MAGNETS & MAGNETISM

PURPOSE:

This section introduces magnets, magnetism, magnetic induction and applications of permanent magnets.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Draw the magnetic field patterns of bar and horseshoe permanent magnets.
- State the laws of magnetic attraction and repulsion.
- Describe magnetic lines of force and list their characteristics.
- Define magnetic flux and flux density and solve calculations involving these quantities in relation to bar magnets.
- Explain magnetic induction and its effects.
- Describe the principles of magnetic screening and its application.
- List practical applications for permanent magnets.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 95-98.

2. ARTIFICIAL MAGNETS

A magnet may be defined as -

____

____

The property of attracting in this way has already been referred to as magnetism. It was also pointed out that if a magnetic substance, such as a piece of steel, is brought within the influence of a natural magnet, the steel will have magnetism induced in it, that is, it will become a magnet and possess all the properties of magnetism. To distinguish this "made" magnet from a natural one, it is called an **artificial magnet**, that is, a magnet made by the art of man.

Modern magnets are all artificial and are magnetised by electrical means.

Artificial magnets can be separated into two distinct groups -

- ____________________

A magnet which, under the influence of a magnetising agency such as another magnet or a current-carrying coil of wire,

____

____

____

____

____

(Usually, temporary magnets are associated with suitable coil windings and their magnetic properties are dependent upon the magnetic effect of the current in the coil.)

- ____________________

A magnet which,

____

____

____

____

Both permanent and temporary magnets have their particular application in electrical work.

Non-magnetic materials are not affected by a magnetic field (don't become magnetised) and have no effect on the field. While materials are usually grouped as either ferromagnetic or non-magnetic, there are two other groups worth mentioning, although their uses are beyond the scope of this book.

Paramagnetic materials, which include aluminium, platinum, manganese and chromium. They have a permeability slightly higher than one and become weakly magnetised in the same direction as the magnetising force.

Diamagnetic materials, which include copper, gold, silver and zinc. They become weakly magnetised, but in the opposite direction to the magnetising force and have a permeability less than one.

For the purposes of this module, think of materials as either being ferromagnetic or non-magnetic.

4. MAGNET POLES

It has already been pointed out that if a magnet is dipped into a pile of iron filings, the filings will cling to each end of the magnet but not to the middle, as illustrated in figure 4.

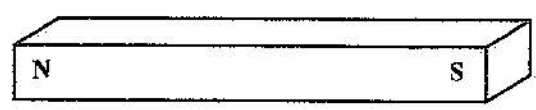


Figure 4

These regions of concentration of magnetic flux are called -

magnetic field

A permanent magnet can have a number of pairs of poles but usually it has only one pair.

5. FUNDAMENTAL LAWS OF MAGNETISM

If a bar magnet is pivoted so that it is free to move, figure 7, it will be observed that the north pole of another bar magnet brought near to it will repel the north pole of the suspended magnet but will attract the south pole. Also the south pole of a bar magnet will repel the south pole of a suspended magnet but attracts its north pole. Figure 8.

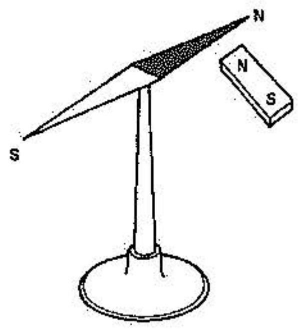


Figure 6

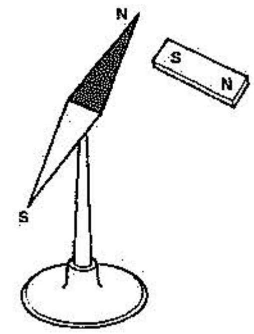


Figure 7

These simple tests verify the following fundamental laws of magnetism -

- Differed ~~Same~~ poles are attracted each other
- Same poles are repelled eachother

Repulsion (not attraction) is the test for permanent magnetism. If a magnet attracts another substance, this substance may not be a permanent magnet of opposite polarity, but merely a magnetic substance.

6. MAGNETIC FIELDS AND LINES OF MAGNETIC FLUX

The region immediately surrounding a magnet is obviously different from other regions because a mechanical force acts upon all magnetic materials placed in the region. This region, where the influence of magnetism is apparent, is called the magnetic field.

The magnetic field may be regarded as everywhere traversed by what are called -

magnetic lines.

These lines are really hypothetical, that is, they serve to explain to us what would otherwise be unexplainable. The mind would not grasp the idea of one substance acting upon another unless through some intervening medium, or means of communication. Lines of magnetic flux are regarded as the medium through which one magnet pole acts upon another.

Although the map of the field examined may give the impression that there is space between the lines of magnetic flux, this is not the case. It must be realised that the magnetic effect covers the whole of the area and that there are no gaps between the lines.

Figure 9 illustrates the map of the field of a horseshoe magnet. A horseshoe magnet is a bar magnet bent until its two poles are brought near to each other, the effect being to concentrate the field in the small space between the poles.

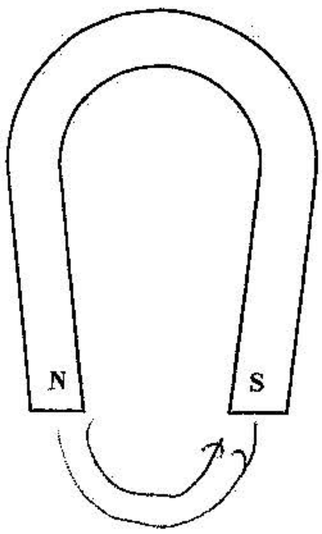


Figure 9

Figure 10 shows the field produced when the unlike poles of two bar magnets are brought near to each other.

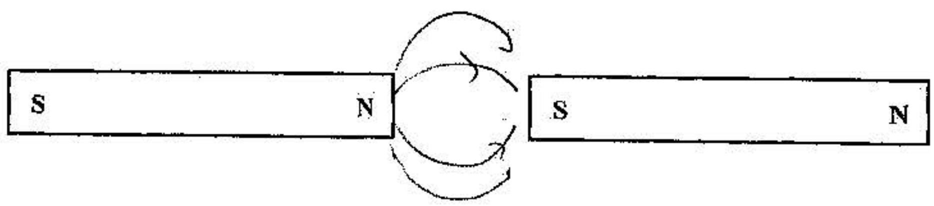


Figure 10

The fields are shown to interlink or combine, resulting in a concentrated field which produces a force of repulsion between the two dissimilar poles.

This force of attraction is due to the characteristic of perfect elasticity of the lines of magnetic flux which always tend to shorten themselves as much as possible.

Unlike poles repels one another.

As the lines of magnetic flux pass from N pole to S pole outside and S pole to N pole inside the magnet, they produce a S pole where they enter and a N pole where they leave the iron.

It will be observed, by reference to figure 12, that the pole of a magnet must always induce in any magnetic substance such polarity that unlike poles are adjacent.

Therefore, attraction always exists between a magnet pole and a magnetic substance.

Repulsion can occur only between like magnet poles. This fact is utilised when it is desired to test a specimen of steel to determine whether it is magnetised or not. If it is not magnetised, each end of the specimen will attract each pole of a magnetic needle.

8. METHODS OF MAGNETISING

A piece of steel, or other magnetic substance, is magnetised when it is brought into a magnetic field. This field may be produced by means of -

- a permanent magnet or magnets, or
- by a coil of wire carrying an electric current.

The methods of magnetising with permanent magnets are:

- **single touch method** - the specimen of steel to be magnetised is stroked from end to end several times by the same pole of a magnet and in the same direction; returning the magnet clear of the specimen after each stroke to prevent demagnetising. The polarity is determined by the direction of stroking and the pole of the magnet used; the end of the material which the magnet leaves being of opposite polarity to the pole of the magnet.

- **double touch method** - of magnetising usually provides more uniform magnetisation. In this method the material to be magnetised is secured to the bench by wax, or it may be partly embedded in a block of wax to prevent it moving. It is then stroked by two bar magnets of equal pole strength. Dissimilar poles are placed together at the centre of the specimen and both magnets are simultaneously drawn outwards; the magnets are returned clear of the specimen to prevent demagnetising, repeating the operation from six to 12 times. It is observed that the intensity of magnetisation of the material increases with each stroke for about six to eight strokes, after which any further stroking will produce no additional magnetising effect.
- **horseshoe magnet** - short specimens of magnetic substances may be conveniently magnetised by placing them across the poles of a powerful horseshoe magnet. Gently tapping the specimen, when in position, will increase magnetisation. It will be observed that the N pole produced in the specimen is adjacent to the S pole of the magnet.

The Tesla (T) is the SI unit of magnetic flux density.

The tesla is the flux density in a magnetic field when 1 Wb of flux occurs in a plane of $1m^2$.

That is,

One tesla = 1T = 1 Wb/m^2

The relationship between flux and flux density is stated by the equation -

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

where: B = the flux density in teslas
Φ = the total flux in webers
A = the cross-sectional area in m^2.

The flux density is frequently different from one point to another in the same magnetic field. For example, in the case of the bar magnet in figure 13, the flux density is obviously greatest at points close to the poles of the magnet, or within the metal.

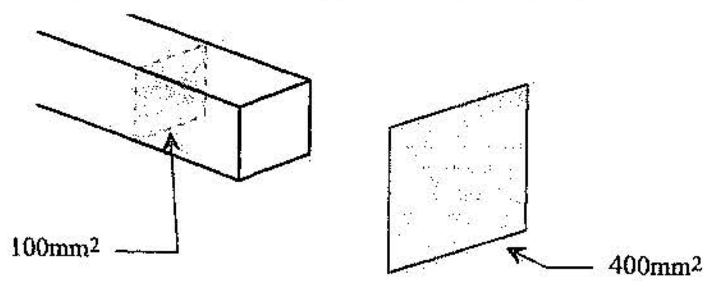


Figure 13

11. MAGNETIC KEEPERS

When magnetic material is introduced into a magnetic field, the lines of magnetic flux will crowd into the magnetic material and in most cases will increase in number owing to the reduced reluctance of the magnetic circuit.

An application of this principle is the employment of magnetic ~~induction~~ keeper for permanent magnets.

Keepers are small pieces of soft iron used to complete an all-iron path between the poles of a permanent magnet during storage. A keeper enables relatively strong magnetic flux to be maintained in the magnetic circuit; this strong field enables the magnet to retain its strength.

When not in use, bar magnets should be stored in pairs with unlike poles adjacent; preferably apart with keepers forming links in the magnetic chain. See figure 14.

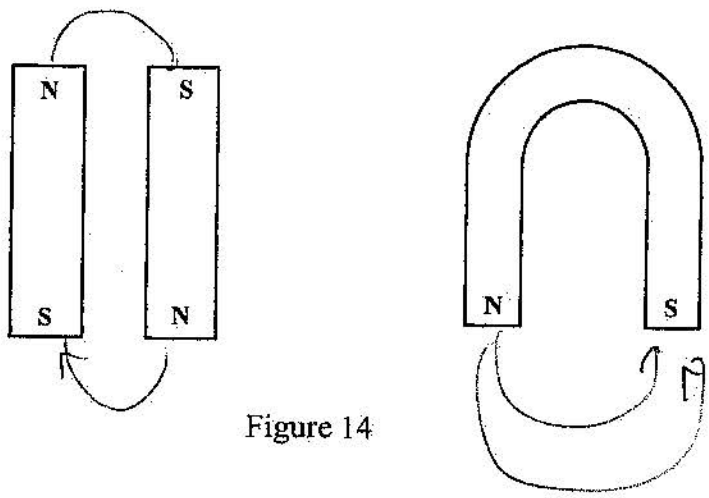


Figure 14

Magnetic keepers should be applied immediately -

- whenever permanent magnets are removed from apparatus, for example, instruments and magnetos.
- remagnetisation, as it is considered that a permanent magnet has a considerable decline in strength immediately after being removed from the magnetising agent. In fact, strong recommendation is advised in some cases for use of keepers before the magnet is removed from the magnetising agent.

MAGNETS & MAGNETISM

PURPOSE:

This practical assignment will be used to verify the basic magnetic laws, to examine the effects of magnetic and non-magnetic materials on magnetic fields and to map the magnetic fields of permanent magnets under various conditions.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Use a magnetic compass to identify the poles of a bar magnet.
- Map the magnetic field of a bar magnet.
- Map the magnetic field patterns of permanent magnets under a variety of conditions.
- Examine the effects of magnetic screening.
- Examine the effects on a magnetic field by magnetic and non-magnetic materials.

EQUIPMENT:

- ☐ 1 x magnetic compass
- ☐ 1 x magnetic field demonstration set - with round bar magnets, mild steel and brass rods
- ☐ 2 x rectangular bar magnets
- ☐ 1 x mild steel rings
- ☐ 1 x resistance proportionality panel
- ☐ 1 x various materials - copper strip, mild steel strip, plastic strip
- ☐ 1 x drawing pin

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

2. MAPPING MAGNETIC FIELDS

1. Shake the oil filled container until all the iron filings are in suspension.
2. Place one of the circular magnets into the centre tube of the container, with the north pole of the magnet to the left as shown in figure 2.
3. Allow the iron filings to settle in the form of the magnetic field around the magnet. Sketch the field pattern in figure 2.

Figure 2

4. Remove the magnet from the centre tube, then shake the oil filled container until all the iron filings are in suspension.
5. Place the two circular magnets into the centre tube of the oil filled container, arranged as shown in figure 3, with unlike poles facing. Be sure not to let the magnets touch one another.
6. Allow the iron filings to settle in the form of the magnetic field around the magnets. Sketch the field in figure 3.

Figure 3

7. Remove the magnets from the centre tube, then shake the oil filled container until all the iron filings are in suspension.
8. Place the two circular magnets into the centre tube of the oil filled container, arranged as shown in figure 4, with like poles facing.
9. Allow the iron filings to settle in the form of the magnetic field around the magnets. Sketch the field in figure 4.

13. Repeat the procedure using a combination of one circular magnet and a brass rod, arranged as shown in figure 6.

Figure 6

14. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

3. FUNDAMENTAL LAWS OF MAGNETISM

1. Place two rectangular bar magnets approximately 100mm apart on the bench, as shown in figure 7. The magnets must be arranged to have **unlike poles** facing.

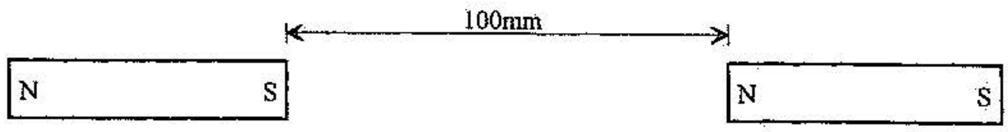


Figure 7

2. Move the magnet on the left towards the magnet on the right and note the effect as the magnets get close to one another.
3. Record your results in table 2.

5. MAGNETIC & NON-MAGNETIC MATERIALS

1. Place a rectangular bar magnet and a mild steel strip approximately 100mm apart on the bench as shown in figure 9.

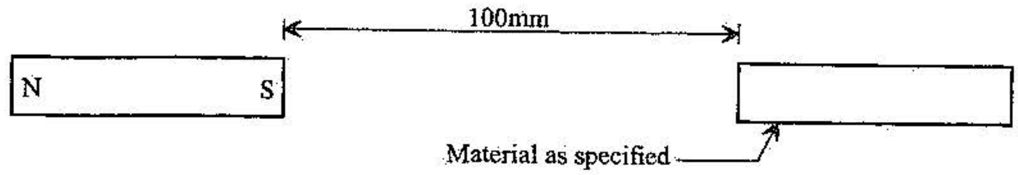


Figure 9

2. Move the magnet until it touches the steel, then move the magnet back to its original position. Observe and record in table 4, the effect of the magnet on the steel strip.

