EDEXCEL NATIONAL CERTIFICATE/DIPLOMA

UNIT 5 - ELECTRICAL AND ELECTRONIC PRINCIPLES
NQF LEVEL 3

OUTCOME 3 - MAGNETISM and INDUCTION

3 Understand the principles and properties of magnetism

***Magnetic field*:** magnetic field patterns e.g. flux, flux density (B), magnetomotive force (m.m.f) and field strength (H), permeability, B/H curves and loops; ferromagnetic materials; reluctance; magnetic screening; hysteresis

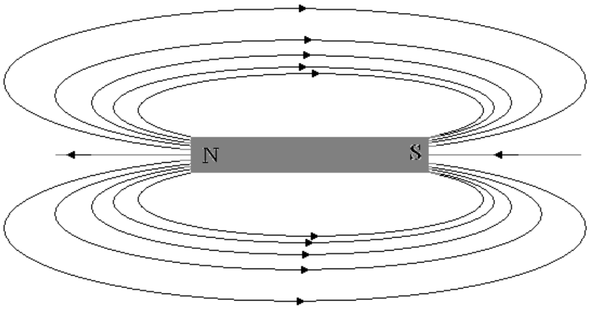
***Electromagnetic induction*:** principles e.g. induced electromotive force (e.m.f), eddy currents, self and mutual inductance; applications (electric motor/generator e.g. series and shunt motor/generator; transformer e.g. primary and secondary current and voltage ratios); application of Faraday's and Lenz's laws

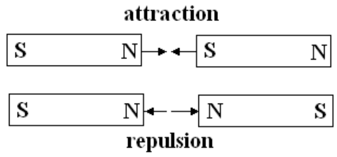
This outcome requires knowledge of alternating current so it might make sense if you study outcome 4 before outcome 3.

1. MAGNETISM

1.1 PERMANENT MAGNET

A permanent magnet produces a magnetic field with lines of magnetism running from North to South. This is a three dimensional field with the lines radiating out in all directions. In two dimensions, these lines may be traced out with a needle compass or by spreading iron filings around the magnet. The diagram shows a typical pattern.



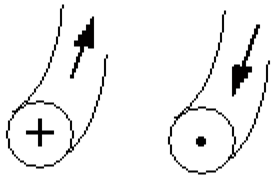


When two magnets are placed close as shown, opposite poles attract and like poles repel. Only certain materials are magnetic, mainly those containing iron.

It is thought that the molecules themselves are like magnets and line up along the length of the magnet in a pattern of N – S – N – S –..... If this is broken up by hammering or heating, the permanent magnetism is lost.

1.2 ELECTRO-MAGNETISM

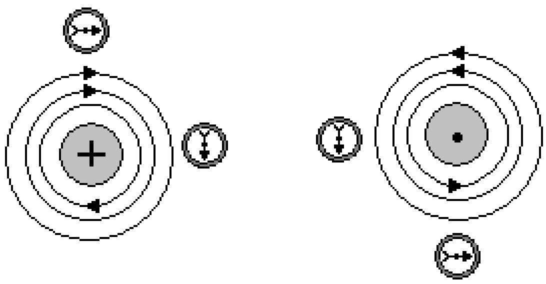
CURRENT CONVENTION



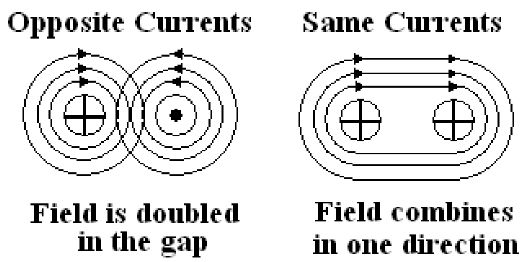
In the following work you should be aware of the following convention for indicating the direction of an electric current. When a cross section through a conductor is carrying current away from you, a cross is used. When the current is coming towards you, a dot is used. This should be seen as an arrow or dart. Moving away you see the tail feathers as a cross. Coming towards you, you see the point as a dot.

MAGNETIC FIELD AROUND A CONDUCTOR

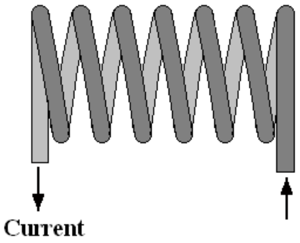
When a current flows in a conductor, a magnetic field is produced and the lines of magnetism are concentric circles around the cross section as shown. The direction may be found with a compass needle. The direction of the lines is determined by the CORK SCREW RULE. Point your finger in the direction of the current and turn your hand clockwise as though doing up a screw. The rotation is the direction of the magnetic flux.

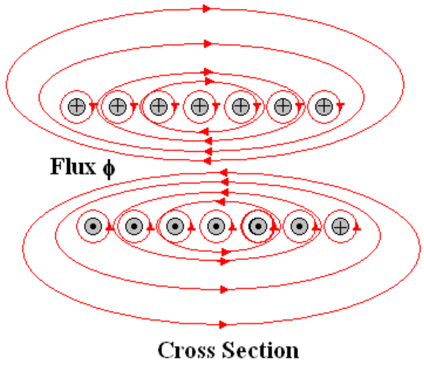


Consider the resulting magnetic field when two conductors are placed parallel to each other. When the current is in opposite directions, the field is concentrated in the space between them. When the current is in the same direction, the lines join up. Lines of magnetism do not flow easily in the opposite direction to each other and take an easier route by joining up.



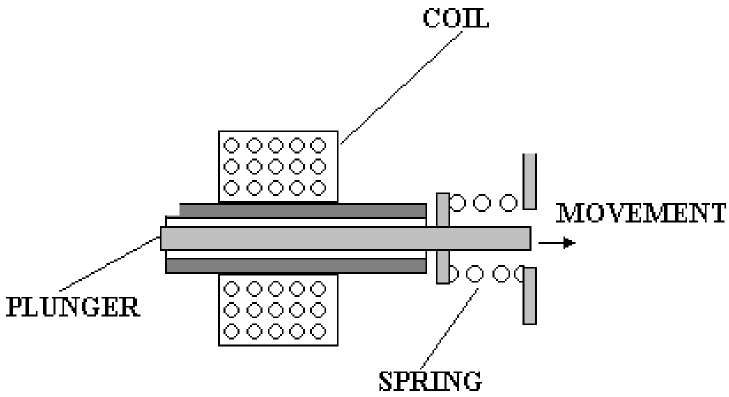
Now consider what happens when a conductor is wound into a coil. Taking a cross section we see that the current is always flowing into the page on top and out on the bottom. The circular lines of magnetism join up to form a pattern very similar to the bar magnet. This may be switched off or reversed by reversing the current. This is the way an electro-magnetic field is created. This affect is used in solenoids and magnetic cranes.





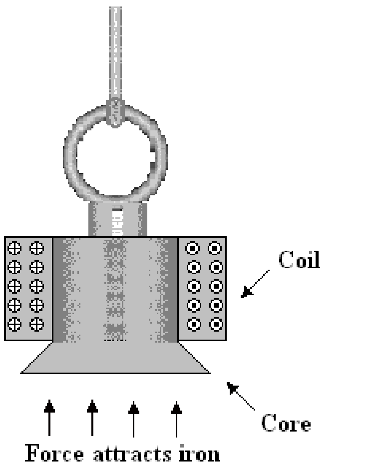
SOLENOIDS

A solenoid is a coil with an iron plunger inside it. When current flows in the coil, the plunger becomes magnetised and tries to move out of the coil. If a spring is used to resist the movement, the distance moved is directly proportional to the current in the coil. Solenoids are used in relays where they operate an electric switch. They are also used in hydraulic and pneumatic valves to move the valve element.



