Hwa Chong Institution (High School) Name : __________________________ (    )
PHYSICS Notes Class : __________
Date : __________

# Electromagnetic Induction

## A. Introduction

1. Observations

- when the wire is moved up across the magnetic lines of force, the galvanometer shows a momentary deflection to the left
- when the wire is moved down across the field lines, there is a momentary deflection but in the opposite direction
- when the wire is moved up across the field lines at a faster rate, the galvanometer shows a greater deflection to the left

◊ when the wire is moved in the same direction as the magnetic lines of force (i.e. without cutting the lines of force), the galvanometer shows no deflection

2. Conclusion

**When the magnetic lines of force are cut by the moving wire, an induced current flows in the wire.

3. Fleming's Right-Hand Rule

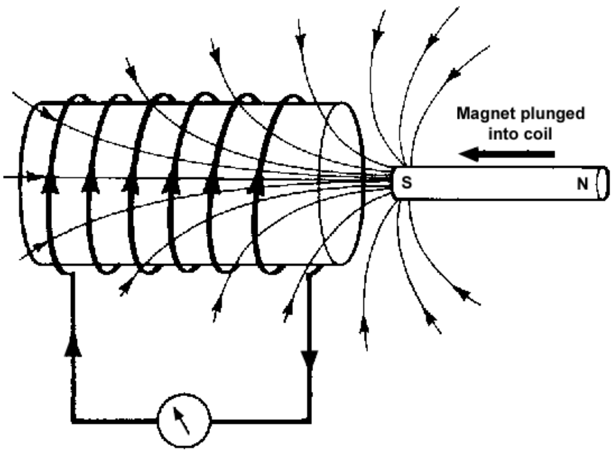
Fleming's RH rule is used to determine the direction of the flow of the induced current.

## B. How does an induced current arise?

[Note: There is no source of e.m.f. (e.g. a cell) in the above circuit. But e.m.f. is necessary for charges to flow. So how does an induced e.m.f. arise?]

1. Faraday's Law of Induction

"The e.m.f. generated in a conductor is proportional to the rate of change of magnetic flux linking the circuit".




Illustration

| Time (s) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| | | | | |

| time (s) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| | | | | |

**Conclusion**

The stationary coil cut the approaching/retreating magnetic lines of force to give rise to a **rate of change of magnetic field**.

2. Lenz's Law

"The direction of the induced e.m.f., and hence the induced current in a closed circuit, is always such as to oppose the change in magnetic flux producing it".

Illustration

3. What are the factors that affect the strength of the induced current?

* the number of turns per unit length of the solenoid
* the strength of the magnet
* the speed with which the magnet is plunged into (or withdrawn from) the solenoid

4. Other ways to create changing magnetic field

a) Moving the coil towards the magnet

b) Using two coils

When switch is closed:

- There is a momentary deflection in the galvanometer. Why?
- The magnetic field from coil **P** cut coil **Q**, causing a rate of change of magnetic field across coil **Q**. This gives rise to an induced e.m.f. across coil **Q**, and since the circuit is closed, it produces an induced current in coil **Q**.

When switch remains closed:

- There is no deflection in the galvanometer. Why?
- Although the stationary magnetic field from coil **P** cut coil **Q**, there is no rate of change of magnetic field across coil **Q**. So there is no induced e.m.f. across coil **Q**. Therefore there is no induced current in coil **Q**.

When switch is opened:

- There is a momentary deflection in the opposite direction. Why?
- The collapsing (or retreating) magnetic field from coil **P** cut coil **Q**, causing a rate of change of magnetic field across coil **Q**. This gives rise to an induced e.m.f. across coil **Q**, and hence produces an induced current in coil **Q**, but in the opposite direction.

5. Summary

The following summarises what had been discussed.

♦ Since the galvanometer shows a deflection towards the left, there must be a current flowing through the circuit.

♦ The presence of this induced current also means that an induced e.m.f. is generated in the circuit. This induced e.m.f. is responsible for driving the induced current round the closed circuit. The induced current on the right-hand side of the coil flows in a clockwise direction.