Table 4

	Type of Material			
	Mild Steel	Copper	Plastic	Wood
Effect Produced By Magnet on the Material				

3. Repeat the procedure for each of the materials shown in table 4.
4. Please return all equipment to its proper place.

6. OBSERVATIONS:

1. What is the magnetic polarity of the marked end of a magnetic compass?

____

____

2. Is the magnetic field surrounding a magnet three dimensional? Base your answer on observations made during this practical assignment.

____

____

____

____

Magnets & Magnetism

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. Magnets are classified as either ______ magnets or ______ magnets.
   (a) temporary, electro-
   (b) electro-, induced
   ✓ (c) permanent, temporary
   (d) induced, temporary

2. Magnetic properties state that like magnetic poles ______ each other, whilst ______ poles ______ each other.
   (a) repel, unlike, attract
   ✓ (b) attract, unlike, repel
   (c) repel, equal, attract
   (d) repel, neutral, attract

3. The north pole of a magnet is said to be:
   (a) north repelling, repelling the earth's north magnetic pole
   ✓ (b) north seeking, seeking the earth's north magnetic pole
   (c) south seeking, seeking the earth's south magnetic pole
   (d) north repelling, seeking the earth's south magnetic pole

4. A an example of a material which will have a magnetic field induced into it whilst under the influence of an adjacent magnet is:
   (a) copper
   (b) wood
   ✓ (c) soft iron
   (d) aluminium

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

11. The laws of magnetism state that magnetic lines of force never ___(a)___ cut, they are ___(b)___ parallel and unbroken, they can be ___(c)___ extended indefinitely, and are said to flow externally from the ___(d)___ North pole to the ___(e)___ South pole.

12. The greatest concentration of flux in a magnet will be at the North & South poles.

13. Laws of magnetism state the ___(a)___ Like poles repel, and ___(b)___ unLike pole will ___(c)___ attract each other.

14. List two materials that are:
    (a) ferromagnetic Iron, Nickel
    (b) dia-magnetic copper gold

15. Reproduce the diagram of figure 1 on your answer sheet using drawing instruments to complete your drawing. Show the field pattern produced by the permanent magnet, and label all magnetic poles.

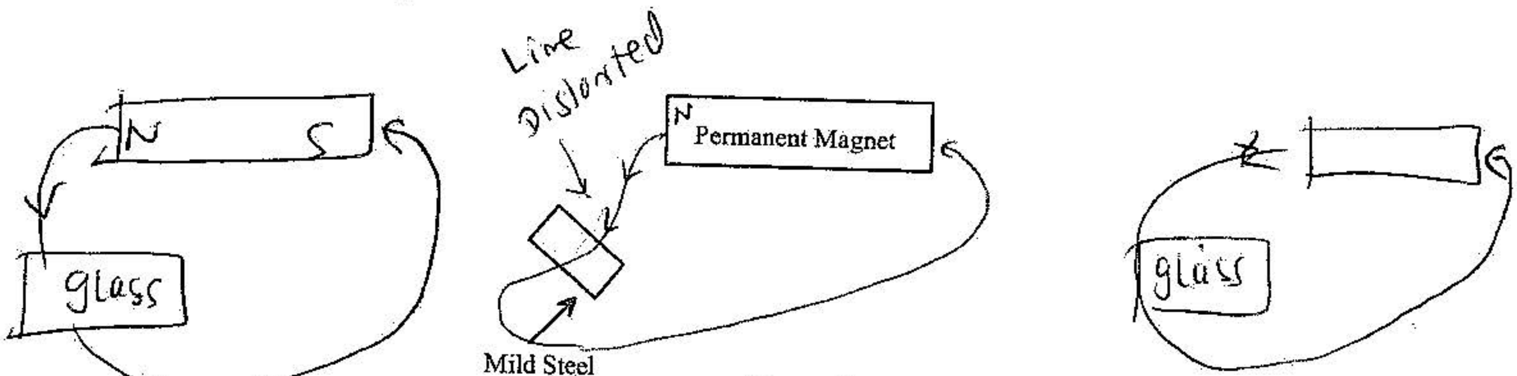


Figure 1

16. If the piece of mild steel shown in figure 1 was removed from the influence of the permanent magnet, would the mild steel become completely de-magnetised? State the reasoning for your answer. No It will still maintain the residual magnetism

17. Reproduce the diagram of figure 1 on your answer sheet using drawing instruments to complete your drawing, replacing the piece of mild steel with a piece of brass. Show the field pattern produced by the permanent magnet, and label all magnetic poles.

18. Flux density is measured in ___(a)___ Tesla and is a measure of the amount of ___(b)___ magnetic flux for a given ___(c)___ unit area

19. Describe the precautions you should take when storing permanent magnets. Accompany your answer with neat diagram, using drawing instruments to complete your diagram.

20. Describe what is meant by magnetic screening. It needs to apply magnetic keeper

Effect of magnetism by providing a path of low magnetic reluctance around the article to be protected

ELECTROMAGNETISM

PURPOSE:

This section introduces magnetic fields associated with straight and coiled current carrying conductors. Also, the magnetic fields associated with solenoids and electromagnets are covered.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Draw the magnetic field pattern around a current carrying conductor and a solenoid.
- Apply the Right Hand Conductor Rule and the Right Hand Solenoid Rule to determine the relationship between current flow and the resultant magnetic field.
- Draw the magnetic field pattern of two adjacent current carrying conductors.
- Describe the factors effecting the force between adjacent current carrying conductors and state the direction in which the force will act.
- List the factors that determine the field strength of an electromagnet.
- Define the term magnetomotive force and calculate its value.
- List practical applications for electromagnets.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 98-101.

It should be noted that current flow in a conductor is represented by the following convention:

- if the observer looks at a conductor end-on while the current is flowing away from him, this is indicated by an X, as shown in figure 3.
- current flowing towards the observer is indicated by a dot in the centre of the circle representing the conductor, see figure 4.

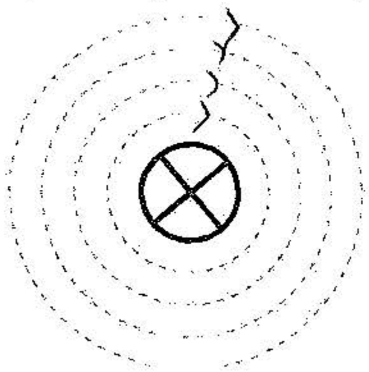


Figure 3

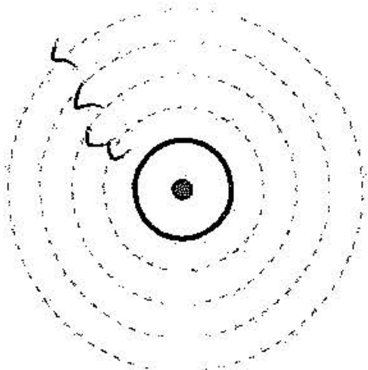


Figure 4

A current flowing in a conductor creates a magnetic field which has a definite direction. The direction in which the field acts can be determined using the right-hand conductor rule, see figure 5, which states -

- Place the right hand with the palm on to the conductor and grip it.
- The thumb is outstretched and parallel with the conductor, pointing in the direction of current flow.
- The fingers will now point in the direction of the magnetic flux.

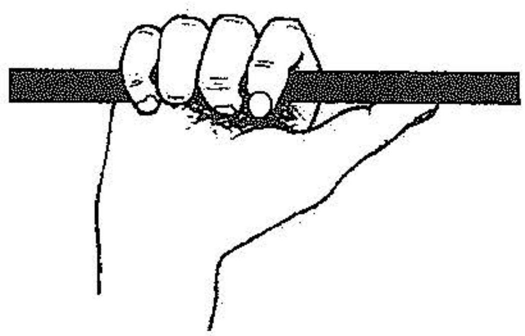


Figure 5

It is thus possible not only to determine at any time the direction of the magnetic field if the direction of current is known, but it is also possible to determine the direction of the current when the direction of the magnetic field is known.

The laws of parallel conductors carrying current may be summarised as follows -

- Parallel conductors carrying current in the same direction will combine one another.
- Parallel conductors carrying current in opposite directions will subchract one another.

3. MAGNETIC FIELD OF A SOLENOID

Consider a current-carrying conductor bent into a single loop as shown in figure 8.

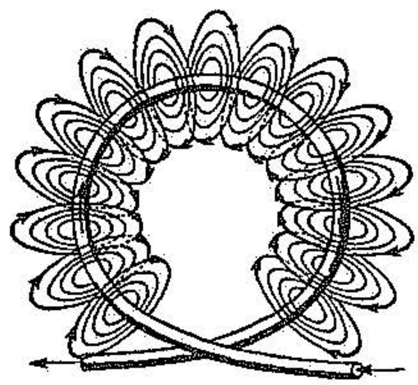


Figure 8

A number of hypothetical discs of magnetism have been drawn around the loop, and the right-hand conductor rule applied to obtain their directions. It can be seen that all the lines of magnetic flux produced pass through the loop and all in the same direction, resulting in a concentration or crowding of the lines of magnetic flux in the space within the loop.

If a conductor is wound into several loops the resulting coil is called a solenoid. Figure 9 illustrates a section of a solenoid together with its resulting field.

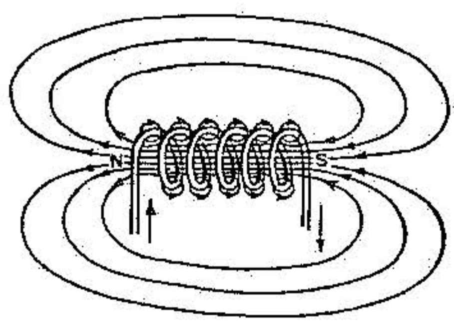


Figure 9

The strength of an electromagnetic field depends on three factors -

- the magnitude of the current flowing in the coil
- the number of turns on the coil
- the materials used in the core.

The greater the current flowing in an electromagnet, the greater the strength of the field produced.

Each time a turn of wire is added to a coil more lines of magnetic flux are concentrated into the space within the coil; producing the effect of a combined field whose strength is equivalent to the sum of the separate loops or turns.

The field strength of an electromagnet is Proportional to the number of turns of wire in the coil.

It has already been stated that lines of magnetic flux pass more readily through a magnetic substance than they do through air, therefore it is possible to increase the strength of the field of a coil very considerably by using a magnetic core. Many materials may be used for this purpose, their usefulness being determined by their reluctance.

The Smaller the reluctance of the magnetic core, the stronger the magnetic field for a given current and number of turns.

6. APPLICATIONS OF SOLENOIDS & ELECTROMAGNETS

Practically all the intense fields of electrical machinery are produced by electromagnets. There is wide use of electromagnets for providing the mechanical force required to operate various kinds of mechanism.

Three principal types of electromagnets are used -

- the attract'd armature type - in which the electromagnet attracts an armature to which the mechanism is attached, for example, a relay or a contactor.
- the plunger type - in which the coil surrounds a sliding plunger which is drawn into the coil, when the latter is energised.
- the induction type - in which the electromagnet poles attract magnetic material for transportation purposes.

The tractive type of electromagnet is used in such apparatus as buzzers and electric bells. They are also widely used for the operation of contactors and relays for a variety of purposes requiring the automatic opening and closing of circuits.

Figure 12 illustrates a typical relay. If the operating coil is energised, a magnetic field is established across the air-gap and the armature is attracted to the pole-piece of the magnet core, thus bringing the contacts together.

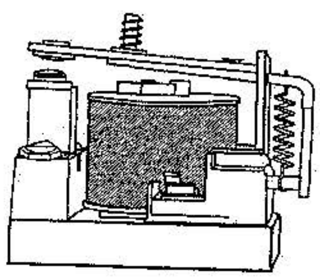


Figure 15

The case or shell of the electromagnet is of high-quality magnet steel and is provided with suspension lugs for the supporting chains. The coil windings are contained in a ring-shaped cavity in the shell and are retained in position by a non-magnetic plate of manganese steel.

Very powerful forces can be developed in electromagnets of this type, lifts of from 7 kilograms to 14 kilograms per square centimetre of pole face being quite common.

It should be understood, however, that the electromagnet itself does not lift, it merely acts as a holding device. The actual lifting is done by the machinery which operates the chains attached to the suspension lugs.

Other applications of the electromagnet similar in their principle of operation to the lifting magnet, are:

- the magnetic chuck employed for holding the work on the faceplate or table of machine tools to avoid the use of clamps during the machining operation;
- the magnetic clutch used for coupling the driving and driven shafts in power transmission work;
- magnetic brakes in which the brake-shoes are held against a brake drum;
- the magnetic separator used for sorting iron and steel from other material.

A typical DC crane brake is illustrated in figure 16.

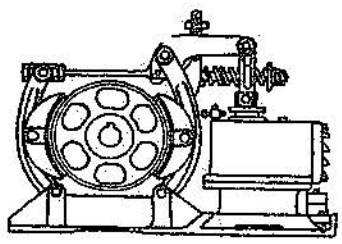


Figure 16

The operation of the brake is as follows -

When the supply voltage is switched OFF to the lifting motor, the brake is applied immediately. The coil winding of the brake is connected in parallel with the motor. When the supply is disconnected from the motor the coil loses its magnetic field and a heavy spring applies the friction brake immediately.

When the supply voltage is switched ON again the magnetic attraction set up by the coil pulls on a lever, the action drawing the shoes away from the drum and compressing the spring.

Name: ____________________ **Practical 2**

ELECTROMAGNETISM

PURPOSE:

This practical assignment will be used to verify the basic magnetic laws associated with solenoids and electromagnets.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Use a magnetic compass to identify the poles of an electromagnet.
- Map the magnetic field of an electromagnet.
- State the effect on the magnetic field produced of varing the number of turns on a solenoid.
- State the effect on the magnetic field produced of varing the current flowing in a solenoid.
- Examine the effects on the magnetic field of an electromagnet by magnetic and non-magnetic materials.

EQUIPMENT:

- ☐ 1 x DC power supply
- ☐ 1 x 0 -1A DC ammeter
- ☐ 1 x magnetic compass
- ☐ 1 x length of 16mm PVC conduit
- ☐ 1 x length of 25mm PVC conduit
- ☐ 2 x metal rods - 1 x mild steel strip and 1 x brass
- ☐ 4mm connecting leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

6. Adjust the power supply for minimum output voltage.
7. Turn on the power supply, close the circuit switch and then adjust to give a circuit current of 0.2A.
8. Open and close the circuit switch, observe any effect on the compass needle when the switch is closed. **Note**, this step may need to be repeated several times in order to observe the effect.
9. Record your observations in table 1.

Table 1

	Effect on Compass Needle				
	0.2A	0.4A	0.6A	0.8A	1A
Single Layer Solenoid					

10. Repeat the procedure for each of the current values shown in table 1.
11. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

2. THREE LAYER SOLENOID

1. Construct a three layer solenoid using a piece of 25mm PVC conduit as a former.
2. Each layer of the solenoid should be 40 turns.
3. Tape the ends of the solenoid with masking tape to prevent the coil from unwinding.
4. Mark the start of the coil, then strip the ends of the wire and connect to the terminal block.
5. Connect the circuit as shown in figure 3. **Note:** Be sure to connect the coil so the start of the coil is positive.

