Electromagnetic Induction

Electricity and Magnetism

Laws of Electromagnetic Induction

Faraday's law of electromagnetic induction

The magnitude of the electromotive force (e.m.f) induced in a closed circuit is directly proportional to the rate of change of the magnetic flux linkage through the area bounded by the circuit.

- Thus, the magnitude of the electromotive force (e.m.f) induced in a conductor is directly proportional to the rate at which magnetic field lines and the conductor cut each other.
- If the conductor is part of a closed circuit, the induced e.m.f produces an induced current through the conductor.

Lenz's Law

The direction of the induced electromotive force (and hence the direction of the induced current in a closed circuit) is such that its magnetic effect opposes the motion or change producing it.

- If the conductor is part of a closed circuit, the induced current produces induced magnetic poles that oppose the cause of the induced emf.

Electromagnetic induction when magnetic field strength changes

Faraday's experiments demonstrate electromagnetic induction by moving a pole of a magnet moves nearer or further away from a solenoid, such that magnetic field lines cut through the solenoid.

Case 1: S moves towards solenoid

1. The South pole of the magnet moves towards the solenoid
2. (By Faraday's law of induction,) the changing magnetic flux linkage through the solenoid (or the magnetic field lines cutting the solenoid) induces an e.m.f in the solenoid.
3. Since the circuit is closed, the induced e.m.f produces an induced current.
4. By Lenz's law, the magnet is repelled by the south pole induced on the right of the solenoid produced by the clockwise induced current when viewed from the right (using the right hand grip rule) that flows from B to A.

Case 2: N moves toward solenoid

1. The **north** pole of the magnet moves **toward** the solenoid.
2. (By Faraday's law of electromagnetic), the **changing magnetic flux linkage** through the solenoid (or the magnetic field lines cutting the solenoid) **induces** an **e.m.f** in the solenoid.
3. Since the circuit is **closed**, the induced e.m.f produces an **induced current.**
4. By Lenz's law, the magnet is repelled by the **north pole induced on the right** of the solenoid produced by the **anticlockwise induced current** when viewed from the right (using the right-hand grip rule) that flows from A to B