CRANES

When the coil is energised with current a powerful magnetic field is created and this is concentrated by the iron core and attracts any iron. It is useful for lifting iron and for sorting iron from non-magnetic materials.



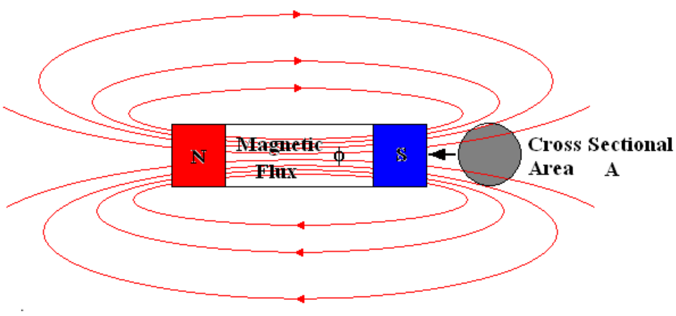
2. MAGNETIC CIRCUIT

2.1 FLUX AND FLUX DENSITY

The magnetic field is more correctly known as the magnetic flux and has the symbol ϕ or Φ. It is measured in units called the Weber (Wb). In the iron part of the magnet, the flux flows through a cross section of area A. The flux per unit cross sectional area is called the flux density and has a symbol B. The unit is the Weber/m^2 or Tesla (T).

ϕ - flux (Wb)

B – flux density (T)



$B = \phi/A$

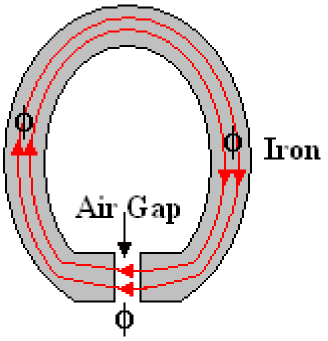
2.2 MAGNETIC CIRCUIT

Note that the flux is assumed to have a direction North to South on the outside but South to North on the inside. The poles of a magnet are Red for North and Blue for South. The flux flowing on the outside has an indeterminate cross section and length but flux flowing in a magnetic core has a definite cross sectional area and length and this is important in the next section.

In the horse shoe magnet shown in the next example, the flux runs through the iron and then jumps across the air gap. The flux is concentrated in the gap and the gap has a definite cross sectional area and length.

WORKED EXAMPLE No. 1

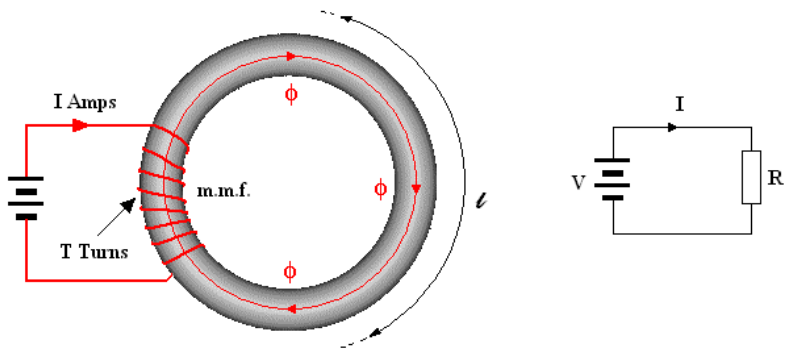
The flux flowing through a horse shoe magnet is 0.16 Wb.
The cross sectional area of the gap is 200 mm^2.
Calculate the flux density in the gap.



SOLUTION

ϕ = 0.16 Wb   A = 200 x 10^{-6} m^2.
B = ϕ/A = 0.16/200 x 10^{-6} = 800 Tesla

In the following work, it is useful to think of a magnetic flux created by a coil wound on a ring (toroid) of magnetic material as shown. This ring forms a complete circuit of uniform cross sectional area A and length ℓ. In the simple electric circuit shown, the current flowing depends on the voltage V and the resistance R.



In the magnetic circuit, a flux ϕ flows. The strength of the flux depends on the coil and this property is called the **MAGNETO MOTIVE FORCE** (m.m.f.). This is equivalent (analogous) to the voltage. We need a property equivalent to resistance to describe how easy it is for the flux to flow. This property is called **RELUCTANCE.**

Electrical resistance depends on a property of the material called the conductivity (or resistivity). Different materials have different electrical resistance (Silver is the best but copper is very good). In the same way, the reluctance of a material depends on a property called the **PERMEABILITY** (iron is good but there are even better materials).

2.3 MAGNETO MOTIVE FORCE m.m.f.

The m.m.f. is created by the current flowing in the coil. It is directly proportional to the current 'I' and the number of turns of the coil 'T'.

m.m.f. = I T The units are Ampere Turns (A T)

Permanent magnets have a theoretical m.m.f to explain the permanent flux. In order to understand magneto motive force, we need to study the closely related topic of magnetising force next.

2.4 MAGNETISING FORCE H

The toroid in the previous section formed a complete ring of uniform cross section. The length ℓ is the mean circumference of the ring. The magnetising force is defined as the m.m.f. divided by ℓ.

$H = IT/\ell$ The units are Ampere turns per metre.

WORKED EXAMPLE No. 2

A coil is wound on a toroid core 50 mm mean diameter. There are 500 turns. Calculate the m.m.f. and the Magnetising force when a current of 2 A is applied.

SOLUTION

m.m.f. = I T = 2 x 500 = 1000 Ampere Turns
ℓ = circumference = $\pi D = \pi \times 0.05 = 0.157$ m
H = m.m.f./ℓ = 1000/0.157 = 6366.2 AT/m

2.5 RELATIONSHIP BETWEEN B AND H

The toroid has a uniform cross sectional area A so the flux density is simply $B = \phi/A$.

The flux and hence flux density depends on the m.m.f. and hence the magnetising force.

For any coil it is found that B/H = constant. Here it gets a bit difficult because unless the material is magnetic, the flux will flow through the air and the length of the magnetic circuit is not apparent. It has been found that for a simple coil with no core at all (a complete vacuum), the constant is 12.566×10^{-7} and this is called the ABSOLUTE PERMEABILITY OF FREE SPACE and has a symbol μ_o.

If a magnetic material such as iron is placed inside the coil, the constant increases. The ratio by which the constant increases is called the RELATIVE PERMEABILITY AND has a symbol μ_r. It follows that: **$B/H = \mu_o\mu_r$**

It is difficult to apply this to a simple coil as the length of the magnetic circuit is not obvious unless the coil is wound on a magnetic material to produce a circuit. Suppose our circuit is the simple toroid again. For the electric analogy we have Ohm's Law V/I = R
By analogy, in the magnetic circuit m.m.f/ϕ = reluctance

Substitute $B = \phi/A$ and H = m.m.f./ℓ into the equation above and ϕ l /(A m.m.f.) = $\mu_o\mu_r$
Rearrange and m.m.f/ϕ = $\ell/(A\mu_o\mu_r)$ = Reluctance

$$\text{Reluctance} = \ell/A\mu_o\mu_r$$ The units are A T/Wb

WORKED EXAMPLE No. 3

In example No.2 the magnetic core has a relative permeability of 300. Calculate the reluctance, the flux and the flux density. The cross sectional area of the core is 50 mm^2.