12. Replace the brass rod with a mild steel rod and repeat steps 6 to 8.
13. Record which end of the compass needle is attracted to the electromagnet, that is, north or south.
14. Record your observations in table 3.

Table 3

	Effect on Compass Needle					
	0.2A	0.4A	0.6A	0.8A	1A	End of compass needle attracted
Three Layer Solenoid mild steel core						
Reversed Polarity Three Layer Solenoid mild steel core						

15. Reverse the polarity of the coil connections and observe the effect on the compass needle.
16. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

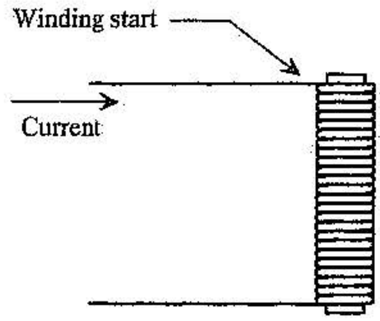


Figure 6

8. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Does the number of turns on a solenoid effect the strength of the magnetic field produced by the solenoid?

____

____

____

2. Does the magnitude of the current flowing in a solenoid effect the strength of the magnetic field produced by the solenoid?

____

____

____

3. What effect did the brass rod have on the strength of the magnetic field produced by the solenoid?

____

____

____

Electromagnetism

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. The magnetic field surrounding a single current carrying conductor is:
   (a) circular and independent of the direction of current flow
   ✓ (b) circular and dependent of the direction of current flow
   (c) axial and independent of the direction of current flow
   (d) axial and dependent of the direction of current flow

2. The direction of the magnetic field around a single current carrying conductor can be determined by:
   (a) Fleming's right hand rule
   (b) Fleming's left hand rule
   (c) the right hand conductor rule
   ✓ (d) the right hand solenoid rule

3. In a single current carrying conductor, current flowing towards the viewer can be shown by a ______, whilst current flowing away from the viewer can be shown by a ______.
   (a) cross, dot
   (b) cross, asterisk
   (c) dot, asterisk
   ✓ (d) dot, cross

4. If two single current carrying conductors adjacent to each other have currents flowing through them in opposite directions, then a/an ______ force exists between the two coils.
   (a) attraction
   ✓ (b) repulsion
   (c) magnetomotive
   (d) inductive

11. For the circuit of figure 1, determine which end of the electromagnet will be the north pole.

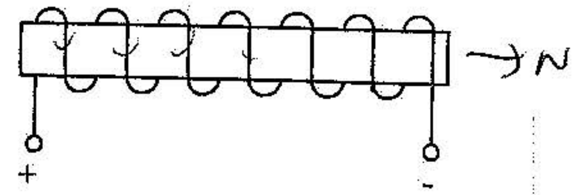


Figure 1

12. For the circuit of figure 2, determine which end of the electromagnet will be the north pole

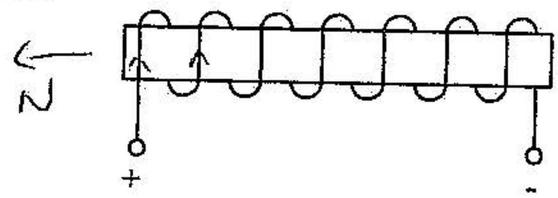


Figure 2

13. For the circuit of figure 3, determine which end of the electromagnet will be the north pole

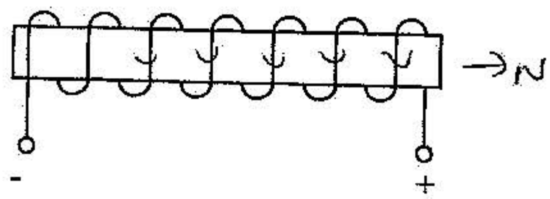
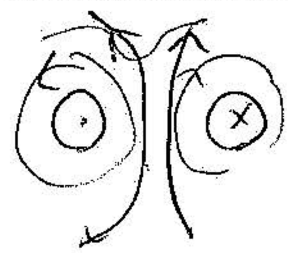


Figure 3

14. Two parallel conductors have currents flowing through them in opposite directions. Draw a sectional view of the two conductors, and show the following:
    (a) the relative current directions in each conductor;
    (b) the correct magnetic field around each conductor;
    (c) the resultant magnetic field of the two conductors together;
    (d) the direction of the force exerted between the conductors.



SECTION C

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A coil of 120 turns has a current of 250mA flowing through it. Determine the magnetomotive force produced by the coil. (30At)

   $F_m = NI = 120 \times 250 \times 10^{-3} = 300 \times 100 \times 10^{-3} = 30$ AT

2. If the power supply for question 1 has a current limitation of 120mA, how many turns must the coil be varied by to maintain the same magnetomotive force? (Add 130 turns)

   $30 = N \times 120 \times 10^{-3}$ → $N = 30 \times 10^{3} / 120 = 250$ | Add 130T

3. How much current must flow in a coil of 1000 turns to produce a magnetomotive force of 125At? (125mA)

   $F_m = NI \rightarrow 125 = 1000 \times I \rightarrow I = 0.125$ Amp

MAGNETIC CIRCUITS

PURPOSE:

This section introduces the relationship between magnetomotive force, magnetising force, flux density, permeability and reluctance in magnetic circuits. Also, calculations involving these quantities will be covered.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Describe and draw the magnetic circuit.
- Describe the term reluctance and how it effects the flux established in a magnetic circuit.
- Describe the relationship that exists in the magnetic circuit between magnetic flux, magnetomotive force and reluctance.
- Describe permeability and explain the terms permeability of free space and relative permeability.
- Explain what is meant by flux density and state how it is affected by flux and cross-sectional area.
- Describe magnetising force and state its unit of measurement.
- Calculate values of magnetomotive force, magnetising force, flux density, permeability, reluctance and total flux in a magnetic circuit.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 101-104.

THE RELAY

PURPOSE:

This practical assignment will be used to examine the operation of the electric relay.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect an electric relay using a circuit diagram as a guide
- Describe the operation of the electric relay.
- Experimentally determine the pick-up and drop-out voltages and currents of a relay.

EQUIPMENT:

- ☐ 1 x DC power supply
- ☐ 1 x 0 -2V DC voltmeter
- ☐ 1 x 0 - 50mA DC ammeter
- ☐ 1 x relay panel
- ☐ 4mm connecting leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

2. RELAY PICK-UP and DROP-OUT VALUES

1. Adjust the power supply to give minimum output.
2. Turn on the power supply, close the circuit switch and adjust the power supply such that the voltmeter indicates 2 volts. Record the current taken by the coil and the condition of the LED (lit or not lit) in table 1.

Table 1

Supply Voltage	Coil Current	LED Condition
2V		

3. Slowly increase the supply voltage whilst observing the LED. Record the voltage at which the LED just turns on in table 2. Record the coil current at this voltage.

Table 2

Supply Voltage	Coil Current	LED Condition
		ON

Repeat this step to check accuracy of results.

4. Increase the supply voltage to 12V. Record the coil current and the LED condition.

Table 3

Supply Voltage	Coil Current	LED Condition
12V		

2. Answer true or false to each of the following statements.
   Allowing for experimental error, the resistance of the relay coil -
   (a) increases in proportion to the applied voltage ______________
   (b) decreases as the magnetic field strength increases ______________
   (c) remains unchanged regardless of change in voltage ______________
   (d) changes when the relay 'picks-up' ______________

3. Answer true or false to each of the following statements.
   When electric current flows through the coil of a relay -
   (a) the coil will usually overheat ______________
   (b) a magnetic field is produced ______________
   (c) the magnetic field strength is proportional to the current ______________
   (d) the magnetic field strength is proportional to the applied voltage ______________

4. If the voltage applied to a relay coil is gradually increased, a voltage value is reached (called the 'pick-up voltage') where the magnetic field is strong enough to overcome the spring tension and pull the armature towards the coil, thus operating the relay contacts.
   The relay is now said to be energised.
   (a) The pick-up voltage of the relay used in this experiment was ______________
   (b) The relay will energise provided that coil current is at least ______________
   (c) The rated coil voltage for the relay used in this experiment was ______________
   (d) The relay pick-up voltage was (greater than/less than/same as) the rated coil voltage.
   ____

5. If the voltage applied to the coil of a relay is gradually reduced, a voltage value is reached (called the drop-out voltage) where the spring tension on the armature will overcome the weakened magnetic field of the coil, and the relay will de-energise causing the relay contacts to revert to their normal state.
   (a) The drop out value of the relay used in this experiment was ______________
   (b) The relay will de-energise if the coil current is decreased to less than ______________

The Magnetic Circuit

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. The magnetomotive force produced by a coil depends on:
   (a) the number of coil turns and the length of the magnetic circuit
   (b) the coil current and the C.S.A of the magnetic core
   (c) the length of the magnetic circuit and the core reluctance
   ✓ (d) the number of coil turns and the coil current

2. The flux set up by a coil depends on the ______ produced by the coil and ______ of the iron core:
   ✓ (a) mmf, reluctance
   (b) magnetising force, C.S.A.
   (c) mmf, magnetising force
   (d) mmf, flux density

3. The flux surrounding a coil is ______ to the coil current and ______ to the reluctance of the core.
   (a) proportional, proportional
   (b) inversely proportional, inversely proportional
   (c) inversely proportional, proportional
   ✓ (d) proportional, inversely proportional

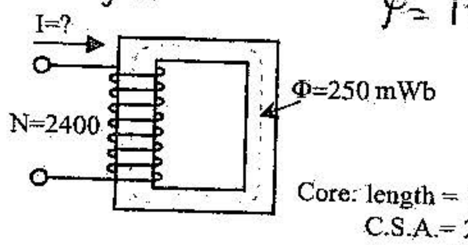
13. The best size and shape for a magnetic core would be one with a ___(a)___ length and a large ___(b)___

14. Neatly reproduce (or cut and paste) the diagram of figure 1 on your answer sheet, then label those parts identified with an arrow.

SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A coil of 150 turns has a current of 3.5A flowing through it. Determine the magnetomotive force produced by the coil. (525At)
2. Determine the flux produced by a coil of 1000 turns when 1.5 amperes flows through it. The reluctance of the magnetic circuit is determined to be 45 000At/Wb. (33.3mWb)
3. Determine the current that must flow through a coil of 1500 turns to produce a flux of 15mWb. The reluctance of the magnetic circuit is determined to be 5 000At/Wb. (0.05A)
4. Determine the flux density at the poles of an electromagnet which produces a flux of 15mWb if the area of the poles is 200mm^2. (75T)
5. A magnetic circuit has a core area of 250mm^2 and a flux density of 2T. If the reluctance of the core is 60 000 At/Wb, determine the current flowing through the coil of 600 turns. (50mA)
6. An electromagnet has a core length of 400mm, is wound with 2000 turns and carries a coil current of 200mA. Determine the magnetising force of the magnetic circuit. (1000At/m)
7. Determine the current flowing in a coil of 600 turns which produces a magnetising force of 2000 At/m in a core 150mm long. (500mA)
8. A magnetic core is 300mm long with a cross sectional area of 50mm^2 and has a permeability of 125.7x10^{-3}. Determine the reluctance of the core. (47 732 At/Wb)
9. For the circuit of figure 2, determine the coil current for the conditions shown. (625mA)



Core: length = 150mm
C.S.A.= 250mm^2
Permeability = 100x10^{-3}

Figure 2

MATERIALS & MAGNETISATION CURVES

PURPOSE:

This section will be used to compare the magnetic characteristics of various materials and to explain the terms 'saturation', 'hysteresis' and 'losses'. Also, the magnetisation or B-H curve is covered.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Draw and explain typical magnetisation curves for magnetic and non-magnetic materials.
- Draw and explain typical hysteresis loops for magnetic materials.
- Describe the meaning of the terms saturation, hysteresis and losses in relation to magnetic materials and circuits.
- Compare the magnetic characteristics of various materials from magnetisation curves and hysteresis loops.
- Describe how magnetic losses occur and the resulting effects on the performance of electrical machines.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 97 and 104-107.

2. THE MAGNETISATION CURVE

In section 2 it was stated that when a core of magnetic material is introduced into a solenoid the flux density is increased because such materials are better than air as carriers of magnetic flux.

The graph showing the relationship between magnetising force and the flux density induced within the material is called the magnetisation curve for that material. The graph is also called the B-H curve. The arrangement of the axes for the B-H curve is shown in figure 2.

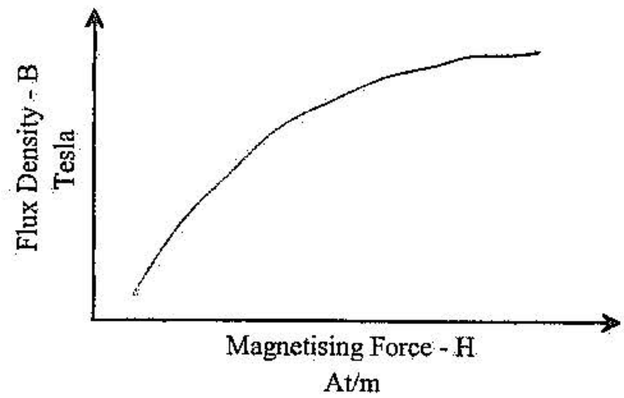


Figure 2

3. MAGNETISATION CURVE FOR A NON-MAGNETIC MATERIAL

The relative permeability for all non-magnetic materials is ________. Therefore, the permeability for all non-magnetic materials is a constant.

For non-magnetic materials, flux density is ______________________________ to the magnetising force.

Therefore, the relationship between flux density and magnetising force is ________________.
The magnetisation curve for air and all non-magnetic materials is shown in figure 3.

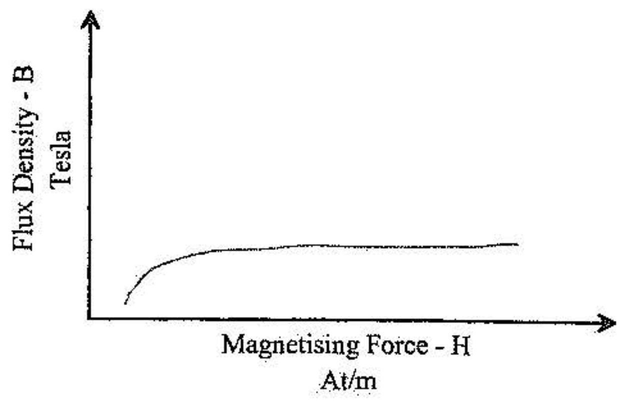


Figure 3

As shown in figure 6, when the point "R" is passed, small increases in magnetising force (H) produce large increases in flux density (B). However when the point labelled "S" is passed the flux density increase is very much reduced; large increases in magnetising force are required to produce even small increases in flux density.

The point "S" is called the ____________________ of the magnetisation curve.

The section beyond "S" is called the ______________________________ of the curve since the magnetic circuit is saturated in this range.

It is not usual to work the magnetic circuit so that it is highly saturated because too much magnetising force is required to produce the additional flux density. The flux can be increased after the "knee" of the curve but it is generally uneconomical.

A number of curves for typical materials is shown in figure 7. The curves have been plotted for -

- cast iron
- mild steel (that is wrought iron)
- cast steel
- silicon sheet steel - a special steel used in the manufacture of electrical equipment such as transformers, motors and generators.

