Unit 6

Electrostatics and Electric Circuit

Introduction

In this lesson, we will explore the properties of electric charges, the concept of electrostatic force, and the behavior of electric fields. Understanding these fundamental concepts is crucial for studying electricity and magnetism.

Properties of Electric Charges

Charge

Charge is a basic property of matter that comes from the presence of protons and electrons in atoms. There are two types of electric charges: positive and negative. Electrons carry a negative charge, while protons carry a positive charge.

When an object has an equal number of protons and electrons, it is electrically neutral. If an object has more electrons than protons, it becomes negatively charged. Conversely, if it has more protons than electrons, it becomes positively charged.

Properties of Charges

1. **Two Kinds of Charges**: There are two kinds of electric charges: positive and negative.
2. **Attraction and Repulsion**: Like charges repel each other, and unlike charges attract each other.
3. **Conservation of Charge**: Electric charge is conserved. It cannot be created or destroyed. When an object is charged, it only transfers charge from one object to another.
4. **Quantization of Charge**: Charge is quantized, meaning it occurs in discrete amounts. The smallest unit of charge is the charge of an electron, which is 1.6×10^{-19}C.

Electrostatic Force

Definition

The electrostatic force is the force of attraction or repulsion between two charged bodies. This force is either attractive or repulsive depending on the charges involved: opposite charges attract, while like charges repel.

Coulomb's Law
In 1785, Charles Coulomb formulated a law that describes the force between two point charges. Coulomb's law states that the electrostatic force between two charges is directly proportional to the product of their charges and inversely proportional to the square of the distance between them. Mathematically, it is expressed as:

F=$\frac{kq_1q_2}{r^2}$

Where:

- F is the magnitude of the electrostatic force,
- q_1 and q_2 are the magnitudes of the charges,
- r is the distance between the charges,
- k is Coulomb's constant ($k=9.0\times10^9$ N.m^2/C^2).

Example Calculation
Suppose two small water droplets with identical charges of -1.0×10^{-10}C are separated by 1.0 cm. The electrostatic force between them can be calculated using Coulomb's law:

F=$\frac{(9.0\times10^9 N^2/c^2)\times(-1.0\times10^{-10})2}{(0.01m)^2}$ =9.0×10^{-17} N

Force on a Charge due to Multiple Electric Charges

When multiple charges are present, the electrostatic force on a charge is the vector sum of the forces due to each individual charge. This principle is known as the superposition principle.

Electric Fields

Definition
An electric field is a region around a charged particle where another charged particle experiences a force. The strength and direction of the electric field depend on the magnitude and sign of the charge creating the field.

Electric Field Lines
Electric field lines are used to visualize the direction and strength of an electric field. They point away from positive charges and toward negative charges.

Properties of Electric Field Lines

1. Electric field lines never cross each other.
2. They begin on positive charges and end on negative charges.
3. Electric field lines are perpendicular to the surface of a charged object.
4. The density of the lines indicates the strength of the field.
5. Equally spaced lines indicate a uniform electric field.

Visual Examples
Electric field lines can show different charge arrangements, such as the field around a single charge, two like charges, or two opposite charges.

By understanding these concepts, students can better grasp the principles governing electric charges, forces, and fields, which are foundational to studying electricity and magnetism.

Electric Field Strength

Electric Field Strength (E):
The electric field strength or electric field intensity (E) represents the force per unit positive charge acting on a stationary point charge. It describes both the magnitude and direction of the electric field. The equation is:

$$E=\frac{F}{q}$$

Where:

- E is the electric field strength,
- F is the force acting on the charge,
- q is the test charge.

Electric Field of a Point Charge: The electric field created by a point charge can be determined using Coulomb's law. Coulomb's law states that the force FFF between two charges is:

$$F=\frac{k\cdot q\cdot Q}{r^2}$$

Where:

- k is Coulomb's constant ($9\times10^9\,Nm^2/C^2$),
- q is the test charge,
- Q is the source charge,
- r is the distance between the charges.

To find the electric field strength:

$$E=\frac{F}{q}=\frac{k\cdot q\cdot Q}{r^2}$$

This equation shows that the electric field strength E depends on the source charge Q and the distance r from the charge, but not on the test charge q.

Direction of Electric Field: The electric field direction is determined by the force a positive test charge would experience. For a positive source charge, the field points away, while for a negative source charge, it points towards the charge.

SI Unit: The SI unit for electric field strength is newton per coulomb (N/C).

