Chapter 12: Magnetic Effects of Electric Current - Detailed Notes

1. Introduction to Magnetism

- **Magnets and Their Properties:**
  - **Definition:** A magnet is a material or object that produces a magnetic field.
  - **Natural Magnets:** Lodestone (magnetite) is a natural magnet.
  - **Artificial Magnets:** Bar magnets, horseshoe magnets, electromagnets, etc.
  - **Properties:**
    - **Attractive Property:** Attracts magnetic substances like iron, nickel, cobalt.
    - **Directive Property:** When freely suspended, a magnet always aligns itself in the North-South direction. The end pointing North is the North pole, and the end pointing South is the South pole.
    - **Like Poles Repel, Unlike Poles Attract:** North pole repels North pole, South pole repels South pole. North pole attracts South pole.
    - **Poles Exist in Pairs:** Individual North or South poles cannot be isolated (monopoles do not exist). If a magnet is broken, each piece becomes a new magnet with both a North and South pole.
- **Magnetic Field:**
  - **Definition:** The region around a magnet where its force can be detected. It's a vector quantity, having both magnitude and direction.
  - **Direction of Magnetic Field:** Conventionally, the direction of the magnetic field at any point is taken to be the direction in which a North magnetic pole would tend to move.
  - **Magnetic Field Lines (Lines of Force):** Imaginary lines used to represent the magnetic field.
    - **Properties of Magnetic Field Lines:**
      1. Originate from the North pole and merge into the South pole **outside** the magnet.
      2. Inside the magnet, they are directed from the South pole to the North pole, forming continuous closed loops.
      3. They never intersect each other. If they did, it would mean that at the point of intersection, the compass needle would point in two directions, which is impossible.
      4. The density of field lines (closeness) indicates the strength of the magnetic field. Where lines are crowded (near poles), the field is stronger. Where they are spread out, the field is weaker.
      5. The tangent to a field line at any point gives the direction of the magnetic field at that point.

2. Oersted's Experiment and Magnetic Effect of Electric Current

- **Discovery:** In 1820, Hans Christian Oersted discovered that an electric current flowing through a conductor produces a magnetic field around it.
- **Observation:** When current flows through a wire, a compass needle placed nearby deflects, indicating the presence of a magnetic field. The direction of deflection

changes when the direction of current is reversed. The deflection also changes if the compass is placed above or below the wire.
- **Conclusion:** Electricity and magnetism are interrelated phenomena. This laid the foundation for the study of electromagnetism.

3. Magnetic Field Due to a Current-Carrying Conductor

- **Right-Hand Thumb Rule (Maxwell's Corkscrew Rule):**
  - **Statement:** If you hold a current-carrying straight conductor in your right hand such that your thumb points in the direction of the current, then your fingers wrapped around the conductor will give the direction of the magnetic field lines.
  - **Application:** Used to find the direction of the magnetic field around a straight current-carrying wire. The magnetic field lines are concentric circles around the conductor.
- **Magnetic Field Due to a Current Through a Straight Conductor:**
  - The magnetic field lines are concentric circles centered on the wire.
  - The strength of the magnetic field (B) at a point:
    - Is directly proportional to the current (I) flowing through the conductor ($B \propto I$).
    - Is inversely proportional to the perpendicular distance (r) from the conductor ($B \propto 1/r$).
  - The field is stronger near the conductor and weaker as you move away.
- **Magnetic Field Due to a Current Through a Circular Loop:**
  - The magnetic field lines are concentric circles near the wire segments.
  - As you move towards the center of the loop, the circles become larger and larger.
  - At the exact center of the loop, the magnetic field lines are almost straight and parallel to each other, indicating a uniform magnetic field.
  - The direction of the magnetic field inside the loop can also be determined by the Right-Hand Thumb Rule for each segment of the loop.
  - **Clock Face Rule:** If current flows in a clockwise direction in a loop, the face of the loop behaves as a South pole. If current flows in an anticlockwise direction, it behaves as a North pole.
- **Magnetic Field Due to a Current in a Solenoid:**
  - **Solenoid:** A coil of many circular turns of insulated copper wire closely wound in the form of a cylinder.
  - **Magnetic Field Pattern:**
    - The magnetic field lines inside a solenoid are nearly parallel to the axis of the solenoid, indicating a **uniform magnetic field** inside.
    - The field lines outside the solenoid resemble those of a bar magnet.
    - One end of the solenoid acts as a North pole, and the other end acts as a South pole. The polarity can be determined by the Clock Face Rule.
  - **Strength of the Magnetic Field:** The strength of the magnetic field produced by a solenoid depends on:
    1. **Number of turns (N):** Directly proportional ($B \propto N$). More turns, stronger field.
    2. **Current (I):** Directly proportional ($B \propto I$). More current, stronger field.