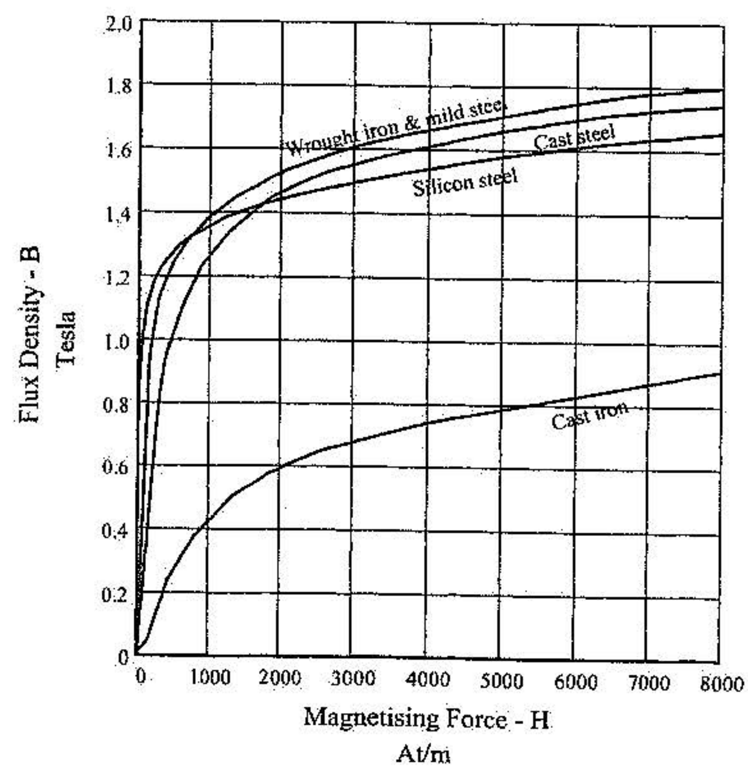


Figure 7

Electrical equipment is normally designed for its magnetic components to operate in the linear portion of the curve, that is, in the region from the origin of the curve to the knee.

5. HYSTERESIS

It has been shown that the magnetisation curve of an originally completely demagnetised piece of ferromagnetic material follows the B-H curve shown in figure 9, which starts from zero through the knee into the saturation region.

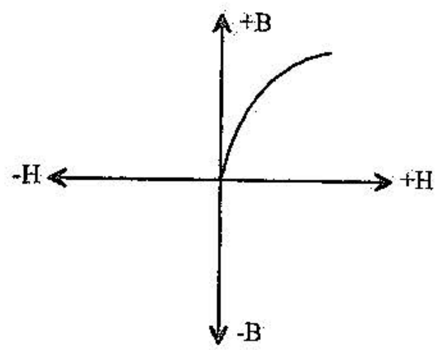


Figure 9

If the magnetising force is reduced in such a sample after a point on the magnetisation curve has been reached, the flux density drop within the sample will not follow the same path (that is the B-H curve) along which it had increased, but it will follow a curve above the original B-H curve. It is found that when the magnetising force is completely removed, some flux density in the sample still remains. See figure 10.

The amount of this remaining magnetism is called the Residual magnetism.

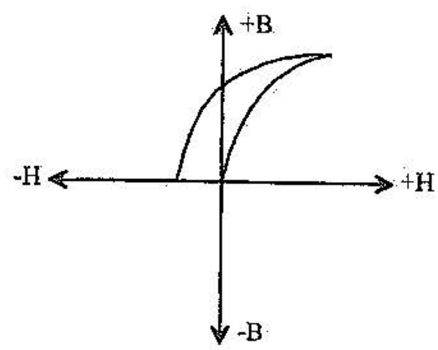


Figure 10

If the direction of the magnetising force is now reversed (the direction of the current through the exciting coil is reversed) and gradually increased from zero to the previously achieved maximum value, but in a reversed direction.

At a certain stage, this negative magnetising force will completely overcome, that is cancel, the remanent magnetism in the sample.

The amount of magnetising force to do this is called the coercive force.

When following the hysteresis curve in figure 13, some of the domains remained aligned thus creating remanent or residual magnetism. They have to he jumbled up again and then realigned in the opposite direction and so on.

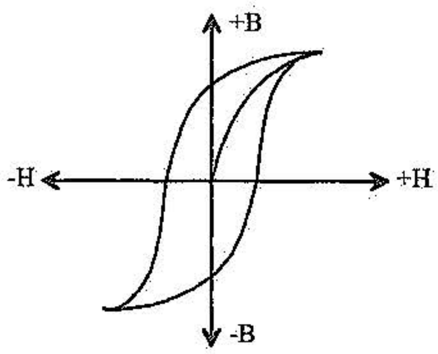


Figure 13

Clearly, a certain amount of work must be done to align the domains into a uniform direction for each reversal of the polarity of the magnetic field and thus for every time a complete hysteresis loop has been traversed.

This work is called the ___Hysteresis___ of a material.

It is called a loss because there is no useful return for the energy spent on each reversal of direction of the magnetic field.

Figure 14 shows the hysteresis loop for soft iron, one type of which is silicon sheet steel.

The following characteristics of the material can be identified from the hysteresis loop -

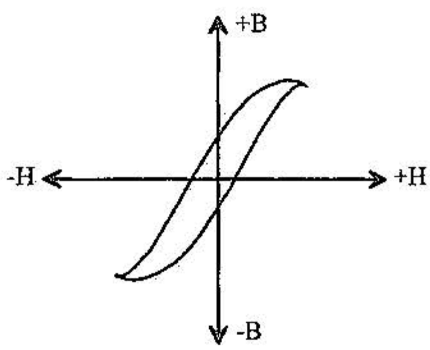


Figure 14

- The area within the loop is small, this indicates the hysteresis loss is ___Small___.
- The residual magnetism is ___Small___.
- Soft iron is not suitable for ___electrical machines___
- Used in applications where the magnetic field has to undergo a large number of reversals per second.

7. MAGNETIC LEAKAGE

When only a portion of a generated magnetic flux reaches its intended destination or use, the portion of the flux which is being lost in the process is deemed to have "leaked" away and is therefore called the - Leakage Flux.

Useful and leakage flux are shown in the magnetic circuit of figure 17. The effect of a number of ampere-turns is wasted in producing the leakage flux, which will not reach the air gap where it is required.

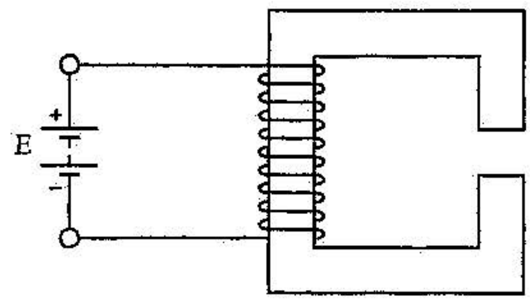


Figure 17

8. MAGNETIC FRINGING

The magnetic flux through an air gap, because of the repulsion between magnetic flux lines, will tend to bulge out at the edges of the air gap, as shown in figure 17. This is called magnetic fringing and its amount is a function of the length of the air gap.

Magnetic fringing, in effect, increases the area between pole faces and consequently reduces the average air gap flux density.

****

THE MAGNETISATION CURVE

PURPOSE:

This practical assignment will be used to examine the magnetisation curve of a DC generator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect a DC generator using a circuit diagram as a guide
- Carry out a test to determine the magnetisation curve for a DC generator.
- Plot the magnetisation curve for a DC generator.

EQUIPMENT:

- ☐ 1 x variable DC power supply
- ☐ 1 x Betts DC compound machine
- ☐ 1 x Betts single phase prime mover
- ☐ 1 x Betts machine bed to accommodate two machines
- ☐ 1 x digital multimeter
- ☐ 1 x 0-2A analogue DC ammeter
- ☐ 4mm connecting leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

9. Reduce the field current to 1.4A, then measure the generator output voltage. Record the voltage value in table 1.

10. Repeat the procedure for each of the values of field current shown in table 1.

11. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

12. Turn the DC power supply and the prime mover off.

13. Please return all equipment to its proper place, safely and carefully.

1. OBSERVATIONS:

1. What effect did increasing the magnetising force have on the output voltage of the generator?

___

___

___

2. What effect did decreasing the magnetising force have on the output voltage of the generator?

___

___

___

3. Were the generator output voltages the same when the field current was decreased as compared to when the field current was increased? If not, what caused the difference?

___

___

___

3

1. NATURE OF MAGNETISM

It was common knowledge among ancient people that certain iron ores had the property of attracting other pieces of the same ore. This iron ore (Fe_3O_4) was found near Magnesia in Asia Minor and was called magnetite. The words magnet and magnetism are derived from the word magnetite; the iron ore is referred to as a magnetic substance.

It is historically recorded that the Chinese as far back as 2634 BC, used pieces of iron ore in a crude device for the navigation of ships. These pieces of iron ore are now referred to as **natural magnets**, that is, magnets found in nature, or lodestone.

As shown in figure 1, if a piece of lodestone is dipped into iron filings, the filings picked up will be concentrated in two regions at opposite ends of the stone. The attraction is obviously greatest at these two places which are called the poles of the lodestone. If the lodestone is freely suspended, it will come to rest with the line joining its poles approximately north and south. See figure 2.

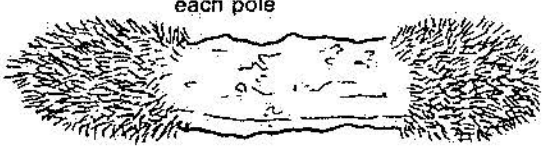


Figure 1

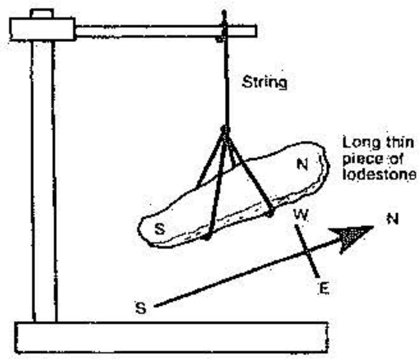


Figure 2

A bar of iron, or steel, if stroked by one of the poles of a lodestone also acquires the same powers as the lodestone, and the bar in turn can impart these properties to other bars of iron or steel.

A body possessing the attractive and directional properties of a lodestone is called a natural magnet, and these properties are said to be due to magnetism.

Magnetism is involved in the operation of a very large proportion of electrical apparatus, and an understanding of the principles of magnetism is very essential to the student of electricity.

As with electricity, knowledge of the exact nature of magnetism is incomplete, but recent research has been able to build upon. the foundations laid by such men as Gilbert, Oersted, Ampere, Arago, Faraday and Coulomb to provide a much more definite idea of magnetism.

However, before attempting to provide a more complete definition of the term magnetism the further properties of magnets and magnetic substances should be considered.

Permanent magnets are manufactured in a variety of forms, the most common being the bar magnet and the horseshoe or U-shaped magnet. Figure 3 shows examples of each type.

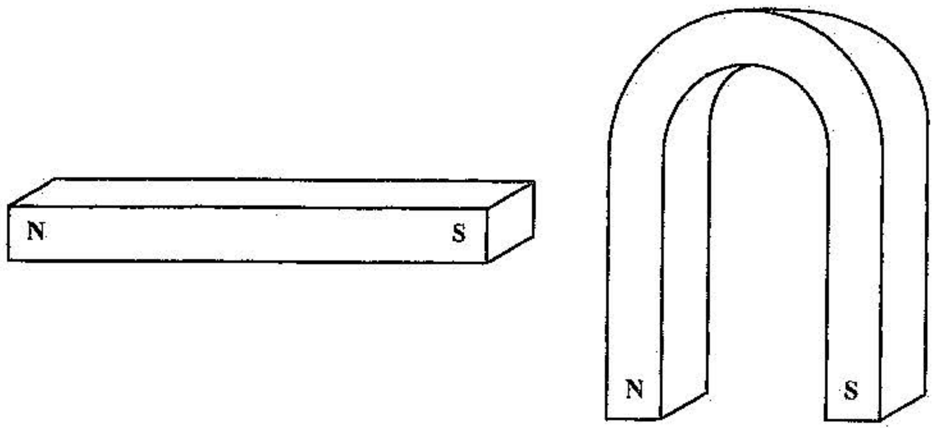


Figure 3

3. MAGNETIC MATERIALS

A magnetic material is a substance that can be magnetised, and therefore it can also affect a magnetic field. A non-magnetic material has neither of these properties.

A magnetic material has a high Permeability (or low resistance to lines of magnetic force) and is therefore a good conductor of a magnetic field. The symbol for permeability is the Greek letter mu ______.

Substances that have a high permeability are called permanent magnetic materials. They include -

- iron } most common
- ferrite }
- steel
- nickel
- cobalt
- alnico.

Non-magnetic materials have a permeability of one. They include -

- air
- wood
- plastic
- water
- paper
- cloth fabrics.

If a bar magnet is suspended or pivoted in such a way that it is free to turn, as in figure 5, it will point in a north-south direction. The same end of that magnet always points in the same direction

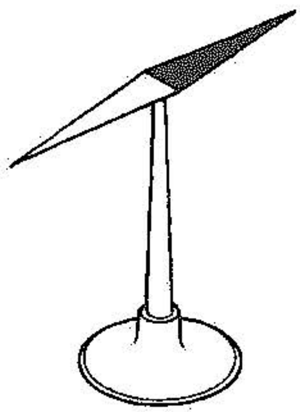


Figure 5

The pole which is attracted towards the North-mangetic pole of the earth is called the - ______North______ pole of the magnet.

The other pole of the magnet is the ______South______ pole, because it is attracted towards (seeks) the South-magnetic pole.

The correct terms of north-seeking pole and south-seeking pole are usually abbreviated to north pole and south pole respectively.

Every magnet has two poles, a north pole and a south pole. Single, that is isolated, magnetic poles do not exist. If a bar magnet is cut into smaller pieces, it will be found that each of the pieces becomes a smaller magnet with a north and south pole of its own. This is shown in figure 6.

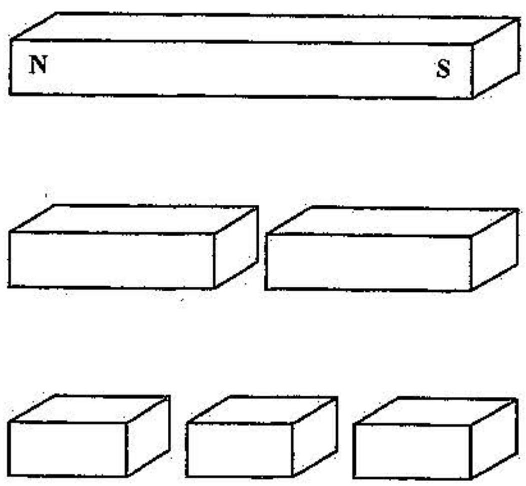


Figure 3

These lines of magnetic flux, though hypothetical, have certain well-defined characteristics or distinguishing methods of behaviour -

- they are a force field in a specified physical medium
- they have a depicted as lines in a plane that contains of intersect/ electric charge pole, / magnetic pole,
  For convenience, it is considered that the lines pass from N to S outside the magnet, and from S to N inside the magnet, this being the direction in which a free N pole would move if brought into that field.
- lines of magnetic flux are visual tool used to represent magnetic field
  They may be distorted or bent to any shape, but they do not intersect each other.
- the lines are moving charges and magnetic dipoles.
  They may be extended to any length, or contract and vanish when the magnetising agent is removed.
- the lines pass the surface through any non-magnetic substance, such as copper, silver, wood, and glass.

Many of the characteristics of the lines of magnetic flux of a magnetic field may be examined by means of a sectional map of the field along a definite plane.