Electric Field for Multiple Point Charges

When multiple point charges are present, the net electric field at a point is the vector sum of the electric fields due to each charge. If there are nnn charges with electric fields $E_1, E_2, \ldots, E_n$, the net electric field E_{net} is:

$E_{net}=E_1+E_2+E_3+\ldots+E_n$ Each individual electric field's direction corresponds to the direction of the force exerted by each charge on a positive test charge.

Example: Calculating Electric Field Between Two Charges

Two charges $q_1=5$ nC and $q_2=-4$ nC are 10 cm apart. The electric field at a point between the charges can be calculated as follows:

1. **Electric Field Due to q_1:**

   $$E_1=\frac{k\cdot q_1}{r^2}=\frac{9\times10^9\times5\times10^{-9}}{(0.05)^2}=1.8\times10^4\,\text{N/C}$$

   Direction: To the right (repulsive force).

2. **Electric Field Due to q2q_2q2 :**

   $$E_2=\frac{k\cdot q_2}{r^2}=\frac{9\times10^9\times4\times10^{-9}}{(0.05)^2}=1.44\times10^4\,\text{N/C}$$

   Direction: To the right (attractive force).

3. **Net Electric Field:**

   $E_{net}=E_1+E_2=1.8\times10^4+1.44\times10^4=3.24\times10^4$ N/C

Electric Flux

Electric Flux (Φ):
Electric flux measures the number of electric field lines passing through a given area. It is the product of the electric field EEE and the area AAA perpendicular to the field:

$\Phi=E\times A$

If the surface is not perpendicular, the flux is:

$\Phi=E\times A\times\cos\theta$

Where θ is the angle between the electric field and the normal to the surface. In vector form:

$\Phi=E\cdot A$

SI Unit: The SI unit for electric flux is newton meter squared per coulomb ($N\cdot m^2/C$).

Key Properties of Electric Flux:

- Electric flux is zero if the electric field lines are tangent to the surface and do not penetrate it.
- It is a scalar quantity.

Electric Current, Resistance, and Ohm's Law

Electric Current

- **Definition**: Electric current is the flow of electric charge through a conductor, typically a wire.
- **In Metals**: The current is due to the movement of electrons, but conventionally, we describe current as the flow of positive charge.
- **Direction**: By convention, electric current flows from the positive terminal (+) to the negative terminal (–) of a power source.

Formula:

- Electric current (I) is defined as the rate of flow of charge (Q) through a cross-sectional area over time (t): I=$\frac{Q}{t}$
- **Unit**: The SI unit of current is the ampere (A). 1 A = 1 coulomb/second (C/s).

Current Density

- **Definition**: Current density (JJJ) describes the current per unit cross-sectional area of a conductor. J=$\frac{I}{A}$
- **Unit**: Amperes per square meter (A/m^2).
- **Relation to Electric Field**: J=σEJ Where:
  - σ is the conductivity of the material,
  - E is the electric field.

Drift Velocity

- **Concept**: Free electrons in a conductor move randomly when no electric field is applied. When a potential difference (voltage) is applied, these electrons move in a directed manner with a certain average velocity called **drift velocity** (vd).
- **Relation to Current**: I=nAve Where:
  - n is the number of electrons per unit volume,
  - A is the cross-sectional area,
  - e is the charge of an electron.

Resistance

- **Definition**: Resistance (R) is the opposition that a material offers to the flow of electric current. It is caused by collisions between the flowing electrons and the atoms in the material.
- **Unit**: The SI unit of resistance is the ohm (Ω).

Ohm's Law

- **Statement**: At a constant temperature, the current (III) flowing through a conductor is directly proportional to the voltage (V) across it. V=IR Where:
  - V is the potential difference,
  - R is the resistance.
- **Graph**: For ohmic conductors (materials that obey Ohm's Law), the graph of I versus V is a straight line through the origin.

Resistors

- **Resistor**: A component used in circuits to provide resistance.
- **Symbols**: Resistors are represented in circuits by the following symbols:

Resistor Combinations:

1. **Series Combination**:
   - **Connection**: Resistors connected end-to-end, providing a single path for current.
   - **Total Resistance**: $R_{total}=R_1+R_2+R_3+\ldots$
   - **Current**: The same current flows through all resistors.
   - **Voltage**: The total voltage is the sum of the voltages across each resistor.
2. **Parallel Combination**:
   - **Connection**: Resistors connected across the same two points, providing multiple paths for current.
   - **Total Resistance**: $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
   - **Voltage**: The voltage across each resistor is the same.
   - **Current**: The total current is the sum of the currents through each resistor.