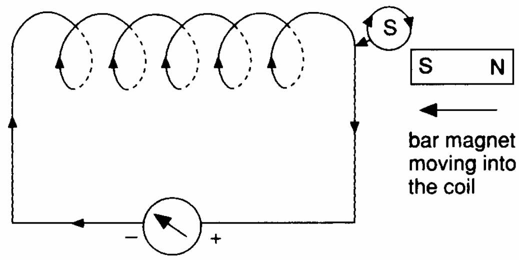


Figure **A** Pointer deflects left

◊ Since the galvanometer shows no deflection, there is no induced current flowing in the circuit.

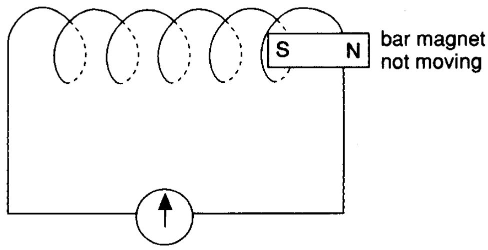



Figure **B** Pointer at centre-zero

♦ Since the galvanometer shows a deflection towards the right, there must be a current flowing through the circuit.
♦ The direction of the induced current is opposite to that for Fig A as shown by the deflection in the opposite direction. The induced current on the right-hand side of the coil flows in an anticlockwise direction.

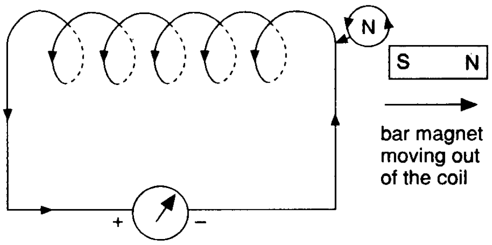



Figure **C** Pointer deflects right

◊ The galvanometer shows a deflection towards the right indicating the presence of an induced current.
◊ The induced current on the right-hand side of the coil flows in an anticlockwise direction.

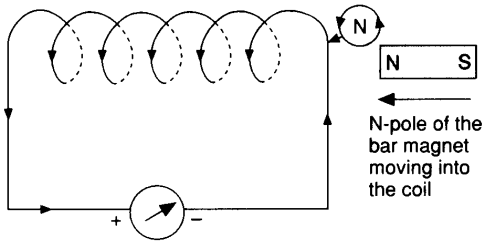



Figure **D** Pointer deflects right

♦ The galvanometer shows no deflection and this indicates the absence of any induced current.

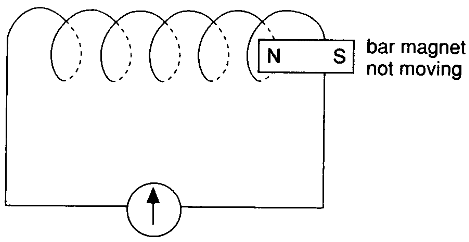



Figure **E** Pointer at centre zero

◊ The galvanometer shows a deflection towards the left indicating the presence of an induced current.
◊ The direction of the induced current for Fig F is opposite to that for Fig D. The induced current on the right-hand side of the coil flows in a clockwise direction.

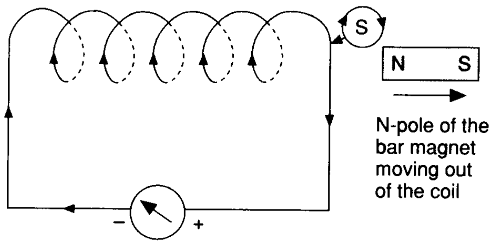



Figure **F** Pointer deflects left

We can make two important conclusions:

⇒ Whenever there is movement of the magnet relative to the coil an induced e.m.f. (and hence an induced current in a closed circuit) is generated in the circuit. An induced e.m.f. can also be generated by moving the coil relative to the magnet so long as there is a change in the magnetic lines of force passing through the coil (Faraday's Law).