Figure 8 shows the map of the field of a bar magnet and if it is examined carefully it will be noticed the lines of magnetic flux appear to come from, or crowd to, points near the ends of the magnet. These points are the poles, one a north pole and the other a south pole.

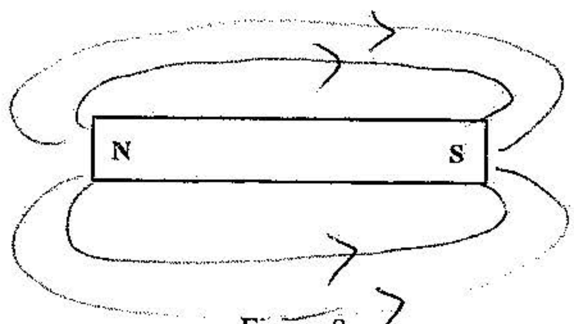


Figure 8

It sometimes occurs that a bar may become irregularly magnetised, resulting in more than one pair of poles; the additional poles being called consequent poles.

The magnetic Neutral is located approximately midway between the poles and, as its name implies, is that part of the magnet not possessing the property of magnetism. At the neutral zone all the lines of magnetic flux are traversing the magnet, and it is only when the lines leave the magnet to pass through air, or other non-magnetic substances, that poles are produced, a north pole occurring where the lines leave the magnet and a south pole where they enter it.

Figure 11 shows the field produced when two similar poles are brought near to each other.

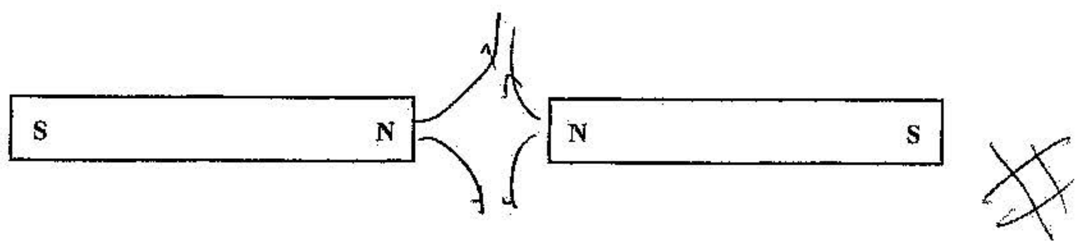


Figure 11

(In this case the fields are in repulsion, and since lines of magnetic flux do not cross each other, the field is distorted out of its true shape. Considering again the lines as tiny elastic bands, some force must be exerted upon them to produce distortion.)

Since action and reaction are equal and opposite, this force reacts upon the magnet, resulting in ______________________.

Like poles attracts. one another.

7. MAGNETIC INDUCTION

Consider a magnetic substance, such as a specimen of soft iron brought within the field of a magnet, figure 12.

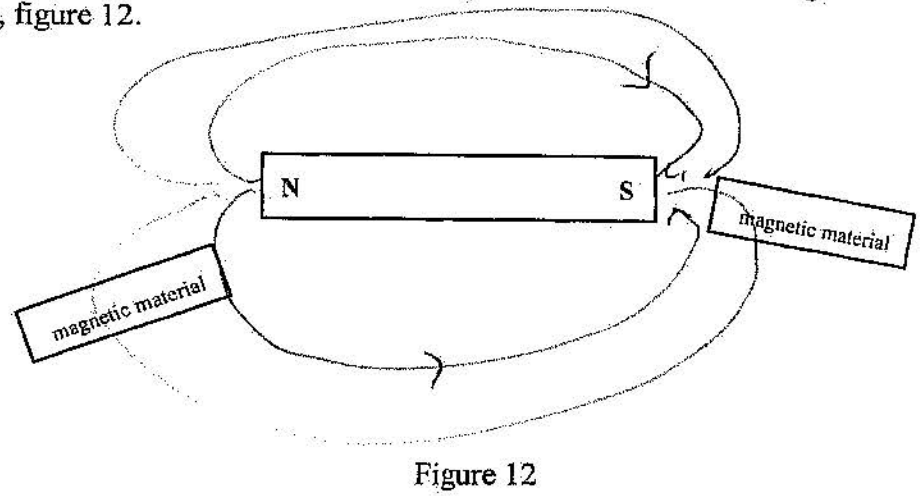


Figure 12

The iron will provide for the lines of magnetic flux a much easier path than air, and there will be as a consequence, a concentration of lines in the iron.

9. RESIDUAL MAGNETISM, RETENTIVITY AND RELUCTANCE

If specimens of hard steel and soft iron are each magnetised to the same degree, it will be observed that the soft iron loses practically all its magnetism when the magnetising agent is removed. The soft iron will quickly lose its remaining magnetism, especially if subjected to vibration, such as knocking with, or against, a solid substance.

Hard steel is more difficult to magnetise and retains practically all its magnetism when the magnetising agent is removed; even when subjected to vibration or knocking.

The magnetism remaining after the magnetising agent is removed is called residual magnetism.

Thus the residual magnetism of soft iron is very low when compared with hard steel.

That is -

The higher the magnetic field strength the higher the residual magnetism

All materials offer some opposition to being magnetised and the term used to describe this opposition is magnetic reluctance.

The greater the reluctance the ~~greater~~ harder it is to magnetise.

10. MAGNETIC FLUX AND FLUX DENSITY

The total lines of force in a magnetic field are referred to as the magnetic flux (symbol Φ), and the flux per unit cross-sectional area of the field is termed the flux density (symbol B).

The weber wb (wb) is the SI unit of magnetic flux.

One weber = 1wb ϕ = 10^8 lines of force.

Example: 1

The total flux emitted from the pole of a bar magnet in figure 13 is 2×10^{-4}Wb.

(a) If the magnet has a cross-sectional area of 100mm^2, determine the flux density within the metal,

(b) If the flux spreads out so that at a certain distance from a pole it is distributed over an area of 400mm^2, find the flux density at that point.

$$B = \frac{\phi}{A} = \frac{2 \times 10^{-4}}{100(10^{-3})^2} = \frac{2 \times 10^{-4}}{100 \times 10^{-6}} = \frac{2 \times 10^{-4}}{10^{-4}} = 2\ T$$

$$B = \frac{\phi}{A} = \frac{2 \times 10^{-4}}{400(10^{-3})^2} = \frac{2 \times 10^{-4}}{400 \times 10^{-6}} = 0.5\ T$$

Example: 2

Determine the flux density within a magnet having a cross-sectional area of 900mm^2 if the total flux is 18μWb.

$$B = \frac{\phi}{A} = \frac{18 \times 10^{-6}}{900(10^{-3})^2} = \frac{18 \times 10^{-6}}{900 \times 10^{-6}} = 0.02\ T$$

Example: 3

A flux density of 1.7T is measured in the air gap between two magnetic poles is found to be constant over an area of 300mm^2. If the poles each have a cross sectional area of 220mm^2, determine the flux density within the poles.

$$B = \frac{\phi}{A} \rightarrow 1.7 = \frac{\phi}{300 \times (10^{-3})^2} \Rightarrow \phi = 1.7 \times 300 \times 10^{-6} = 510 \times 10^{-6}\ \text{Wb}$$

$$B = \frac{\phi}{A} \rightarrow \frac{510 \times 10^{-6}}{220(10^{-3})^2} = \frac{510}{220} = \ T$$

12. MAGNETIC SCREENING

Magnetism acts in every direction and there is no known substance that can act as an insulator for magnetism. However, it is possible to screen ("shield") articles from the effect of magnetism by providing a path of low-magnetic reluctance around the article to be protected.

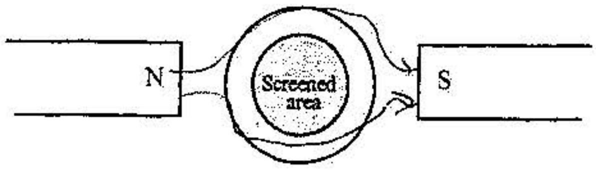


Figure 15

13. APPLICATION OF PERMANENT MAGNETS

Permanent magnets are used in a variety of applications, some of which include -

- small dc motors and generators
- magnetos
- magnetic chucks
- speakers
- indicating instruments such as ammeters and voltmeters
- collision sensors in motor cars.

****

19

PROCEDURE :

1. DETERMINATION OF MAGNETIC POLARITY

1. Using the magnetic compass identify the polarity of the ends of the round bar magnets, that is north or south, by placing one end of the magnet near the compass.
2. Record your results in table 1. Identify the poles of the magnets by their colour.

   Note 1: The end of the magnet which attracts the marked end of the compass needle is the **south pole** of the magnet. See figure 1.

   Note 2: The other end of the magnet should attract the unmarked end of the compass needle.

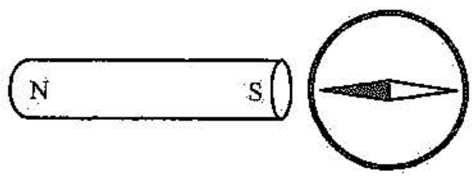


Figure 1

Table 1

	North Pole	South Pole
Magnet 1		
Magnet 2		

3. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

Figure 4

10. Remove the magnets from the centre tube, then shake the oil filled container until all the iron filings are in suspension.
11. Place one circular magnet and a mild steel rod into the centre tube of the oil filled container, arranged as shown in figure 5.
12. Allow the iron filings to settle in the form of the magnetic field around the magnet and rod. Sketch the field in figure 5.

Figure 5

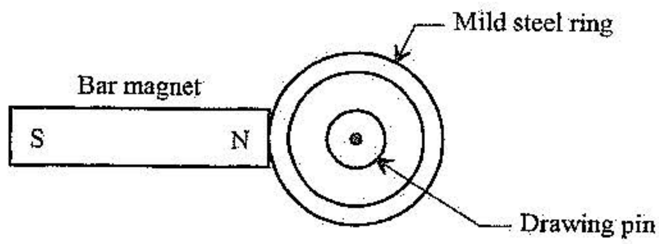
Table 2

	Pole Arrangement		
	Unlike Poles Facing	Like poles Facing	
	North to South	North to North	South to South
Effect			

4. Repeat the procedure with like poles facing, say north to north. Observe and record your results in table 2.
5. Repeat the procedure, again with like poles facing, but this time arranged south to south.
6. Return all equipment to its proper place, safely and carefully.

4. MAGNETIC SCREENING

1. Place a steel ring against any pole of one of the rectangular bar magnets, then drop a drawing pin into the centre of the ring as shown in figure 8.



2. Carefully remove the ring in an upward direction, observe the result and record the effect on the drawing pin in table 3.

Table 3

	Magnet/ring Arrangement	
	Ring in Place	Ring Removed
Effect on Drawing Pin		

3. Of the four materials tested, mild steel, copper, plastic and wood, which were magnetic and which were non-magnetic?

4. How can you identify if a material is magnetic or non-magnetic using a bar magnet?

5. If a magnetic material is placed in a magnetic field, does it have any effect on the magnetic field?

6. If a non-magnetic material is placed in a magnetic field, does it have any effect on the magnetic field?

7. Did the metal ring around the drawing pin in procedure 4 provide magnetic screening? If so, how?

****

5. The opposition of a material to becoming magnetised is known as:
   (a) impedance
   (b) reluctance
   (c) resistance
   (d) inductance

6. A piece of ______ will have a lower amount of residual flux when compared to a piece of ______ when the magnetic influence is removed.
   (a) hard steel, soft iron
   (b) soft iron, copper
   (c) hard steel, copper
   (d) soft iron, hard steel

7. Magnetic flux is measured in:
   (a) Webers
   (b) Teslas
   (c) Henries
   (d) Ohm's

8. Flux density is a measure of the amount of :
   (a) magnetic flux
   (b) reluctance per unit area
   (c) magnetic flux per unit area
   (d) inductance flux per unit area

9. Flux density is measured in:
   (a) Henries
   (b) Ohm's
   (c) Webers
   (d) Teslas

10. Retentivity is an indication of how much:
   (a) magnetism is required to magnetise a material
   (b) residual magnetism a material will have
   (c) magnetism is required to de-magnetise a material
   (d) residual magnetism a material will lose

SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

21. Many of the following equations will be encountered in work on magnetism. Transpose the equations as required.

    (a) $mmf = IN$ $\quad I = ?$ (Note: mmf stands for "magneto-motive-force")

    (b) $H = \frac{IN}{l}$ $\quad N = ?$ No. of Turn

    (c) $\Phi = \frac{mmf}{S}$ $\quad S = ?$ Reluctance

    (d) $B = \frac{\Phi}{A}$ $\quad \Phi = ?$ Flux

    (e) $L = \frac{\mu N^2 A}{l}$ $\quad N = ?$ No. of Turns.

    (f) $e = N\frac{\Delta\Phi}{\Delta t}$ $\quad N = ?$ (Note: Δ (delta) means a "change in" ie change in time)

    (g) $L = N\frac{\Delta\Phi}{\Delta I}$ $\quad \Delta I = ?$ Change of current

22. The flux produced by a magnet is 10mWb. Determine the flux density if the area of the pole is $250mm^2$ (40T)

23. For the magnet in question 22, determine the flux density away from the pole if the flux now spreads out to an area of $600mm^2$. (16.7T)

24. Determine the flux of a magnet if the flux density at the poles is 2T, and the area of the poles is $300mm^2$. (600μWb)

(22) $B = \frac{\phi}{A} = \frac{10 \times 10^{-3}}{250(10^{-3})^2} = \frac{10 \times 10^{-3}}{250 \times 10^{-6}} = \frac{10 \times 1000}{250}$

$= 40\ T$

****

(23) $B = \frac{\phi}{A} = \frac{10 \times 10^{-3}}{600(10^{-3})^2} = \frac{10 \times 10^{-3}}{600 \times 10^{-6}} = \frac{10000}{600} = 16.66\ T$

(24) $B = \frac{\phi}{A} \rightarrow \phi = B \times A = 2 \times 300(10^{-3})^2 = 600 \times 10^{-6}$

$= 6 \times 10^{-4}\ Wb$

E 7/2/12

1. MAGNETIC FIELD OF A CURRENT CARRYING CONDUCTOR

In the year 1819, the Danish physicist, Hans Christian Oersted (1777-1851), accidentally discovered during one of his lectures at the University of Copenhagen that an electric current flowing in a conductor deflected the needle of an adjacent compass. He concluded rightly that the current in the conductor created a surrounding magnetic field.

This field, on account of its source, was called an ______________________________.

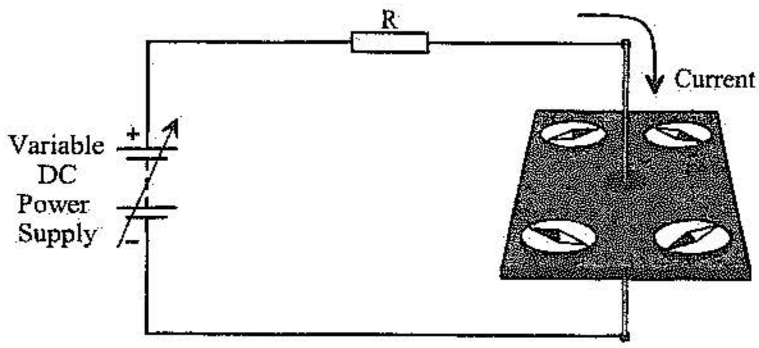


Figure 1

By plotting the magnetic field around the conductor on the setup shown in figure 1 with a small magnetic compass, it was found -

- the electromagnetic field surrounded the wire in a circular fashion, that is the lines of flux formed concentric circles
- the direction of the magnetic field changed with the direction of the current in the conductor.

