Electromagnetic Machines

Magnetic Field Strength

A wire carrying electric current produces a magnetic field around it. The direction of the magnetic field can be worked out with the Right Hand Rule (see Figure 1). The thumb points in the direction of the current while the curled fingers point in the direction of the field.

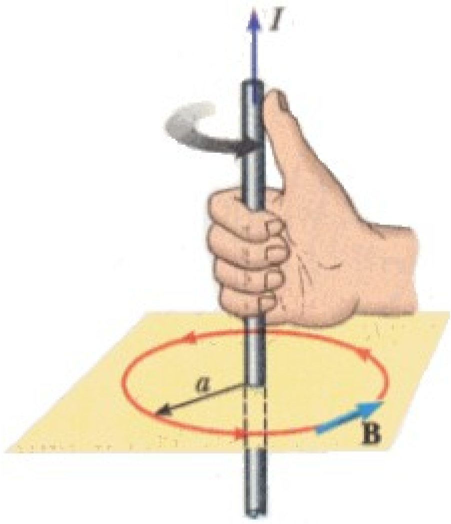

Figure 1 – Right Hand Rule

A current carrying wire placed in a magnetic field experiences a force provided that it is not parallel to the field. The force has a maximum when the current is perpendicular to the field, as it cuts the maximum amount of field lines. *Fleming's Left Hand Motor Rule* (see Figure 2) shows the direction of the force on any current that has a component which is perpendicular to the magnetic field. As you can see, the direction of force is always perpendicular to both the current direction and the magnetic field.

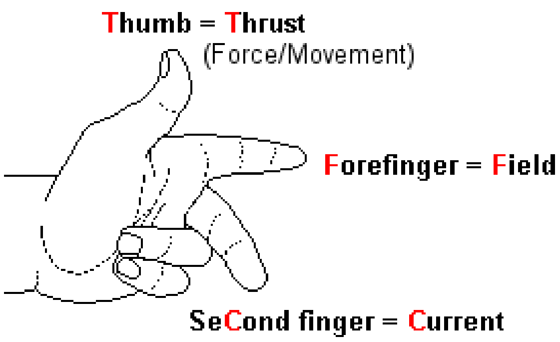

Figure 2 – Fleming's Left Hand Motor Rule

(See also page 92 of Lett's revision guide on how to identify the poles of an electromagnet).

The size of the force on a current carrying conductor in a magnetic field depends on:

- the size of the current
- the length of conductor in the field
- the orientation of the conductor, relative to the field
- the strength of the magnetic field

These factors are used to define the strength of a magnetic field as:

The size of the force per metre of length per unit of current flowing in a wire at right angles to a magnetic field.

Magnetic field strength is also known as **Flux density (B)** and it is measured in **Tesla (T)**. Remember, this is a vector quantity. We can hence work out the force by:

$$F = BIl$$

where F is the Force (N), B is the Flux density (T), I is the current (A) and l is the length of wire in the field (m).

If a current carrying loop is placed in a magnetic field, the forces on the side arms cause the loop to rotate. By using a split ring commutator, the current in the loop can be reversed each time the loop becomes vertical (i.e. each half turn). This allows the loop to rotate steadily, so a motor is made!

Also, **F = BqV**

where F = force (N), B = flux density (T), q = charge of particle (C), V = velocity of particle. This is derived from BIL, by putting I = q/t and t = L/v in (time = distance/speed).

Electromagnetic Induction

Magnetic flux density is a measure of the strength of the magnetic field per unit area. It is also defined as the magnetic flux that induces an emf of 1V in a circuit of 1 turn, when generated or removed in one second. It depends in the amount of current and the number of turns, and its units are Tesla (T).

$$B = \frac{\phi}{A}$$

where B is the Flux Density (T), ϕ is the magnetic flux (Wb) and A is the area (m^2). Note that for the area you may need to do 2πr.

For a **solenoid**, you measure the flux linkage, Φ, which for a coil of N turns is given by:

$$\Phi = BAN$$

where Φ is the flux linkage in a solenoid (capital phi, measured also in Wb), B is the flux density (T), A is the area (m^2), and N is the number of turns.

If a conducting rod moves through a magnetic field its electrons will experience a force, which means that they will accumulate at one end of the rod. This induces an emf across the ends of the rod, exactly as a battery would. If the rod is part of a complete circuit, then an induced current will flow through it. This is called electromagnetic induction.

Faraday's Law

An emf is induced when there is relative motion between a conductor and a magnet. An emf is produced whenever lines of force (flux) are cut. Flux cutting always produces emf but will only induce a current if the circuit is complete.

Flux linking is when an emf is directly induced by changing the magnitude or direction of the magnetic flux (e.g. caused by an alternating current electromagnet).

Faraday's Law is: **The induced emf is directly proportional to the rate of change of flux linkage**.

This can be written as: $$Induced\ emf\ , \epsilon = \frac{(flux\ change) \cdot N}{(time\ taken)} = \frac{(\Delta \phi) \cdot N}{(\Delta t)}$$

where N is the number of coils.

Hence if a graph is plotted (flux against time), the gradient if the emf. The area under a graph of emf against time gives the flux change.

Lenz's Law

The induced emf is always in such a direction as to oppose the charge that caused it.

Hence Lenz's and Faraday's laws can be combined to give one formula that works for both:

$$Induced\ emf\ , \epsilon = \frac{-(\Delta \phi) \cdot N}{(\Delta t)}$$

The minus sign shows the direction of the induced emf. The idea that an induced emf will oppose the change that caused it agrees with the principle of the conservation of energy – the energy used to pull a conductor through a magnetic field, against the resistance caused by magnetic attraction is what produced the induced current.