3. **Nature of the core material:** Inserting a soft iron core inside a solenoid significantly increases the magnetic field strength because soft iron is a ferromagnetic material.

4. Electromagnet

- **Definition:** A temporary magnet formed by passing electric current through a coil of wire wound around a soft iron core.
- **Principle:** Based on the magnetic effect of electric current in a solenoid.
- **Advantages over Permanent Magnets:**
    1. **Strength can be varied:** By changing the current or the number of turns.
    2. **Polarity can be reversed:** By reversing the direction of current.
    3. **Temporary:** Can be switched on or off, making them very useful for various applications.
- **Applications:** Electric bells, loud-speakers, telephone diaphragms, large cranes for lifting heavy iron objects, medical applications (e.g., MRI).

5. Force on a Current-Carrying Conductor in a Magnetic Field

- **Principle:** A current-carrying conductor placed in a magnetic field experiences a force. This effect was first demonstrated by André-Marie Ampère.
- **Factors Affecting the Force:**
    - **Current (I):** Directly proportional to the current ($F \propto I$).
    - **Strength of the magnetic field (B):** Directly proportional ($F \propto B$).
    - **Length of the conductor (L):** Directly proportional ($F \propto L$) within the field.
    - **Angle (θ):** The force is maximum when the conductor is perpendicular to the magnetic field ($\theta = 90^\circ$, $\sin 90^\circ = 1$) and zero when it is parallel ($\theta = 0^\circ$ or 180°, $\sin 0^\circ = \sin 180^\circ = 0$).
    - **Formula (for a straight conductor):** $F = BIL\sin\theta$
- **Fleming's Left-Hand Rule:**
    - **Statement:** Stretch the thumb, forefinger, and middle finger of your left hand such that they are mutually perpendicular to each other. If the forefinger points in the direction of the magnetic field, and the middle finger points in the direction of the current, then the thumb will point in the direction of the force (or motion) experienced by the conductor.
    - **Memory Aid:**
        - **F**orefinger - **F**ield
        - **M**iddle finger - **C**urrent (or **C**entre finger for **C**urrent)
        - **T**humb - **T**hrust (or **T**ension/Force/Motion)
    - **Application:** Used to determine the direction of force on a current-carrying conductor in a magnetic field. This rule is fundamental to the working of electric motors.

6. Electric Motor

- **Principle:** Based on the principle that a current-carrying conductor placed in a magnetic field experiences a force. In a motor, this force causes rotation.
- **Construction:**
    - **Armature/Coil:** A rectangular coil (e.g., ABCD) made of insulated copper wire, having a large number of turns, wound around a soft iron core.

    - **Permanent Magnets:** Provide a strong magnetic field (North and South poles).
    - **Split Ring Commutator:** Two half-rings (P and Q) of conducting material (e.g., copper) that rotate with the coil. Its function is to reverse the direction of current in the coil every half rotation, ensuring continuous rotation in one direction.
    - **Brushes:** Two carbon brushes (X and Y) pressed against the commutator. They provide electrical contact between the coil and the external circuit, and are stationary.
    - **Battery:** Provides the electric current.
- **Working:**
    1. When current flows through the coil (e.g., from A to B and C to D), forces act on sides AB and CD.
    2. Using Fleming's Left-Hand Rule:
        - On side AB, the force is downwards.
        - On side CD, the force is upwards.
    3. These two equal and opposite forces form a couple, causing the coil to rotate anticlockwise.
    4. After half a rotation, the commutator halves switch contact with the brushes. This reverses the direction of current in the coil segments (now current flows from D to C and B to A).
    5. Due to the current reversal, the force on CD (now on the left) becomes downwards, and the force on AB (now on the right) becomes upwards.
    6. This ensures that the coil continues to rotate in the same anticlockwise direction.
- **Energy Conversion:** Converts electrical energy into mechanical energy.
- **Uses:** Used in fans, refrigerators, washing machines, mixers, toys, etc.