With the direction of the current flowing as shown in figure 1, it was found that the magnetic field lines surrounded the conductor in a clockwise direction when looking down at the setup, that is the current is flowing away from the observer. This is represented in figure 2.

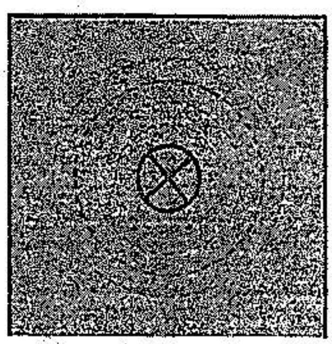


Figure 2

2. MAGNETIC FIELD OF PARALLEL CONDUCTORS

Consider two parallel conductors through which current flows in the same direction, as shown in figure 6.

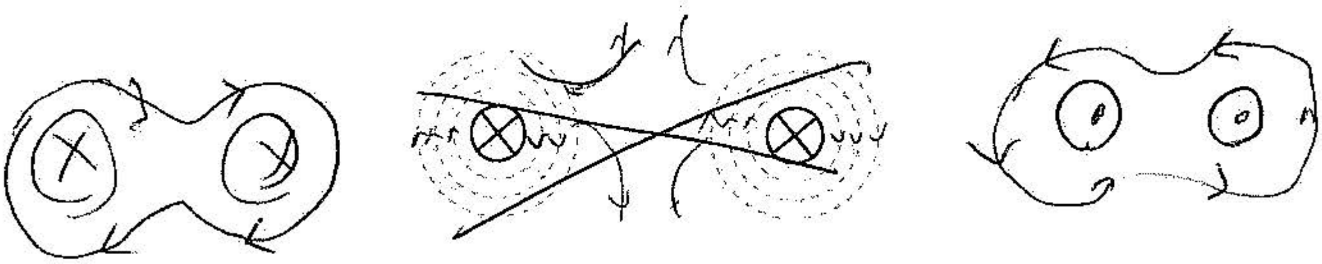


Figure 6

Given the direction of current flow is into the page (that is away from the observer) -

- the direction of both magnetic fields will be the same
- between the conductors the fields will combine
- the combined field between the conductors will be single magnetic flux
- on the outside of the conductors, however, there will be a magnetically combined field due to the addition of the individual fields
- as magnetic lines of force act like rubber bands, they tend to attract the conductors together.

If the direction of the current in the two conductors is dissimilar, as shown in figure 7, the resultant effect will be different -

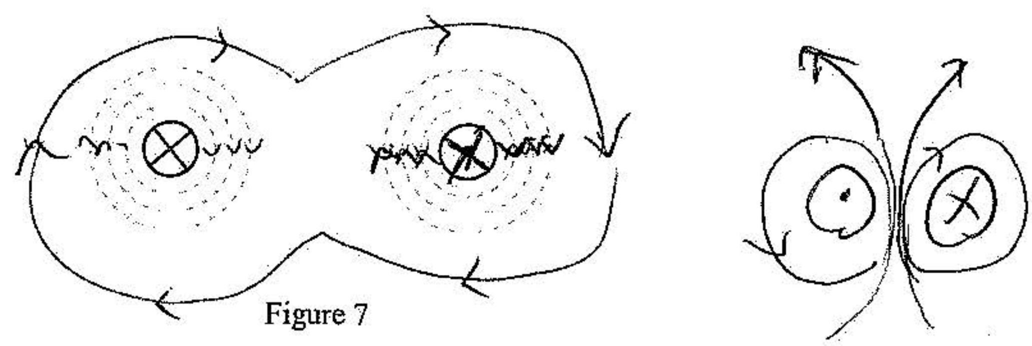


Figure 7

- the fields between the conductors will repel one another
- the magnetic flux lines are difference between the conductors
- the conductors will be forced to ~~be~~ apart

It is thus seen that a current-carrying solenoid behaves as if it were a powerful bar magnet with a N pole at one end and a S pole at the other end.

The polarity of a solenoid may be deduced by adapting the right-hand solenoid rule, see figure 10, as follows -

- Place the right hand with the palm on the outside of the solenoid so that the fingers indicate the direction of current
- The thumb then points to the N pole of the solenoid.

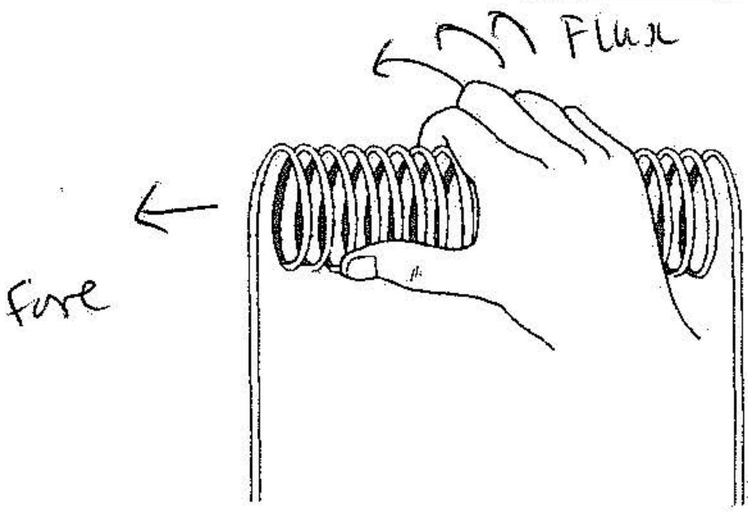


Figure 10

4. THE ELECTROMAGNET

An electromagnet is a solenoid provided with a magnetic core as illustrated in figure 11.

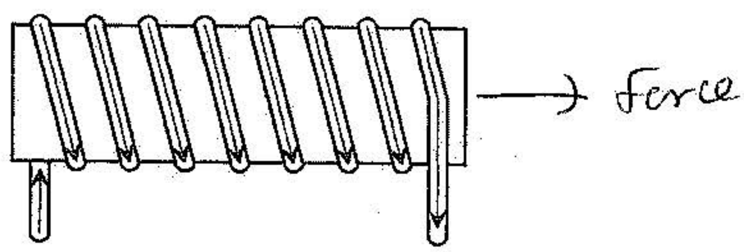


Figure 11

30

5. MAGNETOMOTIVE FORCE

The magnetic flux of an electromagnet is caused by current flowing through the winding, and the higher the current, the greater the flux. As well, increasing the number of turns increases the flux (if the current stays the same).

The product of the turns and current in the turns is called ampere - turn. This force is the magnetic pressure that produces magnetic lines of force, rather like an electromotive force causes an electric current in a circuit.

Because magnetic flux is proportional to the number of turns and the current in the winding, they are combined in an equation that gives magnetomotive force. The equation is:

$$F_m = IN$$

where: mmf = magnetomotive force in ampere-turns (At)
I = current in amperes
N = number of turns

Example: 1

A coil of 20 turns carries a current of 3 amperes. Determine the magnetomotive force produced by the coil.

$F_m = IN = 3 \times 20 = 60$ AT

Example: 2

If the coil in example 1 had its number of turns increased to 60, what current would need to flow in the coil to produce the same magnetomotive force.

$F_m = IN \rightarrow 60 = I \times 60$

$\therefore I = \frac{60}{60} = 1$ Amp

Example: 3

A coil is required to produce an mmf of 2000At. Determine the coil current if the coil has 2500 turns.

$F_m = IN \rightarrow 200 = I \times 2500$

$I = \frac{200}{2500} = 0.08$ Amp

An important feature of the solenoid is its ability to attract magnetic substances.

If a piece of soft iron or steel is in line with the field of a solenoid, figure 16, it is attracted into the core of the solenoid and will move so that its centre coincides with the centre of the coil. This characteristic is adapted for many and varied applications such as magnetic circuit-breakers and solenoid valves.

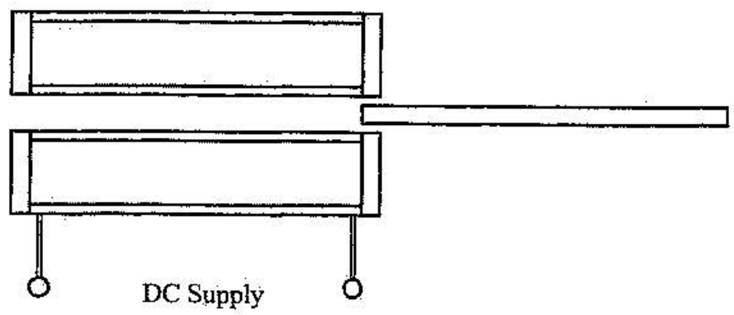


Figure 16

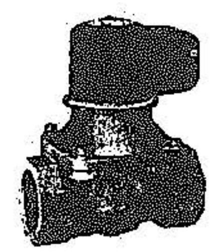


Figure 14

Electromagnets of special design have a wide application in the handling of iron and steel. These electromagnets, known as lifting magnets, do not require the use of slings or hooks; hence provide ease of operation. Figure 15 illustrates a typical winding arrangement in a circular lifting magnet.

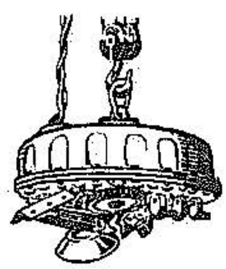


Figure 15

Figure 17 illustrates the principle of operation of the magnetic separator, which is designed to remove pieces of iron and steel from coal, rocks or ore.

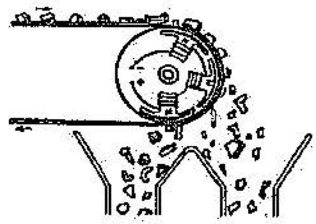


Figure 17

The material is fed on to an endless belt usually travelling at a speed of 30 metres per minute. This belt passes round a pulley fitted with an electromagnetic coil arrangement inside it, the coils being energised through sliprings. As the material passes over the pulley the non-magnetic particles drop off immediately but the magnetic scraps are held by the pulley's attractive force until the belt carries them past the pulley; whereupon they drop off into a separate pile.

A magnetic substance may be magnetised by placing it across the core of an electromagnet supplied from a DC source, as illustrated in figure 18. This procedure is frequently used to magnetise permanent magnets.

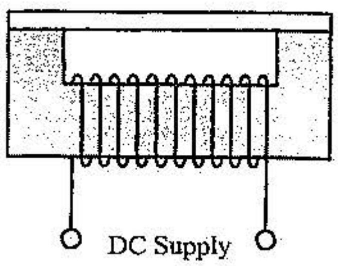


Figure 18

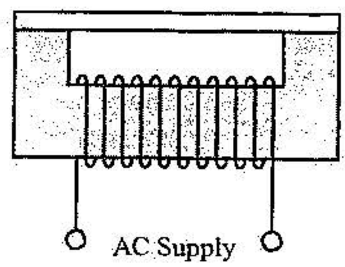


Figure 19

Demagnetising involves disturbing the line-up of the molecular magnets in a material. A method of demagnetising a substance is shown in figure 19. An AC voltage is applied to the terminals of an electromagnet. The specimen to be demagnetised is placed near the core and then gradually withdrawn from its influence. Alternatively, the specimen may remain in position and the alternating current gradually diminished to zero. The latter method is very simple and very effective.

In addition, electromagnets form integral parts of a pieces of machinery, for example -

- electromagnetic clutches and chucks
- contactors
- transformers, electric motors and generators.

****

PROCEDURE :

1. SINGLE LAYER SOLENOID

1. Construct a solenoid by winding 40 turns of $1mm^2$ building wire around a 16mm PVC conduit former as shown in figure 1.

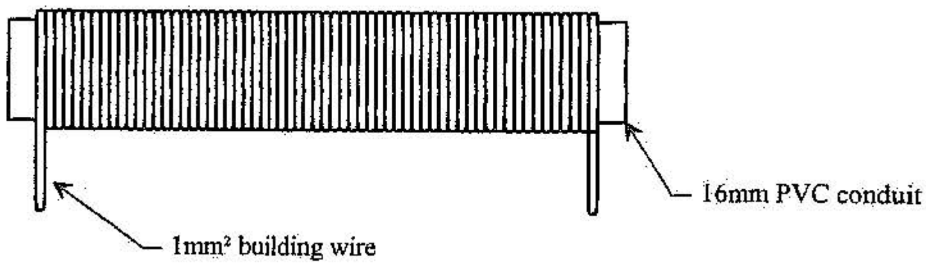


Figure 1

2. Tape the ends of the solenoid with masking tape to prevent the coil from unwinding.
3. Mark the start of the coil, then strip the ends of the wire and connect to the terminal block.
4. Connect the circuit as shown in figure 2. **Note:** Be sure to connect the coil so the start of the coil is positive.

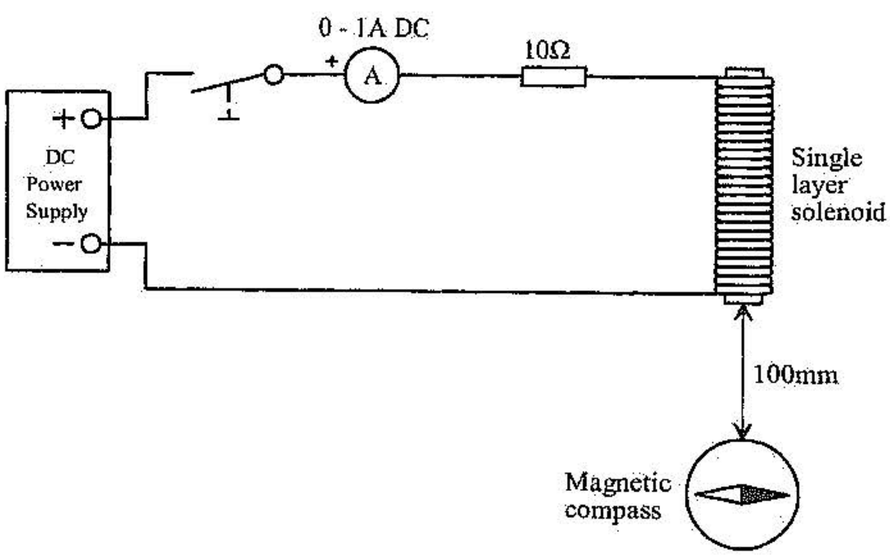


Figure 2

5. __**Do not proceed**__ until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

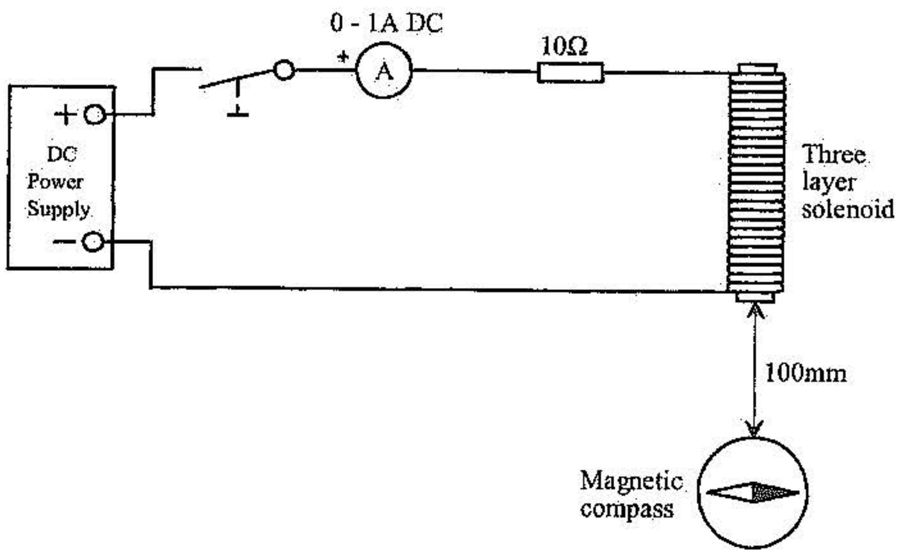


Figure 3

6. Adjust the power supply for minimum output voltage.
7. Turn on the power supply, close the circuit switch and then adjust to give a circuit current of 0.2A.
8. Open and close the circuit switch, observe any effect on the compass needle when the switch is closed. **Note**, this step may need to be repeated several times in order to observe the effect.
9. Record your observations in table 2.

