electronics.

The op-amp has two input ports; assume them to be its ears. The first ear (the inverting input) listens specially. When you speak louder here, your voice actually responds in the opposite direction. The second ear (non-inverting input) is more straightforward. When you speak louder here, your voice follows in the same direction, just much stronger.

What makes op-amps truly special are their superpowers. They can hear incredibly faint whispers without disturbing the speaker (that's the super high input resistance). When they speak, their voice carries powerfully without getting tired (that is, the low output resistance). They can turn a whisper into a shout with amplification up to a million times.

But here is the clever part. We usually do not let them amplify that much. By using something called feedback (where we connect part of the output back to the input), we can control exactly how much amplification we want. This is like telling the superhero exactly how much help we need. You will find these amazing components working hard in all sorts of gadgets around you.

Some of the Applications include

Making the music from your phone loud enough for your headphones, helping medical equipment detect your heartbeat and keeping the voltage steady in solar power systems. The classic 741 op-amp is like the trusty bicycle of electronics. It is simple, reliable, and perfect for learning.

Pin Description of 741 IC Op-Amp

This is how the 741 operational amplifier works:

Imagine it as a tiny, powerful amplifier chip that can make small electrical signals much stronger like how a microphone makes your voice louder through speakers. The chip has 8 pins, but we mainly use 7 of them. First, it needs power to work, just like your phone needs charging. Pin 7 is for positive power (like the red battery wire) and Pin 4 is for negative power (like the black wire). You can power it with anywhere between 5 to 18 volts which is similar to how some devices work with different battery sizes.

The magic happens at the input pins. Pin 2 is called the “inverting input.” If you put a signal here, the output does the opposite. Pin 3 is the “non-inverting input.” Here, the output follows the input. It is like having two volume knobs: one that turns the sound up when you turn it right (Pin 3), and another that turns sound down when you turn it right (Pin 2). The result comes out at Pin 6. This is where you connect things like speakers, LEDs, or other circuits to see or hear the amplified signal. Pins 1 and 5 are special. They help balance tiny imperfections in the chip using a small adjustable resistor, kind of like tuning a radio to get the clearest signal.

There is also Pin 8 that does nothing. It is just there because the chip comes in a standard 8-pin package. Think of it like an extra seat in a car that nobody uses. This little chip is incredibly useful. You can find it in all sorts of electronics, from music amplifiers to temperature sensors. The way it compares voltages at its two inputs and produces an output makes it perfect for building all kinds of interesting circuits. **Figure 3.12.2** shows the diagram of the pin connections of the IC 741 Op-amp

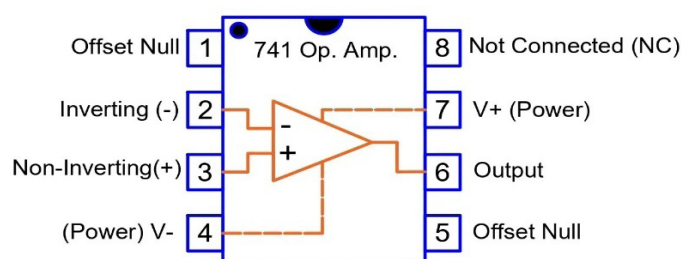


Figure 3.12.2: Diagram showing the pin connections of IC 741 Op-amp

Functions of the various pin connections

1. Power Supply Pins (Pin 4 and Pin 7)

Pin 4 and Pin 7 are the legs of the IC that provide it with power. Pin 4 is for the negative voltage (-) and Pin 7 is for the positive voltage (+). Without these, the op-amp cannot work. The voltage between them is usually between 5 volts and 18 volts, depending on the circuit design.

2. Output Pin (Pin 6)

This is where the output signal comes from. Whatever the op-amp does with the input signals is shown at Pin 6. If the output voltage is high, it means it is close to the positive power supply (Pin 7). If it is low, it means the voltage is close to the negative power supply (Pin 4). The actual output depends on what's happening at the input pins and the type of feedback used.

3. Input Pins (Pin 2 and Pin 3)

These are the pins where the input signals go.

- Pin 2 is the inverting input (-): When the voltage here is higher than Pin 3, the output will go low.
- Pin 3 is the non-inverting input (+): When the voltage here is higher than Pin 2, the output will go high.

So, the op-amp compares the two voltages and gives a result depending on which one is greater.

4. Offset Null Pins (Pin 1 and Pin 5)

These pins are used to remove small errors in the op-amp's output. Sometimes, even when there is no input, the op-amp still gives a little voltage at the output. Using a small device called a potentiometer connected to these pins helps to fix this error and make the output more accurate.

5. Not Connected Pin (Pin 8)

Pin 8 does not do anything. It is just there to fill space so the IC fits well into the socket. It has no function in the circuit no power, no signal, nothing.

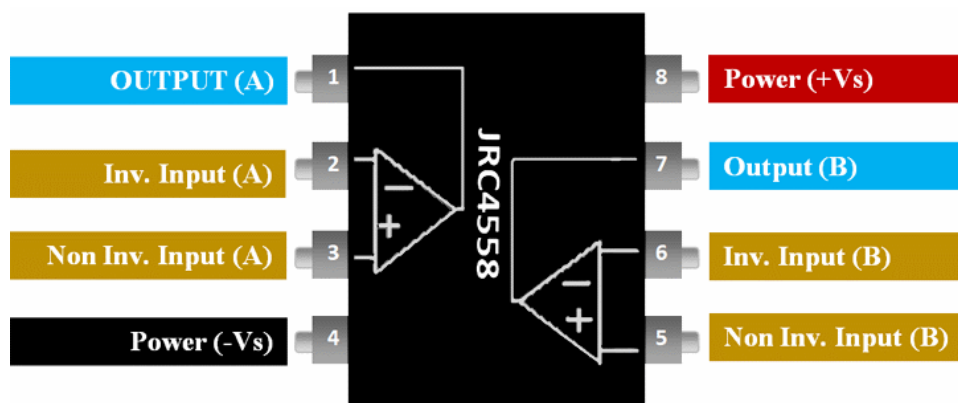


Figure 3.12.3: Diagram showing the pin connections of the 4558 IC Op-amp

The JRC4558 op-amp is shown in the diagram. Picture it as two super-powered amplifiers packed into one small black box, each working independently to make your audio signals crystal clear. This clever device needs power to work, just like your phone needs to be charged. There is a positive power pin (Pin 8) where you connect your battery's red wire (anywhere from 5 to 18 volts will do, and a negative power pin (Pin 4) for the black wire or ground connection. Without these, it is just a silent piece of plastic.

What makes the 4558 special is its two identical amplifier circuits. The first one uses Pin 2 and Pin 3 as its ears; Pin 2 flips the sound upside down while Pin 3 keeps it right-side up, with the result coming out of Pin 1. The second amplifier does the same thing using Pin 5 and Pin 6 as inputs, with its output at Pin 7. You will find this chip working hard in all sorts of audio gear, from the sound systems at your local church to the guitar pedals musicians use. It is particularly good at making weak signals stronger without adding noise or distortion, which is why professionals love it. It is surprisingly easy to work with.

You could use one amplifier to boost vocals while the other handles instruments, creating your own mini mixing console. Or build a simple equaliser to adjust bass and treble separately. Imagine being able to repair the sound system at your school or church because you understand how this chip works. That's the kind of practical skill that makes learning electronics so valuable.

Note

The 4558 IC Op-am houses two operational amplifiers within its internal circuit, providing dual operational amplifiers in a single package.

Table 3.12.1: Pin configuration description of IC 4558 Op-amp

PIN	Pin Name	Pin Description
1	OUT (A)	The output pin of Op-amp A
2	Inverting Input (A)	The Inverting input pin of the Op-Amp A
3	Non- Inverting Input (A)	The Non - Inverting Input Pin of Op-Amp A
4	Power (-Vs)	Ground or Negative supply terminal
5	Reference	The non-inverting Input Pin of Op-Amp B
6	Output	The Inverting input pin of the Op-Amp B
7	Power (+Vs)	The output pin of Op-amp B
8	+VS	Positive supply terminal

Features of Operational Amplifiers (Op-Amps)

1. High Gain

Op-amps are very powerful when it comes to amplifying weak signals. Even if the input signal is very small, the op-amp can make it much stronger at the output. For

example, a tiny sound signal from a microphone can be amplified to be heard through a speaker.

2. **Differential Input**

An op-amp works by comparing two input voltages: one from the inverting input (-) and one from the non-inverting input (+). It checks the difference between the two and amplifies that difference. This helps in making precise decisions in electronic circuits.

3. **High Input Impedance**

This means that the op-amp does not draw much current from the source connected to it. It simply listens to the input signal without disturbing it, like someone quietly observing without interfering.

4. **Low Output Impedance**

Op-amps can send out a strong signal without being affected by what is connected to them. This helps the op-amp to drive other components like speakers or sensors easily, without losing strength.

5. **Feedback**

Op-amps are often used with a system called feedback, where part of the output is sent back to the input to control the performance. Negative feedback makes the output more stable and accurate, while positive feedback can be used in special cases like oscillators.

6. **Versatile Applications**

Op-amps are very useful in many different types of circuits. They can be used for amplifying signals, removing noise, building filters, or even converting signals from analogue to digital; which is how radios, TVs, and many phone components work.

Principles of How Operational Amplifiers (Op-Amps) Work

Input Voltage Amplification

The main job of an op-amp is to amplify the difference in voltage between its two input pins; V_+ (non-inverting) and V_- (inverting). For example, if one input has 2 volts and the other has 1 volt, the op-amp will amplify the difference of 1 volt and give a stronger signal at the output.

Open-Loop Gain

When no feedback is used, the op-amp works in what's called open-loop mode, where the output becomes very large even for a small difference between the inputs. This is useful only in a few special cases because it's too sensitive and hard to control.

Feedback

Feedback means connecting part of the output back to the input. This helps control how much the op-amp amplifies and makes the output steadier and more useful.

Negative Feedback

In most circuits, we use negative feedback, which reduces the gain (amplification) but makes the op-amp more stable and accurate. This is important when you want a smooth and exact output, such as in a sound system or measuring device.

Positive Feedback

Positive feedback increases the output until it reaches its maximum or minimum. It is not used for amplifying, but for switching or generating signals, like in oscillators (which produce wave signals) or comparators (which choose between two levels).

Open-Loop Operation

Open-loop operation of an op-amp means the op-amp is working without any feedback. That is, nothing is connected from the output back to the input. In this mode, the op-amp amplifies the difference between the two input voltages (V_+ and V_-) with very high gain. Even a very small difference in the input voltages will cause the output to jump to a very high positive or negative voltage, close to the power supply limits.

This type of operation is very sensitive and unstable, so it is mostly used in special cases, like in comparator circuits, where the output needs to switch quickly between high and low. *Figure 3.12.4* shows Open Loop Operation.

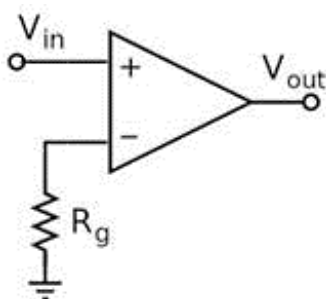


Figure 3.12.4: Open Loop Operation

An operational amplifier, often called an op-amp, is a very useful electronic component that can amplify weak signals. Imagine it as a tiny device that takes a small input signal and makes it much stronger at the output. When we talk about an op-amp in an “open loop” configuration, it means the output of the op-amp is not connected back to its input in any way. In this setup, the op-amp works at its maximum gain, meaning it amplifies the input signal as much as it can. However, because there’s no feedback (no connection from output back to input), the op-amp becomes very sensitive. Even the tiniest difference between the two input voltages can cause the output to swing to its highest or lowest possible value, like a switch turning fully on or off.

For example, if you touch the two input pins lightly or connect a small battery, the output might jump to its maximum voltage (like +12V) or drop to its minimum (like -12V),

depending on which input is slightly higher. This makes the open-loop op-amp great for comparing signals but not so good for precise amplification. Think of it like a seesaw with no one holding it back; just a tiny push sends it flying all the way up or down. Later, you'll learn about "closed loop" configurations, where feedback is added to control the amplification more carefully. For example, if you give 2.001V to the non-inverting input and 2.000V to the inverting input, the op-amp might suddenly give 12V (as a realistic, common value for many circuits) or more at the output, which is open-loop behaviour.

An ideal op-amp amplifies the difference between the two applied input signals (i.e. at the inverting and the non-inverting) signals. This difference between the two input signals is called the differential input voltage.

The equation below gives the output of an operational amplifier.

$$V_{\text{out}} = \text{AOL} (V^+ - V^-)$$

Where,

AOL = open-loop gain (which means, the gain of the op-amp component all by itself, with all the different components removed and significantly with the feedback element removed).

Note

In open loop, the op-amp can work only as a comparator. The open-loop gain of an op-amp is very high. Hence, an open-loop operational amplifier amplifies a small applied differential input voltage to a huge value, but this significant value at the output cannot go beyond the supply voltage of the op-amp. Hence it does not violate the law of conservation of energy.

Example 1: Output with Small Input Difference

Given:

Open-loop gain, $A=100,000$

Non-inverting input $V^+ = 2.005\text{V}$

Inverting input $V^- = 2.000\text{V}$

Power supply = $\pm 12\text{V}$

Step 1: Find the input voltage difference:

$$V_{\text{in}} = V^+ - V^- = 2.005\text{V} - 2.000\text{V} = 0.005\text{V}$$

Step 2: Multiply by the open-loop gain:

$$V_{\text{out}} = A \times V_{\text{in}} = 100,000 \times 0.005\text{V} = 500\text{V}$$

Step 3: But the op-amp cannot output 500V. It is limited by the power supply ($\pm 12\text{V}$).

Final Output Voltage: +12V (Saturated at supply limit)

Example 2: Output When Inverting Input is Higher

Given:

Open-loop gain $A=200,000$

$$V^+ = 1.000\text{V}$$

$$V^- = 1.001\text{V}$$

Power supply = $\pm 15\text{V}$

Step 1: Input voltage difference:

$$V_{in} = V^+ - V^- = 1.000\text{V} - 1.001 = -0.001\text{ V}$$

Step 2: Multiply by gain:

$$V_{out} = 200,000 \times (-0.001\text{V}) = -200\text{V} \{\text{out}\}$$

Step 3: Output is below power supply limit $\rightarrow$ gets clipped

Final Output Voltage: -15V (Saturated at negative supply)

In summary,

1. Even a tiny voltage difference gives a very large output due to high gain.
2. But in real life, the op-amp cannot go beyond the supply voltage.
3. So, the output “saturates” at either the positive or negative supply limit.

Closed – Loop Operation

Closed-loop operation means the output of an op-amp is connected back to its input through a path called feedback which is usually a resistor or a group of resistors. This setup controls and reduces the gain of the op-amp, making it more stable and predictable. The most common type is negative feedback, where part of the output is fed back to the inverting input (-). With this, the op-amp adjusts its output in a way that keeps the voltage difference between the inputs very small (almost zero). This makes it perfect for use in amplifiers, filters, and other circuits where accurate output is needed.

In simple terms, imagine you are driving a car downhill. Open-loop means you remove your hands from the steering wheel; anything can happen, but in closed-loop, you keep your hands on the wheel (feedback), so you stay on track and in control.

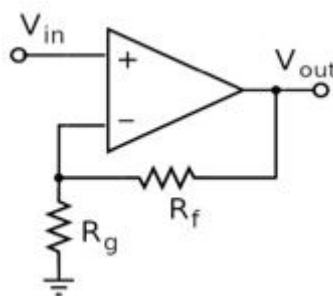


Figure 3.12.5: Closed Loop Operation

The diagram shows a closed-loop operation of an operational amplifier (op-amp). In this setup, you will notice that part of the output signal is sent back to the inverting input (–) of the op-amp through a component like a resistor. This path is called negative feedback.

Here, the op-amp compares the voltages at its two inputs: the non-inverting input (+) and the inverting input (–). Because of the feedback, the op-amp tries to keep the difference between these two inputs very small, almost zero. As a result, the output becomes stable and controlled, rather than jumping to high or low extremes like in open-loop operation. This kind of circuit is used when we want the op-amp to amplify signals accurately, without too much sensitivity.

This system is used in things like audio amplifiers, filters, and measuring instruments, where precise performance is needed.

Note

Feedback is introduced in the closed-loop configuration. This feedback path feeds the output signal back to the input. Hence, at the inputs, two signals are simultaneously present. One of them is the original applied signal, and the other is the feedback signal

The equation below shows the output of a closed-loop op-amp:

$$V_{out} = ACL (V_+ - V_-)$$

Where ACL is the closed-loop gain. The feedback circuit connected to the op-amp determines the closed-loop gain ACL.

The gain of an inverting amplifier (closed-loop gain) is, $ACL = \frac{-R_F}{R_1}$,

Where, R_F = Feedback Resistor and R_1 = Input Resistor

The gain of the non-inverting amplifier (Closed loop gain) is, $ACL = 1 + \frac{R_F}{R_1}$

Where, R_F =Feedback Resistor and R_1 =Input Resistor,

Feedback is said to be positive if the feedback path feeds the signal from the output terminal back to the non-inverting (+) terminal. Positive feedback is used in oscillators. The feedback is negative if the feedback path feeds the part of the signal from the output terminal back to the inverting (–) terminal. Negative feedback to the op-amps is used in amplifiers

Example 1: Inverting Amplifier Gain

Given:

Feedback resistor $R_F = 10\text{k}\Omega$

Input resistor $R_1 = 2\text{k}\Omega$

Find the closed-loop gain (ACL) of the inverting amplifier.

Solution

Use the formula:

$$ACL = -\frac{RF}{R1} = -\frac{10k\Omega}{2k\Omega} = -5$$

The closed-loop gain is -5 . This means the output will be 5 times bigger than the input, but in the opposite direction (inverted).

Example 2: Non-Inverting Amplifier Gain

Given:

Feedback resistor $RF = 15k\Omega$

Input resistor $R1 = 5k\Omega$

Find the closed-loop gain (ACL) of the non-inverting amplifier.

Solution

Use the formula:

$$ACL = 1 + \frac{RF}{R1} = 1 + \frac{15k\Omega}{5k\Omega} = 1 + 3 = 4$$

The closed-loop gain is 4. This means the output will be 4 times the input voltage, and not inverted.

Example 3: Output Voltage of Inverting Amplifier

Given:

$RF = 12k\Omega$, $R1 = 4k\Omega$

Input voltage $V_{in} = 1.5V$

Find the output voltage, V_{out}

Solution

First, calculate the gain:

$$ACL = -\frac{RF}{R1} = -\frac{12k\Omega}{4k\Omega} = -3$$

$V_{out} = ACL \times V_{in} = -3 \times 1.5 = -4.5V$. The output voltage is $-4.5V$ (inverted and amplified).

Try: Output Voltage of Non-Inverting Amplifier

Given: $RF = 20k\Omega$, $R1 = 10k\Omega$ and Input voltage $V_{in} = 2V$, find the output voltage V_{out} .

Answer: The output voltage is **6V** (same direction, amplified 3 times)

Op-Amp Characteristics

An Operational Amplifier (or Op-Amp for short) is an electronic device used to boost (amplify) weak signals.

Some key features or characteristics of an op-amp in a simple way:

1. Input Impedance (Z_{in})

This shows how much the op-amp resists the flow of current at its input. Think of it like a bucket with a very tiny hole, almost no water (or current) gets in. In an ideal op-amp, this resistance is infinite, meaning it does not allow any current to enter at all. In real life, it is not perfect, but when we use negative feedback (a trick used in circuits to make things more stable), the input impedance becomes:

$$Z_{in} = (1 + AOL \times \beta) \times Z_i$$

Where: Z_i = input resistance without feedback, AOL = open-loop gain (we will explain this soon) and β (beta) = feedback factor

2. Output Impedance (Z_{out})

This tells us how much resistance the op-amp has at its output, in other words, how easily it can send current to other parts of the circuit. Imagine a power bank with thick wires vs one with thin wires, the thicker ones give out more power. An ideal op-amp has zero output impedance, meaning it gives out full voltage without any power loss. But in real life, it does have some resistance. With feedback, the output impedance becomes very low, which is good because it allows more power to reach the next part of the circuit. The Z_{out} equation is given by:

$$Z_{out} = \frac{Z_o}{(1 + AOL \beta)}$$

where,

Z_o = output impedance of op-amp without feedback

AOL = open-loop gain

β = feedback factor

Example 1: Input Impedance (Z_{in})

An op-amp has: Input impedance without feedback: $Z_i = 10 \text{ k}\Omega$, open-loop gain (AOL) = 100,000 and feedback factor (β) = 0.01. Find the input impedance (Z_{in}) with negative feedback.

Solution

We use the formula: $Z_{in} = (1 + AOL \times \beta) \times Z_i$

Substitute the values: $Z_{in} = [1 + (100,000 \times 0.01)] \times 10,000 = 10.01 \text{ M}\Omega$

This shows that with feedback, the input impedance becomes much higher, which is good, because it draws almost no current.

Example 2: Output Impedance (Z_{out})

An op-amp has: output impedance without feedback: $Z_o = 100 \text{ }\Omega$, $AOL = 50,000$ and $\beta = 0.02$. Find the output impedance (Z_{out}) with negative feedback.

Solution

The formula is:

$$Z_{out} = \frac{Z_o}{(1 + A_{OL} \beta)}$$

$$Z_{out} = \frac{100}{1 + (50000 \times 0.02)} = 0.1 \, \Omega$$

$$Z_{out} \approx 0.1 \, \Omega$$

This shows that the output impedance becomes very low with feedback, meaning the op-amp can send strong signals to the load without much resistance.

Example 2

An op-amp has: $Z_i = 5 \, \text{k}\Omega$, $A_{OL} = 200,000$ and $\beta = 0.005$. Find Z_{in} .

Solution

$$Z_{in} = (1 + A_{OL} \beta) \times Z_i = (1 + (200000 \times 0.005)) \times 5000$$

$$Z_{in} = 5.005 \, \text{M}\Omega$$

Try Examples

- An op-amp has: $Z_i = 50 \, \text{k}\Omega$, $A_{OL} = 80,000$ and $\beta = 0.02$. Find Z_{in} .
Answer: $Z_{in} = 80.05 \, \text{M}\Omega$
- An op-amp has: $Z_o = 200 \, \Omega$, $A_{OL} = 40,000$ and $\beta = 0.025$. Find Z_{out} .
Answer: $Z_{out} \approx 0.2 \, \Omega$
- An op-amp has: $Z_o = 150 \, \Omega$, $A_{OL} = 60,000$ and $\beta = 0.01$. Find Z_{out} .
Answer: $Z_{out} \approx 0.25 \, \Omega$

3. Open-Loop Gain (AOL)

The open-loop gain of an op-amp tells us how much it can increase a signal when no feedback is added to the circuit. Think of it like a microphone connected to a loudspeaker. If the microphone is super-sensitive and the speaker is very loud, even a small whisper can become a booming sound.

In an ideal op-amp (a perfect one), this gain is said to be infinite which means it can boost even the tiniest signal to a huge one. But in real life, op-amps are not perfect. The gain is still very large but limited, usually between 20,000 and 200,000 times the original signal. So, if you input a small voltage like 0.001 volts, the op-amp could boost it up to 20 volts or even more, depending on the gain.

4. Bandwidth (BW)

Bandwidth is the range of frequencies (like the speed of vibration in sound or signal) that the op-amp can handle or amplify properly. Imagine a radio that can only tune into stations between 88 and 108 MHz – that's its bandwidth. An ideal op-amp should work for all signals, from DC (0 Hz) to very high-speed AC (like radio waves), meaning it should have infinite bandwidth.

But in real life, this is not possible. The op-amp's bandwidth is limited because as the frequency of the signal increases, the gain decreases. This limitation is described by something called the Gain-Bandwidth Product (GB). It means, if the gain is high,

the frequency range must be low, and if the frequency range is wide, the gain must be lower. So, you must balance between gain and frequency when designing circuits.

Examples of Op-Amp Applications (Where We Use Them)

Op-amps are very useful in electronics, and we use them in many types of circuits. Some common ones include:

1. Inverting Amplifier: Flips the input signal and increases its size (like changing +2V to -10V).
2. Non-Inverting Amplifier: Boosts the signal without flipping it.
3. Differentiator: Produces an output that depends on how fast the input changes (like detecting motion).
4. Integrator: Does the opposite of a differentiator; useful in making wave shapes or filters.
5. Summing Amplifier: Adds multiple signals together (used in audio mixers).
6. Differential Amplifier: Finds the difference between two signals (used in sensors and measurement tools).
7. Instrumentation Amplifier: Very accurate amplifier used in medical devices like ECG or in industrial sensors.

Summary (In Simple Terms)

1. Open-loop gain = how much the op-amp can amplify a signal without feedback (very large number).
2. Bandwidth = the range of signal frequencies the op-amp can work with (not infinite in real life).
3. Op-amps are like the “amplifying engine” inside many smart devices, from radios and speakers to hospital machines and measuring instruments.

Activity 3.12.1 Discovering Operational Amplifiers (Op Amps)

Scenario

An engineering team is designing electronic control systems for household and industrial devices. Operational amplifiers (Op-amps) are key components for amplification, signal processing, and switching in these circuits. Understanding how Op-amps work, their configurations, and how to control gain through feedback is essential. By studying popular Op-amps like the 741 and 4558, the team aims to build skills in designing practical circuits such as amplifiers and comparators, which are widely used in everyday electronics and automation.

Task

Explore the concept of operational amplifiers, explain their principle of operation, and determine the feedback resistor value for an Op-amp with a given gain and input resistance.