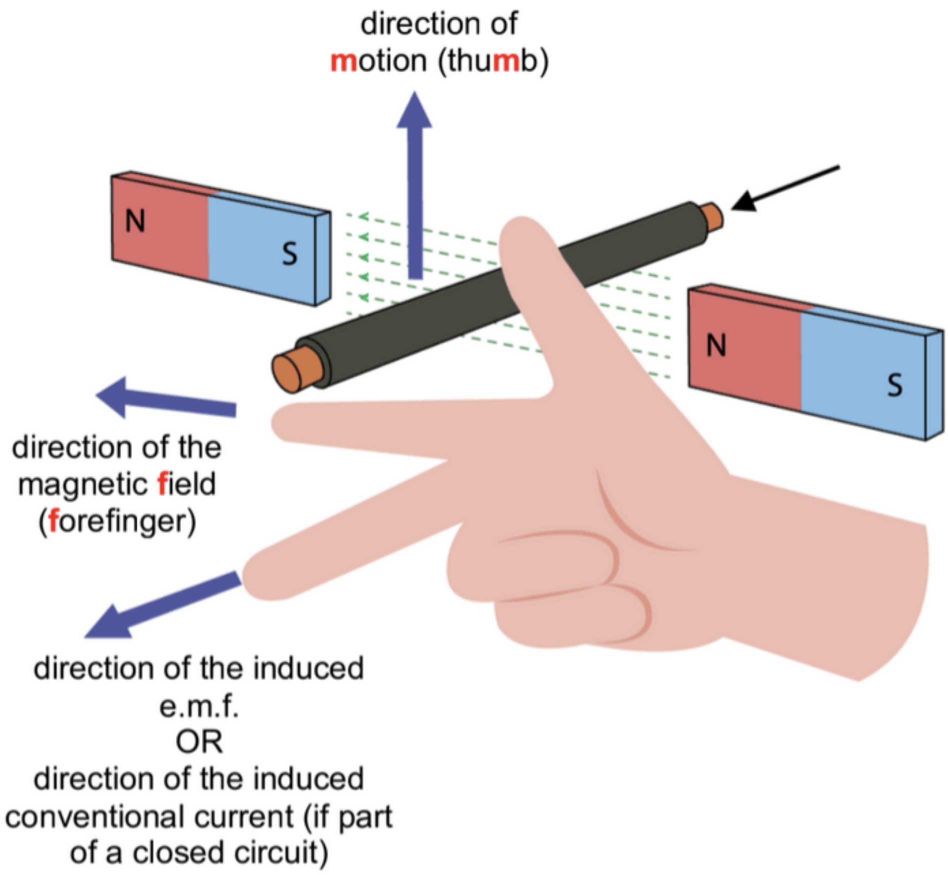
Case 3: S moves away from solenoid

1. The **south** pole of the magnet moves **away from** the solenoid.
2. (By Faraday's law of electromagnetic induction,) the **changing magnetic flux linkage** through the solenoid **induces** an **e.m.f.** in the solenoid.
3. Since the circuit is **closed,** the induced e.m.f. produces an **induced current.**
4. By Lenz's law, the magnet is attracted by the **north pole induced on the right of the solenoid** produced by the **anticlockwise induced current** when viewed from the right (using the right-hand grip rule) that flows from A to B.

Motional e.m.f. induced on a conductor moving through a magnetic field

When a conductor moves perpendicular through a magnetic field, an e.m.f. is induced on the conductor.

Fleming's right hand rule (for generators) shows the direction of the **induced e.m.f.**



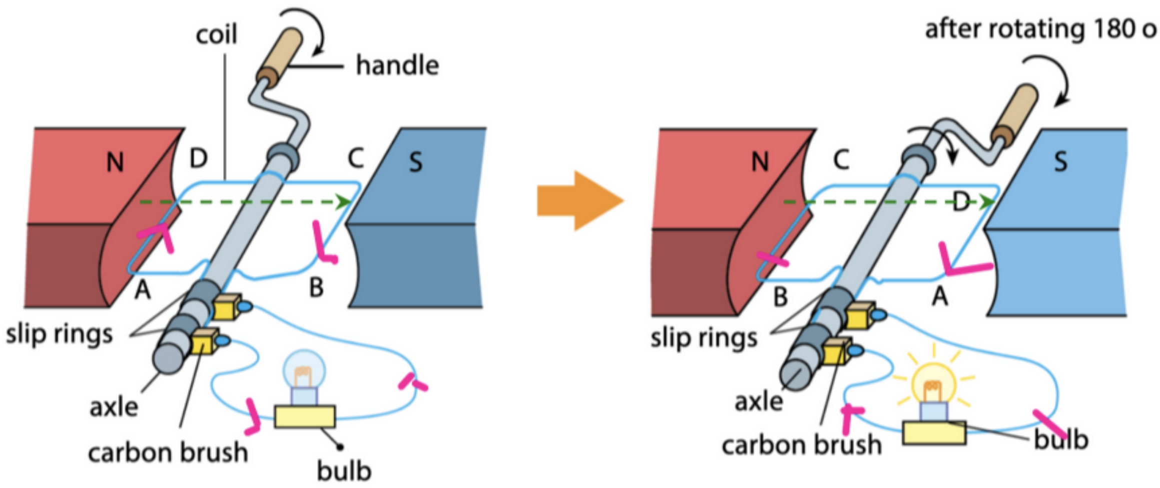
If the conductor is part of a **closed** circuit, the induced e.m.f. produces an **induced current** through the conductor.

Alternating Current (a.c.) Generator

As work is done to turn an a.c. generator, energy is transferred electrically by the alternating current to the connected electrical load, e.g.