Table 2

	Effect on Compass Needle				
	0.2A	0.4A	0.6A	0.8A	1A
Three Layer Solenoid air core					
Three Layer Solenoid brass core					

10. Repeat the procedure for each of the current values shown in table 2.
11. Insert the brass rod into the conduit and repeat steps 6 to 9.

3. RIGHT HAND SOLENOID RULE

1. Apply the right hand solenoid rule to predict which end of the single layer solenoid would have a north magnetic polarity. Assume that current is flowing into the start of the winding.

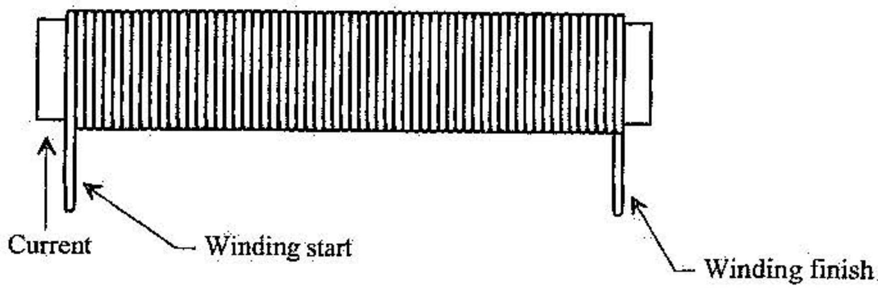


Figure 4

2. Connect the solenoid in circuit as shown in figure 5.

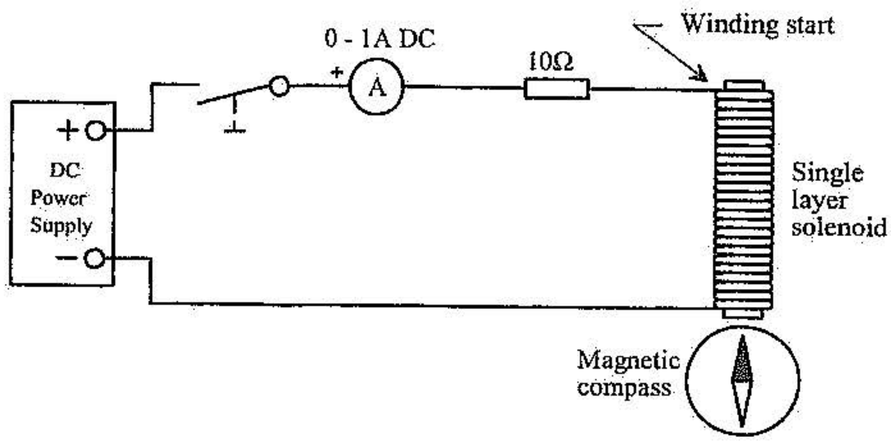


Figure 5

3. Adjust the power supply to deliver a circuit current of 1A.
4. Using the magnetic compass identify the north pole of the solenoid.
5. Does the north pole as identified with the compass match the north pole predicted using the right hand solenoid rule?

YES or NO __________

6. Move the compass around the solenoid and note the direction taken by the compass needle.
7. Based on your results sketch the solenoid's field pattern. Use the layout shown in figure 6.

4. What effect does the reversal of current flow through a solenoid have on the polarity of the solenoid's magnetic field?

5. What effect did the introduction of the mild steel core have on the strength of the magnetic field produced by the solenoid?

6. Why did the mild steel rod effect the solenoid's magnetic field strength, yet the brass rod did not?

7. Does the right hand solenoid rule work when applied in practice?

****

5. The magnetic field around a copper conductor can be increased by:
   (a) winding the conductor into a coil
   (b) increasing the current through the conductor
   (c) inserting an iron bar into the wound
   (d) all of the above

SECTION B

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

1. State the type of electromagnet action employed in the following practical applications:
   (a) circuit breakers
   (b) relays and contactors
   (c) magnetic chucks and electric crane brakes.
2. Winding a conductor into a coil has the effect of __electromagnetic
3. The two effects of current that are always present when current flows through a conductor are the __(a)__ effect and __(b)__ effect
   magnetic thermal
4. What is the force that exists between two adjacent conductors that have currents flowing in:
   (a) opposite directions?
   (b) the same direction?
   Right hand Thumb rule - conductor
5. State the rule used to determine the magnetic field around a single conductor, and briefly describe how you would apply that rule.
   Right hand thumb rule
6. State the rule used to determine the magnetic field around a coil, and briefly describe how you would apply that rule.
   Solenoid
7. Describe a method you would use to:
   (a) magnetise a piece of magnetic material
   (b) de-magnetise a piece of magnetic material

   Accompany your answer with a diagram for each example.
8. State three advantages of using an electromagnet over a permanent bar magnet.
   (1) Adjustable magnetic field (2) Direction can be changed (3) De magnetisation can be done

For the following questions, complete the questions as directed.

9. Draw a cross sectional view of a conductor. On your diagram, clearly mark how would show current flowing towards the viewer through the conductor .
10. Draw a cross sectional view of a conductor. On your diagram, clearly mark how would show current flowing away from the viewer through the conductor .

4. The coil as shown in figure 4 has various *tapping's* to vary the magnetomotive force produced by the coil. If the number of turns per tapped section is 35 turns, determine the magnetomotive force produced by the various tapping's using position "1" as a reference. The current through all of the coil has been measured at 2.5 amperes . (1-2: 87.5At;1-3: 175At;1-4: 262.5At;1-5: 350At)

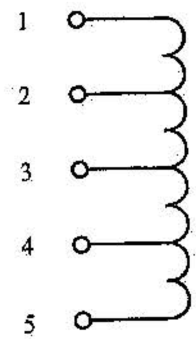
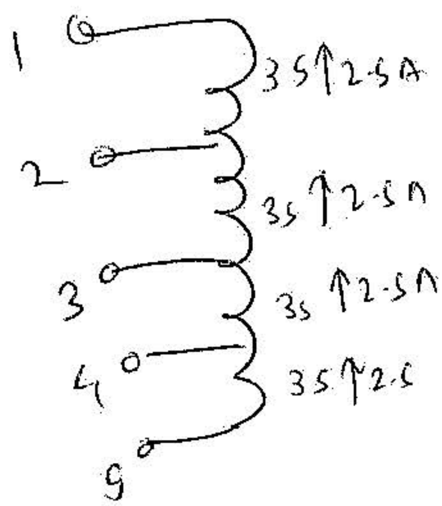


Figure 4



1 → 5 140 × 2.5 AT = 350 AT

1 → 4 = 105 × 2.5 AT = 262.5 AT

1 – 3 = 70 × 2.5 AT = 175 AT

1 – 2 = 35 × 2.5 AT = 87.5 AT

****

NOTES:

PROCEDURE :

1. RELAY OPERATION

1. Arrange the equipment on the bench in a neat and logical manner.
2. Using the relay panel connect the circuit as shown in figure 1.

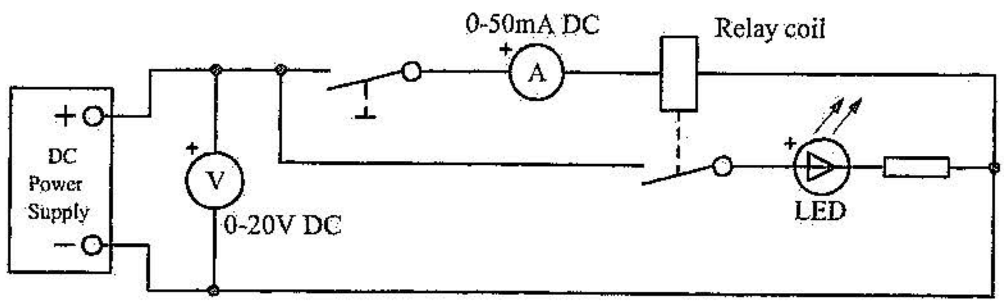


Figure 1

3. **<u>Do not proceed</u>** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

4. Turn on the power supply and adjust for an output voltage of 12V.
5. Watching the relay closely, close the circuit switch and note what happens to the relay, its normally open contact and the light emitting diode (LED).

   - When the switch was closed the relay ______________________
   - The normally open contacts of the relay ______________________
   - The LED ______________________

6. Watching the relay closely, open the circuit switch and note what happens to the relay.

   - When the switch was opened the relay ______________________
   - The normally open contacts of the relay ______________________
   - The LED ______________________

5. Slowly decrease the voltage observing the LED. Record, in table 3, the voltage at which the LED turns off completely. Record the current at this voltage.

Table 4

Supply Voltage	Coil Current	LED Condition
		OFF

Repeat this step to check accuracy of results.

6. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

7. Please return all equipment to its proper place, safely and carefully.

3. OBSERVATIONS:

1. By applying Ohm's law, calculate the resistance of the relay coil using the results obtained from each table. Use the equation $R = \frac{V}{I}$

From Table 1: ______________________________

____

From Table 2: ______________________________

____

From Table 3: ______________________________

____

From Table 4: ______________________________

____

6. Answer true or false to the following statements.
   The pick-up voltage of the relay was -

   (a) approximately the same value as the drop-out voltage ______________

   (b) much higher than the drop-out voltage ______________

   (c) about one quarter of the rated coil voltage ______________

7. Answer true or false to the following statements.
   In this practical assignment, when the LED was lit, it indicated that -

   (a) the relay was energised ______________

   (b) the relay was de-energised ______________

   (c) the voltage applied to the coil was definitely greater than the pick-up voltage ______________

8. Using a red pen, neatly draw a dotted line onto the diagram of figure 2 to indicate the path of the magnetic flux when the coil is energised.

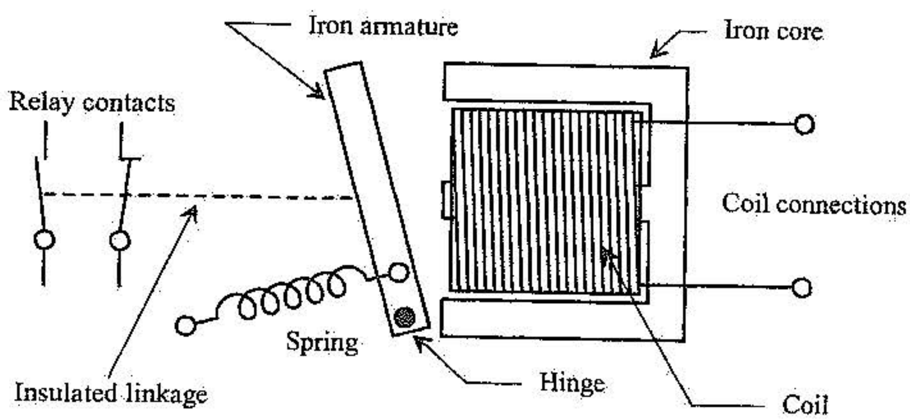


Figure 2

****

4. A material with a high permeability will easily ______ magnetic flux.
   (a) concentrate
   (b) oppose
   (c) generate
   (d) produce

5. A material with a high reluctance will ______ the establishment of magnetic flux.
   (a) concentrate
   (b) generate
   (c) control
   (d) oppose

6. In a magnetic circuit, reluctance is _____ to the length of the core and ______ to the cross sectional area of the core.
   (a) proportional, proportional
   (b) inversely proportional, inversely proportional
   (c) inversely proportional, proportional
   (d) proportional, inversely proportional

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

7. Flux density is a measure of the ___(a)___ of magnetic flux for a given ___(b)___, and is measured in ___(c)___

8. To increase the flux produced by a coil, either increase the coil ___(a)___ or the number of coil ___(b)___, or decrease the core ___(c)___.

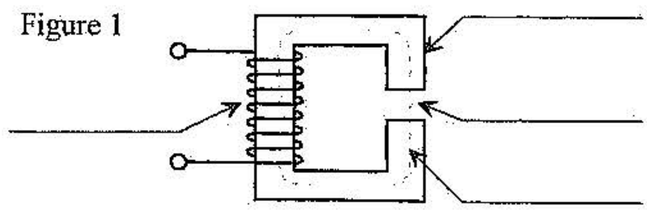
9. Materials with a relative permeability of 1 are classified as ___(a)___, whilst materials with a high to very high relative permeability are classified as ___(b)___

10. μo is the permeability of ___(a)___, μr is the ___(b)___ of a material, whilst μ is the ___(c)___ of a material.

11. If a material has a high ______ it is difficult to magnetise.

12. When comparing a magnetic circuit to an electrical circuit, ___(a)___ is the equivalent of an emf, ___(b)___ is the equivalent of circuit current and ___(c)___ is the equivalent of circuit resistance.

Figure 1



NOTES

S2

1. PERMEABILITY

In simple terms, the flux density in the core of the magnetic circuit shown in figure 1 is dependent upon two factors -

- N
- I

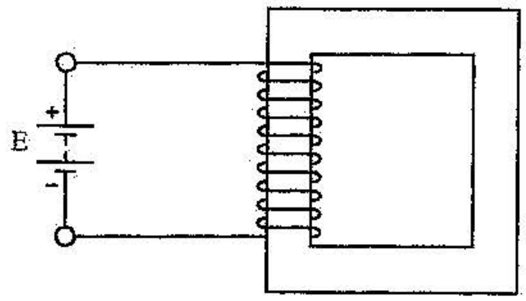


Figure 1

The magnetising force and the flux density of a magnetic field are linked by the expression -

$$B = \mu H$$

where: B = flux density in tesla (T)

μ = permeability of core material

H = magnetising force in ampere turns per metre (At/m)

The permeability of the core material is determined by taking the product of the permeability of free space and the relative permeability of the material -

$$\mu = \mu_o \mu_r$$

where: μ = permeability of core material

μo = permeability of free space = 12.57×10^{-7} (a constant)

μr = relative permeability of the core material

As previously discussed, the relative permeability of a ferromagnetic material is variable and depends on the applied magnetising force.

(54)

4. MAGNETISATION CURVE FOR A MAGNETIC MATERIAL

Consider the effect of increasing the magnetising force applied to the magnetic core shown in figure 4.

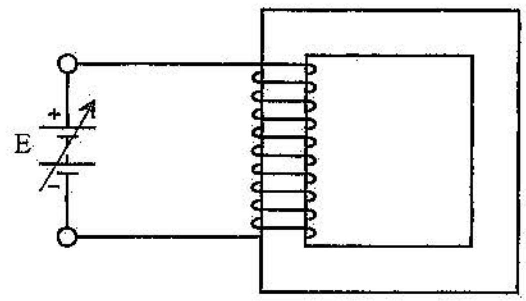


Figure 4

As the magnetising force is increased, the flux density in the core is ___increased___.

When viewing the cross-sectional area of the core, at different values of magnetising force, a large variation in how tightly packed the flux is packed will be seen. Figure 5 illustrates this concept.

Figure 5

Figure 6 shows the typical magnetisation curve for a magnetic material.