Materials needed

1. Diagrams or models of 741 and 4558 Op-amp ICs
2. Worksheet with guiding questions
3. Internet-enabled devices for research and videos
4. Large paper, markers, pens
5. Circuit simulation software (e.g., Multisim), if available
6. Notebooks, pens

Step 1: Class Brainstorm

Discuss with classmates

1. What is an operational amplifier?
2. What are the common uses of Op-amps in circuits?
3. What does it mean for an Op-amp to have a gain?
4. Why is feedback important in Op-amp circuits?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 learners.
2. Assign roles: Researcher, Note-taker, Presenter, Artist.
3. Research the 741 and 4558 ICs using books, internet, and videos. Complete the table below.
4. Watch a short video explaining how IC 741 and 4558 work.
 - a. <https://youtu.be/2k3EvKRp3w0?feature=shared>
 - b. <http://sharevideo1.com/v/ZFZGWEw2cWpKYVvk=?t=ytb&f=co>

Aspect	741 IC	4558 IC
Pin connections		
Typical voltage supply		
Principle of operation		
Circuit connection types	(e.g., inverting, comparator)	

Step 3: Calculate Feedback Resistor

Using the formula for inverting amplifier gain: $\text{Gain} = -R_f \div R_{in} \Rightarrow R_f = |\text{Gain}| \times R_{in}$, calculate the value of the feedback resistor (R_f) for an Op-amp with gain -10 and input resistance $10\text{k}\Omega$.

Step 4: Create Your Poster and Circuit Diagrams

1. Draw diagrams of the 741 and 4558 ICs with pin connections.

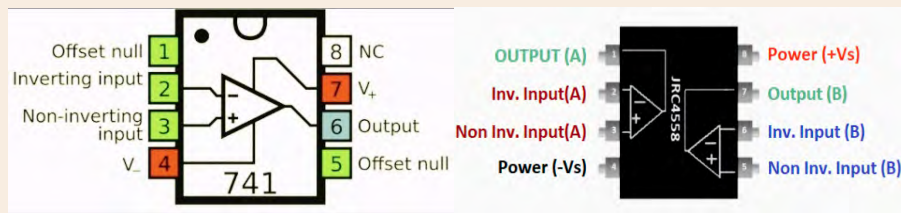


Figure 12a: IC 741 Figure 12b: IC 4558

2. Design a circuit for an inverting amplifier and comparator.
3. Make a poster showing:
 - a. Concepts of operational amplifiers
 - b. Principle of operation
 - c. Feedback resistor calculation
 - d. Example applications

Step 5: Present Your Work

Present your poster and diagrams to the class. Explain:

1. What an operational amplifier is
2. How it works
3. How the feedback resistor is calculated
4. Practical circuit uses of 741 and 4558 ICs

Step 6: Ask and Answer Questions

1. Listen carefully to questions from classmates.
2. Answer clearly and help others understand.
3. Provide meaningful feedback to other groups.

Step 7: Reflect and Write

In your notebooks or tablet, answer these reflective questions:

1. What is an operational amplifier and how does it work?
2. How do the 741 and 4558 ICs differ or relate?
3. Why is feedback important in Op-amp circuits?
4. How was the feedback resistor calculated and why is it important?

EXTENDED READING

1. <https://www.elprocus.com/ic-741-op-amp-tutorial-and-characteristics/#:~:text=What%20is%20an,Wind%20Sound%20Generation>
2. <https://www.ic-components.com/blog/your-guide-to-rc4558-op-amp-datasheet,features,and-alternatives.jsp#:~:text=The%20RC4558%20dual,world%20of%20technology>

REVIEW QUESTIONS

1. You are building a sound system for a local event. How can a 4558 op-amp improve the audio quality?
2. Why is high input impedance useful in a solar-powered light sensor?
3. How could you use an op-amp to turn on an LED when it gets dark?
4. A friend's guitar pedal sounds distorted. How might feedback in an op-amp fix this?
5. Design a simple circuit where clapping turns on a fan using an op-amp. What pins would you use?

SECTION

4

UNIT 13 DIGITAL ELECTRONICS

INTRODUCTION

In Year 2, you learned about binary (0s and 1s) and decimal number systems, and how to convert between them. This is important because digital circuits work with binary signals. Logic gates are tiny electronic switches made from parts like diodes, resistors, and transistors. They follow specific rules to process binary inputs and produce a binary output. These gates are the building blocks of devices you use every day, such as calculators, security alarms, washing machines, and traffic lights.

In this unit, you will study common gates: *AND*, *OR*, *NOT*, *NAND*, *NOR*, and learn their symbols, truth tables, and Boolean algebra expressions. You will also design and test circuits using simulation software and breadboards. This hands-on work will help you understand digital circuit design and prepare you for advanced topics like microcontrollers, automation, and troubleshooting.

KEY IDEAS

- AND Gate produces a high output only when all inputs are high
- Each logic gate responds differently based on the combination of binary inputs it receives.
- Logic Gates – Basic building blocks of digital electronics used to process binary signals (0s and 1s).
- NOT Gate – Inverts the input; if the input is 1, the output is 0, and vice versa.
- Output Function – The result from a gate based on its input pattern, shown clearly using a truth table.
- Truth Table – A chart that lists all possible input combinations and the matching output for a logic gate.

TYPES OF LOGIC GATES AND THEIR PROPERTIES

Logic gates are grouped into three basic types, and two more that are slightly advanced:

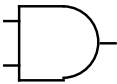
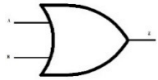
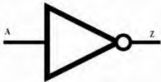
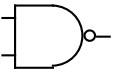
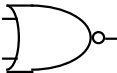
Basic Gates

- 1. AND Gate – Gives a high output only if all inputs are high.
- 2. OR Gate – Gives a high output if at least one input is high.
- 3. NOT Gate – Flips the input; if it is high, the output becomes low—and vice versa.

Advanced Gates

- 1. NAND Gate – This is short for Not AND. It is the opposite of the AND gate.
- 2. NOR Gate – This stands for Not OR. It’s the opposite of the OR gate.

Table 4.13.1 Symbols of logic gates

S/N	Symbol	Name
1		AND gate
2		OR gate
3		NOT gate
4		NAND gate
5		NOR gate

Properties of Logic Gates

Logic gates follow specific rules that control how they behave. Below are the key properties for each type of gate:

AND Gate

- 1. Accepts two or more inputs at the same time.
- 2. The output is High (1) only when all inputs are High (1).
- 3. It performs logical multiplication (like $1 \times 1 = 1$).

OR Gate

- 1. Also accepts two or more inputs.
- 2. The output is Low (0) only when all inputs are Low (0).
- 3. It performs logical addition (like $1 + 0 = 1$).

NOT Gate

1. Has only one input and one output.
2. The output is the opposite (inverse) of the input.
3. If the input is 0, the output is 1—and if the input is 1, the output is 0.

NAND Gate

1. Takes two or more inputs.
2. The output is Low (0) only when all inputs are High (1).
3. It works as the opposite of the AND gate.

NOR Gate

1. Accepts two or more inputs.
2. The output is High (1) only when all inputs are Low (0).
3. It performs the opposite of the OR gate.

Truth Table of Logic Gates

A truth table shows how a logic gate responds to every possible input combination. Let us break down each gate with its inputs and expected outputs.

NOT Gate (Inverter)

1. The NOT gate has one input and gives one output.
2. It reverses the input: if the input is 1, the output becomes 0, and vice versa.
3. It's written as $\bar{A}$, meaning “NOT A.”

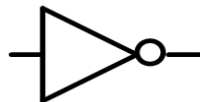


Figure 4.13.1: NOT gate

Notice the small circle at the output of the inverter. This circle indicates inversion in logic circuits. Using the binary digits, if the input is 1, then the output will be 0 and vice versa. The behaviour of a NOT gate can be summarised in the truth **Table 4.13.2**

Table 4.13.2: Truth table for NOT gate

Input A	Output $F = \bar{A}$
0	1
1	0

The AND gate

The AND gate consists of two or more input terminals and a single output terminal, as shown in **Figures 4.13.2a** and **4.13.2b**

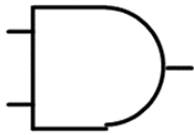


Figure 4.13.2a: Two-input AND gate

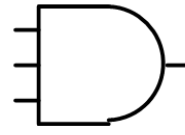


Figure 4.13.2b: Three-input AND gate

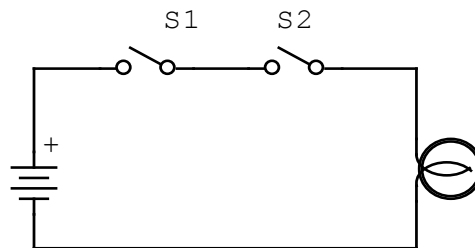


Figure 4.13.3: Switches in series

Understanding the AND Gate with Switches

The AND gate gives an output of true (1) only when all its inputs are true (1). You can think of it like a series of switches connected in a row.

Analogy: Switches in Series

1. Imagine two switches connected in series with a light bulb.
2. The light bulb turns on (output = 1) only if both switches are ON (inputs = 1).
3. If one switch is OFF, the current will not flow, so the light stays OFF (output = 0).

This helps show how an AND gate needs all inputs to be ON for the output to be ON, as shown in **Figure 4.13.3**. The light can only switch on when both switches S_1 and S_2 are closed

Truth table for 2-input AND gate

INPUT		OUTPUT
A	B	$F = A.B$
0	0	0
0	1	0
1	0	0
1	1	1

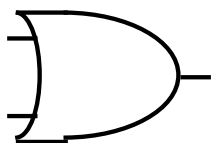


Figure 4.13.4: Two-input OR gate

Truth table for 3 input AND gate

INPUTS			OUTPUT
A	B	C	$F = A.B.C$
0	0	0	0
0	0	1	0
0	1	0	0
1	0	0	0
0	1	1	0
1	0	1	0
1	1	0	0
1	1	1	1

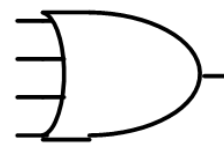


Figure 4.13.5: Three-input OR gate

Understanding the OR Gate with Switches

An OR gate gives an output of true (1) if at least one of the inputs is true (1). You can picture this using switch connected in parallel. The OR gate also consists of two or more inputs and a single output.

Analogy: Switches in Parallel

- Imagine two switches wired in parallel to a single light bulb.
- If either switch is ON, electricity flows and the light turns ON (output = 1).
- The only time the light stays OFF is if both switches are OFF (inputs = 0).

This shows that an OR gate requires only one active input to produce a high output. Either switch S1 or switch S2 can turn the light on.

Table 4.13.3: Truth table for a two-input and a three-input OR gate

INPUT		OUTPUT	INPUT			OUTPUT
A	B	$F = A + B$	A	B	C	$F = A+B+C$
0	0	0	0	0	0	0
0	1	1	0	0	1	1
1	0	1	0	1	0	1
1	1	1	1	0	0	1
			0	1	1	1
			1	0	1	1
			1	1	0	1
			1	1	1	1

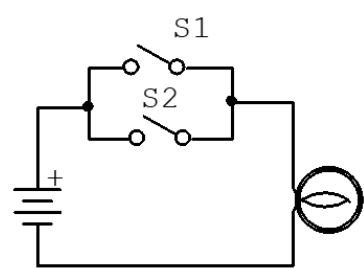


Figure 4.13.6: Switches in parallel

NAND Gate – “Not AND”

The NAND gate is a combination of two logic gates:

- First, an AND gate performs its usual operation.
- Then, a NOT gate is applied to invert the output of the AND gate.

So basically, a NAND gate works as “Not AND”.

How It Works

- If all inputs are true (1), the NAND gate gives a false (0) output.
- In every other case, the output is true (1).

Think of it like saying: “I will only say NO if everyone agrees YES.”

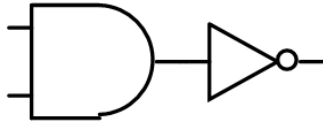


Figure 4.13.7: AND followed by NOT

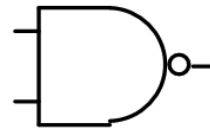


Figure 4.13.8: Symbol of the NAND gate

Table 3.13.4: Truth table of a 2-input NAND gate

INPUT		OUTPUT
A	B	$F = (A \cdot B)'$
0	0	1
0	1	1
1	0	1
1	1	0

NOR Gate – “Not OR”

The NOR gate is built by combining two operations:

1. First, it uses an OR gate to process the inputs.
2. Then, a NOT gate is added to invert the output of the OR gate.

So, the NOR gate means: “Not OR”.

How it Works

1. The output of a NOR gate is true (1) only when all the inputs are false (0).
2. In any other case, it gives false (0) as the output.

Think of it like saying: “I will only say YES if nobody presses their button!”

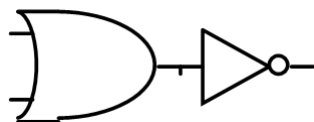


Figure 4.13.9: OR followed by NOT



Figure 4.13.10: NOR gate

Table 4.13.5: Truth table NOR gate $F = \bar{A} + B$

A	B	$\bar{A}$	$F = \bar{A} + B$
0	0	1	1
0	1	1	1
1	0	0	0
1	1	0	1

Output Functions of Logic Gates

Every logic gate gives an output based on the type of gate and the combination of inputs it receives.

How Logic Gates Are Built

Digital logic gates are made using electronic parts like:

1. Diodes – they allow electric current to flow in only one direction.
2. Transistors – used to switch signals ON and OFF.
3. Relays – used sometimes, but not as common as transistors and diodes.

The two main types of transistors used are:

1. Bipolar Junction Transistors (BJTs)
2. Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs)

Example: TTL – NOR Gate (Transistor – Transistor Logic)

One common way of building logic gates is using BJTs in a setup called Transistor-Transistor Logic (TTL).

Parts of a BJT

1. Base – controls the switch
2. Collector – receives current
3. Emitter – releases current

How it Works

1. When a small current flow into the base, it turns on the transistor, allowing a larger current to pass from collector to emitter.
2. If no current is sent to the base, the transistor is OFF and no signal flows through.

In TTL logic gates

1. The input goes into the base of the transistor.
2. The output is taken from the collector or emitter, depending on how it is connected.

Multiple transistors can be linked together to create different types of logic gates—like the NOR gate, which gives an output of 1 only when all inputs are 0.

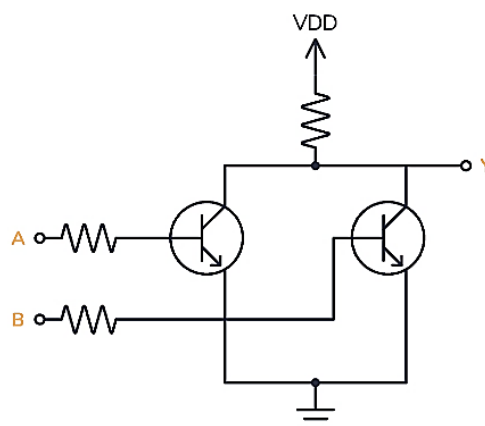


Figure 4.13.11: Transistor-transistor logic circuit of a NOR Gate

When both inputs A and B of the circuit in **Figure 4.13.11** are LOW (logic 0), the bases of the two transistors experience low voltage and are therefore OFF, and so no current is drawn from the supply. Note that since no current is drawn from the supply, no voltage is dropped across the resistor connected to the power supply VDD. As a result, the output goes High (logic 1).

On the other hand, if any input is HIGH, or both inputs are HIGH, the transistors will switch on, drawing current through their collectors to ground. This makes the resistor connected to VDD drop high voltage; the output Y, therefore, goes LOW (logic 0). The output will therefore be HIGH if and only if both inputs are LOW. Hence the output function is $Y = (A+B)'$

Table 4.13.6: Truth table of a NOR gate

INPUT		OUTPUT
A	B	$Y = (A + B)'$
0	0	1
0	1	0
1	0	0
1	1	0

Advantages of TTL Logic Gates

TTL (Transistor-Transistor Logic) gates have several benefits that make them useful in electronics:

1. They are strong against noise, which means they do not easily pick up unwanted signals.
2. They are cheap and can be found easily in the market.
3. They work quickly and are generally reliable for most operations.

Disadvantages of TTL Logic Gates

Despite their benefits, TTL logic gates also have some drawbacks:

1. They use more power than some other types of logic gates.
2. They can produce more heat, especially when many gates are used.
3. Their voltage range is limited—they mostly work between 4.75V and 5.25V, which means they are less flexible in some circuits.

Diode – Transistor Logic Circuit – 3-Input AND Gate

In a 3-input diode-transistor logic (DTL) circuit for an AND gate, the setup includes:

1. A base resistor (R_1) and an emitter resistor (R_e).
2. The base resistor R_1 is connected between the 5V power supply and the base of the transistor (point B).
3. The output (Y) is measured between the emitter of the transistor and the emitter resistor (R_e).
4. Because of this connection, the output voltage is the same as the voltage across R_e .

How It Works

1. The circuit uses three diodes at the input to control the current going to the transistor base.
2. All three inputs must be high (1) for the transistor to turn ON.
3. If the transistor is ON, current flows through the emitter resistor (R_E), giving a high output.
4. If any input is low (0), the transistor stays OFF, and the output is low.

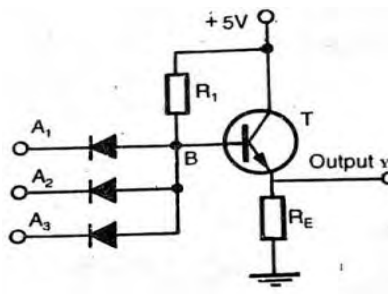


Figure 4.13.12: A 3-input diode transistor logic of an AND gate

How a 3-Input Diode-Transistor AND Gate Works

This circuit uses three inputs— A_1 , A_2 , and A_3 —to control the output. Let us see what happens when the inputs are LOW or HIGH.

When All Inputs Are LOW (0)

1. The diodes become forward biased, which means they allow current to flow from the 5V power supply, through resistor R_1 , and down to ground.
2. This current causes a voltage drop across R_1 .
3. As a result, the base of the transistor does not get enough voltage to switch it ON.
4. So, no current flows from the collector to the emitter.
5. That means no current through R_E , which is where the output (Y) is taken.
6. Therefore, the output is LOW (0).

Even if just one input is LOW, the same thing happens—the output remains LOW.

When All Inputs Are HIGH (1)

1. The diodes become reverse-biased, which means they block the current.
2. This allows the base voltage of the transistor to rise.
3. Now the transistor switches ON.
4. Current flows through the emitter and R_E , which creates a voltage across R_E .
5. The output is now HIGH (1).

Table 4.13. 7 Truth table for 3 input AND gate

INPUTS			OUTPUT
A	B	C	F = A. B. C
0	0	0	0
0	0	1	0
0	1	0	0
1	0	0	0
0	1	1	0
1	0	1	0
1	1	0	0
1	1	1	1

Diode Logic – OR Gate (2-Input)

A diode logic OR gate uses two inputs—X and Y—to decide what the output Z will be.

How it Works

1. If X is HIGH (1), or Y is HIGH (1), or both are HIGH, the output Z becomes HIGH (1).
2. If both X and Y are LOW (0), the output Z stays LOW (0).

This behaviour shows that the gate follows the logic function: $Z = X + Y$

(This means “Z equals X OR Y”)

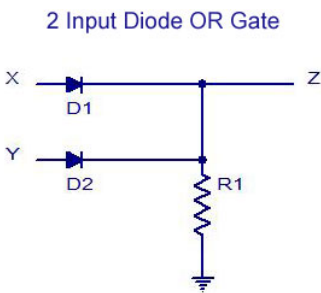


Figure 4.13.13: A 2-input Diode logic OR gate

Table 4.13.7 input OR gate

INPUT		OUTPUT
X	Y	Z = A + B
0	0	0
0	1	1
1	0	1
1	1	1

COMPLEMENTARY METAL-OXIDE-SEMICONDUCTOR (CMOS)

CMOS is a type of logic gate system that uses a special type of transistor called MOSFET to build digital circuits.

What is a MOSFET?

A MOSFET (Metal Oxide Semiconductor Field-Effect Transistor) is a type of FET (Field-Effect Transistor) with three parts:

1. Gate – controls current flow.
2. Source – where the current comes from.
3. Drain – where current flows to.

When voltage is applied to the gate, it controls how much current flows between the source and the drain.

How CMOS Works

1. CMOS logic gates use two types of MOSFETs:
2. NMOS (N-channel MOSFETs) – faster and more compact.
3. PMOS (P-channel MOSFETs) – uses positive and negative voltages to work.

These two are paired together—complementary—to perform logic functions. They can be connected in series or parallel, depending on the gate being built.

You can think of NMOS and PMOS transistors as switches controlled by the gate-to-source voltage. That means, when you change the voltage on the gate, it turns the transistor ON or OFF.

CMOS and NAND Gate Example

To create an AND function using NMOS transistors:

1. You connect two NMOS transistors in series.
2. The output is actually the opposite of AND, which makes it a NAND gate.
3. This setup is one-way CMOS is used to build gates like NAND.

Figure 4.13.14 shows this in action

NAND Gate

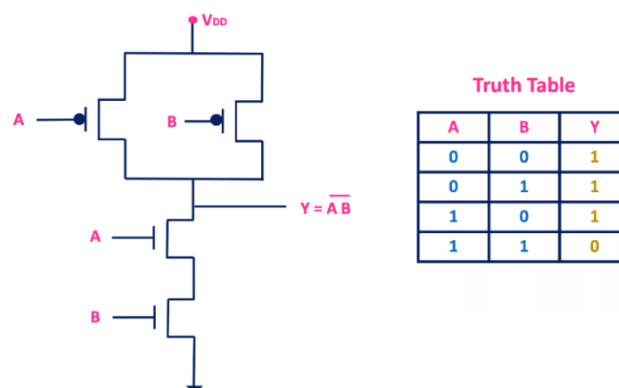


Figure 4.13.14: CMOS implemented as a NAND gate

For a two-input NAND gate, if A and B are the inputs, then its output $Y = (A \cdot B)'$ or $\overline{A \cdot B}$

Advantages of CMOS Logic Gates

CMOS (Complementary Metal-Oxide-Semiconductor) logic gates have several benefits:

1. They use very little power, especially when not switching.
2. They give off small amounts of heat in steady operation.
3. They can handle high noise levels and fan-out without affecting performance.
4. They can work with a wide range of voltages, which makes them flexible.

Disadvantages of CMOS Logic Gates

Even though CMOS gates are useful, they also have some weaknesses:

1. They are slower at switching compared to other logic types.
2. They can be easily damaged by electrostatic discharge (tiny electric charges).
3. They can be physically bigger, meaning they take up more space.

Applications of Logic Gates

Logic gates are used in many areas of science and technology:

1. Digital circuits – used in calculators, mobile phones, and TVs.
2. Computer architecture – for designing how computers process data.
3. Programming languages – especially in writing code for machines.
4. Error detection and correction – helps fix data problems in systems.
5. Artificial Intelligence (AI) – used in smart systems and robots.

Activity 4.13.1 Logic Gates Principles, Operation and Applications

Scenario

You are part of an engineering club tasked with designing a smart school security system. The system will receive signals from motion sensors at the gates and doorways. It should decide automatically whether to trigger an alarm or keep it off, depending on the combination of signals received. To achieve this, you need to understand how logic gates work, how they are built using BJTs, and which logic technology (DTL, TTL or CMOS) is best for the design.

Task

1. Explain how the BJT can be used to obtain Transistor –transistor logic
2. Compare the DTL, TTL and COMOS in terms of their design and performance

Materials needed

1. Internet-enabled devices (if available), Breadboards, BJTs, diodes, resistors (if available)
2. Worksheets with truth tables and Boolean expressions

- Reference textbooks or printed guides, large paper, markers, notebooks, pens/pencils

Step 1: Class Brainstorm

- Think about devices that make “yes/no” or “on/off” decisions automatically e.g. alarms, washing machines, traffic lights.
- Discuss with your classmates:
 - What is a logic gate?
 - Can you name some types of logic gates?
 - Where might logic gates be used in daily life?

Step 2: Group Research and Table Completion

- Form groups of 3 to 5 people by the guidance of your teacher.
- Each group member takes a role: Researcher, Note-taker, Presenter or Artist.
- Use books, internet, and other resources to complete the tables below.

Table 1 – Types of Logic Gates

Gate Type	Symbol	Boolean Expression	Truth Table	Application Example
AND				
OR				
NOT				
NAND				
NOR				

Table 2 – Logic Family Comparison

Logic Family	Main Components	Power Consumption	Switching Speed	Noise Immunity	Typical Applications
DTL					
TTL					
CMOS					

- These questions will guide group research:
 - What does each gate do?
 - How does a BJT help create TTL circuits?
 - Which logic family works best for low power use?
 - Where is each logic family most often used?

Step 3: Create Your Model and Poster

1. Draw a labelled diagram or build a model showing:
 - a. Each logic gate studied
 - b. Its symbol, Boolean expression, and truth table
 - c. The working principle in simple words
 - d. One real-life application
2. Include your completed DTL–TTL–CMOS comparison on your poster.

Step 4: Present Your Work

Present your diagrams, posters and comparison table to the class. Explain:

- a. How logic gates process binary inputs to give binary outputs
- b. How BJTs are used in TTL
- c. Differences between DTL, TTL, and CMOS

Step 5: Ask and Answer Questions

1. Listen to classmates' presentations and ask questions.
2. Answer questions about your own work clearly and give helpful feedback to other groups.

Step 6: Reflect and Write

In your notebook or tablet reflect and answer:

1. What did you learn about logic gates and their applications?
2. Which logic family is most suitable for my school security system? Why?
3. How can you explain the importance of logic gates to someone who has never studied electronics?