SOLUTION

Reluctance = $\ell/A\mu_o\mu_r$ = 0.157 /(50 x 10^{-6} x 12.566 x 10^{-7} x 300) = 8.33 x 10^6 AT/Wb

m.m.f/ϕ = reluctance ϕ = m.m.f. / reluctance = 1000/8.33 x 10^6 = 120 x 10^{-6} Wb

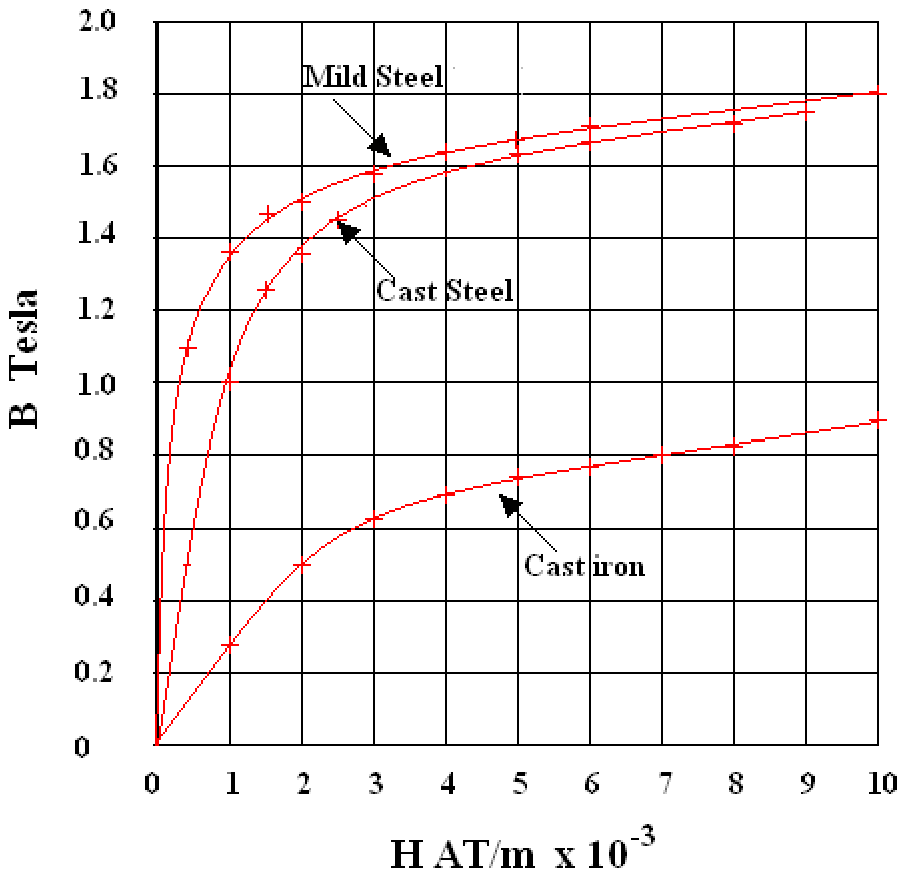
B = ϕ/A = 120 x 10^{-6}/50 x 10^{-6}) = 2.4 T

CHECK WITH

B = $\mu_o\mu_r$H = 12.566 x 10^{-7} x 300 x 6366.2 = 2.4 T

2.6 **B – H GRAPHS**

For non-magnetic materials μ_r is always about 1.0. For magnetic materials, the relative permeability μ_r is not constant as implied previously and B is not directly proportional to H. This is not a major problem as manufacturers produce the information in the form of a B – H graph and we can find the values of one if the other is known. A typical graph is shown below.



Typically, the value of B increase directly with H when the values of I are small but when the values of H become large, B becomes constant. When B is constant, the magnetic core is said to be **SATURATED**.

WORKED EXAMPLE No. 4

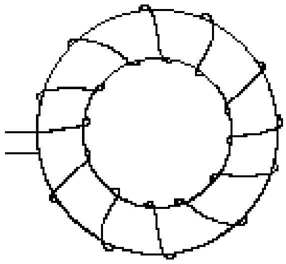
Using the B – H graph, determine (i) the value of H when B = 0.6 for cast iron and (ii) the value of B when H = 6000 AT/m for mild steel sheet.

SOLUTION

(i) H = 2800 AT/m (ii) B = 1.7 Tesla

WORKED EXAMPLE No. 5

The toroidal coil shown has 50 turns and the mean circumference is 250 mm. The diameter of the circular cross section is 10 mm. The relative permeability is 700. Calculate the current needed to produce a flux of 0.002 Wb in the core.



SOLUTION

Reluctance = $\ell / A\mu_o\mu_r$ = $0.25(12.566 \times 10^{-7} \times 700 \times \pi \times 0.005^2)$

Reluctance = 3618720 Ampere Turns/Wb

mmf = ϕ x reluctance = 0.002 x 3618720 = 7237.4 Ampere Turns

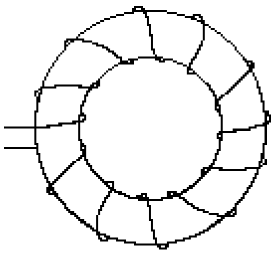
mmf = IT hence I = 7237.4/50 = 144.7 A

SELF ASSESSMENT EXERCISE No. 1

1. The diagram shows a coil wound on a toroid. Determine the following.

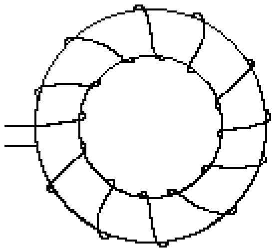
(i) The m.m.f. (320 Ampere Turns)
(ii) The flux. (1.675×10^{-4} Wb)
(iii) The flux density. (3.35 T)
(iv) The magnetising force. (5333 Ampere Turns/metre)

$A = 50\ mm^2$
$\ell = 60$ mm
T = 80 Turns
$\mu_r = 500$
I = 4 Amps



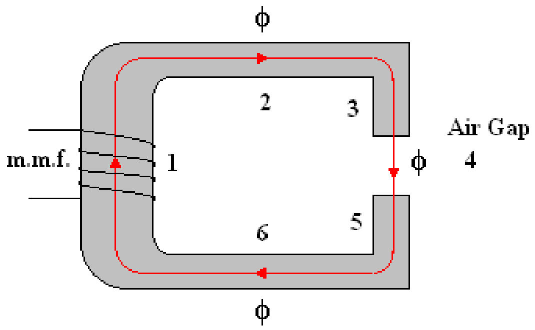
2. The diagram shows a coil wound on a ring core.
Determine the current which produces a flux of 800 μWb. (8.5 Amps)

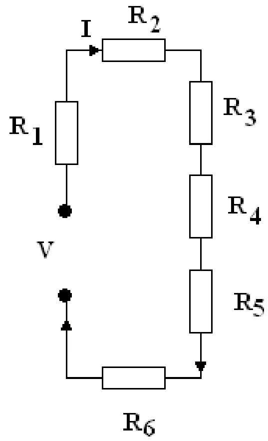
Material – Cast Steel core.
$A = 500\ mm^2$
$\ell = 0.4$ m
T = 200 Turns



2.7 NON – UNIFORM MAGNETIC CIRCUITS

This section is for those wanting some more advanced knowledge on the subject. Consider a magnetic core as shown with six different sections. One of these is the air gap. The flux is generated by the coil producing the m.m.f. and driven through all six sections in series. Each section has a length, area and relative permeability so each has reluctance. The analogous electric circuit is six resistors in series. The solution of problems involves finding the reluctance of each section and adding them to find the overall reluctance. As the next example shows, it is probably simpler to calculate the m.m.f. required to drive the flux through each section and add them up





WORKED EXAMPLE No. 6

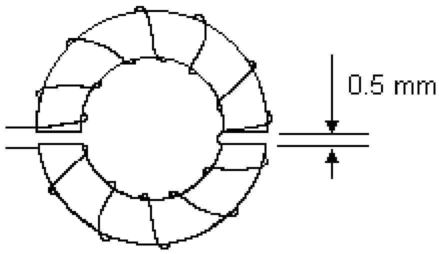
The toroid shown has two air gaps of 0.5 mm width as shown. Determine the current which produces a flux of 800 μWb.