⇒ The direction of the induced e.m.f. (taken to be the direction of the induced current) is such that the magnetic field created always opposes the motion which produces it (Lenz's Law). This can be seen in Figs A, C, D and F. For example in Fig A, as the S-pole of the magnet moves into the right-hand side (RHS) of the coil, there is an increase in the strength of the magnetic field affecting the coil. To oppose the increase in the strength of the magnetic field, the induced current moves in a direction so as to create a S-pole at the RHS of the coil. The S-pole at the RHS of the coil repels the S-pole of the approaching magnet. Similarly, in Fig C, when the S-pole of the magnet moves away from the RHS of the coil, the magnetic field affecting the coil decreases. To oppose the decrease in the strength of the magnetic field, the induced current moves in a direction so as to create an N-pole at the RHS of the coil. The N-pole at the RHS of the coil attracts the S-pole of the magnet that is moving away.

6. Lenz's Law and the conservation of energy

When a magnet is moved into a coil, mechanical work is done to overcome the repulsion between like poles. This mechanical work is transformed into electrical energy as indicated by the induced current flowing in the circuit.

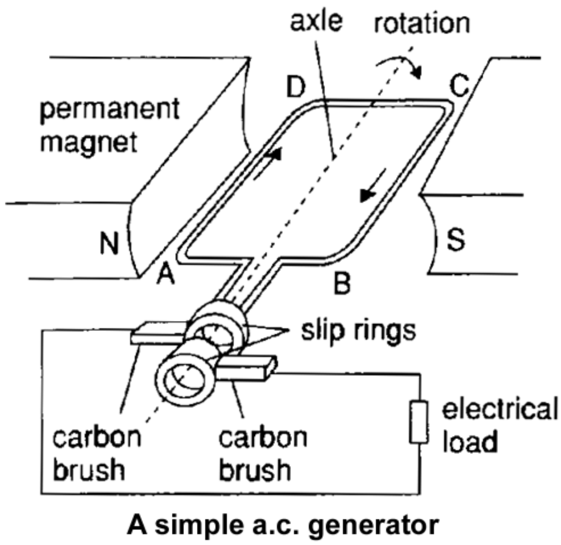
The same effect is experienced when the magnet is pulled out of the coil. Mechanical work is done to overcome the attraction between the unlike poles which is again transformed into electrical energy.

### C. Generating Electricity

1. The simple a.c. (alternating-current) generator

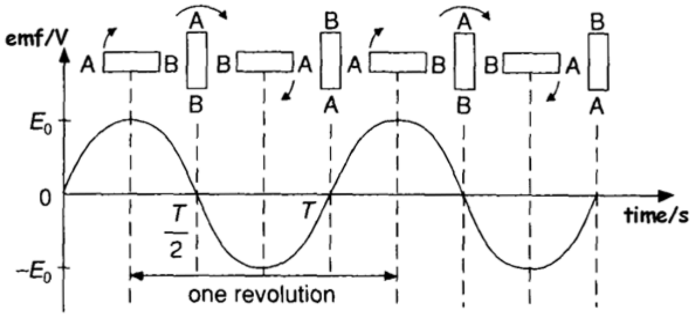
♦ The figure shows a simple a.c. generator. As the coil <u>rotates</u>, the <u>magnetic field through the coil changes</u> and therefore induces an e.m.f. between the ends of the coil. The induced current does not flow unless the ends of the coil are connected to an external circuit with an electrical load such as a resistor.

♦ The <u>slip rings</u> ensure that the direction of the induced current flowing in the external circuit changes every half revolution. In other words, the <u>output voltage or current is alternating</u>. The carbon brushes provide sliding contact with the rotating slip rings.