EXTENDED READING

1. [Logic Gates – Definition, Types, Uses | GeeksforGeeks](#)
2. [Introduction to Logic Gates | NOT, AND, NAND, OR, NOR](#)
3. [Logic Gate: Types including Circuit Diagram, Symbols and Uses](#)
4. [A Comprehensive Guide to Digital Logic Gates | Electrical4U](#)
5. [Diode Transistor Logic \(DTL\): Circuit, Working & Its Applications](#)
6. <https://www.electronicsforu.com/technology-trends/learn-electronics/mosfet-basics-working-applications>
7. <https://www.allaboutelectronics.org/cmos-logic-gates-explained/>

REVIEW QUESTIONS

1. Analyse the output response for OR truth table which has two input signals.
2. Design an automatic door using NOT gate, the door should close automatically when the occupant forgets to close it.

UNIT 14 BOOLEAN ALGEBRA

INTRODUCTION

You have explored the types of logic gates, their switching arrangements, logic symbols, truth tables, and Boolean algebra expressions. Boolean algebra, developed by George Boole, is the language of digital electronics. It uses only two states: 1 or 0, on or off, high or low, to describe and control how circuits work. You will now go deeper by learning how to simplify logic expressions to make circuits more efficient. You will study De Morgan's Theorem, which changes between AND, OR, and NOT operations, and the Redundancy Theorem, which removes terms that do not affect the final output. You will also practice drawing circuit diagrams from simplified expressions. These skills are essential for designing faster, cheaper, and more reliable digital systems. The same principles are used in calculators, traffic lights, and computer processors. You will apply them through problem-solving, group work, and circuit-building activities.

KEY IDEAS

- Boolean Algebra: A way of using 1s and 0s to show how logic circuits work.
- Combination Logic: Uses two or more gates; output depends only on current inputs.
- Each gate (AND, OR, NOT, etc.) has a symbol used in circuit diagrams.
- Logic simplification involves making Boolean expressions shorter and easier to build in circuits.
- Sequence Logic: Output depends on current and past inputs; used in memory circuits.
- Truth Table: A chart that shows all possible inputs and their matching outputs.

BOOLEAN ALGEBRA

Introduction to Boolean Algebra

Boolean algebra was developed by George Boole (1815–1864), a brilliant English mathematician. He came up with rules that help us solve logical problems using Maths. Just like regular algebra, Boolean algebra has *elements*, *operations*, and *laws* that guide how it works.

Elements of Boolean Algebra

Boolean algebra works with two types of elements: variables and constants.

1. Variables are usually written with capital letters like A, B, or C.
2. Each variable can only have two values: either 1 (true) or 0 (false).
3. Constants always stay the same and are also just 1 or 0.

Operations (Functions)

In regular Maths, we use operations like plus (+), minus (-), divide ($\div$), and times ($\times$). But in Boolean algebra, we only use three main operations: AND, OR and NOT

Let us break them down:

AND Operation

The AND operation checks if both values are true. It is written like $A \bullet B$, and we read it as “A AND B”.

Here is how the AND operation works:

A	B	$A \bullet B$
0	0	0
0	1	0
1	0	0
1	1	1

As you can see, the result is 1 only when both A and B are 1.

The following rules can thus be derived from the truth table above.

1. $A \bullet 1 = A$
 Proof: when $A = 0$
 $0 \bullet 1 = 0$
 When $A = 1$
 $1 \bullet 1 = 1$
2. $A \bullet 0 = 0$
 Proof: when $A = 0$
 $0 \bullet 0 = 0$
 When $A = 1$
 $1 \bullet 0 = 0$
3. $A \bullet B = B \bullet A$
 Proof: if $A = 1$ and $B = 0$
 then $1 \bullet 0 = 0$

$$0.1 = 0$$

$$A.B = B.A$$

4. $A. \bar{A} = 0$

Proof: if $A = 1$ then $\bar{A} = 0$ and if $A = 0$ then $\bar{A} = 1$

$$1.0 = 0.1 = 0$$

5. $A.A = A$

Proof: if $A = 0$ then $0.1 = 0$

$$0.0 = 0$$

if $A = 1$, then $1.1 = 1$

OR Operation in Boolean Algebra

The OR operation compares two Boolean values and checks if at least one of them is 1 (true). It is written like: $A + B$. We read it as: “A OR B” — even though it uses the plus sign +, we do not read it as addition.

Key point: The result of an OR operation is 1 when either A, B, or both are 1.

OR Operation Truth Table

A	B	A + B
0	0	0
0	1	1
1	0	1
1	1	1

So, anytime at least one of the variables is 1, the result will be 1.

Consider the following rules:

1. $A + 1 = 1$

Proof: when $A = 0$

$$0 + 1 = 1$$

when $A = 1$

$$1 + 1 = 1$$

2. $A + 0 = A$

Proof: when $A = 0$

$$0 + 0 = 0$$

when $A = 1$

$$1 + 0 = 1$$

3. $A+B = B + A$

Proof: when $A = 1$ and $B = 0$ then $0 + 1 = 1$

when $A = 0$

$$0 + 1 = 1$$

$$A + B = B + A$$

$$4. \quad A + \bar{A} = 1$$

Proof: when $A = 1$, then $\bar{A} = 0$ and vice versa

$$\text{But } 1 + 0 = 0 + 1 = 1$$

$$5. \quad A + A = A$$

Proof: when $A = 0$

$$0 + 0 = 0$$

when $A = 1$

$$1 + 1 = 1$$

The NOT Operation

The NOT operation is also called the negation or complementation and is denoted by a bar over the variable. Thus, the complement of $A = \bar{A}$ and vice versa. Also, if $A = 1$, then $\bar{A} = 0$. It should be obvious that a double inversion leaves the value unchanged.

$$\text{i.e.} \quad \overline{\bar{B}} = B$$

$$\overline{\bar{A}} = A$$

Summary

Below is a summary of the basic laws derived in this section.

Commutative property (law)

$$A + B = B + A$$

$$A.B = B.A$$

Associative property

$$(A + B) + C = A + (B + C)$$

$$(A.B).C = (A.B).C$$

Identity law

$$A + A = A$$

$$A.A = A$$

Negation law

$$(\bar{\bar{A}}) = \bar{A}$$

$$\overline{\bar{A}} = A$$

Algebraic Simplification and Manipulation

In Maths, to **simplify an equation** means to make it easier to work with by reducing it to its simplest form. The same idea is used in **digital electronics**, where we deal with logic circuits. Sometimes, these circuits can be a bit complex, with lots of components. But using **Boolean algebra**, we can simplify the logic expressions that control these circuits. When we simplify the expressions, we end up designing circuits that are:

1. Cheaper to build
2. Faster to operate
3. Easier to understand

Basic Axioms

Do you still remember the basic axioms of Boolean algebra? Below is a summary.

NOT Algebra	AND Algebra	OR Algebra
$\bar{0} = 1$	$0.0 = 0$	$0 + 0 = 0$
$\bar{1} = 0$	$0.1 = 0$	$0 + 1 = 1$
	$1.0 = 0$	$1 + 0 = 1$
	$1.1 = 1$	

Boolean Operations on a Constant and a Variable

NOT Operation	AND Operation	OR Operation
$\overline{\bar{A}} = A$	$0.A = 0$	$0 + A = A$
	$1.A = A$	$1 + A = 1$
	$A.A = A$	$A + A = A$
	$A.\bar{A} = 0$	$A + \bar{A} = 1$

The basic laws or properties of Boolean algebra led to three theorems which are very useful for simplifying Boolean expressions.

These include the Redundancy theorem, the Race Hazard theorem and De Morgan's theorem.

The Redundancy Theorem

When **2 binary variables** are **AND** operated and then **OR** operated on any of the variables, the result is the variable. (The variable makes the other AND-operated variables redundant.)

i.e. $(X \cdot Y) + X = X$

Also $(X \cdot Y) + Y = Y$

Proof

$$\begin{aligned}
 1. \quad (X \cdot Y) + Y & \\
 &= Y(X + 1) \\
 &= Y \cdot 1 \\
 &= Y
 \end{aligned}$$

Since: $X + 1 = 1$

$$\begin{aligned}
 2. \quad (X \cdot Y) + X & \\
 &= X(Y + 1) \\
 &= X \cdot 1 \\
 &= X
 \end{aligned}$$

If the operations are exchanged, the result is the same

$$\begin{aligned}
 (X + Y) \cdot X &= X \\
 (X + Y) \cdot Y &= Y
 \end{aligned}$$

Proof

$$\begin{aligned}
 1. \quad X \cdot (X + Y) & \\
 &= X \cdot X + X \cdot Y \\
 &= X + X \cdot Y \\
 &= X(1 + Y) \\
 &= X
 \end{aligned}$$

Since: $X \cdot X = X$

$$\begin{aligned}
 2. \quad Y \cdot (X + Y) & \\
 &= Y \cdot X + Y \cdot Y \\
 &= Y \cdot X + Y \\
 &= Y(X + 1) \\
 &= Y
 \end{aligned}$$

Since: $Y \cdot Y = Y$

The redundancy theorem can also be applied to operations involving more than 2 variables

$$\begin{aligned}
 (X + Y)(X + Y + Z) &= X + Y \\
 (X \cdot Y) + (X \cdot Y \cdot Z) &= X \cdot Y
 \end{aligned}$$

De Morgan's Theorem

When building digital circuits, **NAND gates** are often chosen over **AND gates**. Why? Because NAND gates are:

1. Faster to operate
2. Made with fewer parts in an integrated circuit
3. Cheaper and more efficient

Because of this, we sometimes need to change AND gates into NAND gates in our designs. That is where De Morgan's Theorem comes in.

What Does De Morgan's Theorem Say?

De Morgan's Theorem helps you **flip a logic expression** by: Changing **AND (•)** into **OR (+)**

Inverting each variable (putting a bar over it or writing NOT)

$$\begin{aligned}
 \text{i.e. } \overline{(X + Y)} &= \bar{X} \cdot \bar{Y} \\
 \overline{(X \cdot Y)} &= \bar{X} + \bar{Y}
 \end{aligned}$$

Note that $(\overline{X + Y}) = \overline{X} + \overline{Y}$

Example 1

Use De Morgan's theorem to simplify the following expression: $F = A \cdot B + A \cdot C$

Solution

$$F = A \cdot B + A \cdot C$$

$$F = \overline{A \cdot B + A \cdot C} \quad (\text{applying De Morgan's theorem})$$

$$= (\overline{A} + \overline{B}) \cdot (\overline{A} + \overline{C})$$

$$= \overline{A} \cdot \overline{A} + \overline{A} \cdot \overline{C} + \overline{A} \cdot \overline{B} + \overline{B} \cdot \overline{C}$$

$$= \overline{A} + \overline{A} \cdot \overline{C} + \overline{A} \cdot \overline{B} + \overline{B} \cdot \overline{C} \quad (\text{since } \overline{A} \cdot \overline{A} = \overline{A})$$

$$= \overline{A} + \overline{B} \cdot \overline{C} \quad (\text{applying redundancy theorem})$$

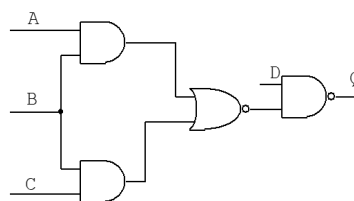
Obtaining logic expressions from circuits

1. Write a logic expression when a circuit diagram is given
2. Draw a circuit diagram when you are given a logic expression

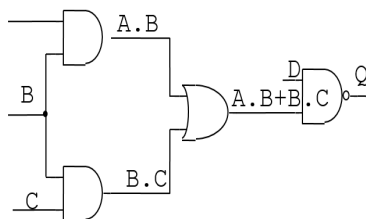
These two go hand in hand. If you understand one, the other becomes easier. To help you get better at this, we will go through examples that show you step-by-step how it works. With practice, you will be able to switch between diagrams and expressions confidently, like decoding and translating your own secret language.

Example 2

The diagrams below are circuits designed using logic gates. Obtain the logic expression for each circuit.



Solution



$$\text{Therefore } Q = \overline{(A \cdot B + B \cdot C)}$$

Activity 4.14.1 Boolean Algebra – Principles, Operations and Applications

Scenario

A smart traffic control system is being developed for a busy Accra junction. It will use sensors and logic circuits to manage traffic lights efficiently. Understanding Boolean algebra and applying rules such as De Morgan's theorem and the Redundancy theorem are essential to designing circuits that work quickly, use fewer components, and are easy to maintain.

Task

1. Explain the concept of Boolean algebra.
2. Describe the three basic operations of Boolean algebra.
3. Use De Morgan's theorem to find F if: $F = (X + Y) \cdot (+ Z)$
4. Write the Boolean expression for the circuit shown in **Figure K**.

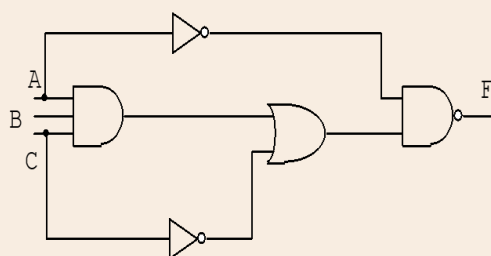


Figure K

Materials needed

1. Worksheets with sample Boolean problems
2. Diagram of **Figure K**.
3. Internet-enabled devices (if available)
4. Large paper, markers, pens, notebooks
5. Breadboards and simple logic gate ICs (if available)

Step 1: Class Brainstorm

Discuss with your classmates

1. What is Boolean algebra?
2. Why is it important in electronics and computing?
3. Can you name devices or systems that use Boolean logic?

Step 2: Group Research and Table Completion

1. Form groups of 3–5 people, with roles assigned such as researcher, note-taker, presenter or diagram artist.
2. Use books, the internet, and other resources to complete the table:

S/N	Concept/ Theorem	Description	Example	Importance
1	Rules of Boolean Algebra			
2	Basic Axioms			
3	De Morgan's Theorem			
4	Redundancy Theorem			
5	Race-Hazard Theorem			

3. These guiding questions will help you to fill in the table
 - a. How do the three basic operations work?
 - b. How does De Morgan's theorem change AND to OR (and vice versa)?
 - c. Why is redundancy removed from logic expressions?

Step 3: Solve and Apply

1. Use De Morgan's theorem to simplify $F = (X + Y) \bullet (+ Z)$.
2. Write the Boolean expression for **Figure K**.
3. Draw a circuit diagram for one simplified Boolean expression.

Step 4: Create Your Poster or Model

Make a poster showing

1. Definition of Boolean algebra
2. The three basic operations with examples
3. Application of De Morgan's theorem and other theorems
4. One real-life application, e.g., a traffic light system, etc.

Step 5: Present Your Work

Explain to the class

1. What Boolean algebra is and why it matters
2. How you applied De Morgan's theorem
3. Your circuit diagram and its function

Step 6: Ask and Answer Questions

Engage with classmates by asking and answering questions about the theorems, solutions, and applications.

Step 7: Reflect and Write

In your notebook reflect and answer these questions:

1. What did you learn about Boolean algebra and its applications?
2. Which theorem was easiest or most difficult to apply? Why?
3. How could Boolean algebra improve the design of real-world systems like traffic control?

REVIEW QUESTIONS

1. Design a simple digital lock system that opens only when the following condition is met: The user presses Button A AND either Button B OR Button C.
 - a. Write the Boolean expression for the system.
 - b. Justify your design by explaining how the logic gates would be connected, why simplification is important for reliability and energy efficiency.
2. Develop a digital 3-input majority voting system where the output is HIGH if at least 2 out of 3 inputs (A, B, C) are HIGH.
 - a. Derive and simplify the Boolean expression.
 - b. Build the truth table.
 - c. Design the circuit using only universal gates (NAND or NOR).
 - d. Evaluate the design for scalability e.g. for 5 inputs instead of 3.



SECTION

5

UNIT 15 LOGIC EXPRESSIONS FROM CIRCUITS

INTRODUCTION

You have explored logic gates, truth tables, and Boolean expressions. This unit builds on that knowledge by showing how Boolean algebra is used to design and simplify digital circuits for devices like mobile phones, traffic lights, and robots. You will learn the elements of Boolean algebra, including how to use De Morgan's Theorem to simplify expressions involving NOT, AND, and OR, and the Redundancy Theorem to remove unnecessary terms. These simplifications help create faster and more efficient circuits.

Once simplified, Boolean expressions are converted into physical circuits using actual gates (gate-level implementation). You will also learn to write Boolean expressions for combinational circuits and use them to design multivibrator circuits; monostable, astable, and bistable used in timers, memory devices, and control systems.

By the end, you will be able to design, simplify, and implement logic circuits for real-world applications in automation, communication, and control.

KEY IDEAS

- Binary Logic – Digital circuits operate using binary values: 0 (low/off) and 1 (high/on).
- Boolean Expressions: Logic circuits can be described using Boolean algebra to show how inputs produce outputs.
- Logic gates are connected in specific ways to form circuits that perform desired functions.
- Logic expressions define how different input values determine the circuit's output.
- Each gate (AND, OR, NOT, etc.) follows a rule for processing inputs.
- Truth Tables: A truth table shows all possible input combinations and their corresponding outputs.

LOGIC EXPRESSIONS FROM CIRCUITS

To get a logic expression from a logic circuit, follow these simple steps:

1. Start from the **input side** (the left side of the circuit).
2. Look at each logic gate and write down the output it produces.
3. The output of one gate becomes the input for the next gate.
4. Keep doing this gate by gate until you reach the **final gate** on the right.
5. The output of the last gate gives you the final logic expression for the whole circuit.

This step-by-step approach helps you break the circuit down and understand how each part affects the final result. Take **Figure 5.15.1** as an example.

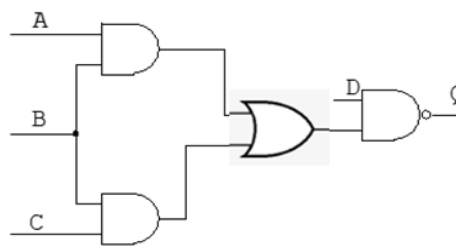


Figure 5.15.1

The output of the circuit, in **Figure 5.15.1**, is Q. The solution is as follows:

1. The first gate is an AND gate. Its output is $A.B$
2. Next is another AND gate with an output of $B.C$
3. Note that the outputs of the first two gates become the inputs of the third gate, which is an OR gate. Thus, one input of the third gate is $A.B$, and the second input is $B.C$
4. The output of the third gate then becomes $A.B + B.C$ (since it is an OR gate).

One input of the fourth gate is D, and the other input is $AB+BC$, but note that the fourth gate is a NAND gate.

Therefore, its output, $Q = \overline{(A.B + B.C) D}$

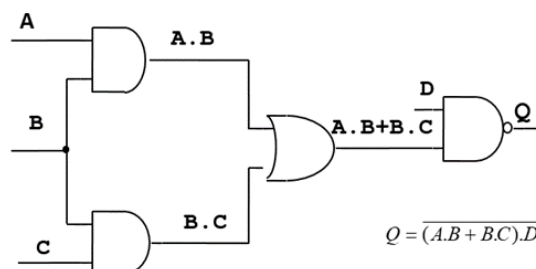


Figure 5.15.2: Output expression of a logic circuit

Let us look at another example in **Figure 5.15.3**.

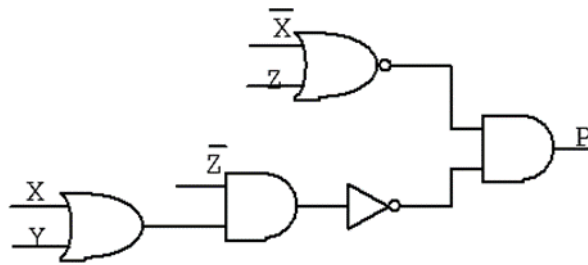


Figure 5.15.3: logic circuit

Using the same process as in the first circuit in **Figure 5.15.1**, the output expression P of the circuit in **Figure 5.15.3**, therefore, is $P = (\bar{X} + Z)(Z + \bar{X}\bar{Y})$, as shown in **Figure 5.15.4**. Note that the final expression has been simplified using De Morgan's theorem.

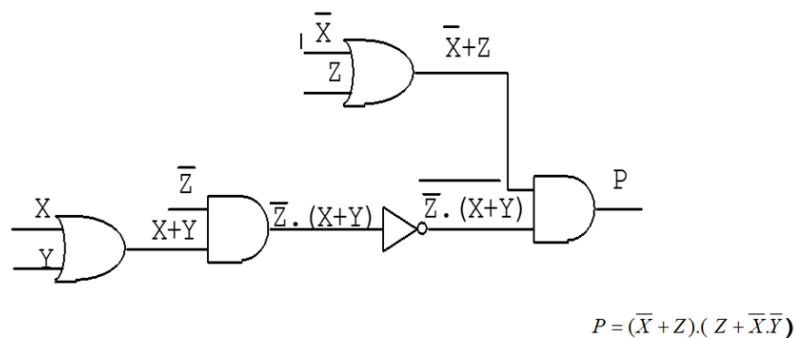


Figure 5.15.4: Output expression of the logic circuit

Designing with Logic Gates

Logic gates can be joined in different ways to create useful circuits. One type is called a multivibrator, which can be used in electronics to make signals or flashes.

Astable Multivibrator Using NAND Gates

An astable multivibrator is a circuit that never stays in one state. It keeps switching between two states—so it works like an oscillator (a circuit that produces a repeating signal).

In the diagram (**Figure 5.15.5**), the circuit uses two NAND gates. It also includes two LEDs so you can see the output from each gate as it flashes. This setup is great for learning how signals behave in circuits, especially in timing and flashing systems like blinkers.

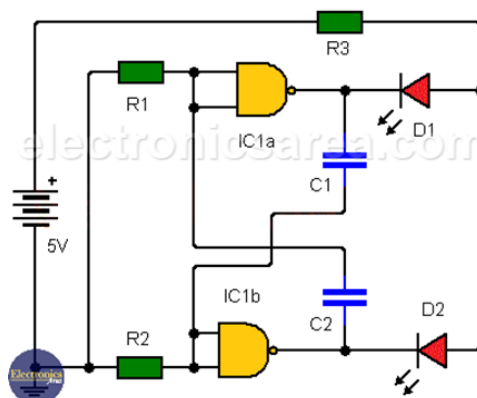


Figure 5.15.5: An astable multivibrator using NAND gates

Table 5.15.1: Components required

S/N	Component	Quantity
1	TTL 4011 IC	1
2	10K resistors (R1, R2)	2
3	220 ohm resistor (R3)	1
4	100 uF (microfarads) capacitors (C1, C2)	2
5	LEDs of any colour (D1, D2)	2

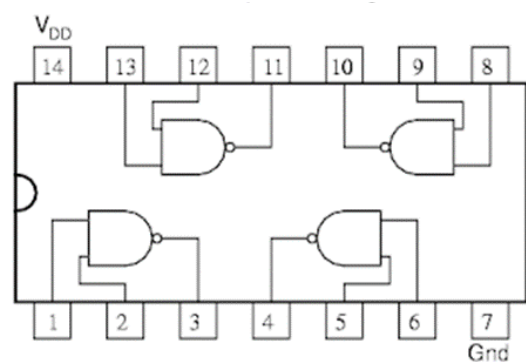


Figure 5.15.6: Pin connection of 4011 Quad NAND gate

Bistable or Flip-Flop

A bistable circuit, also called a flip-flop, is a type of logic circuit with two outputs that are always opposite.

1. If one output is 1, the other is 0. If one is 0, the other is 1.
2. The outputs are usually called Q and not-Q (which means the opposite of Q).
3. The circuit has two inputs: Set and Reset.
4. The Set input makes the output Q become 1.
5. The Reset input makes Q go back to 0.

You can use this type of circuit to store a single bit of data, like in memory chips or counting systems.

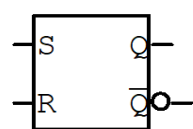


Figure 5.15.7: Block diagram of a flip-flop

Flip-flops can be designed using either NAND gates or NOR gates. *Figure 5.15.8* shows a flip-flop.

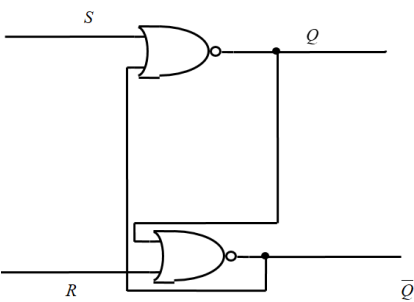


Figure 5.15.8: Flip-flop using NOR gates

When $S = 1$ and $R = 0$, the $\overline{Q} = 0$ resulting in $Q = 1$. This is the set state. It will remain in this state until the inputs are changed.

If S is changed to 0 and $R = 1$, then $\overline{Q} = 1$ and $Q = 0$ when both inputs are zero, the circuit remains in its last state: either set or reset (there will be no change).

You should note, however, that when NOR gates are used to design a flip-flop, both inputs should not be put at 1; both outputs will be zero, which is not acceptable in a flip-flop. The behaviour of this circuit can be summarised in Table 2

Table 5.11.2: Output of NOR gate flip-flop

Table 4.2 Output of the NOR gate flip-flop

S	R	Q
1	0	1 0
0	1	0 1
0	0	No change
1	1	not acceptable

Figure 5.15.9 shows a NAND gate flip-flop

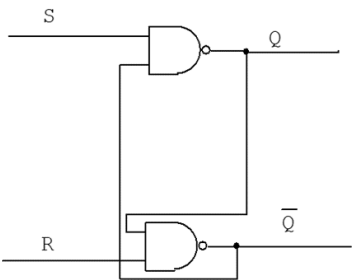


Figure 5.15.9: NAND gate Flip-flop

Operation

If $S = 1$ and $R = 0$, then $Q = 1$ and $\overline{Q} = 0$, this is the set state.

If $S = 0$ and $R = 1$, then $Q = 0$ and $\overline{Q} = 1$, this is the reset state.

When $S = 1$ and $R = 1$, the outputs remain unchanged, and when $S = 0$ and $R = 0$, the outputs are unacceptable (i.e. both will be zero). This type of flip-flop is called a Set and Reset flip-flop or S-R flip-flop. Its main disadvantage is that only one of its inputs is allowed to go low or 0 (when using NAND gates) or high, 1 (when using NOR gates).