Lenz's law can be used to find the direction of an induced emf and current in a conductor travelling at right angles to a magnetic field:

Lenz's law says that the induced emf will produce a resistive force.

- Using Fleming's Left Hand Rule, point your thumb in the direction of the force of resistance – which is in the **opposite direction** to the motion of the conductor.
- Your second finger will now give you the direction of the induced emf. If the conductor is connected as part of a circuit, a current will be induced in the **same direction** as the induced emf.

Transformers and Alternators

Transformers are devices which make use of electromagnetic induction to change the size of the voltage for an alternating current. An alternating current flowing in the **primary coil** produces magnetic flux. The magnetic field is passed through the iron core to the **secondary coil** where it induces an alternating voltage of the same frequency.

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

where V_p is the voltage of the primary coil and N_s is the number of turns in the secondary coil.

Step-up transformers increase the voltage by having more turns on the secondary coil than the primary. Step-down transformers reduce the voltage by having fewer turns on the secondary coil.

Transformers are not 100% efficient. But for an ideal transformer is would be true that:

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

where I_s is the current in the secondary coil. (Notice the current is a different way!)

In practice there will be small losses of power from the transformer, mostly in the form of heat. Heat can be produced by **eddy currents** in the transformer's iron core -this effect is reduced by **laminating** the core with **layers of insulation**. (NB eddy currents in a moving conductor interact with the magnetic field producing them to retard the motion of the conductor).

Heat is also generated by resistance in the coils. To minimise this, thick copper wire is used, which has low resistance.

The efficiency of a transformer is the ratio of power out to power in, so:

$$Efficiency=\frac{(V_s \cdot I_s)}{(V_p \cdot I_p)}$$

Electricity from power stations is sent round the country in the National Grid at the lowest possible current because losses due to the resistance in the cables are proportional to I^2 – so if you double the transmitted current you quadruple the power loss. Since P = IV a low current means a high voltage. Transformers allow us to step up the voltage to around 400000V for transmission through the national grid, and then reduce it again to 230V for domestic use.

An alternator is a generator for alternating current. Generators, or dynamos, convert kinetic energy into electrical energy – they induce an electric current by rotating a coil in a magnetic field.

A simple alternator looks similar to a motor but with slip rings and brushes instead of split ring commutators. The output voltage and current change direction with every half rotation of the coil, producing AC.

Flux linkage and induced voltage are 90° out of phase. The amount of flux cut by the coil (flux linkage) is given by:

$$\Phi = BANsin\theta$$

where θ is the angle from the coil to the lines of flux.

This means that the flux linkage varies sinusoidally between +BAN and −BAN. θ can be expressed in radians as 2πft. Hence: $\Phi = BAN \cdot \sin(2\pi \cdot ft)$

Using Faraday's Law, $V=\frac{-(\Delta\phi)}{(\Delta t)}$, we can show that:

$$V=-BAN\cdot 2\pi f\cdot\cos(2\pi\cdot ft)$$

[because the differential of sin(2π.ft) = 2πf.cos(2πft)].

This tells us that the output voltage is directly proportional to the flux linkage (BAN), the alternator frequency (f) and the cosine of the angle (θ) of the coil to the magnetic field (since 2πft = θ). The induced emf reaches its peak value when cosθ= 1 (i.e. when the coil is parallel to the field lines) and its minimum value when cosθ = 0 (i.e. when the coil is perpendicular to the field lines).

Permeance – how easy it is for magnetic flux to "travel", denoted Λ. (similar to conductance)

$$\Lambda = \frac{\phi}{(N \cdot I)} = \frac{\mu \cdot A}{L}$$

where Λ is the permeance of the circuit (WbA^{-1}), ϕ is the flux density (Wb), N is the number of turns, I is the current (A), μ is the permeability of the magnetic material ($WbA^{-1}m^{-1}$), A is the area (m^2) and l is the length (m).

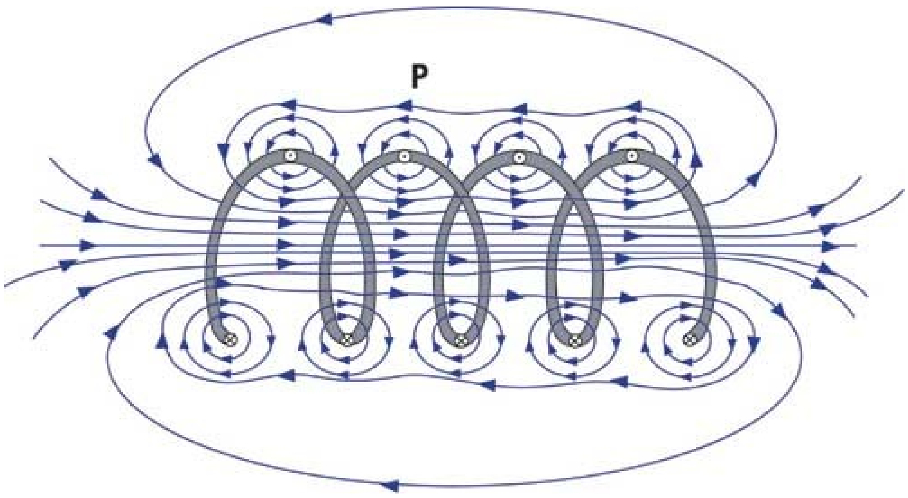

Figure 3 – flux lines of a solenoid.