Measuring Instruments and Their Uses

1. Measurement of Current:

- **Ammeter:** An ammeter is used to measure the current flowing through a circuit. It must be connected in series with the circuit element so that the same current passes through both the element and the ammeter. The ammeter's internal resistance should be very low to ensure minimal energy loss.

Key Point: Always connect an ammeter in series with the component whose current you want to measure.

2. Measurement of Voltage:

- **Voltmeter:** A voltmeter measures the potential difference (voltage) between two points in a circuit. It should be connected in parallel with the component across which the voltage is to be measured. Voltmeters should have a very high resistance to minimize the current drawn from the circuit.

Key Point: Always connect a voltmeter in parallel with the component across which you want to measure voltage.

3. Conversion of Galvanometer to Ammeter and Voltmeter:

- **Galvanometer:** This instrument is used to detect small currents. It consists of a coil suspended in a magnetic field. When current flows through the coil, it deflects, and the amount of deflection is proportional to the current.

- Converting to an Ammeter: A galvanometer is converted into an ammeter by connecting a low-resistance "shunt" in parallel with it. The shunt allows most of the current to bypass the galvanometer, preventing it from being damaged by high currents.

- Converting to a Voltmeter: A galvanometer can be converted into a voltmeter by connecting a high resistance (called a multiplier) in series with it. This allows the voltmeter to measure higher potential differences without allowing too much current through the galvanometer.

Key Point:

- To convert a galvanometer to an ammeter, add a low-resistance shunt in parallel.
- To convert a galvanometer to a voltmeter, add a high-resistance multiplier in series.

4. The Potential Divider:

- **Potential Divider Circuit:** A potential divider consists of two or more resistors connected in series with a voltage source. The voltage across each resistor is a fraction of the total voltage and is proportional to its resistance.

Key Point: The potential divider allows you to obtain different voltages from a single voltage source.

5. Potentiometer:

- **Potentiometer:** A potentiometer is a three-terminal resistor with an adjustable sliding contact. It can measure the electromotive force (emf) of a cell, compare the emf of different cells, and act as a variable resistor.

  - Measuring emf: The potentiometer measures the unknown emf by finding the point along the wire where the galvanometer shows zero deflection. This point indicates that the potential difference across the wire segment equals the emf of the cell.

Key Point: A potentiometer is a precise instrument for measuring emf by balancing voltage drops.

6. Measurement of Resistance:

- **Ammeter-Voltmeter Method:** Resistance can be calculated using Ohm's law, R=$\frac{V}{I}$, where V is the voltage measured by a voltmeter and I is the current measured by an ammeter.
- **Wheatstone Bridge:** This is a more precise method for measuring resistance. It involves balancing a bridge circuit so that no current flows through the galvanometer. When the bridge is balanced, the unknown resistance can be calculated using the known resistances in the circuit.

Key Point: Use the Wheatstone bridge for more precise resistance measurements.

7. Comparing the Brightness of Bulbs:

- **Brightness and Power:** The brightness of a bulb is measured in lumens, not watts. However, bulbs with higher wattage typically consume more power and are brighter, provided they have the same efficiency.
- **Series vs Parallel:** Bulbs connected in parallel will have the same voltage across them and therefore glow brighter compared to bulbs in series, where the voltage is divided among the bulbs.

Key Point: For maximum brightness, connect bulbs in parallel rather than in series.

Kirchhoff's Rules: Understanding Circuit Analysis

Kirchhoff's Rules are essential tools for analyzing any direct current (DC) circuit, regardless of how complex it might be. These rules help us understand how currents and voltages distribute themselves within a circuit. Kirchhoff's rules consist of two main principles: the Junction Rule and the Loop Rule.

1. Kirchhoff's First Rule (Junction Rule)

Statement: At any junction (a point where multiple wires meet) in a circuit, the total current entering the junction equals the total current leaving the junction.

Explanation: This rule is based on the conservation of electric charge. Since charge cannot accumulate at a junction, the amount of current flowing into the junction must equal the amount of current flowing out.

Example: Imagine a point in a circuit where three wires meet. If 2 A (amperes) flow into the junction through one wire, and 3 A flow in through another wire, then 5 A must flow out through the third wire.

Mathematical Form: If I_1 and I_2 are currents entering the junction, and I_3 and I_4 are leaving, the rule is written as: $I_1+I_2=I3+I_4$.

2. Kirchhoff's Second Rule (Loop Rule)

Statement: For any closed loop in a circuit, the sum of the electromotive forces (emfs) is equal to the sum of the potential drops across the components in that loop.