**A simple a.c. generator**

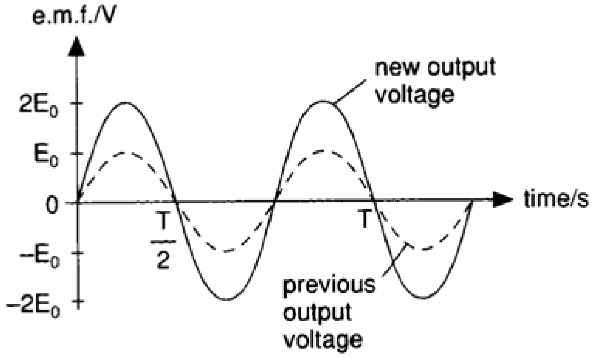
◊ If the coil is viewed end-on, the positions of the coil that correspond to the induced e.m.f. are shown in the next figure. The induced e.m.f. is maximum ($E_o$) when the plane of the coil is parallel to the magnetic lines of force because the sides AD and BC are cutting through the magnetic field at the greatest rate.




**Positions of coil relating to induced e.m.f.**

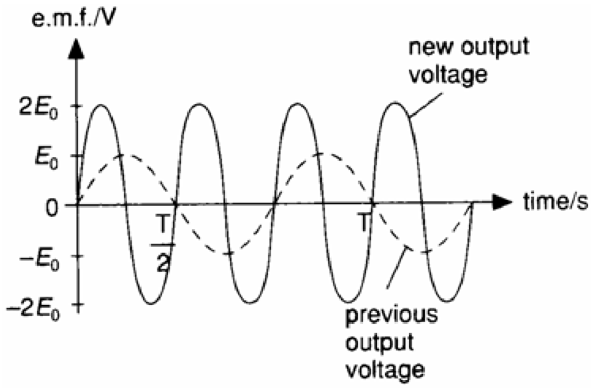
◊ The induced e.m.f. is zero when the plane of the coil is perpendicular to the magnetic lines of force because the sides AD and BC are moving parallel to the magnetic field and hence not cutting through the magnetic field lines. The frequency of the rotation is related to its period by the equation: $\mathbf{f = \frac{1}{T}}$

⇒ If we double the number of turns on the coil without changing the frequency of rotation of the coil, the output voltage has the waveform shown.




Doubling the turns doubles the maximum output voltage (theoretical)

⇒ If we double the the frequency of rotation of the coil without changing the number of turns on the coil, the maximum output voltage also doubles as shown in the figure.



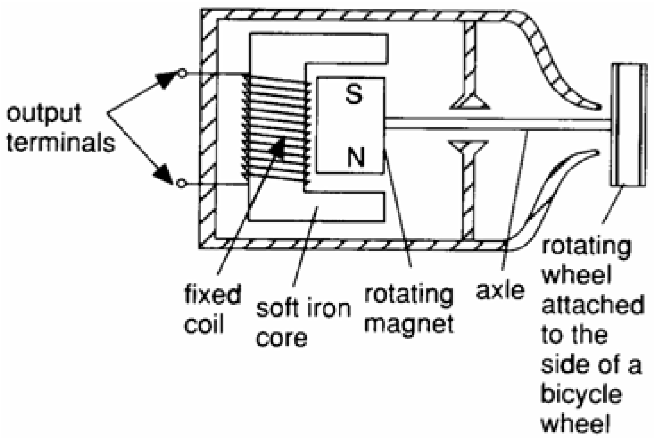

Doubling the frequency $f$ doubles the maximum output voltage (theoretical)

Besides increasing the frequency of rotation of the coil and the number of the turns of the coil, the induced e.m.f. of an a.c. generator can also be increased:

- by using stronger magnetic fields;
- by winding the coil on a soft iron core (to concentrate the magnetic lines of force through the coil)