- Simple rotating coil a.c. generator
- Simple rotating magnet a.c. generator

Simple Rotating Coil A.C. Generator



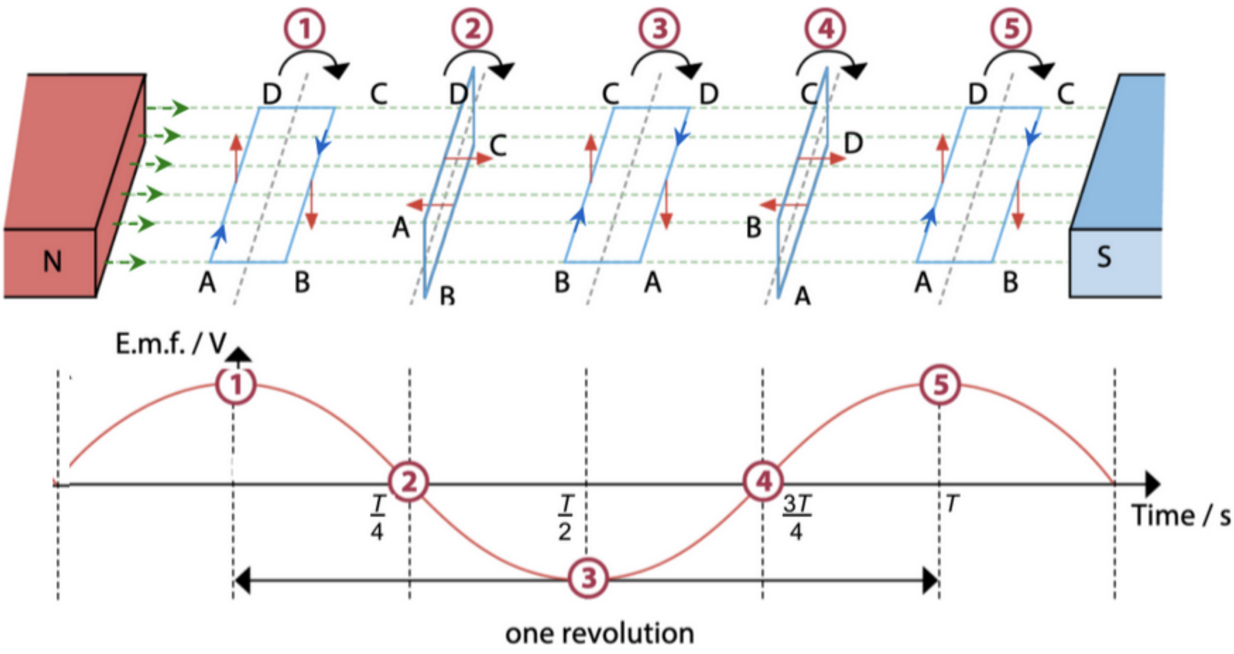
1. The coil is rotated by turning the handle
2. As the coil rotates between the two magnets, the **magnetic flux linkage** through the coil changes at a non-constant rate. (The coil **cuts the magnetic field lines** at a non-uniform rate)
3. By Faraday's law of electromagnetic induction, an **e.m.f** is **induced** in the rotating coil. Fleming's right hand rule tells us the direction of the induced e.m.f. in sides AD and BC.
4. In the **closed** circuit, the **induced alternating current** flows through the coil, the 2 slip rings, the carbon brushes and the bulb.

Function of the 2 Slip Rings

The 2 slip rings maintain **continuous electrical contact** between the rotating **coil** and the **external circuit** via the **carbon brushes**, so that the **induced current flows** through the closed circuit.

Graph of e.m.f output against time for a simple rotating coil a.c. generator

- The direction of the **induced current** through the coil **reverses every half turn** (alternating current)



The **maximum** induced e.m.f of an a.c generator can be **increased** by increasing the rate at which the coil cuts the magnetic field lines, e.g. by

1. increasing the **number of turns** of the coil
2. increasing the **magnetic field strength** (e.g. stronger magnets)
3. increasing the **speed of rotation** of the coil.
4. winding the coil on a **soft iron core** (to strengthen the magnetic field through the coil)

The **maximum induced current** can be **increased** by increasing the induced e.m.f or by **decreasing the resistance** of the coil.

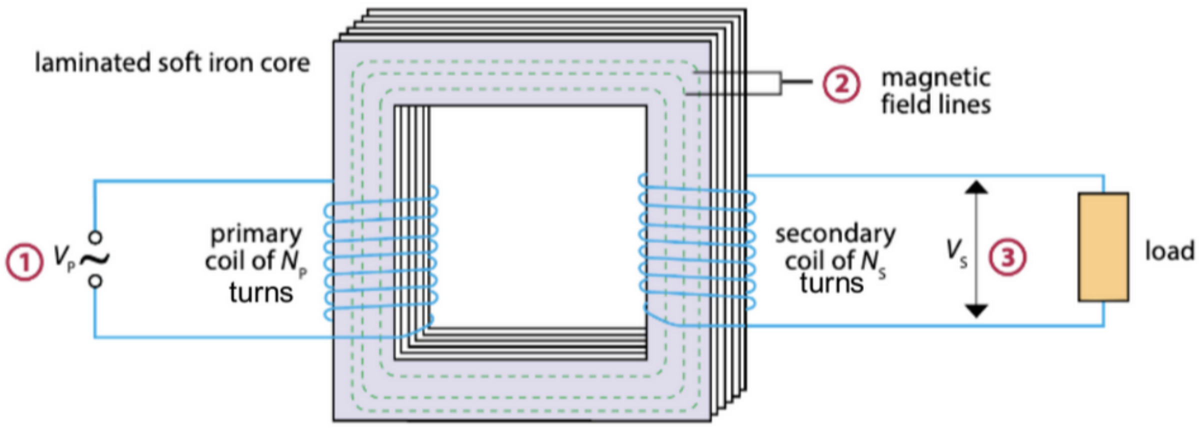
- **Doubling** the **number of turns** of the coil (without changing its frequency of rotation and the magnetic field strength) **doubles the maximum** induced e.m.f
- **Doubling** the **frequency of rotation** (i.e. halving the period) of the coil (without changing its number of turns and the magnetic field strength)
    - **doubles the maximum induced e.m.f** and
    - **doubles the frequency** (i.e. halves the period) of the induced e.m.f.