7. Electromagnetic Induction

- **Discovery:** Michael Faraday (in England) and Joseph Henry (in USA) independently discovered in 1831 that a changing magnetic field can induce an electric current in a conductor.
- **Principle:** When there is a **relative motion** between a conductor and a magnetic field, an electromotive force (e.m.f.) is induced across the ends of the conductor. If the conductor forms a closed circuit, an induced current flows.
- **Ways to induce current:**
    1. Moving a magnet towards or away from a coil.
    2. Moving a coil towards or away from a magnet.
    3. Changing the current in a nearby coil (primary coil) which changes its magnetic field (secondary coil).
- **Galvanometer:** An instrument used to detect the presence and direction of small electric currents in a circuit. Its needle deflects when current flows.

8. Fleming's Right-Hand Rule

- **Statement:** Stretch the thumb, forefinger, and middle finger of your right hand such that they are mutually perpendicular to each other. If the forefinger points in the direction of the magnetic field, and the thumb points in the direction of motion (or force) of the conductor, then the middle finger will point in the direction of the induced current.

- **Application:** Used to determine the direction of induced current when a conductor moves in a magnetic field. This rule is fundamental to the working of electric generators.

9. Electric Generator (Dynamo)

- **Principle:** Based on the principle of electromagnetic induction. It converts mechanical energy into electrical energy.
- **Construction (AC Generator):**
  - **Armature/Coil:** Rectangular coil (ABCD) rotated in a magnetic field.
  - **Strong Magnetic Field:** Provided by permanent or electromagnets.
  - **Slip Rings:** Two full rings (R1 and R2) attached to the ends of the coil. They rotate with the coil.
  - **Brushes:** Two carbon brushes (B1 and B2) pressed against the slip rings, providing contact with the external circuit.
  - **External Circuit:** Usually connected to a galvanometer or a load.
- **Working (AC Generator):**
  1. When the coil is rotated mechanically (e.g., clockwise) in the magnetic field, the magnetic flux linked with the coil changes, inducing an e.m.f. and hence a current.
  2. Consider the coil rotating such that side AB moves upwards and CD moves downwards.
  3. Using Fleming's Right-Hand Rule:
     - On side AB (moving up, field N to S), induced current flows from A to B.
     - On side CD (moving down, field N to S), induced current flows from C to D.
  4. The current flows from B2 to B1 in the external circuit.
  5. After half a rotation, side AB moves downwards and CD moves upwards.
  6. The induced current in AB now flows from B to A, and in CD from D to C.
  7. The current in the external circuit now flows from B1 to B2.
  8. This means the direction of current in the external circuit reverses every half rotation, producing **alternating current (AC)**.
- **DC Generator:** Uses a split ring commutator (like in a DC motor) instead of slip rings to produce direct current (current flows in one direction in the external circuit, although it still reverses inside the coil).
- **Energy Conversion:** Converts mechanical energy into electrical energy.
- **Uses:** Generates electricity in power stations.

10. Domestic Electric Circuits

- **Components:**
  - **Live Wire (Red insulation):** Carries the current from the power station. At a high potential (e.g., 220V in India).
  - **Neutral Wire (Black insulation):** Completes the circuit, connected to the earth at the power station. At zero potential.
  - **Earth Wire (Green insulation):** Connected to a metal plate buried deep in the earth. Used as a safety measure, especially for appliances with metal cases.

It provides a low-resistance path to the earth for any leakage current, preventing electric shock.

- **Wiring Systems:**
    - **Series Arrangement:** Not used for domestic wiring. If one appliance fails, the whole circuit breaks. Appliances get different voltages.
    - **Parallel Arrangement:** Used for domestic wiring.
        - Each appliance has its own ON/OFF switch.
        - If one appliance fails, others continue to work.
        - Each appliance gets the full supply voltage (220V).
- **Safety Devices:**
    - **Electric Fuse:**
        - **Principle:** Based on the heating effect of electric current. A fuse wire has a low melting point.
        - **Function:** Protects electrical appliances and circuits from damage due to excessive current (overloading or short-circuiting). When current exceeds the fuse rating, the fuse wire melts and breaks the circuit.
        - **Connection:** Always connected in series with the live wire.
    - **Miniature Circuit Breaker (MCB):** An electromagnetic switch that automatically turns off when current exceeds the safe limit. Can be reset manually. More convenient than fuses.
    - **Earthing:** Provides a safety path for current to flow to the ground in case of a fault (e.g., insulation breakdown). Prevents electric shock.
- **Hazards:**
    - **Overloading:** Occurs when too many appliances are connected to a single socket or circuit, drawing excessive current. Leads to overheating of wires and potential fire.
    - **Short-Circuiting:** Occurs when the live wire and neutral wire come into direct contact (e.g., due to damaged insulation). This results in a very large current flowing through the circuit, generating excessive heat and potentially causing fire or damage to appliances.