2. Other a.c. generators

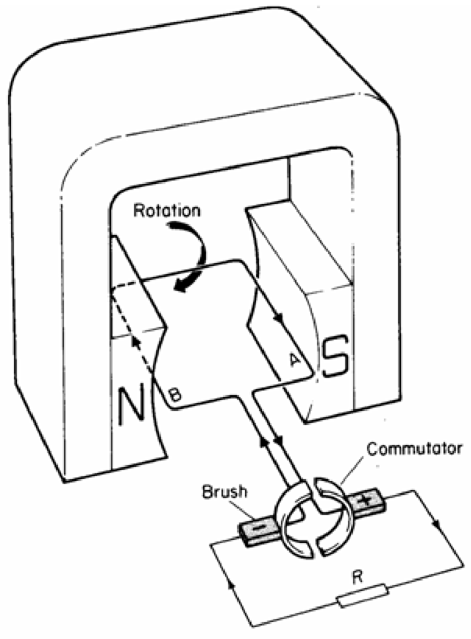
To generate large currents (as in a turbine power stations), it is more practical and advantageous to keep the coil fixed and to rotate the magnetic field (of an electromagnet) around the coil. In this way, instead of the coil cutting the magnetic field as in the simple a.c. generator, the magnetic field cuts the coil to produce the induced e.m.f. Hence we can do away with the slip rings and the carbon brushes which are not capable of carrying large currents in and out of the coil. Other than the turbine, the bicycle dynamo also uses the method of rotating a magnet to produce an induced e.m.f. as shown.



A bicycle dynamo

3. d.c. generator

There is no structural differences between a d.c. motor (which <u>requires</u> a current to flow in the wire) and a d.c. generator (which <u>produces</u> induced current). Instead of the slip-rings as used in the a.c. generator, a split-ring commutator is used. This means that when the coil is vertical, the commutator split is horizontal. The output current is a pulsating d.c.



Simple direct current generator (d.c. dynamo)

**D. Transformers**

1. Various ways to use two coils to induce an output e.m.f.

a)

b)

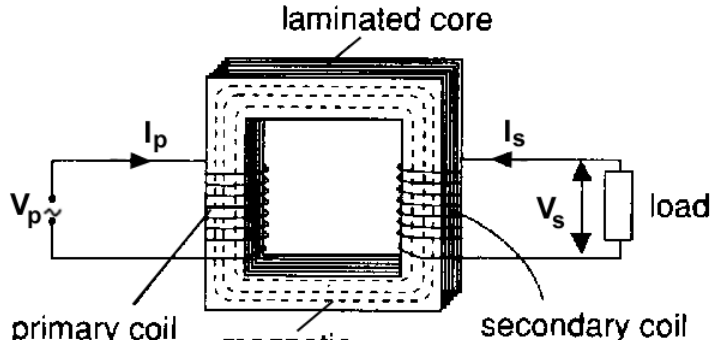
c)

d)

2. The transformer

**A transformer is a device that changes a <u>high alternating voltage</u> (at low current) to a <u>low alternating voltage</u> (at high current)**, or vice versa. It is a useful electrical device that is essential for:

- electrical power transmission from power stations to the consuming loads (households and factories)
- regulating voltages for proper operation of electrical appliances such as mains-operated TV and record player




The **structure** of a closed-core transformer basically consists of two coils of wires (<u>primary</u> and <u>secondary</u>) of an appropriate number of turns. These coils are wound on a laminated soft-iron core for reducing heat loss in the core.

**The principle of operation**

- it transfers electrical energy supplied from the primary coil to the secondary coil by electromagnetic induction between the two coils
- at the primary coil, the applied alternating voltage sets up an alternating magnetic field to cut the secondary coil. This gives rise to a rate of change of magnetic field across the secondary coil, and therefore an induced alternating e.m.f. is produced
- a step-up transformer is one where the e.m.f. in the secondary coil is greater than the e.m.f. in the primary coil. Conversely, a step-down transformer is one where the e.m.f. in the secondary coil is less than the e.m.f. in the primary coil

**Equations**

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

$V_S$ = secondary output voltage
$V_P$ = primary input voltage
$N_S$ = number of turns in secondary coil
$N_P$ = number of turns in primary coil

$\frac{N_S}{N_P}$ is commonly called **turns ratio**.
For a step-up transformer, $N_S > N_P$.
Conversely, for a step-down transformer, $N_S < N_P$.