Transformers

A transformer is a device that can change a large alternating voltage (with a small current) to a small alternating voltage (at large current) and vice versa.

- A transformer does **not** work on direct current (d.c.)

Structure of a Transformer



1. The **alternating input voltage V_P** produces an **alternating current I_P** through the primary coil.
2. Current I_P produces an **alternating magnetic field** (which alternately increases and decreases in strength).
3. The **laminated soft iron core directs** the alternating **magnetic field** produced by the primary coil **toward** the **secondary coil.**
4. By Faraday's law of electromagnetic induction, the **changing magnetic flux linkage** through the secondary coil **induces** an **alternating output voltage V_S** in the secondary coil.
5. Since the secondary coil is part of a **closed** circuit, the alternating output voltage V_S produces an **alternating current I_S** through the secondary coil and the load.

Function of the laminated soft iron core

- The **core directs** the alternating **magnetic field** produced by the primary coil **toward** the **secondary coil**.

- **Iron**, a **soft magnetic material**, is chosen because it **magnetises and demagnetises quickly** in the presence of the alternating magnetic field produced by the primary coil.

Lamination

- However, the changing magnetic field produced by the primary coil also induces __eddy currents __that flow in little loops through the core.
- Some **energy** is **wasted** is being transferred to the **internal** (thermal) **store** of the core.
- A **laminated** soft iron core is made up of thin sheets of soft iron electrically insulated from each other (e.g. by coats of lacquer) reduces the path lengths of these eddy currents, and this **reduces** this unwanted **wasted energy**.
- The transformer allows the alternating input voltage, V_P, and the alternating output voltage V_S to differ, by having a **different number of turns** in the **primary and secondary coils**.

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Efficiency of Transformer

$$\eta = \frac{P_S}{P_P} \times 100% = \frac{V_SI_S}{V_PI_P} \times 100%$$

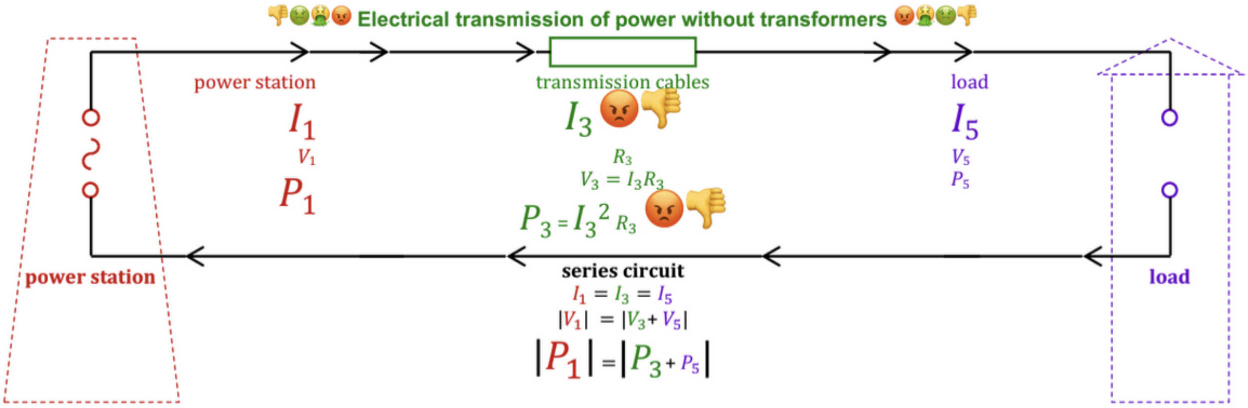
Ideal Transformer	**Non-ideal Transformer**
efficiency η = 100	efficiency η < 100
$\frac{V_SI_S}{V_PI_P} = 1$	
$\frac{I_P}{I_S} = \frac{V_S}{V_P} = \frac{N_S}{N_P}$	