Material - Mild steel core.

A = 500 mm^2 at all points.

ℓ = 0.4 m

T = 200 Turns



SOLUTION

B = ϕ/A = 800 x 10^{-6}/500 x 10^{-6} = 1.6 Tesla at all points.

We have two reluctances, the steel sections form one and the air gaps the other.

First solve the m.m.f. required to drive the flux through the steel sections taking l = 0.4

From the B - H graph H = 3 200 Ampere Turns/ metre for the steel.

mmf = H ℓ = 3 200 x 0.4 = 1280 Ampere Turns

Now repeat for the air gap. This time we use the relationship B/H = $\mu_o\mu_r$ to solve H. The total length is 1 mm. For air μ_r = 1 μ_o = 12.57 x 10^{-7}

B/H = $\mu_o\mu_r$ = 12.57 x 10^{-7} x 1 and B is the same value of 1.6 Tesla

H = B/ 12.57 x 10^{-7} = 1.274 x 10^{6} Ampere turns/metre

ℓ = 1 mm

m.m.f. = H ℓ = 1.274 x 10^{6} x 0.001 = 1274 ampere Turns

Total m.m.f. = 1280 + 1274 = 2554 Ampere Turns

m.m.f. = I T hence I = m.m.f./T = 2554/200 = 12.77 Amperes.

SELF ASSESSMENT EXERCISE No. 2

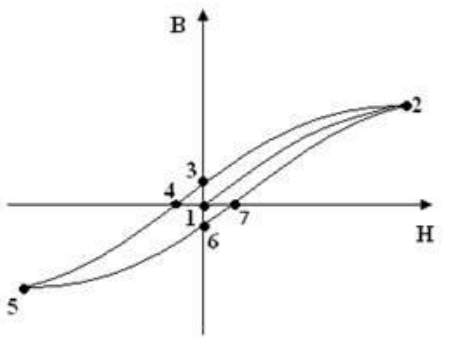
1. A coil is wound on a cast iron core. The core is 300 mm long and 600 mm^2 cross sectional area with an air gap of 10 mm. There are 5000 turns and flux in the core is 500 μWb.
   Calculate the current flowing in the coil. (1.8 Amperes)

2. A coil is wound on a ferrite ring 80 mm long and 100 mm^2 cross sectional area with two air gaps of 0.8 mm. There are 400 turns and flux in the core is 90 μWb. μ_r for ferrite is 1500.
   Calculate the current flowing in the coil. (2.959 Amperes)

2.8 HYSTERESIS

Hysteresis is a phenomenon associated with magnetic materials that are capable of being permanently magnetised. When the magnetic flux is created by a coil carrying a direct current, the material becomes permanently magnetised. If the current is reversed, the material becomes permanently magnetised in the opposite direction. The problem arises when the current is alternating so that it reverses at regular intervals (50 times a second for mains frequency).

Consider a coil wound on an iron core. Follow the process described on the B – H curve. A current is applied and a flux is produced. If the current is gradually increased and the values of B are plotted against H we get a B - H graph from 1 to 2. At point 2, a further increase in current does not produce an increase in B and the core is said to be saturated. If the current is switched off at this point the iron core will remain magnetised and form a permanent magnet.



If the current is gradually reduced from its maximum value and we continue to plot B against H we will get the graph 2 to 3. At point 3 the current is zero but we now have a flux because the core is magnetised in one direction and forms a permanent magnet. In order to reduce the magnetic flux to zero, we must apply a negative current and this takes the graph to point 4. Continuing to increase the current in the negative direction increases the flux in a negative direction (N and S poles are reversed) and the graph 4 to 5 is obtained. At this point the iron is magnetised in the opposite direction to before. If the current is reduced back to zero the graph 5 to 6 is obtained and at point 6 the current is again zero but there is a permanent flux opposite in direction to before.

If the current is now increased in the positive direction again the flux will be reduced to zero at point 7 and then increases positively back to point 2.

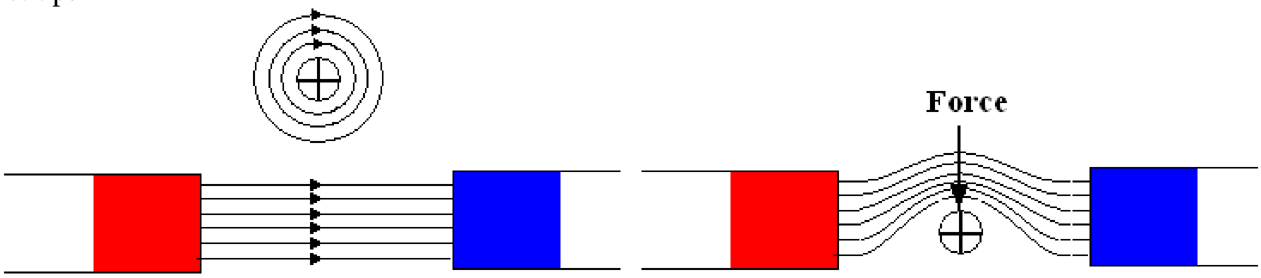
If we continue to alternate the current plus and minus (i.e. apply a.c.) the B - H graph will follow the loop 2,3,4,5,6,7,2 over and over again. This loop illustrates the HYSTERESIS EFFECT. Hysteresis may be defined as a process where a graph takes a different path for increasing and decreasing values.

The hysteresis loop on a B - H graph is the result of the iron being permanently magnetised first in one direction and then the other. The area enclosed by the loop represents energy being lost. This is why an iron core gets hot when ac is applied to the coil. This is important in transformers where part of the heat generated is due to this effect.

3. FORCE ON A CONDUCTOR - MOTOR PRINCIPLE

3.1 FORCE

A major discovery leading to the invention of the electric motor was that a conductor placed in a magnetic field experiences a force when current flows in it. Consider a conductor placed in a gap between the poles of a magnet. When current passes through the conductor, we have two magnetic fields, the circular lines around the conductor and the parallel lines between the poles. The lines of magnetism between the north and south poles would rather pass over the top of the conductor because both lines are in the same direction on top. The lines behave like elastic bands and force the conductor down. If the direction of either the current or the magnetic field is reversed, the force will act up.

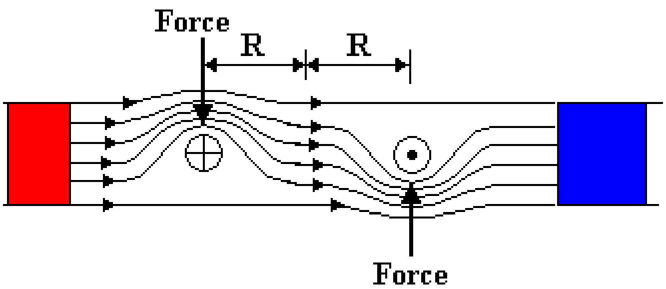


The force on the conductor is directly proportional to the current 'I' , the magnetic flux density 'B' and the length 'ℓ' of the conductor within the flux.This is the important equation for the force on a conductor.