D Flip-Flop (Data Flip-Flop)

The D flip-flop is another type of flip-flop. It's simpler than the S-R flip-flop because it uses just one main input called D (for data).

1. The D input can be either **1** or **0**.
2. This makes it easy to use—no confusion like in the S-R flip-flop, where both inputs might go HIGH or LOW at the same time.

The D flip-flop also has a special input called the **clock**.

1. The **clock input** controls when the flip-flop stores the data.
2. When the clock gives a signal (usually a pulse), the value at the D input is saved into the flip-flop and shown at the output.

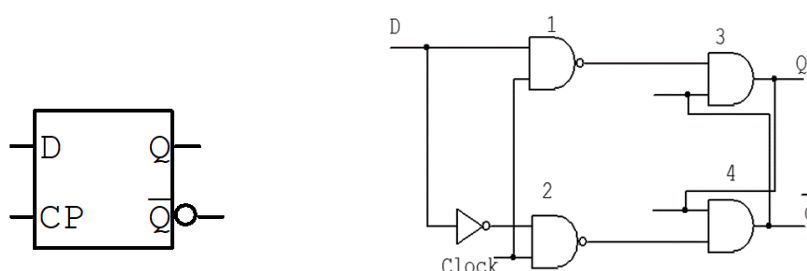


Figure 5.15.10: A logic diagram of a D flip-flop

Operation

When the clock is low or 0, the outputs of NAND gates 1 and 2 will both be 1, whether D is 0 or 1. This is because the NOT gate connected to NAND gate 2 inverts the data into 2, Shown **Figure 5.15.11** below.

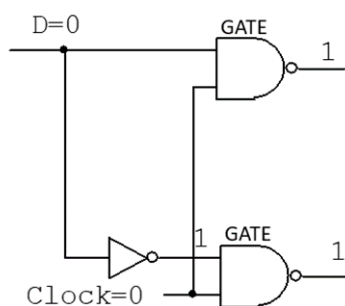


Figure 5.15.11a: When D = 0

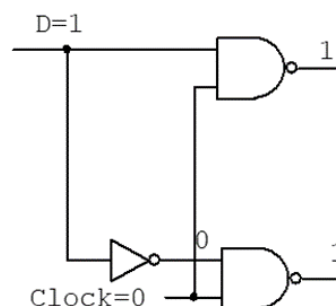


Figure 5.15.11b: When D=1

How the D Flip-Flop Works (Using NAND Gates)

If you are having trouble following the circuit, it can help to look back at the truth table for the NAND gate—this shows what outputs you get for different inputs.

In this setup:

1. Gates 3 and 4 are used to form the S-R flip-flop.
2. Right now, both gates are getting 1 as input.
3. When that happens, the flip-flop does not change; it stays in the same state as before.

- This is called the “hold” state because the output does not move.

What Happens When Clock = 1?

When the clock input is HIGH (1), the flip-flop reacts based on the value of D:

- If $D = 1$, it tries to set the flip-flop (Q becomes 1).
- If $D = 0$, it tries to reset the flip-flop (Q becomes 0).

Because of how gates 1 and 2 are connected, they control how this signal gets passed to gates 3 and 4.

Depending on the clock and D input, gates 1 and 2 will change their output, which then affects the flip-flop.

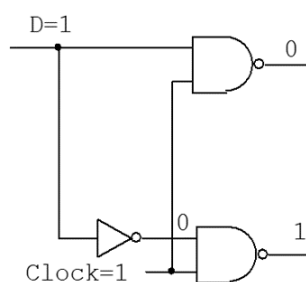


Figure 5.15.12a

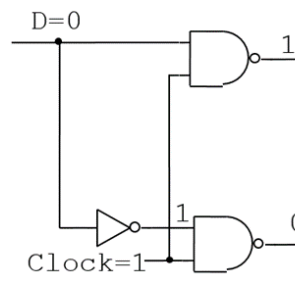


Figure 5.15.12b: When D is 0

From *Figure 5.15.12a* and *Figure 5.15.12b*, you can see how the D flip-flop behaves:

- When $D = 1$, gates 3 and 4 receive **0** and **1** signals.
- When $D = 0$, gates 3 and 4 receive **1** and **0** signals.

This shows that the **S-R flip-flop** is being:

- Set** when $D = 1$
- Reset** when $D = 0$

But here's the important parts

- This change only happens when the clock signal is HIGH (1).
- If the clock is LOW (0), the flip-flop does not change state. It stays in whatever state it was before.

So, the clock signal acts like a switch. It decides when the flip-flop should respond to the data (D) input.

Activity 5.15.1 Boolean Algebra, Logic Gates, Flip-Flops Basics

Scenario

An electronics company is developing a smart traffic control system for Accra. The system will rely on logic circuits and flip-flops to control traffic lights and pedestrian

signals. Your task is to explore how Boolean algebra is used to design these circuits, understand the operation of different flip-flops, and identify their applications.

Materials needed

1. Logic gate kits or simulation software e.g. Logically, Multisim, EveryCircuit, etc.
2. Worksheets with truth tables and Boolean expressions
3. Internet-enabled devices
4. Graph paper, markers, pens
5. Breadboards, wires, and LEDs (if available)

Step 1: Class Brainstorm

Discuss:

1. What is Boolean algebra?
2. What are logic gates and where are they used?
3. How might flip-flops help in a traffic control system?

Step 2: Group Research and Table Completion

1. Form groups of 3-5 and assign roles within the group: researcher, note-taker, presenter, circuit Builder.
2. Complete the table:

S/N	Logic Gate / Flip-Flop	Symbol	Function	Example Use
1	AND Gate			
2	OR Gate			
3	NAND Gate			
4	D Flip-Flop			
5	S-R Flip-Flop			

3. Guiding questions below will help during step 2:
 - a. How does each gate operate?
 - b. What outputs do you get for different inputs (truth table)?
 - c. How does a flip-flop store information?
 - d. What is the role of the clock in a D flip-flop?
 - e. How do S-R and D flip-flops differ in design and operation?

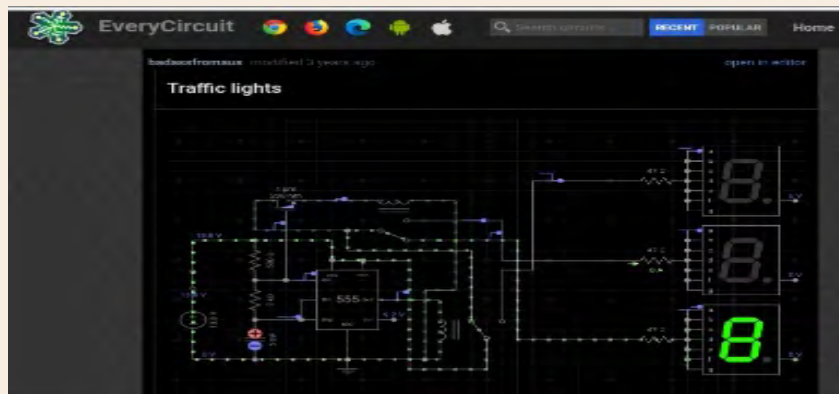
Step 3: Circuit design and simplification

1. Using Boolean expressions, design a simple combinational logic circuit for a two-way traffic light.
2. Simplify the circuit using De Morgan's theorem and Redundancy theorem.

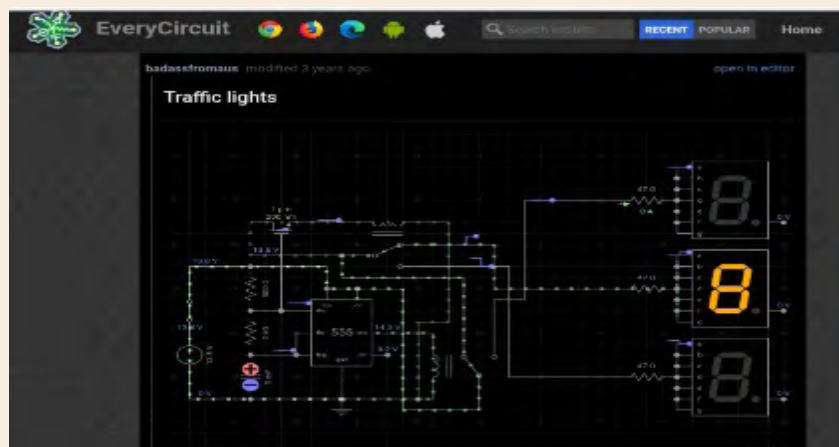
Step 4: Build or Simulate

1. Follow the link to observe simulation using EveryCircuit app:
<https://everycircuit.com/circuit/5833025875869696/traffic-lights>
2. Record what you observed for different input combinations of the traffic light.
3. Draw the circuit diagram for RED, YELLOW AND GREEN traffic light shown below:

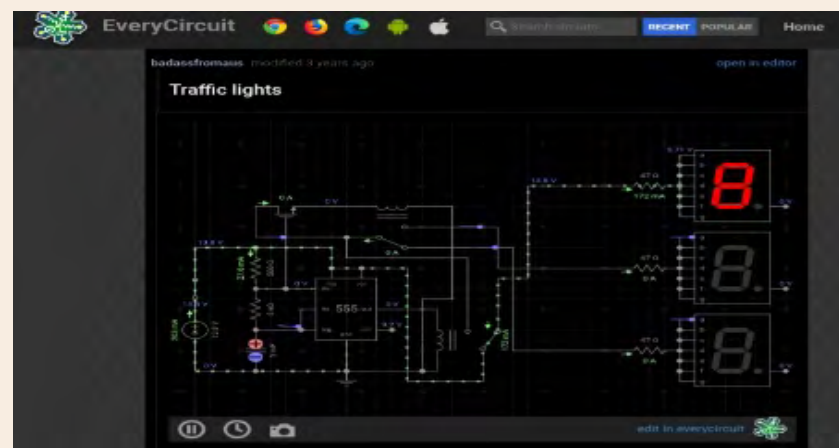
Green Traffic Light



Yellow Traffic Light



Red Traffic Light



Step 5: Present Your Work

1. Show your circuit diagram or simulation.
2. Explain how Boolean algebra helped simplify the design.
3. Describe the role of flip-flops in controlling timing sequences.

Step 6: Reflect and Write

Answer these questions

1. What happens in a flip-flop during the set state?
2. What is the role of the clock in a D flip-flop?
3. How is an S-R flip-flop different from a D flip-flop in design and operation?
4. How could this knowledge help in designing real-life control systems?

EXTENDED READING

1. <https://electronicsareACom/astable-multivibrator-using-nand-gates/>
2. <https://www.electronics-tutorials.ws/waveforms/bistable.html>

REVIEW QUESTIONS

Create a circuit for a system that controls streetlights: the lights should turn on only when it is dark OR there is motion detected but NOT when both conditions occur at the same time.

UNIT 16 ELECTRONIC CIRCUITS AND TRANSMITTERS IN ELECTRONIC COMMUNICATION

INTRODUCTION

Electronic communication is the exchange of information such as voice, data or video through electronic circuits and systems. A communication system consists of a sender, a transmission medium, and a receiver working together to deliver messages clearly and accurately. In everyday life, we use electronic communication when making phone calls, listening to FM radio, watching television, or sending online messages. To transmit signals efficiently over long distances and reduce distortion, modulation is required. Modulation is the process of varying a carrier signal to carry information and is essential for broadcasting, television, and internet-based communication.

This unit introduces the main components of an electronic communication system, explains the importance of modulation, and explores types of analogue modulation such as Amplitude Modulation (AM) and Frequency Modulation (FM). You will understand their principles, how they operate, and where they are applied in real-life communication systems.

KEY IDEAS

- **Electronic Communication System:** A setup of interconnected devices that send, transmit and receive information in the form of signals.
- **Receiver:** The device that captures transmitted signals and converts them back into a usable form, such as sound, text, or video.
- **Modulation:** The process of altering a carrier signal to embed information for efficient and reliable transmission.
- **Transmitter:** The device that processes and sends the information signal, often by modulating it onto a carrier wave.
- **Transmission Channel:** The physical or wireless medium through which the signal travels e.g. cables, fibre optics or radio waves.
- Different methods exist for modifying the carrier signal, such as Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM).

DESCRIPTION OF THE VARIOUS TYPES OF MODULATION IN COMMUNICATION

Components of Electronic Communication system

The essentials of electronic communication system include:

1. Transmitter

It processes the input signals to produce a suitable signal for transmission through the channel. The elements of a transmitter are as follows:

- An input Transducer such as a microphone or a camera that converts one form of energy to another.
- A signal Amplifier which is a multi-stage amplifier used to boost the signal strength before transmitting.
- A modulator, a device in which the amplified message signal is super imposed on a high frequency carrier. The resultant signal is called modulated signal, and it is transmitted at the high carrier frequency.

2. Communication Channel

Is the medium through which signals are transmitted. The channel can be wired, such as fibre optics cable, coaxial cable or wireless such as radio waves or satellite signals.

3. Receiver

The receiver is a device that decode the transmitted signals back into a usable form. Examples include speakers, monitors, and computers that interpret the incoming signals.

4. Noise

It is any unwanted interference that can distort the signal during transmission and affect the quality of communication.

5. Destination

Is the final target that uses or displays the message.

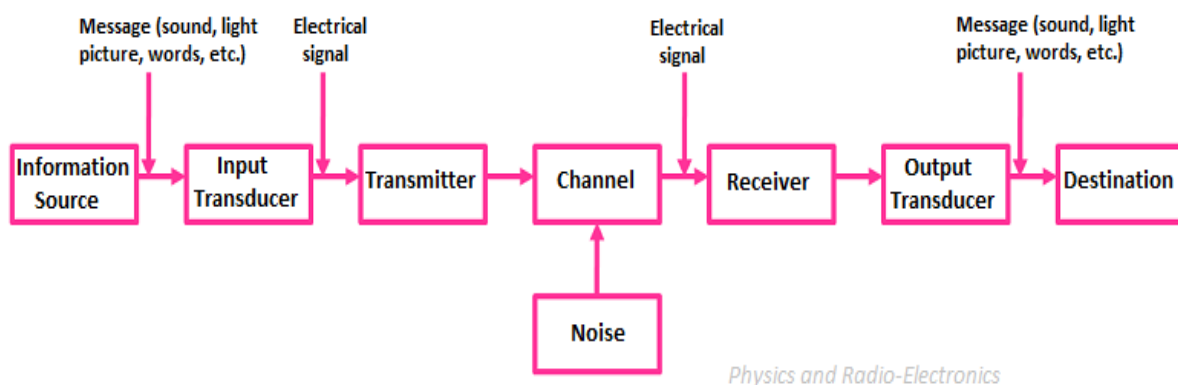


Figure 5.16.1: The diagram showing the stages in electronics communication

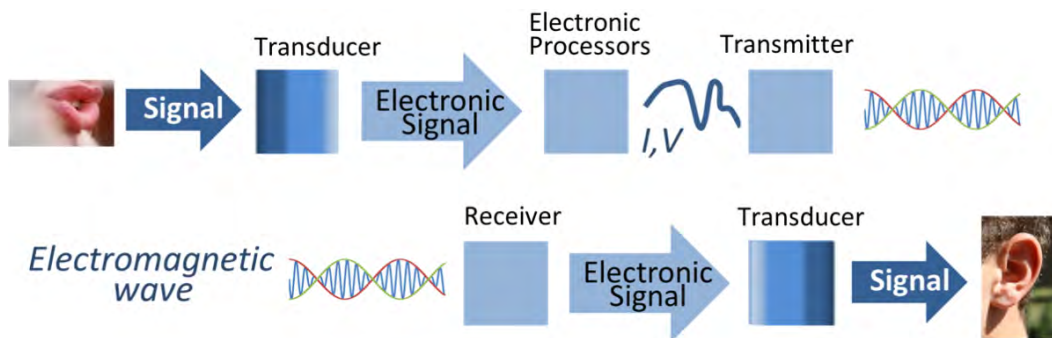


Figure 5.16.2: Diagram showing the electronic Communication system from the input signal to the output signal

Communication systems are divided into two categories: Analogue and digital.

By signal

1. Analogue

An analogue signal is a continuous signal that represents information by varying its amplitude, frequency, or phase over time, closely resembling the original physical phenomena it represents. Telephone and radio transmission are the most common examples of Analog technology.

2. Digital

A digital signal is a type of signal that represents data as a sequence of discrete values, typically using binary numbers (0s and 1s), making it easier to process, store, and transmit information.

By direction

1. Full duplex system

A communication system which allows simultaneous two-way communication, transmission and reception typically on different channels.

2. Half Duplex system

A communication system which allows two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can only either transmit or receive information.

3. Simplex

In the simplex system, communication is possible in only one direction. Paging system in which messages are received but not acknowledged is an example.

By means of transmission medium

1. Wired or line communication

There are four types of wired communication.

- a. Parallel wire communication
- b. twisted wire communication
- c. Coaxial cable communication
- d. Optical fibre communication

2. **Wireless communication**

Is a system that uses:

- a. Electromagnetic waves such as radio, infrared,
- b. Microwave,
- c. Bluetooth,
- d. Wi-Fi and
- e. Satellite for data transmission.

3. **Optical Communication**

Optical communication system **uses light waves to transmit information through mediums such as glass fibres**. It enables the conversion of sound or video signals into encoded light pulses for long-distance transmission.

Examples of Electronic communication system

A wireless communication system allows users to transmit voice, text, and data using portable devices like smartphones and tablets. It relies on cellular networks and technologies such as GSM, 3G, 4G, and 5G.

1. **Voice Calls**

Real-time audio communication between two or more people using telephones or mobile devices. It can occur over traditional landlines, mobile networks, or internet-based services (VoIP).

2. **Text Messages**

Short written messages are sent electronically between devices, typically via SMS (Short Message Service) or instant messaging apps. They are used for quick, asynchronous communication, such as Email, online forums, and recorded video lectures.

3. **E-mail (Electronic Mail)**

A digital system for sending and receiving messages over the internet. Emails can include text, attachments, and multimedia, and are widely used for both personal and professional communication.

4. **Video Conferencing**

A live, visual communication system that allows people in different locations to interact using video and audio. Common platforms include Zoom, Microsoft Teams, and Google Meet, often used for meetings, classes, and interviews.

5. Social media

Online platforms that enable users to create, share, and interact with content and each other. Examples include Facebook, Twitter (X), Instagram, and TikTok. It supports multimedia communication and networking.

6. Computer Networking

A system of interconnected computers and devices that share resources and data. It includes LANs (Local Area Networks), WANs (Wide Area Networks), and the Internet, enabling communication between users and systems.

7. Radio and TV Broadcasting

A one-way communication system that transmits audio (radio) or audiovisual (TV) content to a wide audience via electromagnetic waves or digital signals. It is used for entertainment, news, and public service announcements.

The following terms are foundational in understanding how electronic communication systems work.

Signal

A signal is any time-varying quantity that carries information. In electronic communication, it typically refers to electrical or electromagnetic waves used to transmit data. Signals can be analogue (continuous) or digital (discrete).

Transmitter

A transmitter is a device that sends signals over a communication medium (like air, cable, or fibre). It converts information (like voice or data) into a signal suitable for transmission.

Example: A radio station's transmitter sends audio signals via radio waves.

Attenuation

Attenuation refers to the loss of signal strength as it travels through a medium. It is caused by factors like distance, interference, or material properties. Measured in decibels (dB), and higher attenuation means weaker signals.

Amplification

Amplification is the process of boosting a signal's strength. It is used to counteract attenuation and ensure the signal reaches its destination clearly. Done using devices called amplifiers.

Repeater

A repeater is a device that receives a signal, amplifies it, and retransmits it. Used to extend the range of communication systems by overcoming attenuation. Common in fibre optics, wireless networks, and satellite systems.

Bandwidth

Bandwidth refers to the range of frequencies a communication channel can carry. Measured in Hertz (Hz). Higher bandwidth means more data can be transmitted per unit time. Example: A 100 Mbps internet connection has higher bandwidth than a 10 Mbps one.

Carrier wave

A carrier wave is a pure sinusoidal wave of constant frequency and amplitude. It does not carry meaningful information like voice or data. To transmit information, a message signal (such as audio or data) is superimposed onto the carrier wave through a process called modulation.

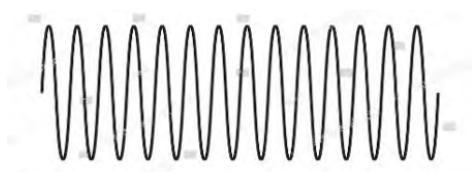


Figure 5.16.3: Picture of a carrier wave

Modulation

Modulation is a process in which some characteristics of a high-frequency sine wave are varied in accordance with the instantaneous value of the low-frequency modulating signal.

The characteristics of the signal are amplitude, frequency and phase.

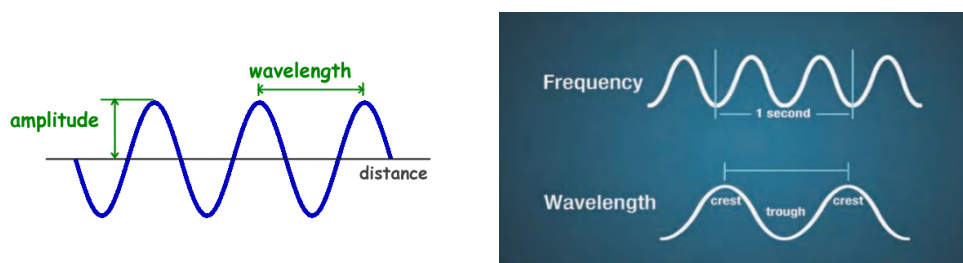


Figure 5.16.4: A diagram of a sinusoidal wave showing amplitude, frequency and wavelength

The process of modulation involves two waveforms, which are: The

1. message or information signal
2. carrier signal.

The message signal could be a physical quantity that varies with time in a smooth, continuous fashion, known as an analogue signal such as human voice, video picture information, TV Signals, music or an ordered set of signal values at specified intervals of time, also known as digital.

Demodulation

Demodulation is the process of **extracting the original information signal** from a **modulated carrier wave**. It is essentially the **reverse of modulation**, and it occurs at the **receiver end** of a communication system.

Types of Modulation

1. Amplitude modulation (AM)

This is a modulation process in which the amplitude (height) of the carrier signal is varied in accordance with the message or information signal. In amplitude modulation, the carrier frequency remains constant.

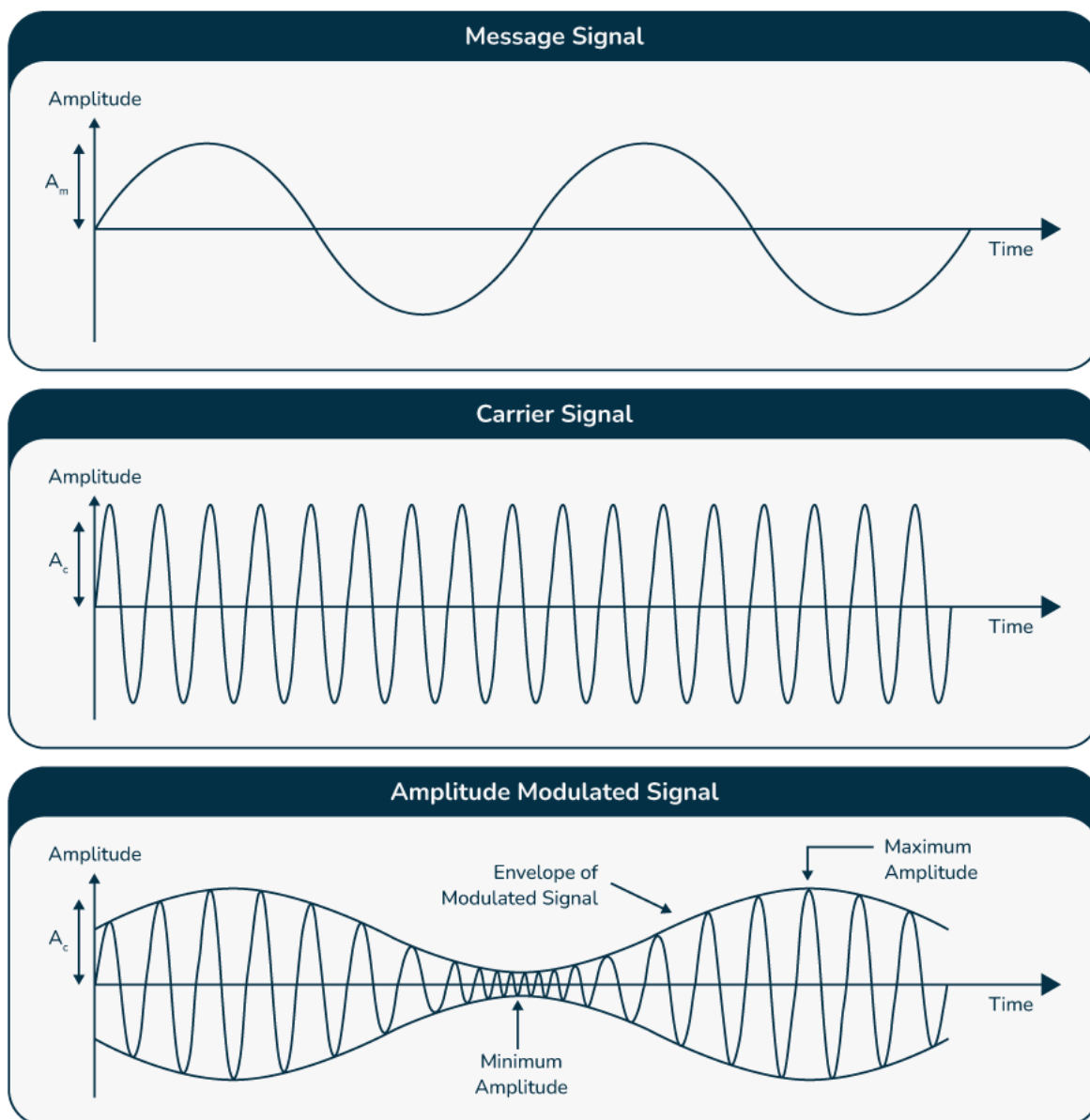


Figure 5.16.5: A diagram of amplitude modulation showing the information and carrier signals and the modulated output signal.