Explanation: This rule is derived from the conservation of energy. When you go around a loop in a circuit, the total energy gained (from emfs like batteries) equals the total energy lost (as voltage drops across resistors, etc.).

Example: Consider a loop in a circuit with a battery and a resistor. As you go around the loop, the energy provided by the battery (emf) is used to push current through the resistor, resulting in a voltage drop. By the time you return to your starting point, the total energy changes add up to zero.

Mathematical Form: If you start at a point in the loop and go around until you reach the same point, the rule is written as: $\sum \text{emf} = \sum \text{voltage drops}$

Applying Kirchhoff's Rules

When using Kirchhoff's rules to solve circuit problems, follow these steps:

1. **Label All Components:** Identify all resistors, voltage sources, and other components with their respective values.
2. **Assign Current Directions:** Assign a direction for the current in each branch of the circuit. If the current direction is later found to be opposite, its value will simply be negative.
3. **Apply the Junction Rule:** Write equations based on Kirchhoff's Junction Rule at each junction in the circuit.
4. **Apply the Loop Rule:** Choose independent loops in the circuit and apply Kirchhoff's Loop Rule to write equations for each loop.
5. **Solve the Equations:** Use algebra to solve the set of equations obtained from the above steps for the unknown quantities like currents and voltages.

Conventions to Remember:

- When moving through a resistor in the same direction as the current, the potential drop (voltage) is negative.
- When moving through a resistor opposite to the current direction, the potential rise is positive.

- When moving from the negative to the positive terminal of a battery (emf), count it as a positive voltage; moving from positive to negative, count it as negative.

Summary

- **Junction Rule:** The total current entering a junction equals the total current leaving it.
- **Loop Rule:** The sum of emfs in any loop equals the sum of potential drops in that loop.

These rules are powerful tools in analyzing complex circuits, making it possible to determine unknown currents and voltages in any part of a circuit.

6.7 Electric Circuits in Our Surroundings

Household Electric Installations

In Ethiopia, the mains voltage typically ranges from 220 V to 240 V. Many common household appliances, like electric kettles, immersion heaters, electric irons, hair dryers, and electric stoves, work by converting electrical energy into heat energy. This conversion happens through a heating element within these appliances.

Color Code of Resistors

Resistors, which are essential components in many electronic devices, have their resistance values indicated by a color code. This code consists of colored bands on the resistor, each representing a specific number according to international standards (ISO).

How to Read the Color Code:

1. **First Band**: Represents the first digit of the resistance value.
2. **Second Band**: Represents the second digit.
3. **Third Band**: Acts as a multiplier (base 10).
4. **Fourth Band**: Indicates the tolerance (the permissible percentage error of the value).

For instance, if a resistor has bands colored brown, black, and red, the first digit is 1 (brown), the second digit is 0 (black), and the multiplier is 10^2 (red). Thus, the resistance is: Resistance=10×10^2=1000 Ω (1 kΩ) If the fourth band is gold, the tolerance is ±5%. Therefore, the resistor value is 1 kΩ ± 5%.

Unit Summary

- **Quantization of Electric Charges**: Electric charges come in discrete units and are multiples of the fundamental charge, e.
- **Types of Charges**: There are positive and negative charges. Opposite charges attract, while like charges repel each other.
- **Coulomb's Law**: The electrostatic force between two charges is proportional to the product of the charges and inversely proportional to the square of the distance between them.
- **Electric Field Lines**: These lines start from positive charges and end on negative charges. They never cross each other and are perpendicular to the charge's surface.

Resistors in Circuits:

- **Series Circuit**: The total resistance, R_s , is the sum of all resistances in the series:

  $R_s=R_1+R_2+R_3+\ldots$

  The same current flows through each resistor.

- **Parallel Circuit**: The total resistance, ReqR_{eq}Req , is calculated using the formula:
  - : $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$

  In this case, each resistor has the same voltage applied, but the current differs based on resistance.

Capacitors in Circuits:

- **Capacitors in Series**: The total capacitance is given by:
  - : $\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$
- **Capacitors in Parallel**: The total capacitance is the sum of individual capacitances:

  $C_{eq}=C_1+C_2+C_3+\ldots$

- **Capacitance**: A capacitor stores charge and energy. The capacitance, C, is defined as the charge q stored per unit voltage V between its plates. The unit of capacitance is the farad (F).

In any circuit, combinations of resistors or capacitors can often be reduced to a single equivalent value by analyzing them as series or parallel connections.