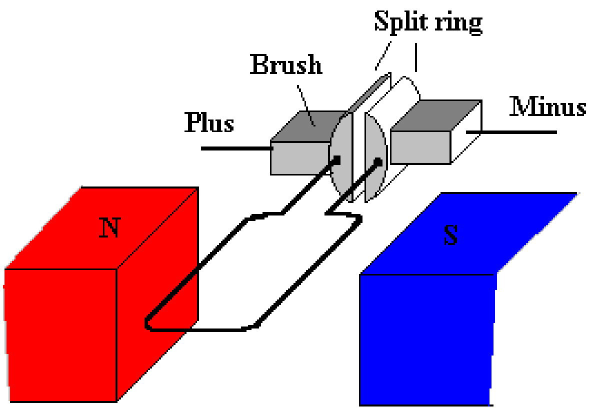
$$F = B \ell I$$

3.2 TORQUE ON A LOOP

This principle may be used to produce a simple electric motor. Consider a single loop coil placed in the magnetic field as shown. The current flows into one side and out of the other. This produces a downwards force on one side and an upwards force on the other at a radius R. This produces a torque on the coil of T = F R. This will make the loop rotate and but when it turns 90^o the radius is zero and the torque is zero so it will stop.

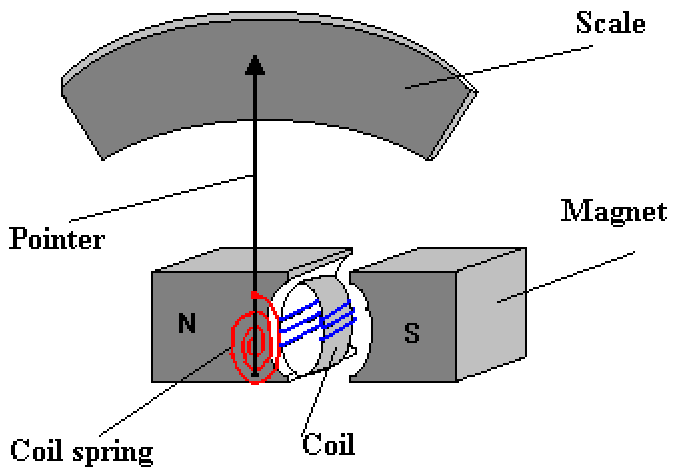


If we reverse the current as it passes the 90^o position the torque will continue to make it rotate. Switching the direction of the current every half rotation will produce continuous rotation. This can be done with a split ring as shown.



The design is further improved by using several loops and switching the current to the one in the horizontal position all the time. The split ring becomes a commutator with many segments. Each pair of segments is connected to a loop and each pair in turn becomes connected to the brushes as it rotates.

3.3 MOVING COIL METER

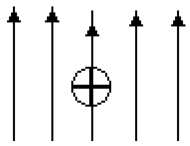


Modern instruments for measuring electric current are electronic with digital indication. The moving coil instrument uses the motor principle to indicate current and although not now used, the same principle is used in many other forms of electro-mechanical equipment.

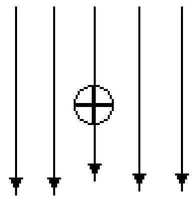
The loop or coil rotates only 90^o and rotation is governed by a spring. The loop is connected to a pointer which moves on a scale. The movement is directly proportional to current in the coil.

SELF ASSESSMENT EXERCISE No. 3

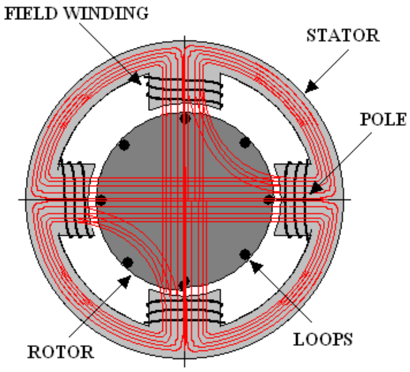
1. The diagram shows a conductor 60 mm long carrying 12 Amperes in a flux of density 1.2 Tesla.
   Calculate the force acting on it and determine the direction of the force.
   (0.864 N to right)



2. The diagram shows a conductor 80 mm long carrying 5 Amperes in a flux of density 0.2 Tesla.
   Calculate the force acting on it and the direction in which it moves.
   (0.08 N to left)



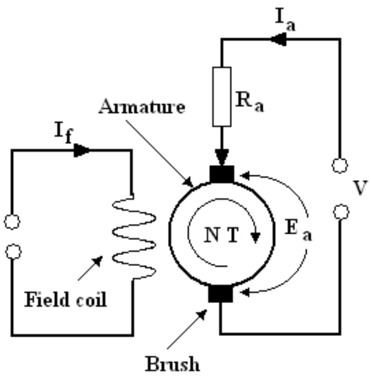
4. THE GENERAL PRINCIPLES OF D.C. MOTORS



The motor principle describe in the preceding work must be turned into a practical design. Usually there are several loops arranged on a **ROTOR** as shown in the cross section. The magnets are placed in the housing or **STATOR.** The current is supplied to the loops within the magnetic field causing the rotor to move. As a new loop enters the magnetic field the current is switched to it to keep the rotation going. This may be done with a **COMMUTATOR** and **BRUSHES** but it can be done electronically.

The magnetic poles may be permanent magnets but in more powerful motors they are electro-magnets with a coils wound on the poles called the **FIELD WINDINGS**. The stator and rotor form a magnetic circuit and the flux crosses the loops on the armature as shown. The strength of the magnetic flux can be changed by changing the current. The rotor in the diagram would be called the **ARMATURE.**

In a basic D.C. motor, current has to be supplied to the field windings to produce the magnetic flux. Current must be supplied to the armature to produce the torque. The basic circuit for a motor is shown. Note the brushes used to contact armature.



TERMINOLOGY USED

I_a = armature Current V = Supply voltage

E_a = EMF at the armature.

R_a = resistance of the armature coils.

$E_a = V - I_a R_a$

If the armature windings were perfect conductors then $E_a = V$

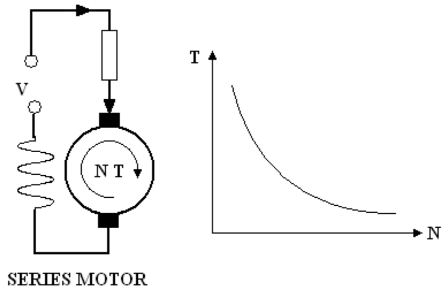
I_f = Field current T = Torque

N = rotor speed in rev/s

There are various ways of arranging the field windings and armature but the two most common ways are in **SERIES** and as a **SHUNT.**

SERIES MOTOR

In this case, the field winding is in series with the armature.
The same current flows through the armature and the field winding.



The mechanical power of any rotor is $P = 2\pi NT$

The electric power of any rotor is ideally $P = E_a I_a$

Equating and rearranging we see that $T = E_a I_a / 2\pi N$

If the electric power is constant, $E_a I_a$ are constant so T = Constant /N

This means that for a constant electrical power the speed would increase as the load is removed and decrease as the load increases as shown by the graph.

DISADVANTAGE

At low torque (no load conditions) the motor is liable to over speed and become damaged.

ADVANTAGE

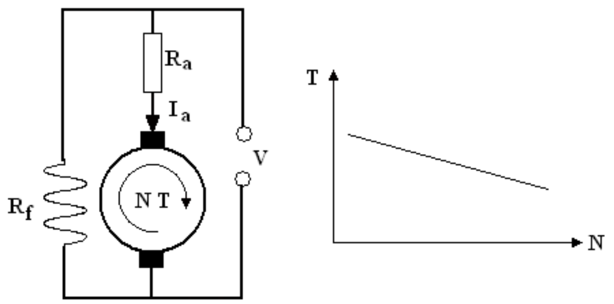
At low speed there is a high torque (starting torque) which is ideal for servo applications.

SHUNT MOTOR

In this case the field winding is connected in parallel with the armature as shown. The field current is constant so flux cannot be changed except by changing the supply voltage.

$E_a = V - I_a R_a$

It can be shown that $T = C_1 - C_2 N$
C_1 and C_2 are constants.