2. Frequency modulation (FM)

Frequency modulation is the process of varying the frequency of the carrier signal in accordance with the modulating signal. In frequency modulation, amplitude remains constant.

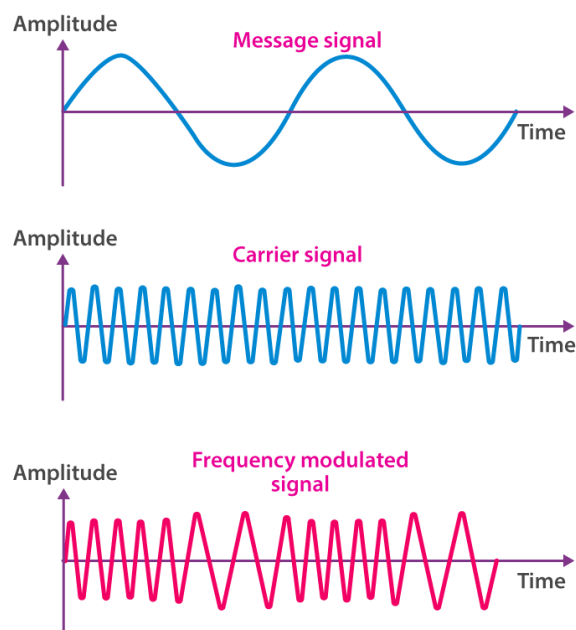


Figure 5.16.6: A diagram of frequency modulation showing the information and carrier signals and the modulated output signal.

3. Phase Modulation (PM)

In this modulation, the phase of the carrier wave is varied in proportion to the information signal. Amplitude and frequency remain constant in phase modulation. Phase modulation is used in digital communication (e.g., Phase Shift Keying) and satellite systems.

The phase of a wave or signal refers to the position of a point in time on the waveform cycle. A phase of 90° means the wave is a quarter of the way through its cycle.

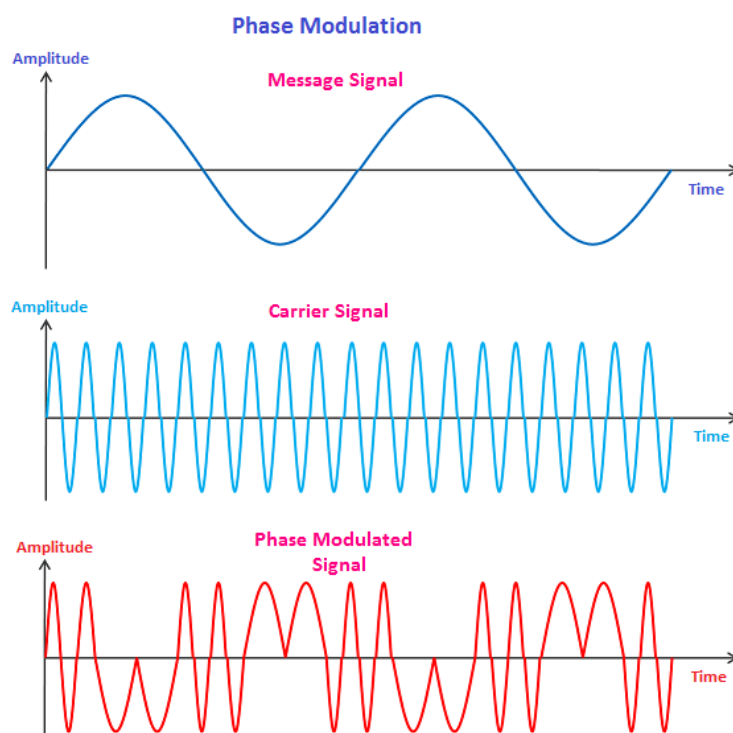


Figure 5.16.7: A diagram of phase modulation showing the information and carrier signals and the modulated output signal

Advantages of Frequency Modulation over Amplitude Modulation

1. Better Noise Immunity

FM is less affected by amplitude noise (like static or electrical interference). Since information is carried in frequency changes, random amplitude spikes don't distort the signal as much.

2. Improved Sound Quality

FM provides higher fidelity audio, making it ideal for music and voice transmission. Used in FM radio for clearer and more consistent sound.

3. Efficient Use of Power

FM transmitters can operate at constant power, making them more efficient and stable.

4. Capture Effect

FM receivers tend to lock onto the strongest signal and ignore weaker ones, reducing interference from nearby stations.

5. Less Distortion

FM signals are less prone to distortion caused by non-linearities in the transmission path.

Disadvantages of Frequency Modulation

1. Wider Bandwidth Requirement

FM requires much more bandwidth than AM. Example: AM radio uses ~10 kHz; FM radio uses ~200 kHz. This limits the number of available channels in a frequency band.

2. More Complex Equipment

FM transmitters and receivers are more complex and expensive to design and maintain. Requires frequency-stable oscillators and advanced circuitry.

3. Line-of-Sight Transmission

FM signals typically use VHF (Very High Frequency), which are line-of-sight. Limited range compared to AM, which can travel farther due to ground and sky wave propagation.

4. Higher Power Consumption

FM systems often require more power to transmit over long distances, especially in mobile or remote applications.

Activity 5.16.1 Understanding Electronic Communication Systems

Scenario

You are part of a technical team tasked with improving communication in a rural community. Your team must design a simple but effective electronic communication setup to help farmers receive weather updates and market prices.

Task

Explore the concept of an electronic communication system, identify its main parts, and explain how modulation (AM and FM) is used to transmit clear signals. Compare AM and FM, and explain the advantages of FM over AM.

Materials needed

1. Diagram of a basic communication system
2. Internet-enabled devices (if available), large paper, markers, pens
3. Sample radios or videos showing AM/FM operation

Step 1: Class Brainstorm

In pair discuss

1. What is an electronic communication system?
2. Where have you seen or used one?
3. Why is modulation necessary in communication?

Step 2: Group Research and Table Completion

1. Your teacher will guide you to form groups of 3–5 learners and assign roles: researcher, note-taker, presenter, artist.
2. Complete the table:

S/N	Main Component	Description	Function	Example Device
1	Transmitter			
2	Receiver			
3	Transmission Channel			
4	Modulator			
5	Demodulator			

3. These guiding questions will help you to complete step 2
 - a. What does each part do?
 - b. How do signals travel from the transmitter to the receiver?
 - c. Why is modulation important for long-distance communication?

Step 3: AM and FM Exploration

Using internet and YouTube resources, research

1. What is Amplitude Modulation (AM)?
2. What is Frequency Modulation (FM)?
3. Differences between AM and FM
4. Advantages of FM over AM

Step 4: Create Your Poster/Model

Draw a block diagram of an electronic communication system showing:

1. Sender, transmitter, channel, receiver

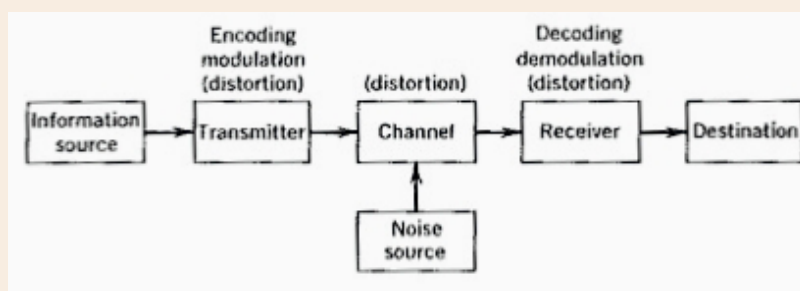


Figure 5.16.8: Sample block diagrams

2. AM vs FM
3. Advantages of FM over AM.

Step 5: Present Your Work

Each group presents:

1. Block diagram of electronic communication
2. AM vs FM
3. Advantages of FM over AM

Step 6: Ask, Answer, and Reflect

1. Ask classmates questions for clarification.
2. Write in your notebook or tablet:
 - a. What did you learn about how communication systems work?
 - b. Which type of modulation seems most useful for rural areas, and why?

EXTENDED READING

1. Introduction to Electronic Communication – Academia.edu: A detailed PDF covering the basics of transmitters, receivers, modulation techniques, and digital signals. Great for foundational understanding.
2. Electronic Communication Tools – Siyavula: An accessible overview of popular tools like email, messaging apps, and their roles in modern communication.

REVIEW QUESTIONS

1. What is the main purpose of a transmitter in an electronic communication system?
2. Name two main types of modulation.
3. What is the role of the receiver in a communication system?
4. Explain the difference between AM and FM.
5. Compare the clarity and noise resistance of AM and FM signals.
6. Why is modulation necessary for transmitting signals over long distances?
7. A rural community needs a radio service that can broadcast over long distances with low cost, even if the audio quality is lower. Based on your knowledge of AM and FM, which should they choose? Justify your answer.
8. Design a simple diagram showing the path of a message in an electronic communication system from sender to receiver. Label each stage and indicate where modulation occurs.

UNIT 17 COMMUNICATION

INTRODUCTION

Imagine listening to your favourite radio station, talking on a walkie-talkie or tracking an aircraft all these rely on electronic communication systems. In the previous unit, we explored the concept of modulation, including Amplitude Modulation (AM) and Frequency Modulation (FM). In this unit, we move from theory to practice, focusing on how AM and FM transmitters and receivers work together to send and receive information. A communication system has key parts: the transmitter generates and modulates a carrier wave with the message, the transmission channel carries it, and the receiver recovers and interprets it. Transmission channels may be wired like coaxial cables or wireless like radio waves. We will study the structure, components, and functions of transmitters and receivers, the role of modulation in long-distance communication, and the different types of transmission channels. This knowledge connects classroom concepts to real-world systems in broadcasting, aviation, and emergency services.

KEY IDEAS

- AM and FM transmitters have different structures and working principles, and understanding their components, such as oscillators, modulators, amplifiers, and antennas, helps explain how they generate and transmit modulated signals.
- The modulation index is a key factor in both AM and FM systems; in AM, it measures the ratio of message signal to carrier amplitude, while in FM, it compares frequency deviation to the modulating frequency, both affecting signal quality.
- AM systems are simple and can cover long distances, but are more affected by noise, while FM systems offer better sound quality and noise resistance but require more bandwidth and complex circuits.
- A limiter circuit is used in FM systems to remove unwanted amplitude variations caused by noise without affecting the frequency of the signal, improving clarity in reception.
- AM and FM transmitters are used in various applications, such as AM in aviation and long-range communication, and FM in commercial radio and mobile systems.
- Choosing between AM and FM depends on the environment; FM is better suited for urban areas with higher quality needs, while AM is useful in rural or long-distance broadcasting, such as in some remote parts of Ghana.

AM AND FM TRANSMITTER

AM TRANSMITTER

Amplitude Modulation (AM) is a method used in communication to send information, like voice or music, over long distances using radio waves. In AM, we change the strength (amplitude) of a high-frequency wave called the carrier wave. This carrier wave is produced by a part of the circuit called the RF oscillator (radio frequency oscillator). On its own, the carrier wave carries no useful message. It is like a car without passengers. The actual information (like someone's voice or a song) is called the modulating signal. This signal is "placed onto" the carrier wave using a process called modulation. The result is a new wave, the AM signal that carries both the high-frequency wave and the original message. This AM signal can now travel through the air and be picked up by a radio receiver far away, where the message (voice, music, etc.) is recovered and played. **Figure 5.17.1** shows the carrier wave, input signal and modulated signal.

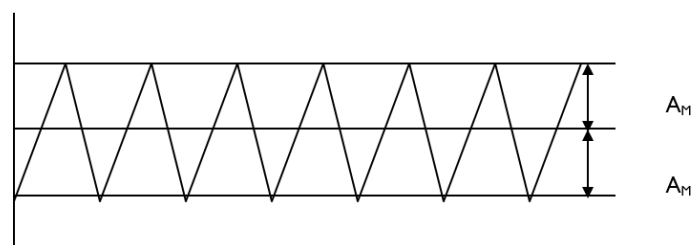


Figure 5.17.1: Carrier wave

Where: A_m = Amplitude of the RF signal.

Figure 5.17.1 shows what happens when we use Amplitude Modulation (AM) to send a message (like sound or music) using a carrier wave. The middle wave (zigzag lines with equal height) is the carrier wave. It is a high-frequency wave that does not carry any information on its own. Think of it like a "vehicle" with no passengers. The top and bottom lines show the modulating signal; this is the actual message (like a person talking into a microphone).

It changes the strength (amplitude) of the carrier wave. The combined wave inside the top and bottom lines is the modulated signal (AM wave). You can see that the size (height) of the wave keeps increasing and decreasing. This is how the message is added to the carrier wave. The label A_m shows the maximum height of the wave from the centre to the top or bottom. It stands for the modulating signal's amplitude. **Figure 5.17.2** shows the carrier wave.

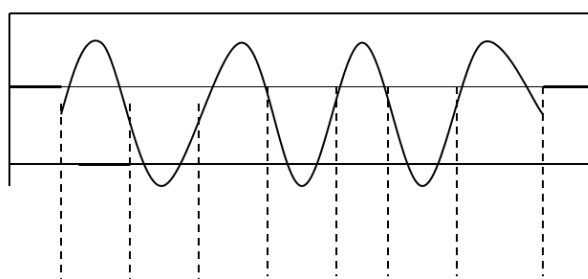


Figure 5.17.2: Carrier wave

Figure 5.17.2 explained

Picture yourself at a Ghanaian beach, watching the waves come in. Every wave has the same pattern, going up and down repeatedly, regardless of how big or tiny it is. In the image shown in **Figure 5.17.2**, that is precisely how a carrier wave appears. The image's curving line repeatedly rises smoothly before falling. We refer to this as a wave. This type of wave conveys information, such as the music on the radio or your voice during a phone call, in the same way that ocean waves carry boats.

Every wave has a crest at its highest point and a trough at its lowest. The distance between the crests is referred to as the wavelength, which is comparable to the gap between two powerful ocean waves. The wave continues to repeat itself predictably.

The image also shows dotted vertical lines and horizontal lines. These allow us to gauge the wave's motion and variations over time. The boundaries or the strongest spots the wave reaches are indicated by the top and bottom straight lines. This wave does not yet convey a message on its own. However, if minor adjustments are made, such as altering its height, speed, or form, it can begin transmitting your preferred radio station or a friend's call. To put it simply, the image depicts a wave that has the ability to transmit signals, just like a trotto transports people between towns. It is referred to as a carrier wave for this reason.

Amplitude Modulated Signal

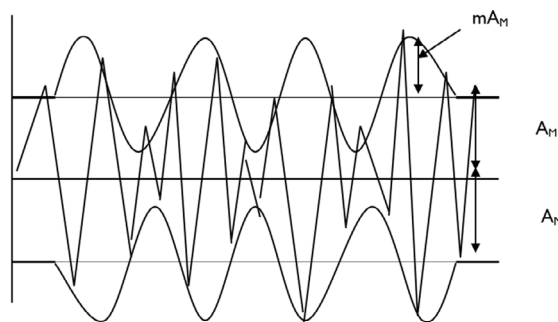


Figure 5.17.3: Amplitude-modulated signal

Where $mAM = \text{modulated index} \times AM$. Note that when there is no signal, the RF is not modulated.

Figure 5.17.3 explained

A messenger delivering a verbal message on a stable bicycle is analogous to an amplitude-modulated (AM) signal. The actual bicycle travels at a steady pace. The carrier wave is this. Just as the wheels continue to move at the same speed, it does not change on their own. Imagine for a moment that the messenger begins to speak while riding. The bicycle wobbles a little up and down due to their voice. These wobbles are caused by variations in the carrier wave's amplitude, or height.

The wobbling increases with vocal strength and decreases with voice quietness. That is precisely how AM radio operates. Your music or the broadcaster's speech "rides" on the station's constant high-frequency wave (the carrier) by changing its power. You can hear

news, music, or football commentary when your radio picks up the signal and reads these wobbles and converts them back into sound.

Consider Accra's Radio XYZ, for instance: the tower transmits the carrier wave, but your radio decodes it after the DJ's voice shapes it. Not a single wobble? Nothing but quiet. That is AM at work.

Modulation Index (Modulating Factor)

A modulation index (M) indicates how much the height (amplitude) of a carrier wave varies when a message, such as voice or music, is added. It helps to determine the signal's strength. It is determined by measuring the peak-to-peak voltage, which is the difference between the modulated wave's highest and lowest points. A modulation index that is too high can distort the message, while one that is too low renders it weak.

Put simply, it indicates the extent to which the message carried by the wave influences it as shown in **Figure 5.17.4**. An oscilloscope is used for this purpose.

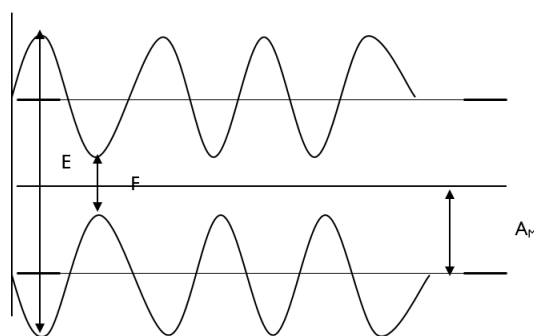


Figure 5.17.4: AM modulation index

Figure 5.17.4 explained

Imagine watching two trotro buses pass by while standing by the side of the road. One is full, the other is empty. Because the full one is heavier, it bounces more when it hits a pothole; this additional bounce is similar to how a signal acts when it is carrying more information.

Examine the wave in the image. This wave is transmitting a message, such as speech or music, much like AM radio. This time, however, much concentration is placed on how powerful that message is, and the graphic illustrates that. The top curve indicates the wave's highest peak, which is also the loudest point for the music or message. The bottom curve displays the lowest point, which is the quietest or weakest sound.

Two arrows with the letters E and F in the centre are visible. The strength of the wave is indicated by E, which is the distance from the centreline to the top of the wave. F is the distance from the smallest wave's centre to its bottom, indicating how weak the wave is at its weakest.

The wave's entire height, from top to bottom, is now indicated as A_M , or amplitude modulation. The way we compare these heights is called the modulation index. It is like asking: "How much is the wave changing compared to its normal size?" If it changes too

much, the message becomes unclear. If it changes too little, you may not hear the sound well.

So, in simple terms:

1. A small change means a weak message.
2. A big change means a strong message.
3. But too big or too small can be a problem.

By altering the amount that the wave wobbles up and down, radio stations can regulate how clearly your radio will pick up the sound.

From the Figure above, the modulation index is given by:

$$M = \frac{E - F}{E + F} \times 100\%$$

What happens when $E = F$? There will be no modulation. For example, if $E = F = 10$.

$$M = \frac{10 - 10}{10 + 10} \times 100\% = 0$$

Worked Examples

1. A radio wave is modulated by a signal. The maximum voltage of the modulated wave is 8 volts, and the minimum voltage is 2 volts. Calculate the modulation index.

$E = 8\text{V}$, $F = 2\text{V}$,

$$M = \frac{E - F}{E + F} = \frac{8 - 2}{8 + 2} = 0.6 = 60\%$$

2. In an AM signal, the highest voltage of the wave is 10 volts, and the lowest voltage drops to 0 volts. What is the modulation index?

$E = 10\text{ V}$, $F = 0\text{ V}$,

$$M = \frac{E - F}{E + F} = \frac{10 - 0}{10 + 0} = 1 = 100\%$$

3. An amplitude-modulated signal has a maximum voltage of 12 volts and a minimum voltage of 1 volt. Find the modulation index and state whether the signal is under-modulated, perfectly modulated, or over-modulated.

$E = 12\text{ V}$, $F = 1\text{ V}$,

$$M = \frac{E - F}{E + F} = \frac{12 - 1}{12 + 1} = 0.85 = 85\%$$

This is still under 100%, so not yet over-modulated, but very close.

A block diagram of an AM transmitter is shown in **Figure 5.17.5**. It consists of a microphone (not included in diagram), a Pre-Amplifier (audio amplifier), an AM modulator, a radio frequency oscillator (RF Oscillator), a power amplifier and an antenna.

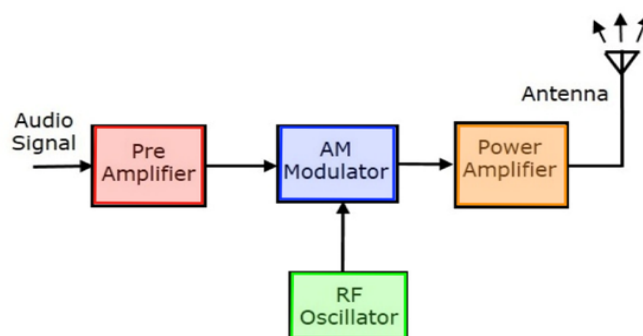


Figure 5.17.5: Block diagram of AM transmitter

The functions of each of the components in the block diagram are as follows:

1. Pre-Amplifier

It is a voice enhancer since this is the first box the sound enters. The signal is too faint to carry very far when someone speaks into the microphone. Like turning up the volume on a speaker, the pre-amplifier takes that weak audio stream and makes it stronger.

2. RF Oscillator

This is a carrier wave, a fast-moving wave that passes through the atmosphere, is produced by this block. It can be compared to a “trotro” (carrier) that will spread the word throughout the nation. This wave needs to carry something, like the voice, because it is empty on its own.

3. AM Modulator

This component is the heart of the system. The AM modulator combines the RF oscillator’s carrier wave with the amplified voice signal. Amplitude modulation, or AM, takes place here. It is similar to putting your voice on the trotro’s back to initiate the trip.

4. Power Amplifier

The signal still needs additional power to travel great distances after modulation. Like fuelling a trotro, the power amplifier provides a powerful boost to the modulated signal. It can now be launched into the air because it is strong enough.

5. Antenna

When the signal finally reaches the antenna, the modulated wave is released into the atmosphere. People with radios can tune in and hear your voice or music this way, even if they live far away.

Similar to getting ready and starting a delivery from your home to another town by trotro, the audio signal is amplified, transported by a wave, blended, powered up, and sent out through the antenna.

AM Transmitter Circuit

Figure 5.17.6 shows a simple AM transmitter circuit

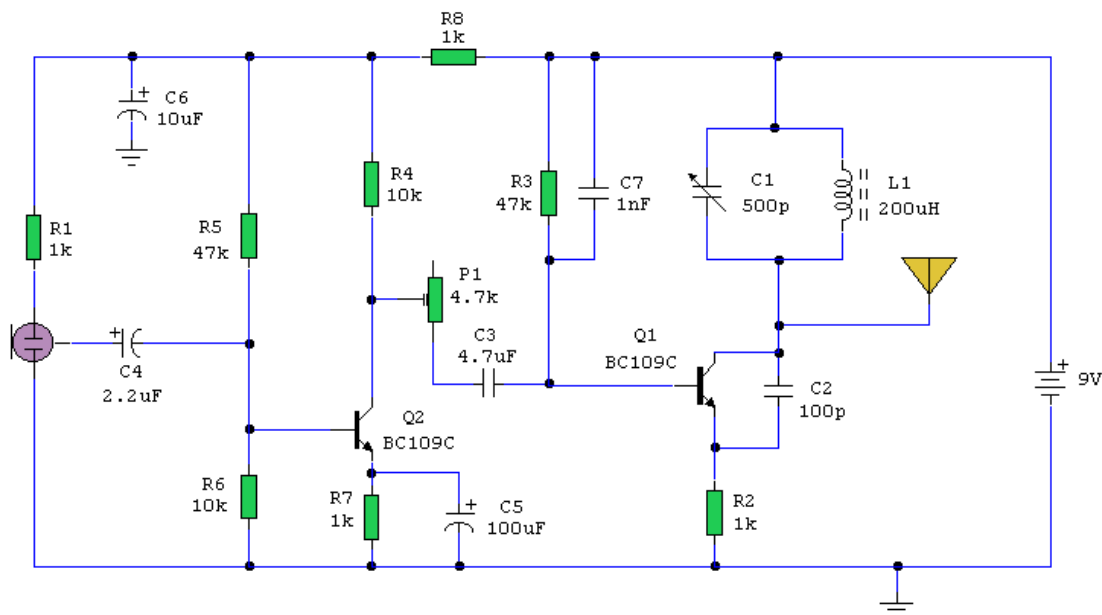


Figure 5.17.6: A simple AM transmitter circuit

How the AM Transmitter Circuit Works

This circuit is like a tiny radio station. It takes sound, perhaps from your voice or music and sends it wirelessly through the air as radio waves.

This is how it works.

1. **Power Up:** The **9V battery** is the heart of the circuit, providing energy to all the components. Without it, nothing happens.
2. **Sound to Signal:** Imagine you speak into a microphone (not shown but connected to the input). Your voice is an *audio signal* that is a tiny, wobbly electrical current. This signal first enters the circuit at **transistor Q1 (BC109C)**. Transistors are like amplifiers; they take weak signals and make them stronger.
3. **Mixing the Signals:** Now, the circuit creates a *radio frequency (RF) signal* using **inductor L1 (200μH)** and capacitors (**C1, C2**, etc.). Think of this RF signal as a steady “carrier wave” (like an empty road). The amplified audio signal from Q1 then “rides” on this carrier wave by changing its strength (*amplitude modulation* AM radio).
4. **Fine-Tuning:** The **potentiometer P1 (4.7kΩ)** acts like a dial on a radio. Adjusting it changes the frequency of the carrier wave, so you can pick a “clear channel” to avoid interference.
5. **Final Boost:** The modulated signal (audio + RF) gets another power boost from **transistor Q2 (BC109C)** to ensure it is strong enough to travel through the air.
6. **Broadcast:** The combined signal exits through an antenna (a simple wire works). Nearby radios tuned to the same frequency can pick it up and play your sound.