$$I_P V_P = I_S V_S$$

$I_P$ = current in the primary coil
$I_S$ = current in the secondary coil
$V_S$ = secondary output voltage
$V_P$ = primary input voltage

For an ideal transformer (i.e. 100% efficient), the power supplied to the primary coil is fully transferred to the secondary coil. Hence by the principle of conservation of energy,
**power in primary coil = power in secondary coil**

3. Causes of loss of efficiency in a transformer

- **Flux leakage**: It is essential that all the flux generated by the primary passes through the secondary. This is best achieved by winding the primary on top of the secondary; and having a 'closed' iron core.
- **Loss due to heating effect of eddy currents**: The metal core is a conductor and the magnetic field varies continually. Hence an e.m.f. and consequently a current are induced in it. If the core is solid, it acts in effect as a secondary of one turn and a very large current is induced. The heating effect is proportional to the square of the current and is therefore quite large. The effect is very considerably reduced by using a bundle of very thin metal stampings (laminations) insulated from each other. Then the current induced in each is very small and there is only a small heating effect.
- **Copper losses**: These represent the energy lost by heating of the wire in both the primary and secondary coils (because $\propto I^2R$ ).
- **Hysteresis losses**: The magnetic field in the core is in one direction 50 times each second and in the opposite direction 50 times each second. Consequently the domains are continually changing their alignment. The energy needed to effect this is taken from the input energy.

Ex.1 : A transformer has 400 turns in the primary winding and 10 turns in the secondary winding. The primary e.m.f. is 250 V and the primary current is 2.0 A. Calculate
(i) the secondary voltage;
(ii) the secondary current, assuming 100% efficiency.

Ex.2 : A step-down transformer is used to light a 12 V 24 W lamp from the 240 V mains. The current through the primary is 125 mA. What is the efficiency of the transformer?

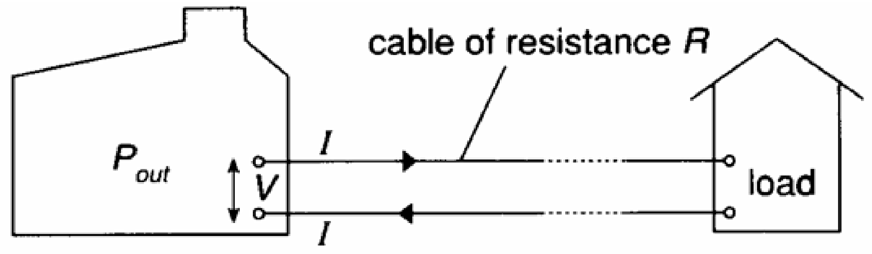
**E. Transmission of Electricity**

1. Transmitting electricity economically

Electricity is transmitted from one part of the country to another by the grid system and is carried by the pylons and wires strung across the countryside. Can you still see all these in Singapore? If not, how are the wires carried around the island?

One of the problems in the transmission and distribution of electrical energy is the power loss as heating ($\mathbf{I^2R}$) in the grid cables. One solution is to have very thick cables so that the resistance **R** is low. Then the power lost as heat in the cables will be a minimum. However, there is a limit to the extent to which this can be done. The thicker the cable used, the heavier is the weight to be supported and hence the higher the construction cost.

Another solution is to reduce the current **I** in transfer. This can be done by using transformers to step up the voltage at which the electrical power is to be transmitted. The greater the value of the voltage, the lower the power loss. Hence electrical power can be transmitted more economically at high voltage and low current




2. Alternating current and direct current

Direct current was used at one time, but alternating current is now preferred. Why? **Because it can be stepped up and down much more easily. Direct current cannot be used with a transformer because a changing magnetic field is required**. To step up d.c. voltages is quite a complicated process. To step it down involves using resistors in series and a considerable amount of energy is lost as heat.

Ex.3 : Find the power wasted as internal energy in the cable when 10 kW is transmitted through a cable of resistance of 0.50 Ω

(i) at 200 V;

(ii) at 200 000 V.

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