SHUNT MOTOR

This shows that at zero speed the starting torque is C_1 and as speed increases, the torque drops off. The ideal Torque - Speed characteristic is as shown. In reality the line is curved down due to other effects not considered.

WORKED EXAMPLE No. 7

A D.C. motor is shunt wound and is supplied with 400 V. The armature resistance is 1.2 Ω and the field winding has a resistance of 300 Ω. When running with a torque of 70 Nm, the motor takes 19 Amps. Determine the speed of the motor assuming the electrical power is converted into mechanical power with 100% efficiency.

SOLUTION

The field is connected across the supply. The current taken by the field winding is

$$I_f = 400/300 = 1.333 \text{ amp}$$

The current taken by the armature is hence 19 - 1.333 = 17.666 A

$E_a = V - I_a R_a = 400 - 17.666 \times 1.2 = 378.8$ V

Electric power converted into mechanical power = $E_a I_a = 378.8 \times 17.666 = 6692$ Watts
Assuming the conversion process is 100% the Mechanical power = 6692 W
$2\pi NT = 6692$

$N = 6692/(2\pi T) = 6692/(2\pi \times 70) = 15.21$ rev/s or 912.9 rev/min

WORKED EXAMPLE No. 8

It is observed that the same motor as in the previous example has a torque of 105 Nm when it stalls. Assuming the torque speed relationship is linear of the form $T = C_1 - C_2 N$ determine the constants c1 and C2.

SOLUTION

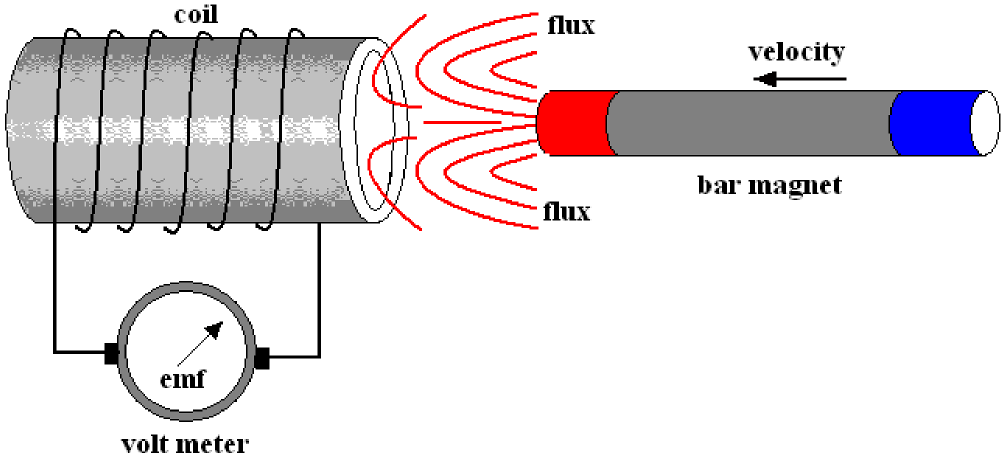
When N = 0, $T = C_1 = 105$Nm
When N = 15.21 rev/s, $T = 70 = 105 - C_2(15.21)$ hence $C_2 = 2.3$ Nm s/rev

5 THE GENERATOR PRINCIPLE

5.1 COIL AND MAGNET

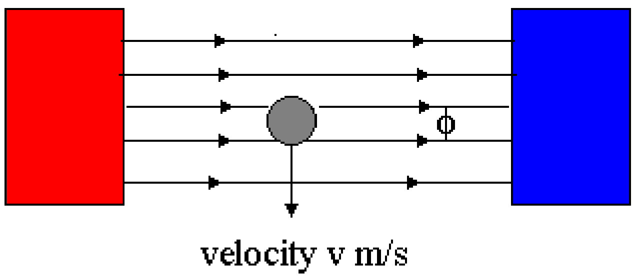
Discoveries by people like Oersted and Faraday established that an electric current can be generated by moving a conductor relative to a magnetic field so that it cuts the lines of flux.

This is best demonstrated by inserting a magnet into a coil as shown. The magnet is inserted in the coil and all the flux cuts across the turns of the conductor at 90^{o} and induces an e.m.f. An e.m.f. is generated only when the magnet is moved. Changing the direction of movement changes the polarity of the e.m.f.



5.2 CONDUCTOR CROSSING A UNIFORM FLUX

We will come back to the coil later. Now consider a conductor crossing a flux as shown. As it moves a voltage is generated in it. If current is produced then the voltage will be reduced slightly by the resistance of the conductor. The ELECTRO MOTIVE FORCE or E.M.F. is the theoretical voltage as though the conductor had no resistance and this is denoted with the symbol e. Note that e is used for e.m.f. when the values are instantaneous and changing. E is used for a constant value.

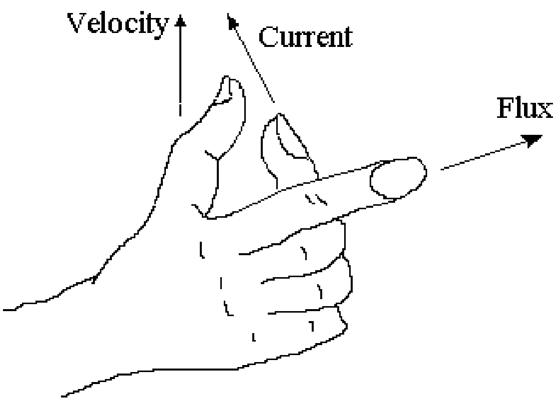


The E.M.F. is directly proportional to the flux density B, the velocity v and the length of the conductor within the flux l. It follows that the e.m.f. is given by:

$$e = B\,l\,v$$

This is the generator equation.

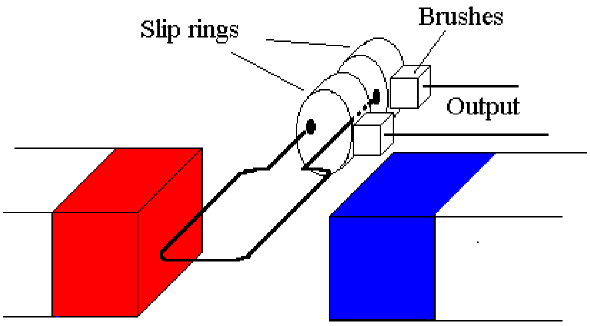
5.3 FLEMING'S RIGHT HAND RULE

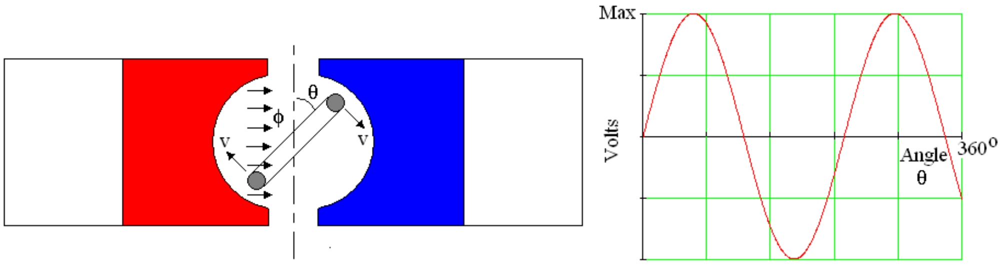


The direction of the current generated is found from Fleming's Right Hand Rule. Point the index finger of your right hand in the direction of the flux (North to South). Point your thumb in the direction of the velocity. Bend over the second finger and it points the direction of the current.

5.4 CONSTRUCTION OF GENERATOR

A simple generator may be constructed exactly the same as the simple motor. Instead of passing current into the loop, the loop is made to rotate and a voltage is generated across the end of the loop. The current flowing from the terminals is governed by the resistance connected between them (e.g. the resistance of a light bulb).