7. **Resistors (R1–R8):** These control how much current flows, like taps controlling water. Without them, components could burn out.
8. **Capacitors (C3–C7):** They block unwanted signals and help smooth out the audio and RF waves.
9. **C5 (100 μ F):** This big capacitor stabilizes the power supply, preventing hiccups in transmission.

Merits of AM Transmitters

1. AM transmitters are simple to design and build, using basic, affordable components.
2. They require less bandwidth compared to FM, making efficient use of radio spectrum.
3. AM signals travel long distances, especially at night, due to ionospheric reflection.
4. The technology is cost-effective, ideal for wide-area broadcasts in rural regions.
5. AM receivers are inexpensive and easy to construct, ensuring broad accessibility.
6. These signals penetrate obstacles well, providing reliable coverage in varied terrain.

Demerits of AM Transmitters

1. AM is highly susceptible to noise and interference from natural or electrical sources.
2. The sound quality is poor due to limited bandwidth, restricting audio fidelity.
3. Power efficiency is low, as most energy is wasted in the carrier wave.
4. Signal fading occurs frequently, especially during daytime or weather changes.
5. AM struggles with overlapping stations, leading to cross-talk and disrupted reception.
6. The operating range is limited compared to modern alternatives like FM or digital.

FM Transmission

Static or crackling sounds can occasionally be heard when listening to an AM radio, particularly during a storm or while moving around. This occurs because AM (Amplitude Modulation) modifies the radio wave's height (amplitude) in order to transmit sound.

However, the amplitude can also be altered by noise from things like lightning, engines, or even phone signals, so the radio also takes up those sounds in addition to the sound itself. Imagine saying something loudly over a football field is an example. Your voice rises and falls when the wind blows. Similar to what happens with AM radio, your voice may be heard by someone far away, but the wind may also be heard.

Nowadays, frequency modulation (FM) is a more effective method of transmitting sound. FM modifies the wave's frequency, or how quickly or slowly it vibrates, while maintaining a constant amplitude. In this manner, external noise, which mostly influences amplitude, does not significantly disrupt the message. So, FM is like using hand signals to talk instead of shouting in a noisy market. Even if there is a lot of noise, your message still gets through clearly. Because of this, FM radio typically has a better, cleaner sound than AM radio, especially when it comes to music.

Figure 5.17.7 shows a block diagram of an FM transmitter. It is similar to the AM transmitter; however, the difference lies in the method of modulation and the inclusion of a unit called a

limiter. Frequency Modulation (FM) involves the impressing of a signal wave onto a carrier wave by changing the frequency of the carrier or RF signal. The FM carrier is either VHF or UHF.

Block Diagram of an FM Transmitter

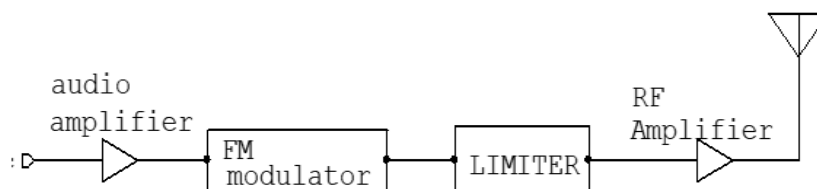


Figure 5.17.7: Block diagram of FM transmitter

How the FM Transmitter Works

1. Audio amplifier

It all begins with the sound you make when you talk into a microphone or play music. Initially, the audio amplifier acts as a loudspeaker for your speech. It takes your soft sound and amplifies it so that it can be processed further. The signal would be too weak to travel very far without this boost.

2. FM modulator

After that, the FM modulator works its magic. Think of it like a skilled painter combining colours. Here, your enhanced sound is mixed with a continuous radio wave, called the carrier signal. But unlike AM radio, which changes the wave's power, FM adjusts the frequency, compressing and extending the wave to meet your sound. FM creates audio that is so clear and devoid of AM crackles because of this clever technology.

3. RF amplifier

The **RF amplifier** jumps into action like a sprinter's final push. It takes the modulated signal and supercharges it, ensuring it can travel long distances through the air. This is the stage that determines how far your broadcast can reach, whether it is across your neighbourhood or an entire city.

4. Limiter

A unique component of the system functions as a stringent gatekeeper in frequency modulation (FM). It ensures that the sound remains clear and smooth by closely monitoring the signal for any unexpected spikes or loud noises and eliminating them. This makes it easier for the listener to perceive conversation or music without abrupt, grating distortions. The addition of an input sound signal, such as music or voice, causes the frequency or how quickly the wave vibrates to move up or down from the typical carrier frequency rather than altering the wave's height, as in AM. This change is called frequency deviation (Fd).

In commercial FM radio, the maximum allowed frequency deviation is 75 kHz, and this happens when the input audio signal reaches 15 kHz (which is about the highest sound we can hear). FM radio stations operate in the 88 to 108 MHz frequency range. **Figure 17.8a**

shows an input signal, **17.8b** is the carrier wave, and **17.8c** shows how the carrier wave varies when the input signal is impressed onto the carrier wave.

Input Signal

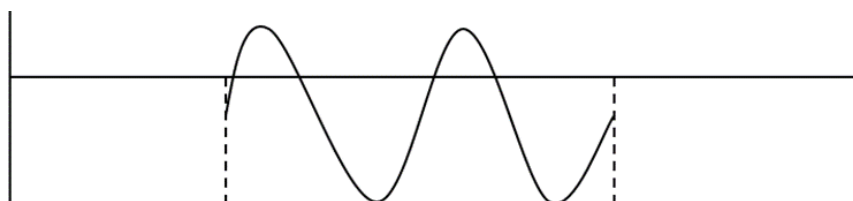


Figure 5.17.8a: An input signal

Figure 5.17.8a is an input signal of an FM transmitter. Consider speaking into a microphone; the sound is represented by an electrical signal produced by your voice. For this signal to go over the air, it must first be boosted (amplified) and then joined with a radio wave (carrier signal).

The FM transmitter broadcasts your speech or music to radios by gently altering the radio wave's frequency to match your voice signal. This first signal, before it is processed and transmitted, is probably depicted in the image. Comparable to preparing a letter before mailing it, it requires the correct address (frequency) to be received by the intended recipient.

Carrier Wave

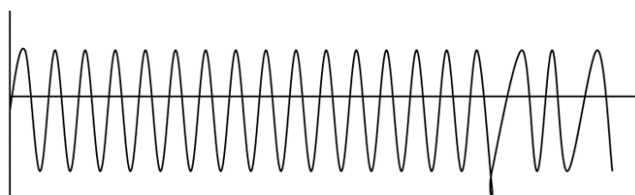


Figure 5.17.8b: Carrier Wave

An FM radio signal's "delivery truck" is represented by the carrier wave as shown in **Figure 5.17.8b**. If you want to communicate with a friend who lives far away, you can not merely shout, so you attach your message to this powerful, constant wave. To transmit your music, the FM transmitter gently alters the carrier wave, which is a smooth, repeating pattern that resembles a perfect ripple in water. You latch onto the frequency of this wave when you adjust your radio to a station (for example, 98.7 MHz). The original sound is regained when the wave reaches the radio after the transmitter modifies its frequency (FM stands for frequency modulation) to match your voice or music. Your favourite tunes would not be able to travel through the atmosphere without this carrier wave.

Frequency-modulated wave

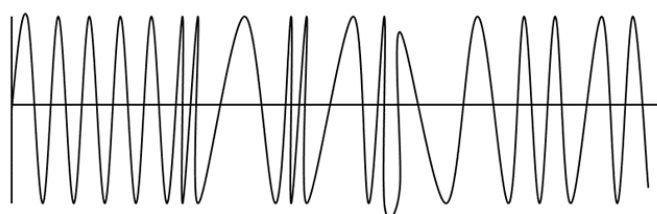


Figure 5.17.8c: Frequency Modulated Signal

The image shown in **Figure 5.17.8c** is a modulated wave, which is the result of the FM transmitter fusing the steady carrier wave with your speech or music (the input signal). Consider it similar to incorporating your own rhythm into a drum beat. The transmitter slightly modifies the wave's frequency (modulates) to match the highs and lows of your audio after your sound is blended in. The initial carrier wave is smooth. Your speech or music travels through the atmosphere thanks to these adjustments. Your radio decodes that minute frequency shifts back into the sound you hear when it detects this wave that appears to be wobbling. Your favourite tunes or radio chatter move from the station to your speakers in this wavy, irregular manner.

Modulation Index of FM

Imagine that you are listening to a highlife music-playing FM radio station. The station's carrier frequency (F_c), such as 99.7 MHz, is its constant home. You can locate it there by tuning your radio. This carrier wave now includes the voice or sound of the person speaking or performing in the studio. However, FM alters the wave's speed, or frequency, in contrast to AM, which modifies the wave's height. The wave moves farther away from its home (carrier frequency) as the speech volume increases. The wave shifts less when the voice is quieter. The amount that the wave deviates from its typical location is known as the frequency deviation (F_d).

In FM, the modulation index simply indicates the magnitude of the wave shifts. It is the proportion of: the degree of frequency shift (F_d), as well as the sound signal's pitch (F_s), such as a high-pitched whistle or a deep drum. So, the modulation index helps us understand how "wide" or "narrow" the FM signal is when it carries different sounds. Bigger shifts mean richer sound, but stations have to keep it within limits so they do not interfere with others.

The modulation index of FM, $M = \frac{F_d}{F_s}$

It can also be expressed as the ratio of the frequency deviation to the maximum allowable frequency deviation. Note that the modulation index of an FM can be more than one.

Examples

1. An Fm transmission has a frequency deviation of 6 KHz. What will be the modulation index if an input signal of frequency 10 KHz is supplied to it?

Solution

$$M = \frac{F_d}{F_s} \times 100$$

Given $F_d = 6\text{KHZ}$ and $F_s = 10\text{ KHz}$

$$\therefore M = \frac{6}{10} \times 100$$

$$= 60\%$$

2. An FM transmission has a frequency deviation of 16.25 KHz. What will be the percentage modulation if it is broadcast in the 88 – 108MHz band?

Solution

Frequency deviation $F_d = 16.25$

Maximum frequency deviation in the 88 – 108MHz band = 175 KHz

$$\begin{aligned}\text{But Modulation index} &= \frac{F_d}{F_M} \times 100 \\ &= \frac{16.25}{75} \times 100 \\ &= 21.67\end{aligned}$$

3. A radio station has a maximum frequency deviation of 60 kHz, and the frequency of the input audio signal is 10 kHz. Calculate the modulation index.

Modulation index of FM,

$$\begin{aligned}M &= \frac{F_d}{F_s} \times 100 \\ &= \frac{60000}{10000} = 600\%\end{aligned}$$

4. An FM transmitter deviates by 75 kHz when transmitting a high-pitched input signal of 15 kHz. What is the modulation index?

Solution

$$\begin{aligned}M &= \frac{F_d}{F_s} \times 100 \\ &= \frac{75}{15} = 500\%\end{aligned}$$

A simple FM transmitter circuit is shown in **Figure 5.17.9**.

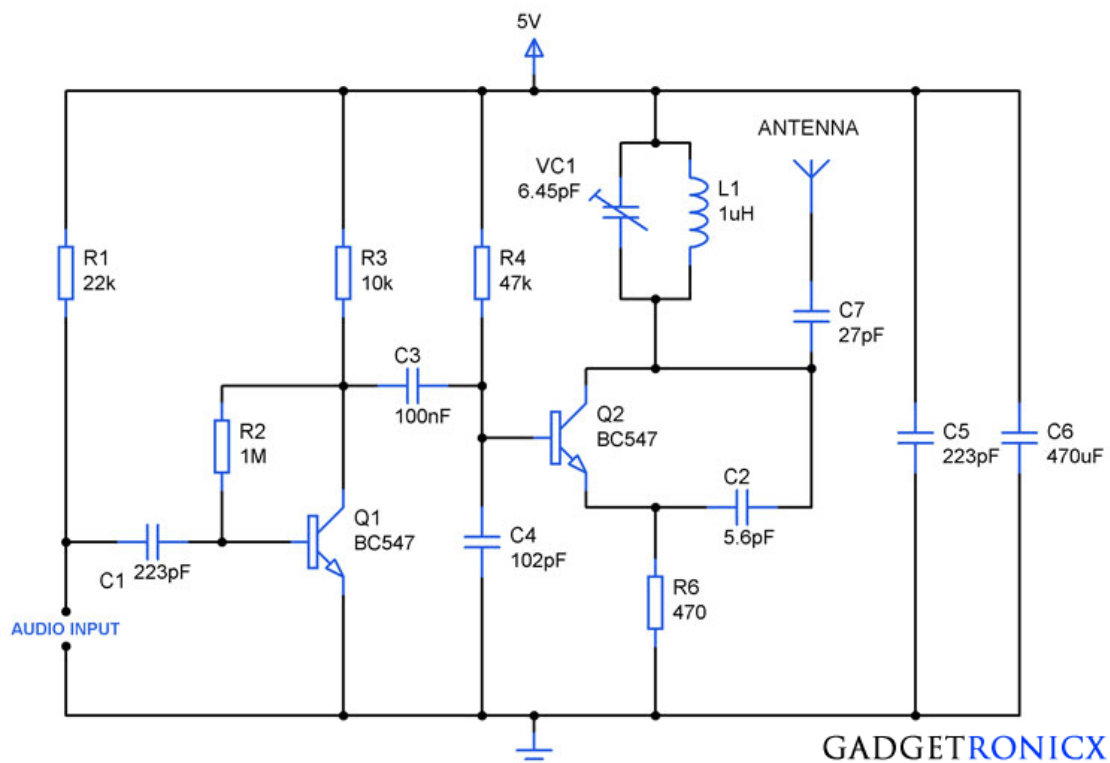


Figure 5.17.9: A simple FM circuit

A basic FM transmitter circuit constructed with transistors, tiny electrical components that amplify and control signals, as shown in the *Figure. 5.17.9*. Think of it as a miniature radio station: music or your speech enters through a microphone, is amplified by transistors, and then combines with a carrier wave (as we previously saw).

To adjust the broadcast frequency, the capacitor and coiled wire (inductor) cooperate, much like when you tune a guitar string to the correct pitch. The circuit converts your sound into radio waves that can reach neighbouring receivers by sending the modulated signal through an antenna when it is powered on. It seems magical, but in reality, it's just smart electronics that make sure your voice can reach someone's radio.

The functions of the various parts are discussed below:

1. Microphone

This is where your voice or music enters. It converts sound into a weak electrical signal, like turning your words into tiny pulses of electricity.

2. Transistors

These act as tiny amplifiers. They take the weak signal from the microphone and boost it, making it strong enough to be processed further.

3. Oscillator (Carrier Wave Generator)

This part creates the steady carrier wave; a high-frequency radio signal (like 98.7 MHz). In the circuit, the coil (inductor) and capacitor work together to set this frequency, just like tuning a radio station.

4. Modulation (Mixing Sound & Carrier)

The amplified sound signal from the microphone is mixed with the carrier wave. In FM, the sound changes the frequency of the carrier slightly higher for loud sounds, lower for soft ones. This creates the modulated wave (the wobbly one you saw earlier).

5. Antenna

Finally, the modulated wave is sent out through the antenna as radio waves. These travel through the air, and when a nearby radio tunes to the same frequency, it picks them up and converts them back into sound.

Uses of FM

1. FM is used in radio broadcasting to deliver clear music and speech over long distances.
2. It is used in homes through wireless sound systems to transmit audio across rooms.
3. FM transmitters are installed in cars to allow drivers to listen to music or traffic updates.
4. In fitness centres, FM systems are used to send music or instructions to wireless headphones.
5. FM is also used in walkie-talkies and two-way radios for clear voice communication.
6. Television audio signals also use FM to ensure better sound quality.

Merits (Advantages) of FM

1. FM transmitters are usually cheaper and simple to operate.
2. They offer high efficiency, meaning they use energy effectively.
3. FM systems provide better sound quality than AM, especially for music.
4. They can cover a large area with fewer disturbances.
5. FM signals are less affected by electrical noise and weather conditions.
6. They reject unwanted signals caused by changes in amplitude.

Demerits (Disadvantages) of FM

1. FM transmitters need more bandwidth than AM, which takes up more space on the spectrum.
2. The equipment used in FM systems is more complex and expensive than AM systems.
3. FM signals do not travel as far as AM signals, especially over long distances or at night.
4. FM transmission may suffer in hilly or mountainous areas without repeaters.
5. It is harder to set up an FM station because of stricter technical requirements.
6. FM receivers are more sensitive to changes in frequency, which can affect tuning.

Activity 5.17.1 Understanding AM and FM Transmitter

Scenario

You are part of a technical broadcast engineering team tasked with improving radio and television coverage in a rural community. To achieve this, you must understand how AM and FM transmitters work, their construction, and how they send signals over long distances. Your role is to research their principles, identify key parts, compare their operation, and present solutions that could improve reliable communication in the area.

Task

1. Explain why an FM transmission has a frequency deviation of 16.25 KHz.
2. What will be the percentage modulation if it is a television broadcast? (HINT: the maximum frequency deviation for T.V transmission is = 25 KHz).
3. Differentiate between AM and FM transmitters in terms of their construction and operation

Materials needed

1. Internet-enabled devices (Google, YouTube)
2. Large paper, markers, pens
3. Worksheets with questions and tables
4. Diagrams of AM and FM transmitters
5. Notebooks, pens/pencils

Step 1: Class Brainstorm

In pairs discuss

1. What is a transmitter?
2. How does it send information?
3. Where are AM and FM transmitters used in real life?

Step 2: Group Research and Table Completion

1. In groups of 3 to 5, assign roles: Researcher, Note-taker, Presenter, Artist.
2. Use your resources to fill in this table

Main Part of Transmitter	Description	Function	Why Important?

3. Guiding questions
 - a. How is AM modulation different from FM modulation?
 - b. How does each transmitter's construction affect its performance?
 - c. What is the role of the modulation stage?
 - d. What is the transmission channel?

Step 3: Draw and Compare Block Diagrams

1. Draw labelled block diagrams of
 - a. AM transmitter
 - b. FM transmitter
2. On your poster, show
 - a. Main parts and their roles
 - b. Differences in construction and operation
 - c. Examples of where each is used

Step 4: Present Your Work

Share your diagrams and findings with the class. Explain:

1. How AM and FM transmitters work
2. Key differences in their operation

3. Why a certain type is more suitable for specific applications

Step 5: Apply and Solve Problems

Work through these tasks

1. Explain why an FM transmission has a frequency deviation of 16.25 kHz.
2. Calculate the percentage modulation if it is for a TV broadcast (max deviation = 25 kHz).
3. Differentiate between AM and FM transmitters in construction and operation.

Step 6: Reflect and Write

In your notebook or tablet reflect and answer these questions

1. What did you learn about AM and FM transmitters?
2. Which transmitter type is more suitable for rural broadcasting and why?
3. How could you explain modulation to someone with no electronics background?

REVIEW QUESTIONS

1. What is the main difference between AM and FM in how they carry sound signals?
2. An AM signal has a maximum voltage of 10V and a minimum voltage of 2V. Calculate the modulation index.
3. Why does AM often suffer from more noise and static compared to FM?
4. Compare one key advantage of FM over AM in terms of sound quality.
5. Why might FM not be suitable for long-distance broadcasting in rural or mountainous areas without repeaters?
6. Explain in simple terms what happens to a carrier wave during Frequency Modulation (FM).

UNIT 18 ELECTRONIC CIRCUITS AND TRANSMITTERS IN ELECTRONIC COMMUNICATION

INTRODUCTION

We have explored the fascinating world of modulation in electronic communication. You learned how a carrier wave or a steady signal is used to transmit information, and how modulation alters this wave to carry sound, data, or images. We also broke down the types of modulation, focusing on Amplitude Modulation (AM) and Frequency Modulation (FM).

We will now shift our attention to how these modulated signals are received and decoded. In simple terms, AM and FM receivers are electronic devices that pick up modulated signals from the air and convert them back into understandable sounds like music or speech. Understanding how these receivers work helps you appreciate the technology behind radios, mobile phones, and even satellite communication. Let us dive into how AM and FM receivers operate, and why they are essential in our daily lives.

KEY IDEAS

- Radio receivers help us to receive signals from the air and turn them into sounds we can hear.
- AM Receiver (Superheterodyne): It uses an antenna, RF amplifier, mixer, local oscillator, IF stage, detector, and audio amplifier. These parts work together to tune the signal, change its frequency, make it stronger, and then recover the audio.
- FM Receiver: It has almost the same parts as an AM receiver but includes a limiter and a discriminator. These make FM signals clearer and reduce the effect of noise.
- Key Differences:
 - o Noise: FM signals are less disturbed by noise than AM.
 - o Complexity: FM receivers have more parts, so they are a bit more complicated.
 - o Bandwidth: FM uses more space (bandwidth) on the radio spectrum than AM.
 - o Sound Quality: FM generally gives clearer and better sound than AM.

AM RECEIVER AND FM RECEIVER

AM RECEIVER

What is an AM Receiver?

An AM receiver is a type of radio that picks up signals sent through Amplitude Modulation (AM). It takes the signal from a transmitter, removes the extra parts used to send it. This process is called demodulation. It brings out the original sound like someone talking, music playing or news being broadcast.

In simple terms, it helps you hear what was sent over the airwaves.



Figure 5.18.1: Shot of a vintage AM / FM Stereophonic Receiver

FM Receiver

FM stands for Frequency Modulation. It is a way of sending sound like music or speech through radio waves.

Here is how the FM receiver works step by step

1. **Signal Reception:** The FM receiver uses an antenna to receive radio waves sent from a radio station. These waves carry sound information.
2. **Tuning:** You choose a station by tuning the receiver to a specific frequency (like 99.50 MHz) This tells the receiver which signal to focus on.
3. **Demodulation:** The receiver removes the “modulation” part of the signal. That means it extracts the original sound, like voice, music, etc., from the radio wave.
4. **Amplification:** The sound is made louder using an amplifier so you can hear it clearly.
5. **Output:** Finally, the sound comes out through speakers or headphones, ready for you to enjoy.



Figure 5.18.2: FM tuner radio with digital frequency display.

Difference Between AM and FM Radio Receivers

Feature	AM Receiver	FM Receiver
How it works	AM (Amplitude Modulation) changes the <i>strength</i> (amplitude) of the signal to send sound. The frequency stays the same.	FM (Frequency Modulation) changes the <i>speed</i> (frequency) of the signal to send sound. The strength stays the same.

History	AM was first used in the 1870s.	FM was introduced in the 1930s by Edwin Armstrong.
Sound Quality	AM has lower sound quality but is cheaper to use. It can reach longer distances and allows more stations in one frequency range.	FM has better sound quality and is more reliable. It is only affected by physical obstacles like buildings or hills.
Frequency Range	AM signals range from 535 kHz to 1700 kHz and have a data rate of about 1200 bits per second.	FM signals range from 88 MHz to 108 MHz and have a data rate of about 1200 to 2400 bits per second.
Complexity	AM is simpler, but it needs careful timing to keep the signal clear.	FM is more complex. It changes voltage to frequency when sending, and frequency back to voltage when receiving.
Noise (Interference)	AM is easily affected by noise because it changes amplitude, which is sensitive to interference.	FM is less affected by noise because the amplitude doesn't change.

Quick Summary of the AM and FM

AM = simpler, cheaper, longer range, lower sound quality

FM = clearer sound, more reliable, shorter range, more complex

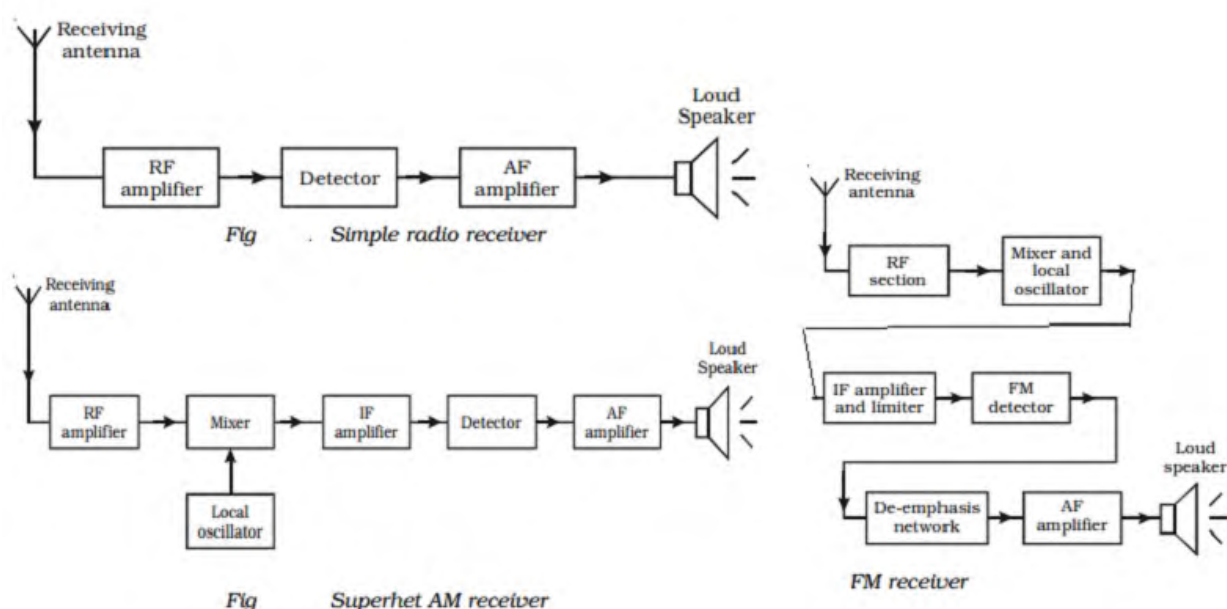


Figure 5.18.3: A Block Diagram of an FM Radio Receiver (Superheterodyne)

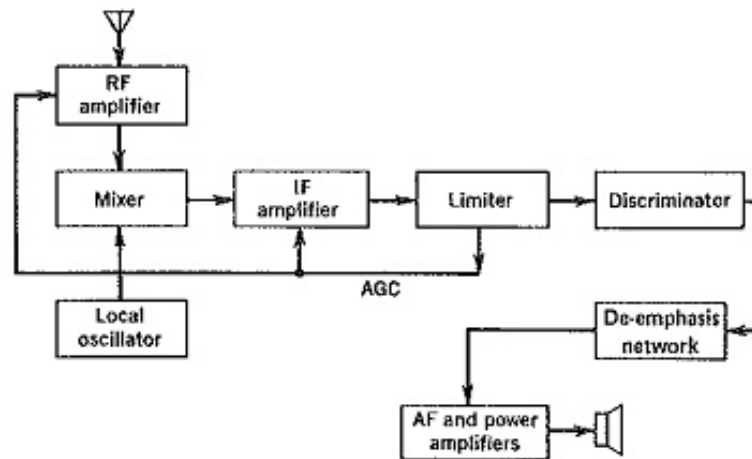


Figure 5.18 4: A Block Diagram of an FM Radio Receiver (Superheterodyne)

Heterodyning

Heterodyning is a technique used in electronics and radio communication. It involves mixing two signals with different frequencies to create two new signals:

1. One with a frequency that is the sum of the two signals ($f_o + f_s$)
2. One with a frequency that is the difference between them ($f_o - f_s$)

This helps devices like radios and TVs to tune into the correct signal or station by shifting frequencies to a more useful range.