For a **non-ideal** transformer, energy is wasted due to:

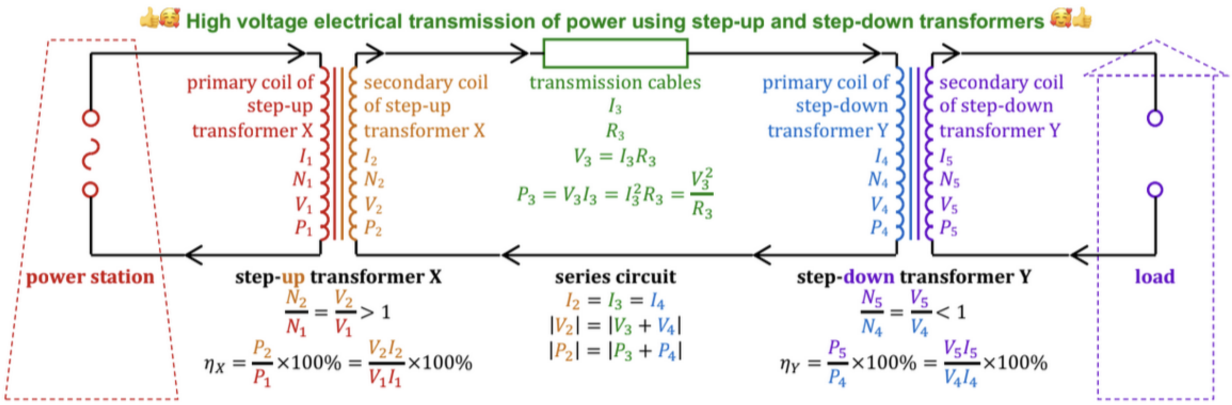
1. Energy being transferred to the internal stores of the coils when current flows through them, since the **coils** have some **resistance**.
2. Energy being transferred to the internal store of the core when **eddy current** flows through the core, since the **core** has some resistance

3. **leakage** of **magnetic field** lines between the primary and secondary coils.
4. **hysteresis loss** caused by the **flipping of the magnetic domains** in the core due to the alternating magnetic field produced by the primary coil. Energy is transferred to the internal store of the core.

High Voltage Electrical Transmission of Power



1. Since the length L_3 is large, the resistance of the power cables, $R_3 = \frac{\rho_3L_3}{A_3}$ is significant.
2. Increasing the cross-sectional area A_3 of the transmission cables is impractical as thick cables are very expensive, heavy and difficult to suspend
3. To reduce the power $P_3 = I_3{}^2R_3$ wasted (transferred electrically to the internal stores of the transmission cables), the current I_3 through the transmission cables should be minimised.



High voltage electrical transmission of power reduces current I_3 through the transmission cables, and thus reduces the power $P_3 = I_3{}^2R_3$ wasted (transferred electrically to the thermal stores of the transmission cables)

1. Near the power station, transformer X steps up the voltage from V_1 to $V_2 > V_1$
2. Since the output power of the secondary coil of transformer X is $P_2 = V_2I_2$, a small current:
   - $I_2 = \frac{P_2}{V_2}$
   - flows through the secondary coil of transformer X
3. Since the secondary coil of transformer X, the transmission cables and the primary coil of transformer Y are connected in series, the same **small current** flows through the transmission cables and the primary coil of transformer Y

$$I_{transmission} = I_2 = I_3 = I_4 = \frac{P_2}{V_2}$$

4. The power wasted (transferred electrically to the internal stores of the transmission cables)

$$P_3 = I_3^2R_3 = \left(\frac{P_2}{V_2}\right)^2R_3$$

   is minimised.

5. By the conservation of energy, the more power $P_4 = P_2 - P_3$ is transferred to the primary coil of transformer Y.
6. In the series circuit, the voltage across the primary coil of transformer Y is $V_4 = V_2 - V_3$
7. Before consumption, transformer Y steps down the voltage from V_4 to $V_5 < V_4$
8. A.C generators are used in the production of power to be transferred electrically. If **D.C** generators are used, voltages **cannot** be **stepped up** or **down** by transformers.