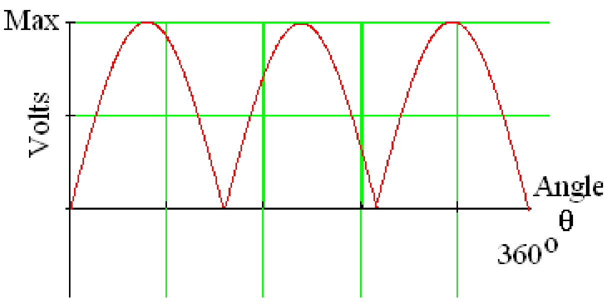


The voltage generated is directly proportional to the angle of the loop to the flux 'θ'. The output voltage is given by

$$V = V_{max} \sin \theta$$

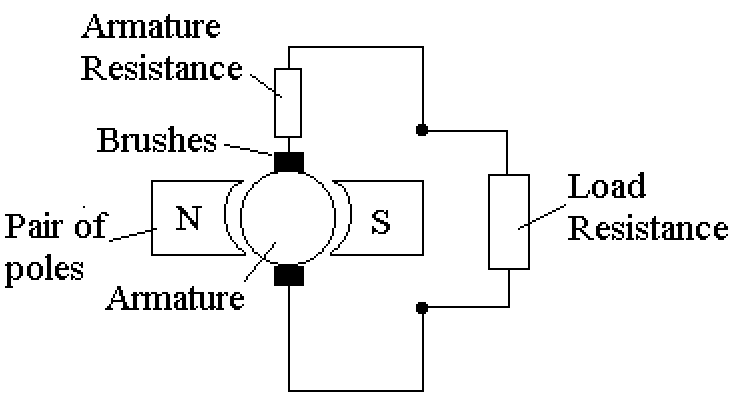
V_{max} is the maximum voltage and θ is the angle of rotation. The simple generator shown produces alternating current which is sinusoidal in form.

If the coil is connected to a split ring, the polarity is reversed every half revolution and the output is a direct current consisting of half sinusoidal waves.



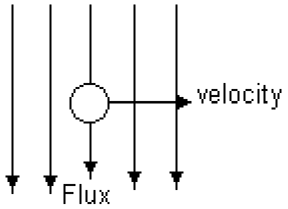
The e.m.f. is generated in the armature and the current is tapped off through brushes. If many coils are used with a commutator, the output can be made into a constant DC form.

The diagram below shows a schematic of the generator with a load across the terminals. The armature resistance represents the resistance of the coil. The ideal voltage generated is E but when a current I flows, the terminal voltage is given by $V = E - I R_a$

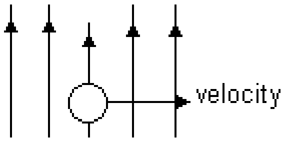


SELF ASSESSMENT EXERCISE No. 4

1. The diagram shows a conductor moving through a flux. The length is 80 mm and the flux density is 2 Tesla. The velocity is 12 m/s. Calculate the emf produced and the direction of the current.
(1.92 V into the page)



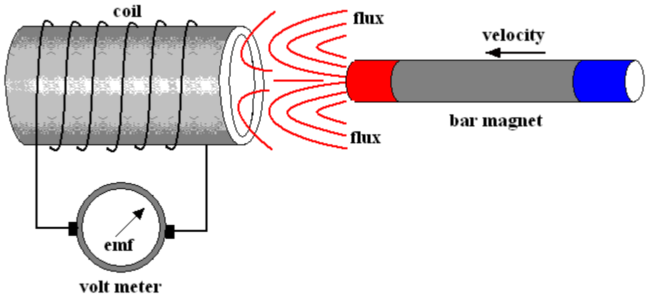
2. The diagram shows a conductor moving through a flux. The length is 100 mm and the flux density is 1.8 Tesla. The velocity is 2 m/s. Calculate the emf produced and the direction of the current.
(0.36 V out of page)



6. ELECTRO-MAGNETIC INDUCTION

In order to understand this topic fully, you need to understand differential calculus and the basics of alternating current theory so the theory is cut down and kept as simple as possible. You will find a fuller version of this tutorial on the web site www.freestudy.co.uk.

6.1 E.M.F. GENERATED IN A COIL

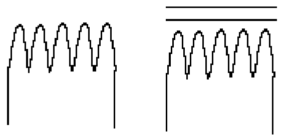


Consider the case of a magnet being moved into a coil as discussed earlier. The generator principle applies and in this case we can say that the e.m.f generated depends on the number of turns on the coil 'n' and the relative velocity of the magnet.

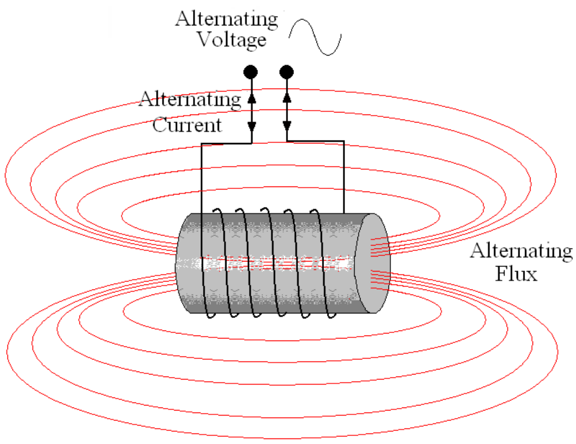
We know that when a current flows in a coil, a magnetic flux is generated. If we generate a current we also generate a magnetic field in the coil and this will produce a force of repulsion between the magnet and the coil so that mechanical work has to be done to move the magnet. This is the source of the energy produced in the current.

6.2 INDUCTORS and BACK E.M.F.

Any coil of wire is an inductor. A coil made specifically for an electric circuit is called an inductor. The diagram shows the symbols for one with an air core and one with a magnetic core.



An ideal Inductor has no affect on direct current. In reality they have a small resistance in the copper wire. When alternating current is applied, electro-magnetic induction produces a reaction. Inductors and capacitors are examples of REACTIVE components because their properties are affected by the frequency of the current flowing through it. Resistors are not affected and are called PASSIVE.



Consider a coil in which alternating current is flowing. The current produces an alternating magnetic flux.

The alternating flux cuts across the coil and generates an e.m.f. that is opposite in sense to the applied voltage. This is called the back e.m.f. This opposes the flow of the applied current (Lenz's Law) and a minus sign is used in Faraday's law. The back e.m.f. is hence:

e = - n x rate of change of flux

The applied voltage must be equal and opposite. This means that even though there is no resistance in the coil, a voltage is required to make alternating current flow. This voltage depends on the rate of change and hence the frequency. This is not resistance it is called REACTANCE. Without theory it can be shown that :

e = - L x rate of change of current

L is a property called the Inductance and the units are called Henries (H). The base unit is very large and mH or μH is more common. It can further be shown that :

$$L = \mu_o \mu_r An^2/l$$

This is a theoretical formula for the inductance of a coil. A is the cross sectional area of the core and l the length of the inductor. The problem with a coil as shown above is that half of the flux is in the core and half in the air outside so we cannot calculate L easily unless the core is a ring.

WORKED EXAMPLE No. 9

An inductor is made by winding 1500 turns on a ring. The mean circumference is 250 mm and the ring has a circular cross section 25 mm diameter. The core material has a relative permeability of 420. Determine the inductance given $\mu_o = 12.5 \times 10^{-7}$.

A current is made to vary in the coil at 300 A/s. Calculate the back e.m.f.

SOLUTION

$L = \mu_o \mu_r An^2/\ell$

$A = \pi \times 0.025^2/4 = 490.87 \times 10^{-6}\ m^2$.