Heterodyning Formulas

Let: f_o = frequency of the original signal (or oscillator) and f_s = frequency of the second signal (or input signal)

Then:

Sum frequency = $f_o + f_s$

Difference frequency = $|f_o - f_s|$ (we take the absolute value)

Calculations

Example 1

$f_o = 1000 \text{ Hz}$ and $f_s = 300 \text{ Hz}$

Sum: $f_o + f_s = 1000 + 300 = 1300 \text{ Hz}$

Difference: $|f_o - f_s| = |1000 - 300| = 700 \text{ Hz}$

Example 2

$f_o = 5000 \text{ Hz}$ and $f_s = 2000 \text{ Hz}$

Sum: $f_o + f_s = 5000 + 2000 = 7000 \text{ Hz}$

Difference: $|f_o - f_s| = |5000 - 2000| = 3000 \text{ Hz}$

Example 3

$f_o = 12000 \text{ Hz}$ and $f_s = 4000 \text{ Hz}$

Sum: $f_o + f_s = 12000 + 4000 = 16000 \text{ Hz}$

Difference: $|f_o - f_s| = |12000 - 4000| = 8000 \text{ Hz}$

Activity 5.18.1 Understanding AM and FM Receivers**Scenario**

You are part of a community radio station project aiming to improve radio reception for rural communities. Your team needs to understand how AM and FM receivers work, their key differences, and how to represent them using block diagrams. This will help in repairing, designing, or selecting the best receiver for different locations.

Learning Tasks

1. Explain the concept of AM and FM receivers.
2. Identify and discuss at least three key differences between AM and FM receivers.
3. Draw the block diagrams for an AM receiver (superheterodyne) and an FM receiver.

Materials needed

1. AM and FM receiver diagrams
2. Internet-enabled devices (phones, tablets, laptops)
3. Large paper, markers, pens
4. Notebooks, pencils
5. Access to YouTube videos and articles
6. Printed comparison table template
7. Radios (if available)

Step 1: Class Brainstorm

Think about the radios you have seen or used. Discuss in pairs or groups:

1. What is an AM receiver?
2. What is an FM receiver?
3. Which do you think gives clearer sound, and why?

Step 2: Group Research and Table Completion

1. Form groups of 3 to 5 and assign roles: researcher, note-taker, presenter or artist.
2. Use Google search and You-Tube to find:
 - a. The block diagram of an AM receiver (superheterodyne).
 - b. The block diagram of an FM receiver.

c. At least three main differences between AM and FM receivers.

3. Fill in the table:

Feature/Part	AM Receiver	FM Receiver	Notes
Signal type			
Main parts			
How sound is recovered			
Bandwidth used			
Resistance to noise			

Step 3: Create Your Poster and Diagrams

1. Draw labelled block diagrams of both AM and FM receivers.
2. On a poster, include:
 - a. How each receiver works (in simple words)
 - b. Key differences between them
 - c. Examples of where each is used and why

Step 4: Present Your Work

Present your poster and diagrams to the class, explaining:

1. How AM and FM receivers operate
2. Key differences between them
3. Which receiver type is better for certain situations and why

Step 5: Ask, Answer, and Reflect

1. Ask classmates questions about their diagrams.
2. Give constructive feedback on clarity and accuracy.
3. Write in your notebook:
 - a. What did you learn about AM and FM receivers?
 - b. Which type would you recommend for rural areas and why?

REVIEW QUESTIONS

1. What is the main function of a demodulator in a receiver?
2. Which component in a receiver separates the desired signal from others?
3. Explain how amplitude modulation works
4. Create a troubleshooting guide for poor FM reception in urban environments. This could be in the form of a booklet, table or poster.

ANSWERS TO REVIEW QUESTIONS

Section 1, Unit 1

1. A motor is a machine that changes electrical energy into mechanical energy.
2. The stator and the rotor.
3. Alternating current (AC).
4. Because a single-phase supply creates a pulsating magnetic field, not a rotating one. The capacitor or inductor creates a phase difference that produces a rotating magnetic field to start the motor.
5. The rotating magnetic field in the stator induces an emf in the rotor bars, creating currents that produce their own magnetic field. The interaction of these fields causes the rotor to turn.
6. Both have stator and rotor parts, but the single-phase motor has two windings (main and starting winding with capacitor) to create a rotating field, while the three-phase motor has three windings spaced 120° apart creating a natural rotating field. The single-phase motor uses a capacitor to start, and the three-phase motor naturally produces a rotating field. The rotor in the squirrel cage motor has embedded bars, while the single-phase rotor is similar but starts with assistance from the capacitor winding.
7. A star-delta starter reduces the voltage and starting current to about one-third compared to DOL, reducing mechanical stress and electrical disturbances. This makes it better for medium-sized motors that would otherwise draw large starting currents.

Section 1, Unit 2

1. Yoke, Armature, Commutator
2. Brushes transfer current from the power source to the rotating commutator.
3. The field winding is connected in series with the armature
4. The commutator rectifies the alternating voltage induced in the armature conductors, allowing the motor to produce unidirectional torque.
5. Interpoles have polarity matching the main poles and counteract distortion in the magnetic field, which reduces sparking and ensures smoother operation
6. $E_b = V - I_a (R_a + R_f) = 400 - 100(0.25 + 0.15) = 400 - 40 = 360 \text{ V}$
7. Back emf opposes the applied voltage and increases with speed. It reduces the net voltage across the armature, limiting current and preventing the motor from running too fast, thereby helping regulate speed under varying loads.

Section 1, Unit 3

1.
 - Introduction
AC generators, also known as alternators, are crucial for power generation in grids, vehicles, and renewable energy systems. Their design is grounded in electromagnetic principles that convert mechanical energy into electrical energy.

A deep look into their construction and operation reveals how each element affects performance.

- Construction Components

An AC generator typically includes:

- o Rotor (Armature): Rotates within a magnetic field; can be either the conductor or the field source depending on configuration.
- o Stator: Stationary part housing windings where induced voltage is collected.
- o Field System: Produces the magnetic field, usually with DC excitation or permanent magnets.
- o Slip Rings: Provide continuous electrical connection as the rotor turns.
- o Bearings & Shaft: Enable smooth mechanical rotation.

These components are engineered for durability, minimal energy loss, and precision in energy conversion.

- Principle of Operation

The fundamental principle is Faraday's Law of Electromagnetic Induction:

- o When a conductor moves through a magnetic field, an electromotive force (EMF) is induced.
- o In AC generators, the rotating magnetic field (either via rotor or stator) induces alternating voltage in the stator windings.
- o The changing polarity of the field results in alternating current—voltage varies sinusoidally with time.

- Design Influence on Performance

- o Number of Poles & Rotation Speed: Determines frequency of generated current.
- o Magnetic Field Strength: Affects voltage amplitude; stronger fields induce higher EMF.
- o Winding Configuration: Affects phase output (single-phase or three-phase).
- o Slip Ring Quality: Impacts current stability and output efficiency.

Structural integrity and electromagnetic precision significantly influence generator behaviour under load and during transient conditions.

- Real-World Examples

- o Hydroelectric Plants: Massive rotors driven by turbines produce AC power for national grids.
- o Vehicle Alternators: Compact generators maintain battery charge and support electrical systems.
- o Wind Turbines: Variable-speed generators coupled with power electronics produce clean energy.

2. Frequency, $f = \frac{PN}{120} = \frac{10 \times 600}{120} = 50 \text{ Hz}$

$$\text{Number of conductors per phase, } Z = \frac{90 \times 12}{3} = 360$$

$$T = \frac{Z}{2} = \frac{360}{2} = 180 \text{ per phase}$$

$$V_{rms}/ph = 4.44 k_c k_d f \Phi T \text{ volts}$$

$$V_{ph} = 4.44 \times 1 \times 0.96 \times 50 \times 0.1 \times 180 = 3836.16 \text{ volts}$$

$$\text{Line voltage, } V_L = \sqrt{3} \times V_{ph} = \sqrt{3} \times 1534.46 = 2,557.69 \text{ V}$$

Section 1, Unit 4

1. Faraday's law of electromagnetic induction states that an electromotive force (EMF) is induced in a conductor when there is a change in magnetic flux linking the conductor. The magnitude of the induced EMF is proportional to the rate of change of the magnetic flux.
2. The induced EMF can be calculated using Faraday's Law of electromagnetic induction:

$$E = B \cdot L \cdot v$$

Substituting the values:

$$E = 1.25 \text{ T} \cdot 0.3 \text{ m} \cdot 4 \text{ m/s} = 1.25 \cdot 0.3 \cdot 4 = 1.5 \text{ V}$$

When the ends of the conductor are open-circuited, there is no closed loop for the current to flow, so the current is:

$$I_{\text{open}} = 0 \text{ A}$$

Using Ohm's Law, we can calculate the current when a resistor is connected across the ends. The formula is given by:

$$I = \frac{E}{R}$$

Where: E = Induced EMF = 1.5 V and R = Resistance = 20 Ω

Substituting the values:

$$I = \frac{1.5 \text{ V}}{20 \Omega} = 0.075 \text{ A} = 75 \text{ mA}$$

3. The design and construction of a DC generator are carefully arranged to enable the conversion of mechanical energy into direct current electrical energy through electromagnetic induction. Key components influence its operation as follows:

- Armature Windings
 - o Function: The armature windings are coils of insulated wire wound on the rotor (armature) where the EMF is induced as the armature rotates in the magnetic field.
 - o Influence on EMF: The number of turns and quality of winding affect the magnitude of induced EMF (more turns = higher voltage). Proper winding reduces resistance and losses, improving efficiency.

- o Effect on Efficiency & Voltage Regulation: Well-designed armature windings minimise copper losses, enhancing efficiency. The winding layout also affects voltage ripple and smoothness.
- Commutator
 - o Function: The commutator is a segmented cylindrical switch connected to the armature windings. It reverses the direction of current in the external circuit, converting the alternating EMF induced in the armature coils into direct current.
 - o Influence on EMF: By ensuring the output current is unidirectional, the commutator maintains steady DC voltage and current output.
 - o Effect on Efficiency & Voltage Regulation: The commutator introduces friction and electrical losses (sparking), which can reduce efficiency. High-quality commutators and brushes improve voltage regulation by providing smooth switching.
- Field System (Field Windings or Permanent Magnets)
 - o Function: The field system provides the magnetic field in which the armature rotates. It can be created by electromagnets (field windings) or permanent magnets.
 - o Influence on EMF: The strength of the magnetic field directly affects the induced EMF (stronger field = higher voltage). Field current regulation allows control of output voltage.
 - o Effect on Efficiency & Voltage Regulation: Efficient field design reduces losses and supports stable voltage output under varying loads. Compound or separately excited field systems offer better voltage regulation compared to simple shunt fields.
- Comparative Analysis in Practical Applications

Component	Influence on EMF & Voltage Regulation	Efficiency Considerations	Typical Application Impact
Armature Windings	Number of turns and winding type affect voltage level and smoothness	Minimize resistance to reduce copper losses	High-turn windings in generators for steady voltage
Commutator	Converts AC to DC; quality affects voltage ripple and sparking	Friction and electrical losses impact efficiency	Heavy-duty commutators for industrial DC machines
Field System	Magnetic field strength controls voltage; adjustable fields aid regulation	Low-loss magnetic materials improve performance	Variable field systems in applications needing voltage control (e.g., battery charging)

In summary, the construction of a DC generator balances these components to maximise EMF generation, maintain voltage stability, and improve efficiency for diverse practical uses such as battery charging, backup power supplies, and electroplating.

Section 2, Unit 5

1. **Tighten Internal Components:** Check for loose windings, core bolts, or mounting frames. Use basic tools to secure or realign parts to reduce vibration.
Balance Load Across Phases: Measure the load on each phase and ensure it is evenly distributed. This improves voltage stability and reduces mechanical stress without needing new hardware.
2. Several transformer factors could lead to voltage instability and vibration:
 - **Magnetic Flux Imbalance:** If the core is not aligned properly or windings are uneven, the magnetic flux can become unstable, causing vibration and voltage fluctuation.
 - **Loose Windings or Coil Mounting:** Poor winding support can lead to mechanical vibration during operation due to electromagnetic forces.
 - **Connection Configuration Errors:** Incorrect phase arrangement (e.g., Delta-Star misalignment) can lead to unequal voltage distribution across phases.
 - **Cooling Issues:** If internal heat is not removed effectively, it may affect winding resistance and cause voltage variation or mechanical stress.
3. **Evaluating the Upgrade to a Three-Phase Transformer, how It Helps Our Community.**
 - **Better Power Supply and Fewer Problems**
 - A three-phase transformer gives out electricity more smoothly and efficiently.
 - It helps keep the voltage stable, so machines at schools, hospitals, and shops do not spoil easily.
 - Less energy is wasted when power travels across long distances.
 - Saves space and is easier to maintain
 - Instead of many small transformers, using one big three-phase transformer takes up less space.
 - It is easier to check, fix, and keep working well.
 - Fewer parts mean fewer problems.
 - Ready for the Future
 - As more people move into the area and use more electricity, this upgrade can handle the bigger demand.
 - It works well with solar and other clean energy sources.
 - New buildings and equipment can be added without stressing the system.
 - **Money-Saving Benefits**
 - Since less power is wasted, it can reduce electricity costs over time.
 - Businesses can work better with good electricity, leading to more jobs and income.

- The government may spend less on fixing old systems and more on health and education.
- Safer and Better for the Environment
- Using power wisely means less harm to the environment.
- Fewer machines mean fewer chances of overheating and electrical accidents.

Section 2, Unit 6

1. Efficiency (%) = (Output Power ÷ Input Power) × 100

$$= (9,800 \div 10,500) \times 100$$

$$= 93.33\%$$
2. Types of Losses Causing Drop
 - Copper Losses – Due to resistance in the transformer windings.
 - Core Losses – Caused by hysteresis and eddy currents in the iron core.
3. Ways to Improve Efficiency
 - Use thicker copper wires to reduce resistance and lower copper losses.
 - Use a laminated silicon steel core to reduce eddy current and hysteresis losses.

Section 2, Unit 7

1. Cooling efficiency is determined by how well the system removes heat.

$$\text{Efficiency} = \frac{\text{Heat Dissipated}}{\text{Maximum allowable Heat}} \times 100\% = \frac{150000}{200000} \times 100\% = 75\%$$
2. Transformer B (ONAN) is better because:
 - Oil cooling is more efficient in high temperatures than air cooling.
 - Natural oil circulation reduces dependency on fans (lower maintenance).
 - Handles overloads better without rapid temperature spikes.

Conclusion: Oil-cooled transformers are more reliable in tropical climates.

3. Voltage regulation, $V.R = \frac{E_2 - V_2}{E_2} \times 100\%$,

$$V.R = \frac{410 - 390}{410} \times 100\% = 4.88\%$$

4. Rearrange the regulation formula:

$$V.R = \frac{E_2 - V_2}{E_2} \times 100\%,$$

$$6\% = V.R = \frac{240 - V_2}{240} \times 100\%,$$

$$V_2 = 240 - (0.06 \times 240) = 225.6 \text{ v}$$

Conclusion: Full-load voltage = 225.6 V

Potential Issues? Yes. A 6% drop may cause:

- Flickering lights
- Overheating in motors
- Reduced efficiency in electronics

Section 2, Unit 8

1. Resistive Load converts all electrical energy into heat (e.g., electric heater, incandescent bulb). On the other hand, inductive load uses coils to create a magnetic field, causing a lag between voltage and current (e.g., fan motor, refrigerator compressor).
2. Causes of wear and tear in switches and how can this be prevented
 - Inductive loads create sparking when switched off due to the collapsing magnetic field, damaging contacts over time.
 - Prevention: Use relays or contactors for heavy inductive loads, or install snubber circuits to reduce arcing.
3. Possible Fault
 - Burnt capacitor (common in fans): prevents proper motor starting.
 - Stuck rotor: due to dirt or bearing failure.

Solution: Replace the capacitor; Clean and lubricate the motor bearing

4. Possible Faults
 - Broken heating element: Test with a multimeter for continuity.
 - Faulty thermostat: Check if it is stuck or damaged.
 - Loose wiring connection: Inspect terminals and connections.

Troubleshooting Steps

- Use a multimeter to check resistance in the heating coil.
- Replace the thermostat if it fails to regulate temperature.
- Tighten or replace damaged wires.

Section 3, Unit 9

1. A
2. B
3. D
4. A
5. C
6. D

Section 3, Unit 10

1. This is a broken rotor bar fault. If it is not repaired, the motor may vibrate more, become weak, overheat, and eventually stop working completely. It may also use more electricity, increasing your electricity bill.
2. This is a stator winding fault, most likely caused by overheating, overloading, or insulation failure. To prevent it, avoid overloading the motor, keep the windings clean and dry, and perform regular maintenance checks.
3. This could be an open circuit fault, possibly caused by a broken wire, loose connection, or damaged switch inside the machine. The flow of electricity is cut off, so the machine cannot run.

4. This is likely due to a voltage surge caused by the lightning, which may have damaged the electrical components in the motor. To prevent this in the future, use a surge protector or a voltage regulator to protect the motor from high-voltage spikes.

Section 3, Unit 11

1. Increasing the resistor or capacitor value increases the delay time, while decreasing them reduces the delay. The delay in monostable mode is calculated using the formula: $T = 1.1 \times R \times C$, Where, T is time in seconds, R is resistance in ohms, and C is capacitance in farads. By adjusting either R or C, you directly control how long the output stays high before returning low.
2. Monostable mode is ideal because it produces a single output pulse when triggered. Pressing the button activates the timer, turning the LED on for 10 seconds. The timing is set using the formula $T = 1.1 \times R \times C$. After 10 seconds, the LED automatically switches off.
3. A 555 timer in monostable mode can trigger a high output for a set time using selected resistor and capacitor values. After activation, it automatically turns the device off when the time elapses.

Section 3, Unit 12

1. The 4558's dual op-amp design can:
 - Boost weak microphone signals (using one op-amp as a preamp).
 - Filter out background noise (with the second op-amp).
 - Deliver clear sound thanks to its low noise and high gain.
2. High input impedance means the op-amp:
 - Will not drain power from the tiny solar panel (like a polite guest who does not eat all your food).
 - Accurately measures small light changes without distortion.
3. Connect a light sensor (LDR) to the op-amp's non-inverting input (+).
 - Set a reference voltage (e.g., 3V) at the inverting input (-).
 - When light drops, the LDR's resistance increases, making the op-amp's output HIGH and lighting the LED.
4. By adding negative feedback (resistor from output to inverting input):
 - You reduce excessive gain causing distortion.
 - Stabilize the sound (like turning down a screechy microphone).
5. (Hint: Use Pin 3 (non-inverting) for the microphone signal and Pin 6 (output) to the fan.)

Components needed

- Op-Amp (741 or 4558)
- Electret Microphone (to detect claps)

- Transistor (e.g., BC547) + Relay (to power the fan)
- Resistors (10k Ω , 100k Ω) and Capacitor (0.1 μ F)
- 5V-12V DC Fan

Circuit Diagram & Connections

- Power the Op-Amp

Connect Pin 7 (+Vcc) to 5V-12V.

Connect Pin 4 (GND) to the battery's negative.

- Microphone Input

Wire the mic to Pin 3 (Non-Inverting Input +) through a 10k Ω resistor (to bias the mic).

- Add a 0.1 μ F capacitor between mic and Pin 3 to block DC noise.

Reference Voltage: Use a voltage divider (two 10k Ω resistors) to set Pin 2 (Inverting Input -) to *half* of Vcc (e.g., 2.5V for 5V supply).

Output to Fan: Connect Pin 6 (Output) to a transistor's base (BC547) through a 1k Ω resistor. The transistor switches a relay to power the fan (use a diode across the relay to protect the circuit).

How It Works

- When you clap, the mic detects sound → sends a small AC signal to Pin 3.
- The op-amp compares this to the reference voltage at Pin 2.
- If the clap is loud enough, the output (Pin 6) goes HIGH → transistor activates → relay turns on the fan.

Section 4, Unit 13

1. Truth Table for 2-Input OR Gate

Input A	Input B	Output (A OR B)
0	0	0
0	1	1
1	0	1
1	1	1

Analysis of Output Response: The OR gate gives an output of 1 (ON) when at least one input is 1. It gives an output of 0 (OFF) only when both inputs are 0. This means the OR gate is useful when the output should happen if any condition is met.

2. Design Idea: Automatic Door Closer Using NOT Gate

Objective: Use a NOT gate to ensure that the door automatically closes when it is left open (forgotten).

How It Works

- A sensor (e.g., limit switch or infrared sensor) detects if the door is open.
- When the door is open, the sensor sends an input of 1 to the NOT gate.
- The NOT gate inverts the signal and sends an output of 0.
- The motor controller connected to the NOT gate interprets the 0 as a command to close the door.

Logic Table: Automatic Door Closer Using NOT Gate

This truth table shows how a NOT gate can be used to automatically close a door when left open.

Door Status	Sensor Input	NOT Gate Output	Action
Closed	0	1	No action needed
Open	1	0	Door closes

Components

- Door position sensor
- NOT gate (inverter)
- Motor or actuator
- Power source
- Control wiring

This setup shows how a NOT gate can be used to automatically reverse an undesired state (door left open) and ensure the system returns to its correct state (door closed).

Section 4, Unit 14

- Boolean Expression: $F = A \bullet (B + C)$
 - The design uses an OR gate for B and C, whose output feeds into an AND gate with A. Simplification minimises hardware, saves power, and improves reliability.
- Boolean Expression: $F = AB + AC + BC$
 - Truth Table:

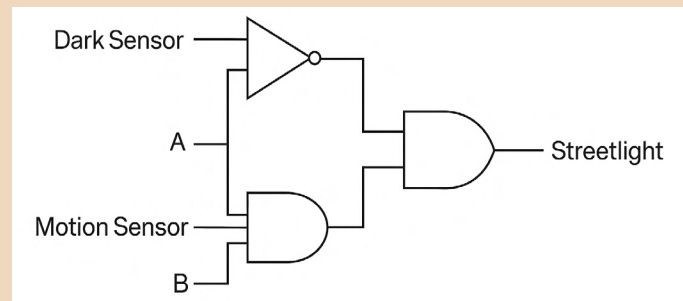
A	B	C	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1

1	1	0	1
1	1	1	1

- c. NAND-only Design: Use NAND gates to build AND and OR logic using De Morgan's Theorem.
- d. Scalability: For more inputs, expressions grow. Use decoders or majority logic circuits.

Section 5, Unit 15

- **Streetlight Control Logic Circuit:** This logic circuit diagram controls a streetlight such that the light turns ON only when it is dark OR when motion is detected, but NOT when both conditions occur simultaneously. The logic is implemented using basic gates: AND, OR, and NOT.



- **Logic Summary**
 Inputs: A – Dark Sensor B – Motion Sensor
 Output: Streetlight ON
 • **Logic Expression:** Light ON = (A AND NOT B) OR (NOT A AND B)

Section 5, Unit 16

1. The transmitter converts the information signal into a form suitable for transmission and sends it through the channel.
2. Amplitude Modulation (AM) and Frequency Modulation (FM).
3. The receiver captures the transmitted signal, demodulates it, and converts it back into the original information.
4. In AM, the amplitude of the carrier wave changes while its frequency remains constant; in FM, the frequency of the carrier wave changes while its amplitude remains constant.
5. FM signals generally have better clarity and are more resistant to noise, while AM signals are more prone to interference and static.
6. Modulation allows the original low-frequency signal to be shifted to a higher frequency range, enabling efficient transmission over long distances and through various channels without excessive loss or interference.
7. They should choose AM because it can travel longer distances, especially at night, and requires simpler, cheaper equipment. Although FM has better sound quality, it has a shorter range and requires more complex receivers.