$\ell = 0.25$ m

$L = 12.5 \times 10^{-7} \times 420 \times 90.87 \times 10^{-6} \times 1500^2/0.25 = 2.33$ Henries

e = - L x rate of change of current = - 2.33 x 300 == -700 Volts

6.3. ENERGY STORED IN AN INDUCTOR

Suppose the current in an inductor is increased uniformly from 0 to I Amps in time t seconds. The rate of change of current is constant and equal to I/t. The e.m.f. required is L I/t

Remember that Electric Power is volts x Current.
The power grows from P = 0 to P = V I in time t. The energy stored is the mean power x time and the mean is half the maximum.

Energy = V I t/2   Substitute V = LI/t and the energy stored is **Energy = L I^2/2**

SELF ASSESSMENT EXERCISE No. 5

1. An inductor is wound on a toroid 50 mm mean diameter and a round cross section 10 mm diameter. There are 300 turns and the relative permeability is 500.
   Calculate the inductance.
   (28 mH)

2. Calculate the energy stored in an inductor of value 1.7 H when 5 Amps flow.
   (21.25 J)

3. An inductor stores 5 Joules when 2 A flow in it. Calculate the inductance value.
   (2.5 H)

7. TRANSFORMERS

7.1 DESCRIPTION

Transformers are devices for changing alternating voltages and currents. The types of transformers vary from very large to very small. Very large ones are used for transforming the a.c. power generated at a power station to and from a high voltage grid. Smaller ones are used to transform the mains voltage down to a useable level such as 12 V for use in electronic equipment. These have largely been replaced by modern electronic devices that are much smaller, lighter and cheaper. In other areas of electronics such as radio receivers, small transformers working at high frequencies are common.

SUB STATION TRANSFORMER

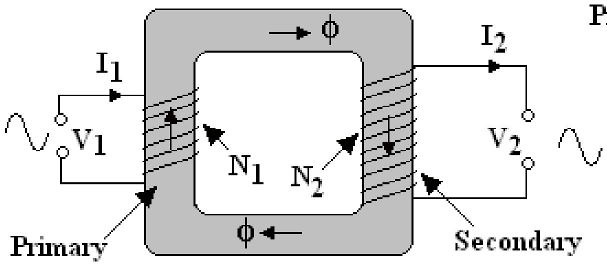
415 V - 240 V

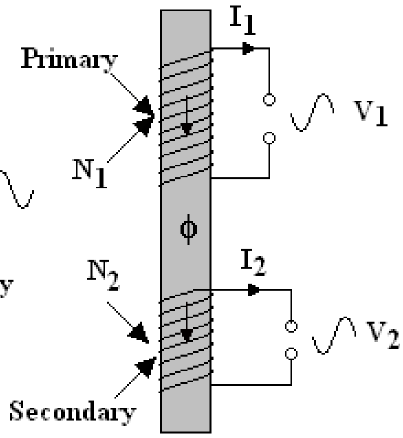
240 V - 110 V

Small transformers for electronic equipment

7.2 PERFECT TRANSFORMER

A perfect transformer has two coils placed in close proximity to each other. An alternating voltage is applied to one coil called the primary winding and this produces an alternating magnetic flux ϕ. The flux cuts the turns of the second coil (called the secondary winding) and generates an e.m.f. at the same frequency. If the secondary voltage is smaller than the primary we have a ‘step down’ transformer. If the voltage is larger we have a ‘step up’ transformer.





In order to make all the flux ϕ cut both windings, they are either wound on a core that forms a closed loop or wound very close to each other. In this event, the ratio of the voltages is in direct proportion to the number of turns on each winding such that:

$$\mathbf{V_1/V_2 = N_1/N_2}$$

In the ideal transformer, the electric power going in at the primary would be the same as the power coming out of the secondary. In this case:

$P_1 = V_1 I_1 = P_2 = V_2 I_2$ Hence $\mathbf{V_1/ V_2 = I_2/ I_1 = N_1/N_2}$

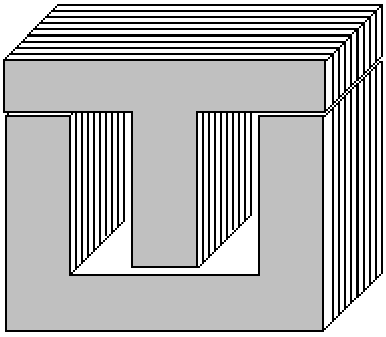
Note that if the voltage is stepped up, the current is stepped down and vice versa.

7.3 REAL TRANSFORMERS

Real transformers are affected by energy losses. These fall into two main groups -CORE LOSS and COIL LOSS

7.3.1 CORE LOSS

Large power transformers have iron cores and these become hot and lose energy because of HYSTERESIS and EDDY CURRENTS. The core losses are near constant and are not affected by the current flowing in the coils. Hysteresis was explained earlier and heats up the iron core of a transformer and this is an energy lost.



EDDY CURRENTS

The alternating flux generates electricity in the magnetic core material. As this is a short circuit, random currents flow in the material and dissipate energy as heat due to the electrical resistance. In order to reduce this, larger transformers have cores made from laminate iron sheets and each layer is insulated from each other.

SCREENING

Transformers (and other induction devices) may produce very strong electro-magnetic fields. These should be contained by placing a screen around them in the form of some kind of iron container.

6.3.2 COIL LOSSES

RESISTANCE

The losses in the primary and secondary coils are due to the Ohmic resistance of the copper windings. Energy is lost in the form of heat. These losses are best calculated with the formula $I^2 R$ and so they increase as the square of the current. There areother losses which are not discussed here.

EFFICIENCY η

In simple terms the efficiency of a transformer is the ratio of the Power in top the power out but this is complicated by the power factor of the load. The primary is referred to as 1 and the secondary as 2.

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{P_2}{P_1} = \frac{P_2}{P_2 + \text{copper loss} + \text{core loss}}$$

$$\eta == \frac{I_2^2 R_2}{(I_2^2 R_2 \text{ x PF}) + \text{copper loss} + \text{core loss}}$$

The copper loss is $I_2^2 R_2 + I_1^2 R_1$

WORKED EXAMPLE No. 10

A 5/1 step down transformer has a full load secondary current of 20 A 500V. The primary winding has 800 Turns.

Assuming ideal conditions determine the following.

(i) The number of turns on the secondary coil.
(ii) The voltage and current in the primary winding.

SOLUTION

$N_2 = N_1/5 = 800/5 = 160$ turns

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} = 5 \quad I_1 = \frac{20}{5} = 4\text{ A}$$

$V_1 = 5V_2 = 5 \times 500 = 2500$ V

If the transformer has losses due to a secondary resistance of 0.3 Ω and no other losses, determine the efficiency of the transformer.

SOLUTION

Power loss in the secondary = $I^2 R = 20^2 \times 0.3 = 120$ W

Ideal Power input = $V_2 I_2 = 20 \times 500 = 10$ kW
Actual Power out = 10 000 – 120 = 9880 W
Ideal Power Input = 10 kW

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{9880}{10000} = 0.988 \text{ or } 98.8\%$$

SELF ASSESSMENT EXERCISE No. 6

1. A simple high frequency transformer with negligible losses is required to transform 0.05 V rms to 1 V rms. The primary has 10 turns. How many turns should the secondary have? (200)

2. An ideal step down transformer must change 240 V rms into 12 V rms. The secondary winding has 20 turns and produces 5 A.

   Assuming ideal conditions determine the following.

   (i) The number of turns on the primary coil. (400)
   (ii) The current in the primary winding. (0.25 A)
   (iii) The efficiency if the 15 W are lost in the secondary winding. (75 %)