8. *(Expected answer – diagram with labels: Information Source → Transmitter (with Modulator) → Transmission Channel → Receiver (with Demodulator) → Destination)*

Section 5, Unit 17

1. AM changes the height (amplitude) of the wave to carry sound, while FM changes the speed (frequency) of the wave.
2. $M = \frac{E - F}{E + F} \times 100\%$, $M = \frac{10 - 2}{10 + 2} = 0.67 \times 100 = 67\%$
3. AM signals carry information by changing amplitude, which is easily affected by electrical noise or interference like lightning or engines.
4. FM offers better sound quality than AM because it is less affected by noise and interference from amplitude changes.
5. FM signals do not travel as far as AM signals and can be blocked by hills or buildings, so they require repeaters to extend coverage in such areas.
6. In FM, the speed or frequency of the wave changes depending on the sound being added, but its height (amplitude) stays the same.

Section 5, Unit 18

1. To extract the original audio signal from the modulated carrier wave.
2. The tuner
3. In AM, the amplitude of the carrier wave is varied in proportion to the audio signal.
4. Include steps like checking antenna placement, avoiding interference sources, using signal boosters and switching to digital alternatives if available, etc.

REFERENCES

1. [B.L. Theraja, A.K. Theraja \(2008\). A Textbook of Electrical Technology. New Delhi: S. Chand & Company Ltd.](#)
2. [Cooling of Transformer and Methods of Cooling - Circuit Globe](#)
3. [https://blogger.googleusercontent.com/img/b/R29vZ2xl/AVvXsEgIAtiyN9BLB3EiDEIUvjSMTvYoLjhgNQ07s8uVCS_SWYLU0ydiVos-fB4Du0JddvDd7gupe93EI7LtKHA6egDR1Pqmj0kHmjic6d8roSuh0R2ZigjRHUsS0UrGhYgN0n3zTVCGFyZI8M3-W/s607/DCM+-+characteristics+of+DCM+-+5.png](#)
4. [https://blogger.googleusercontent.com/img/b/R29vZ2xl/AVvXsEhWbBQZubw7ptzNlehUhnIISDZtPS_GGgUwFNOft_toFtT9a8L6oyEf9-NfRwPs2b4ZXDHtW9Ne2xgE0ZU5OIEMu0VWph77ivBXl-flnO3UfPlooKGVZhGCxVKp9vRo3Anqzw dnxxWPO-b/s609/DCM+-+characteristics+of+DCM+-+4.png](#)
5. [https://cdn1.byjus.com/wp-content/uploads/2021/04/Frequency-Modulation-3.png](#)
6. [https://content-grail-production.s3.amazonaws.com/quetsion-media/8bd239e2-9a67-471b-8eed-576a92e040ab-image.png](#)
7. [https://electricalvoice.com/what-is-electrical-fault-types-causes-effects/](#)
8. [https://electricalvoice.com/what-is-electrical-fault-types-causes-effects/](#)
9. [https://images.saymedia-content.com/_image/t_share/MTc1MDA5NzM1ODIzNjY0ODcy/elements-of-electronic-communications-system.png](#)
10. [https://m.youtube.com/watch?v=cE34YHsRY88&pp=ygUII3BoYWVvbmU%3D](#)
11. [https://m.youtube.com/watch?v=cE34YHsRY88&pp=ygUII3BoYWVvbmU%3D](#)
12. [https://media.geeksforgeeks.org/wp-content/uploads/20240401181835/Amplitude-Modulation.png](#)
13. [https://unacademy.com/content/nda/study-material/physics/types-of-communication-system-transmitter/#:~:text=Communication%20System%2DTransmitter-Types%20of%20Communication%20System%2DTransmitter,-Transmitter%20is%20an](#)
14. [https://www.bing.com/search?q=Direct+current+motor+characteristics&cvid=69ed7b-cf156f41fe97b765fb1c52690e&gs_lcrp=EgRlZGdlKgYIABBFgDkyBgGAEeUYOTIG-CAEQABhAMgYIAhAAGEAyBgGDEAAAYQDIGCAQQABhAMgYIBRAAGEAyB-ggGEAAAYQDIGCAcQABhAMgYICBAAGEDSAQk0NDMzN2owajSoAgiwAgE&-FORM=ANAB01&PC=U531#:~:text=torque%20and%20speed-,The%20performance%20of%20a%20DC%20motor%20is%20given%20by%20the%20relation,show%20the%20behaviour%20of%20the%20DC%20motor%20under%20different%20load%20conditions.,-Characteristics%20of%20DC\)](#)
15. [https://www.electrical4u.com/types-of-dc-motor-separately-excited-shunt-series-compound-dc-motor/#:~:text=Key%20learnings%3A,systems%2C%20highlighting%20their](#)
16. [https://www.electricaldeck.com/2021/01/characteristics-of-dc-motors-shunt-series-compound.html#:~:text=Power%20Systems-,Home,Characteristics%20of%20DC%20motors%20%2D%20Shunt%2C%20Series%20%26%20Compound,-January%2022%2C%202021](#)
17. [https://www.managementstudyguide.com/different-types-of-communication-system.htm/#:~:text=0-,Different%20Types%20of%20Communication%20Systems,-Home%20%C2%BB%20Organizational](#)
18. [https://www.physics-and-radio-electronics.com/blog/elements-of-a-communication-system/](#)



19. <https://www.theelectricalguy.in/tutorials/types-of-electrical-load-resistive-inductive-capacitive-load/>
20. <https://www.theelectricalguy.in/tutorials/types-of-electrical-load-resistive-inductive-capacitive-load/>
21. <https://www.electronics-tutorials.ws/transformer/voltage-regulation.html>
22. <https://www.youtube.com/watch?v=UoZ2kxAc9WE>
23. <https://youtu.be/cE34YHsRY88>
24. [NaCCA. MOE \(2023\), Teacher Assessment Manual and Toolkits \(TAMTK\)](#)
25. [Sraha, E. C., \(2021\) Applied Electricity and Electronics for SHTS. Revised Edition Koforidua: Books Galore Ventures. ISBN 978-9988-2-0594-2.](#)
26. [Synchronous Motor: Construction, Working Principle & Applications](#)
27. [Thompson, F. G. \(1992\) Electrical Installation and Workshop Technology. Fifth Edition.](#)

Online Images

Name of Image	Reference (link)
28. Simple Transformer construction	https://omgfreestudy.com/what-is-transformer-and-its-working-principle/#google_vignette
29. Three- phase transformer	https://www.seably.com/courses/electrical-3-phase-power-transformers-fundamentals
30. Delta-Star connection	https://th.bing.com/th/id/OIP.uq2MOjgTP7TeUht5ZriXAAAAA?w=307&h=133&c=7&r=0&o=5&cb=iwc2&pid=1.7

Online Images for Section 2, unit 6

Name of Image	Reference(link)
31. A diagram showing a breakdown of transformer losses	https://circuitglobe.com/wp-content/uploads/2015/09/types-of-losses-in-transformer-compressor-768x410.jpg

Name of Image	Reference (link)
A Picture of a pressing Iron (An example of a resistive load)	https://img.freepik.com/premium-photo/modern-electric-iron-isolated-white-background-3d-illustration_943642-6131.jpg?w=2000
A picture of a Water Heater (An example of a resistive load).	https://as1.ftcdn.net/v2/jpg/01/41/71/02/1000_F_141710214_jVF37XFSBviYagF1Ryoccm6DunrGghp.jpg
A picture of a Blender (An example of an Inductive load).	https://th.bing.com/th/id/OIP.KqrBKEGJwrjNysspZwRnrgAAAA?c=b=iwp2&rs=1&pid=ImgDetMain

A picture of a Washing Machine (An example of an inductive load)	https://www.lg.com/in/images/washing-machines/md07540887/gallery/FHM1408BDL-Washing-Machines-Right-View-MZ-04-v1.jpg
--	---

Name of Image	Reference (link)
A picture showing different types of bearing faults in electrical machines	https://www.researchgate.net/publication/359414039/figure/fig4/AS:1181552717381656@1658715528107/Some-faults-demonstration-of-ball-element-bearings_Q640.jpg
A Picture showing a broken rotor bar.	https://www.electricalapparatus.net/wp-content/uploads/rotor-bars.jpg
A picture showing failure in a three-phase stator winding of an electrical motor.	https://images.squarespace-cdn.com/content/v1/56c20776f699bbc849dc0a69/1458920265770-J2OWIWOQK5E95CBQA42Z/image-asset.jpeg

Name of Image	Reference (Link)
Schematic Representation of Op-amp	https://www.researchgate.net/profile/Alex-Colburn/publication/350440161/figure/fig1/AS:1006011838132224@1616863321186/Symbolic-representation-of-an-op-amp-and-key-characteristics.png
Diagram showing the pin connections of IC 741 Op-amp	https://i0.wp.com/www.electricalvolt.com/wp-content/uploads/2022/12/op4.png?w=1305&ssl=1
Diagram showing the pin connections of 4558 IC Op-amp	https://components101.com/sites/default/files/component_pin/JRC4558-Pinout_0.png
Open Loop Operation	https://cdn-0.electricalvoice.com/wp-content/uploads/2019/11/open-loop-operation-in-opamp.jpg
Closed Loop Operation	https://electricalvoice.com/wp-content/uploads/2019/11/closed-loop-operation-in-opamp.jpg

Name of Image	Reference (link)
Transistor-transistor logic circuit	https://www.build-electronic-circuits.com/wp-content/uploads/2022/09/RTL-NOR-gate.png
Diode Transistor Logic circuit of a 3 input AND Gate	https://www.elprocus.com/wp-content/uploads/Diode-Transistor-Logic-AND-Gate-300x257.jpg
Diode Transistor Logic circuit of a 3 input NAND Gate	https://ecstudiosystems.com/discover/textbooks/basic-electronics/logic-gates/images/dtl-nand-circuit.jpg

Diode logic circuit	https://i2.wp.com/www.circuitstoday.com/wp-content/uploads/2010/04/2-Input-Diode-OR-Gate.jpg?strip=all
COSMOS implementation as NAND gate circuit	https://www.allaboutelectronics.org/wp-content/uploads/2023/04/Screenshot-2023-04-14-at-4.02.16-PM.png
Name of Image	Reference (link)
Astable multi-vibrator using NAND gates	https://i.pinimg.com/originals/fe/d9/c6/fed9c67506c2c94567a999df6b1fef61.png
Pin connection of 4011 Quad NAND gate	https://1.bp.blogspot.com/_-VwjFK-ofUU/S78NyOWrX0I/AAAAAAAAABAU/aOPK13pNhWI/s320/nand3.png
Name of Image	Reference (Link)
Shot of a vintage AM / FM Stereophonic Receiver	https://www.istockphoto.com/photo/vintage-am-fm-receiver-gm530715421-54980346
Shot of a vintage AM / FM Stereophonic Receiver	https://www.dreamstime.com/stock-photo-fm-tuner-radio-display-stereo-digital-frequency-station-tuned-horizontal-image78769957
A Block Diagram of an FM Radio Receiver (Superheterodyne)	https://img.brainkart.com/article/articleHvhWxaabpicture11.jpg
A Block Diagram of an FM Radio Receiver (Superheterodyne)	https://www.eeeguide.com/wp-content/uploads/2018/11/FM-Receiver-Block-Diagram.jpg

GLOSSARY

- **Air Blast** – Fast air blown by fans to cool parts of a transformer.
- **Air Gap**: The small space between stator and rotor; crucial for magnetic coupling and motor efficiency.
- **Alternating Current (AC)**: A type of electric current that changes direction and is used in transformers.
- **Amplitude Modulation (AM)** – Varies the amplitude (height) of the carrier wave to transmit information.
- **Amplitude**: The strength or height of a wave, showing how powerful a signal is.
- **Analog Signal** – A continuous signal that varies smoothly over time.
- **AND Gate** – A logic gate that gives output 1 only if all inputs are (1)
- **Antenna**: A device that picks up radio signals from the air and sends them to the receiver. A metal rod or wire that sends or receives radio waves.
- **Appliance** – A machine or device used at home or work that runs on electricity e.g. iron, fan.
- **Armature Windings**: Conductors placed in the rotor slots that carry current and interact with the magnetic field.
- **Astable** – A timer mode where the output continuously switches between high and low states.
- **Asynchronous** – A type of circuit where changes happen at any time, not based on a clock signal.
- **Back EMF (Electromotive Force)**: Voltage induced in the armature opposing the applied voltage; increases with speed.
- **Bandwidth** – The range of frequencies an Op Amp can handle without losing signal strength. Wider bandwidth = better sound quality. The range of frequencies a signal uses; FM needs more bandwidth than AM.
- **Bearings**: Support the rotor shaft and reduce friction; impact motor lifespan and noise.
- **Binary** – A number system using only 0 and 1; used in digital circuits.
- **Bit** – The smallest unit of digital data, representing either 0 or 1.
- **Boolean Algebra** – A form of maths using logic values (0 and 1) to solve circuit problems.
- **Boolean Logic** – A system of rules using true (1) and false (0) to control circuits.
- **Box** – A case used to protect or hold wires and electrical connections safely.
- **Brushes**: Carbon or graphite blocks that transfer current from the external circuit to the rotating commutator.
- **Capacitor** – An electronic component that stores and releases electrical energy in a circuit.
- **Carrier Wave** – A high-frequency wave that is modified to carry a signal (audio, video, or data). A basic radio wave that carries the information signal through modulation.

- **Circuit** – A complete path for current to flow through electrical components.
- **Clock Pulse** – A signal used to control when flip-flops change state.
- **Combination Logic** – Logic where output depends only on current input values.
- **Commutator**: A segmented copper ring that reverses current direction in the armature to maintain unidirectional torque.
- **Comparator** – A part of the timer that compares voltage levels to control circuit behaviour.
- **Component** – Any part inside an appliance, like a switch, motor, wire, or plug.
- **Compound Motor**: Combines series and shunt characteristics for balanced performance.
- **Connector** – A device used to join two or more electrical wires together.
- **Conservator** – A small tank that holds extra transformer oil and allows expansion when heated.
- **Control Voltage** – A pin on the 555 timer that adjusts the reference voltage for timing.
- **Cooling** – A method used to remove heat from a machine to stop it from overheating.
- **Copper Loss** – Energy lost as heat in the wires of a transformer.
- **Core Loss** – Energy lost in the iron core due to changing magnetic fields.
- **Core**: The central laminated iron structure where coils are wound; helps transfer magnetic energy.
- **Current** – The flow of electricity through wires or circuits.
- **Cycle** – One complete high and low output signal of a timer circuit.
- **Delta Connection**: A triangle-shaped coil arrangement used in three-phase transformers.
- **Demodulation**: The process of removing the original audio signal from the carrier wave at the receiver.
- **Diagnosis** – The process of finding out what is wrong with an appliance.
- **Dielectric Flux**: The energy flow between high and low voltage windings in a transformer.
- **Differential Input** – The difference between two input voltages that the Op Amp uses to produce output.
- **Digital Logic** – A system of rules used to process binary signals in electronic circuits.
- **Digital Signal** – A signal made of discrete values (0s and 1s), used in modern systems like Wi-Fi and mobile phones.
- **Discharge** – A pin that connects to ground during part of the timing cycle to reset the capacitor.
- **Distortion**: Unwanted changes in a signal that affect sound quality.
- **Duty Cycle** – The ratio of time the output stays high in one complete cycle.

- **Eddy Current** – Small unwanted electric currents that cause heat in the transformer core.
- **Edge Triggered** – A flip-flop that changes its state only on the rising or falling edge of a clock.
- **Efficiency** – How well a machine works without wasting energy.
- **Electricity** – The flow of electric current used to power devices and circuits.
- **Electromagnetic Induction**: The process by which a changing magnetic field induces current in a conductor (Faraday's Law).
- **Electronic Communication** – Transmission of information using electronic systems like radios, phones, or computers.
- **Element** – The heating part inside irons, kettles, and cookers that gets hot.
- **EMF (Electromotive Force)**: The voltage generated in a coil by electromagnetic induction.
- **Excitation System**: Provides DC current to the rotor to create the magnetic field necessary for synchronization.
- **Expression** – A short way of writing a logic rule using letters and symbols.
- **Fans** – Devices used to blow air to cool down the hot oil or transformer body.
- **Faraday's Law**: A rule that explains how changing magnetic flux produces voltage in a coil.
- **Fault** – A problem in an appliance that makes it stop working properly.
- **Feedback** – A process where output is sent back to the input to help maintain memory in circuits.
- **Field Winding**: Coils on the rotor that receive DC excitation to generate a magnetic field.
- **Fleming's Left-Hand Rule**: A rule used to determine the direction of force, current, and magnetic field in motor operation.
- **Flip-Flop** – A basic memory circuit that stores one bit of data, with stable high or low output.
- **Flux**: A magnetic field that links the transformer coils to transfer energy.
- **FM (Frequency Modulation)**: A method of sending signals by changing the frequency of the carrier wave.
- **Forced Cooling** – A cooling method that uses fans or pumps to move air or oil faster.
- **Frequency Modulation (FM)** – Varies the frequency (number of wave cycles per second) of the carrier wave.
- **Frequency**: How many times a wave repeats in one second, measured in Hertz (Hz).
- **Fuse** – A safety device that breaks the circuit if too much current flows.
- **Gain** – How much an Op Amp increases the strength of an input signal.
- **Gate** – A basic building block in digital electronics that controls signals.
- **Heat Dissipation** – The process of removing heat from a transformer.

- **Heat Exchanger** – A machine part that helps oil pass its heat into water.
- **Heterodyning**: Mixing two signals to create new ones with different frequencies.
- **Housing**: The outer casing that protects internal components and aids in heat dissipation.
- **Hysteresis Loss** – Heat loss caused by the repeated magnetising of the core.
- **IC (Integrated Circuit)** – A mini electronic circuit made of many components in a single chip.
- **IC 4558** – A dual Op Amp chip with two amplifiers in one, used for better performance.
- **IC 741** – A popular single Op Amp used in basic amplifier and comparator circuits.
- **Induction Motor**: Also called asynchronous motor; rotor current is induced by stator's magnetic field.
- **Input** – The signal sent into a flip-flop to control its operation.
- **Input Power** – The energy supplied to the transformer.
- **Inrush Current**: The initial surge of current when the motor is first energised.
- **Installation** – The process of fixing electrical parts in a building.
- **Insulation** – Material used to stop electricity from leaking out of wires.
- **Interference** – Unwanted signals or noise that disrupt communication.
- **Inverting Input** – The input that causes the output to go in the opposite direction of the signal.
- **Junction Box** – A box where different wires join and are connected safely.
- **Laminated Core**: Thin layers of iron that reduce energy loss and improve magnetic flow.
- **Lamp Holder** – A device that holds a bulb and connects it to electricity.
- **Latch** – A simple flip-flop that changes output based on input without a clock signal.
- **Load** – The device or equipment that uses power from the transformer.
- **Load Characteristics**: Behaviour of motor speed and torque under varying load conditions.
- **Logic Circuit** – A system of connected logic gates that follow rules to produce outputs.
- **Logic Diagram** – A drawing that shows how logic gates are connected.
- **Logic Expression** – A formula that shows how a logic circuit works using symbols like + and ●.
- **Logic Gate** – A device that performs a logic function using inputs and gives an output.
- **Lorentz Force**: The force experienced by a current-carrying conductor in a magnetic field, responsible for torque generation.
- **Losses** – Energy that is wasted as heat or sound in a machine.
- **Magnetic Field** – The invisible force around a magnet or wire carrying current.

- **Memory** – The ability of a circuit to store data or a logic state.
- **Modulation**: Changing a wave to carry sound; either by amplitude (AM) or frequency (FM).
- **Monostable** – A timer mode that produces one output pulse when triggered.
- **Multimeter** – A tool used to test voltage, current, and resistance in electrical appliances.
- **NAND Gate** – A gate that gives 0 only when all inputs are 1; opposite of AND.
- **Natural Cooling** – A cooling system that works without fans or pumps; uses only air or oil flow.
- **Negative Feedback** – A method of feeding part of the output back to control and stabilise the Op Amp.
- **Noise Resistance** – The ability of a signal to stay clear despite interference. FM is more noise-resistant than AM.
- **Noise**: Random sounds or signals that disturb clear audio, especially in AM.
- **Non-Inverting Input** – The input that makes the output follow the same direction as the input signal.
- **NOR Gate** – A gate that gives 1 only when all inputs are 0; opposite of OR.
- **NOT Gate** – A gate that flips the input; 1 becomes 0 and 0 becomes 1.
- **OFAF** – Oil Forced Air Forced cooling; both oil and air are moved with fans and pumps.
- **Offset Voltage** – A small unwanted voltage at the Op Amp output when inputs are equal.
- **OFWF** – Oil Forced Water Forced cooling; oil is cooled by water using pumps and heat exchangers.
- **ONAF** – Oil Natural Air Forced cooling; oil moves naturally, but air is pushed with fans.
- **ONAN** – Oil Natural Air Natural cooling; uses natural oil and air movement to remove heat.
- **Op Amp (Operational Amplifier)** – A device that boosts small electrical signals with high accuracy.
- **OR Gate** – A gate that gives 1 if at least one input is 1.
- **Oscillator** – A circuit that produces a repeating waveform, such as a square wave.
- **Output** – The result or signal that comes out of a gate or circuit.
- **Output Power** – The energy delivered from the transformer to the load.
- **Output Saturation** – When an Op Amp output reaches its maximum or minimum voltage limit.
- **Overheating** – When an appliance becomes too hot and may stop working or cause damage.
- **Phase Modulation (PM)** – Alters the phase (position of the wave) to encode information.
- **Pin** – A metal leg on an IC used to connect it to a circuit.

- **Plug** – A device with pins that fits into a socket to power an appliance.
- **Poles**: Magnetic structures mounted on the yoke that hold the field windings.
- **Power Supply Voltage** – The voltage needed to power the Op Amp, usually dual positive and negative.
- **Preset** – A control pin used to set the output of a flip-flop to high.
- **Primary Winding**: The coil connected to the input power source.
- **Pulse** – A short burst of electrical signal used for switching or timing.
- **Pump** – A machine used to move oil or water in a transformer's cooling system.
- **Radiator** – A part with pipes where hot oil loses heat into the air.
- **Receiver** – Captures and decodes the modulated signal.
- **Reset** – A pin used to stop or restart the timer circuit.
- **Rotor (Armature)**: The rotating part where current flows and torque is generated.
- **Rotor Resistance Control**: Used in wound rotor motors to adjust speed and torque.
- **Safety** – Protecting people from electrical shock, burns, or accidents.
- **Secondary Winding**: The coil that delivers output voltage to the device or load.
- **Series Motor**: Field winding in series with the armature; provides high starting torque.
- **Servicing** – Checking and fixing an appliance to make sure it works properly.
- **Shaft**: The central rod connected to the rotor that transmits mechanical energy to external loads.
- **Shunt Motor**: Field winding connected in parallel with the armature; offers constant speed.
- **Signal** – A form of electric current used to carry information in circuits.
- **Signal Quality** – The clarity and accuracy of the transmitted signal.
- **Single-Phase Motor**: Operates on single-phase AC supply; used in household appliances.
- **Single-Phase Transformer**: A transformer with one input and one output coil
- **Slew Rate** – How fast the Op Amp can change its output in response to input changes.
- **Slip Rings**: Used in some AC motors (especially synchronous) to transfer current to the rotor.
- **Slip**: The difference between synchronous speed and rotor speed, expressed as a percentage; essential for torque generation in induction motors.
- **Socket** – A fixed point where a plug is inserted to get power.
- **Squirrel-Cage Rotor**: A rotor design with conductive bars shorted by end rings, resembling a cage—common in most induction motors.
- **Star-Delta Starter**: A method to reduce starting current by initially connecting the motor in star configuration, then switching to delta.
- **Starting Torque**: The torque produced when the motor begins rotation; high in series DC motors.

- **Stator:** The stationary part of the motor that generates a rotating magnetic field when energised with AC.
- **Stereo Sound** – Audio using two channels (left and right) for immersive listening. Common in FM broadcasts.
- **Switch** – A device used to turn electricity on or off.
- **Symbol** – A drawing used to represent a component or gate in a circuit diagram.
- **Synchronous** – A circuit where changes occur only with a clock signal.
- **Synchronous Motor:** Rotor rotates at the same speed as the stator's magnetic field; requires external excitation.
- **Synchronous Speed:** The speed at which the stator's magnetic field rotates, determined by supply frequency and number of poles.
- **Terminal** – A point on a device or accessory where wires are connected.
- **Thermostat** – A device that controls temperature inside appliances like irons or fridges.
- **Three-Phase Motor:** Operates on three-phase AC supply; common in industrial applications.
- **Threshold** – The pin that detects when the capacitor's voltage reaches a certain level to change output.
- **Transformer** – A machine that increases or reduces voltage in an electric circuit.
- **Transformer Oil** – A special liquid used inside transformers to take away heat from the windings and core.
- **Transmitter** – Sends out signals by modulating a carrier wave.
- **Truth Table** – A chart showing all input combinations and their matching outputs for a gate.
- **Tuner:** A part of the receiver that selects a specific radio station or frequency.
- **Ventilation** – The movement of fresh air to help cool the transformer naturally or with fans.
- **Virtual Ground** – A point in an Op Amp circuit that acts like ground without being directly connected.
- **Voltage** – The force that pushes electrical current through a circuit.
- **Wave:** A repeating pattern of energy used to send sound through the air.
- **Windings:** Coils of wire (usually copper) placed in stator slots to carry alternating current and generate magnetic fields.
- **Wiring** – The system of wires that carry current inside an appliance.
- **Wiring Accessories** – Electrical parts like switches, sockets, and plugs used to connect and control electricity.
- **Wound Rotor:** A rotor with windings connected to external resistors for variable speed control.
- **Yoke:** The outer frame that supports the poles and provides a path for magnetic flux.