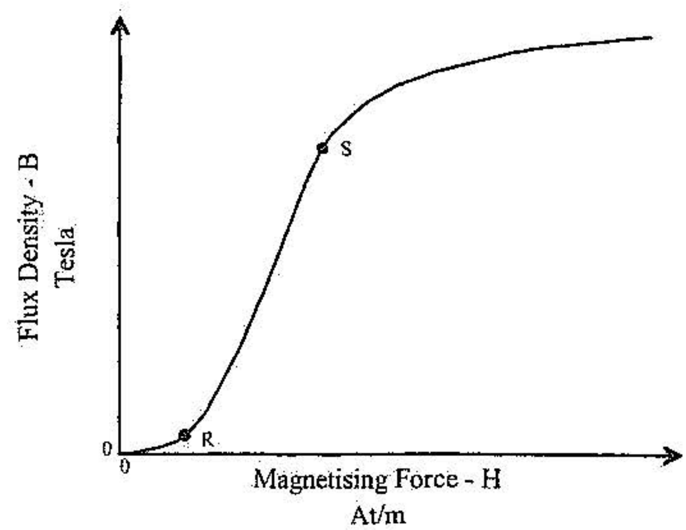


Figure 6

Example: 1

A cast steel ring, as shown in figure 8, has an average length of 300mm and is wound with 500 turns. Determine -

(a) the magnetising force required to produce a flux density of 1.6T
(b) the current required in the coil.

$B = \mu H$ $\qquad$ $H = \frac{NI}{l}$

$\mu_r = 12000$

$\mu_0 = 4\pi \times 10^{-7}$

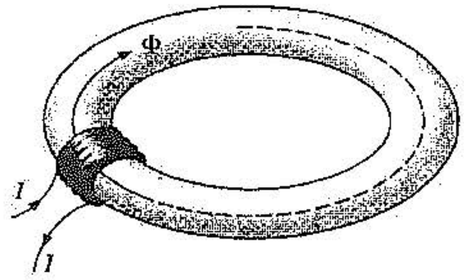


Figure 8

$\therefore B = \mu H$

$B = \mu_0 \mu_r H \rightarrow H = \frac{B}{\mu_0 \mu_r} = \frac{1.6}{4\pi \times 10^{-7} \times 12000}$

$H = \frac{NI}{l}$ $\qquad$ $I = \frac{Hl}{N} = \frac{1.6}{4\pi \times 10^{-7} \times 12000} \times \frac{300 \times 10^{-3}}{500}$

$=$

Example: 2

If the cast steel ring used in the arrangement shown in figure 8 was replaced with a mild steel ring, determine -

(a) the magnetising force required to produce a flux density of 1.6T
(b) the current required in the coil.

for mild steel use $\mu_r = 35000$

If the magnetising force is decreased from its maximum in the reverse direction through zero back to its maximum value in the forward or positive direction, a mirror image of the previous curve will be obtained. It will be found that a closed S-shaped loop has been traced out which is called the -

Hysteresis,

derived from the Greek word "hysteresis" meaning "lagging behind", as indeed the flux density is always lagging behind the magnetising force.

A typical hysteresis curve is shown in figure 11.

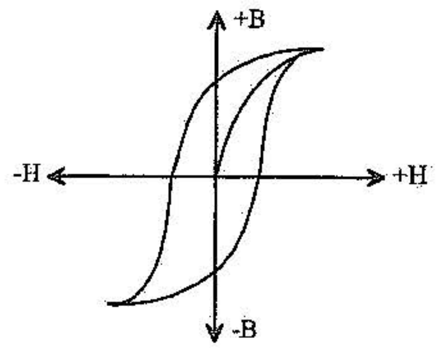


Figure 11

6. HYSTERESIS LOSS

It has been shown that iron atoms are grouped in domains. The magnetic axes of all molecules within a particular domain all point the same way. In a non-magnetised piece of iron, these domains, and thus the direction of their magnetic axes, are all jumbled up and the overall effect is that they neutralise each other. See figure 12.

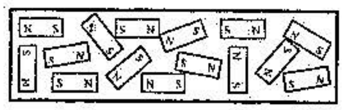


Figure 12

As the piece of iron becomes magnetised, initially only a few, but later many more of these domains "snap" into a uniform direction, the magnetic axes thus aligning with each other and the overall effect is that the piece of iron begins to exhibit magnetic properties.

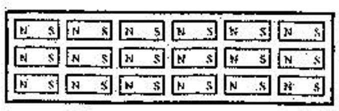


Figure 13

Figure 15 shows the hysteresis loop for hard iron. Its characteristics can also be identified from the loop -

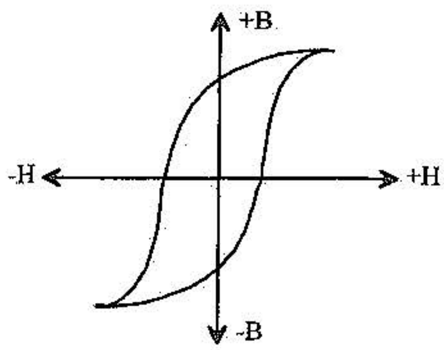


Figure 15

- The area within the loop is large, this indicates the hysteresis loss is Large.
- The residual magnetism is Large.
- Hard iron is suitable for the manufacture of permanet magnet.
- Not suitable for applications where the magnetic field has to undergo a large number of reversals per second.

The third hysteresis loop to be considered, figure 16, is that of a material known as ferrite. This is a ceramic core made up of iron oxides.

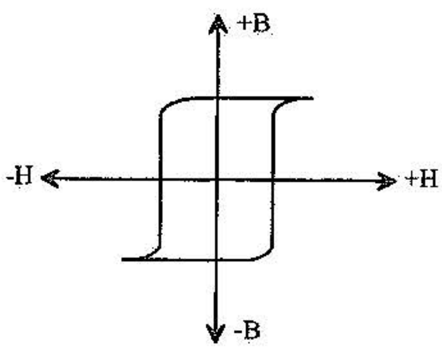


Figure 16

- The shape of the loop indicates the hysteresis loss is High.
- Flux density tends to remain constant in one direction until the value of the magnetising force is increased to its maximum level in the opposite direction - the flux density rapidly reverses.
- Ferrite is used manufacture of magnetic ______________.

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NOTES:

PROCEDURE :

1. Arrange the equipment on the bench in a neat and logical manner.
2. Connect the circuit as shown in figure 1.

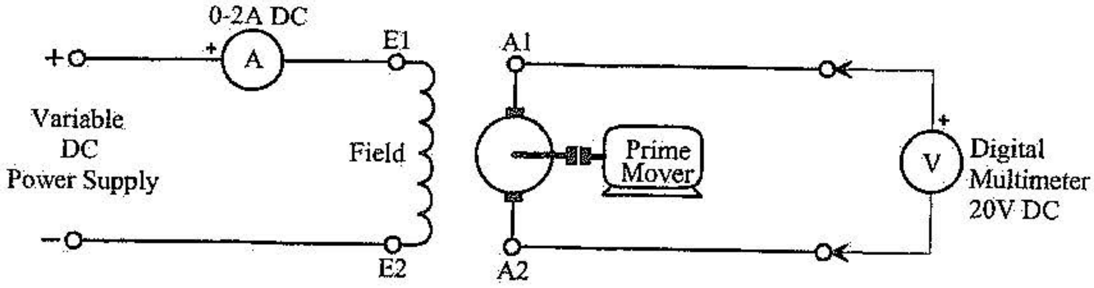


Figure 1

3. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

4. Ensure the DC power supply is switched off.
5. Start the prime mover.
6. Measure the generator output voltage using the digital multimeter and record in the space provided in table 1.

Table 1

Field Current amperes	0	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
Output Voltage Field Current Increasing										
Output Voltage Field Current Decreasing										

7. Turn on the DC power supply, slowly adjust to give a field current of 0.1A, then measure the generator output voltage. Record the voltage value in table 1.
8. Repeat the procedure for each of the values of field current shown in table 1.

4. Using the results recorded in table 1, draw the magnetisation curve for the generator.

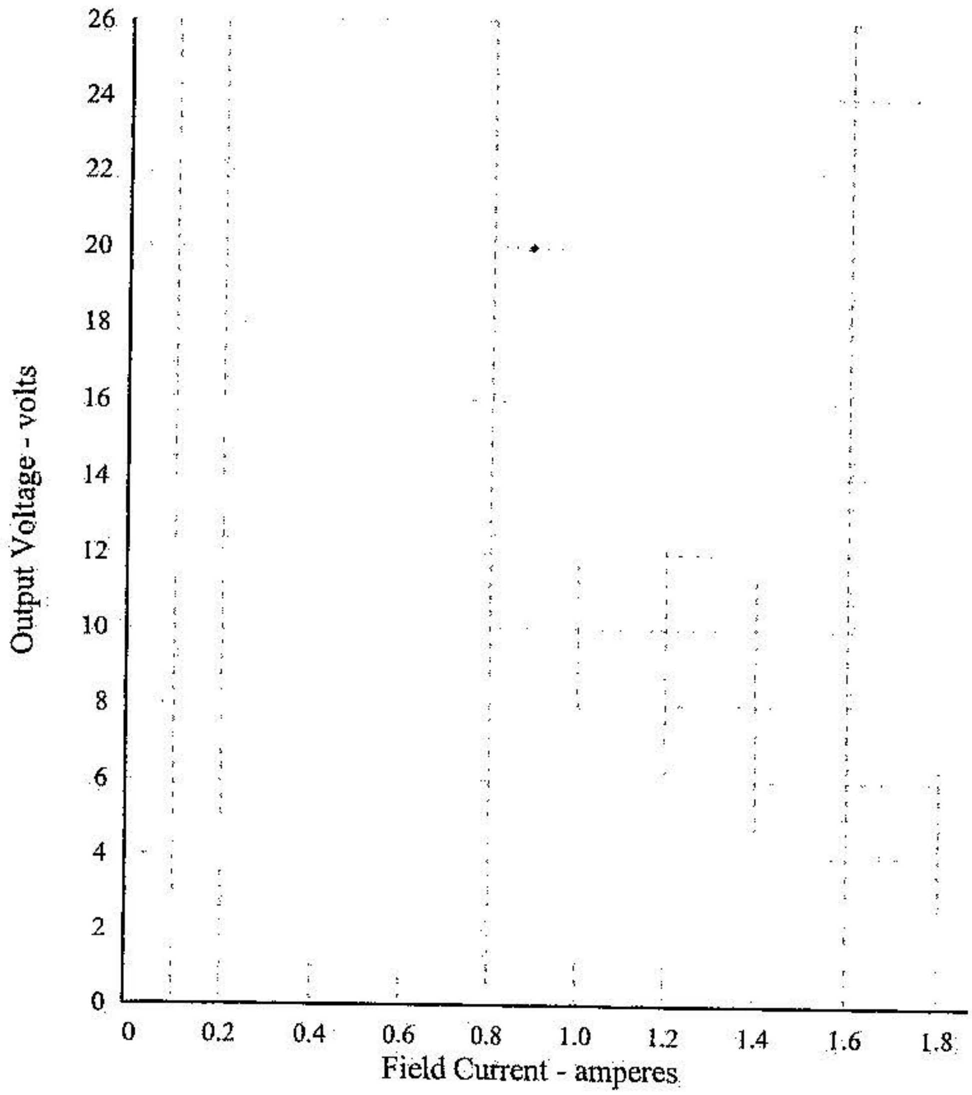


Figure 2

5. In the graph drawn in figure 2, what does the area between the two curves represent? What causes this loss?

****

Magnetisation Curves & Materials

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. Hysterisis loss is due to:
   (a) high reluctance
   (b) low permeability
   (c) high flux density
   (d) residual magnetism

2. A B-H curve shows how the ______ changes for changes in ______.
   (a) material reluctance; mmf
   (b) flux density; magnetising force
   (c) magnetising force; flux density
   (d) flux; reluctance

3. The B-H curve which is shown as a straight line would be that for:
   (a) air
   (b) cast iron
   (c) mild steel
   (d) silicon steel

4. The lagging of changes in magnetic flux density behind changes in magnetising force is known as:
   (a) eddy current loss
   (b) permitivity
   (c) hysterisis
   (d) reluctance

5. ______ occurs when the flux density of a material cannot be increased further for increases in magnetising force.
   (a) Residual magnetism
   (b) Coercive force
   (c) Retentivity
   (d) Saturation

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

6. A magnetisation curve shows the relationship between ___(a)___ and ___(b)___ for magnetic materials.

7. When the magnetisating ___(a)___ is reduced to zero, any magnetic flux remaining in the material is known as ___(b)___, and the force required to reduce this ___(c)___ to zero is known as the ___(d)___

8. ___(a)___ steel is commonly used in transformers and electric motors due to its low ___(b)___

9. Cut and paste the diagram of figure 1 on your answer sheet. On the diagram:
   (a) identify and name the characteristic;
   (b) identify and fully label the horizontal and vertical axes;
   (c) show and label on the diagram the following:
      - the saturation points
      - the amounts of residual magnetism
      - the amounts of coercive force
      - from the text, draw the comparative hysterisis loop for silicon steel.

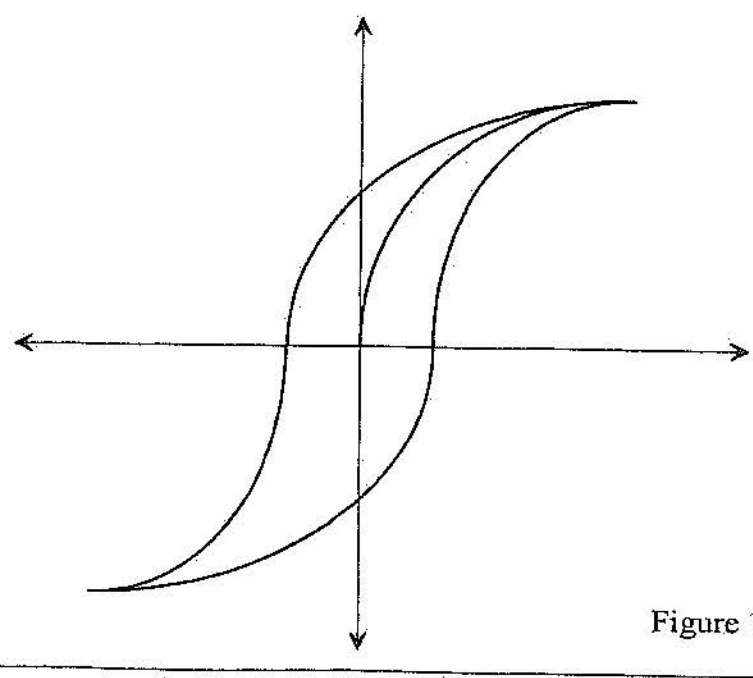


Figure 1

10. The following table represents the results of magnetising the field of a generator and the resulting field flux.

Magnetomotive Force (At)	0	500	1000	1500	2000	3000	4000	6000
Flux (mWb)	5	17.5	32	45	57.5	72	75	78

Table 1

(a) On the 5mm grid on page 92, draw vertical and horizontal axes, and clearly label each axis and title the graph,

(b) Using a scale of 10mm = 500At and 10mm = 5mWb, plot and neatly draw the curve from the results of table 1, using a curve of best fit,

(c) On the graph, show the useful region of the curve, the knee of the curve and the point of saturation.

(d) From the graph determine

- the flux for mmf's of 2500 At and 5000 At;
- the mmf's for a flux of 40mWb and 65mWb.

NOTE:

Include the 5mm grid on page 92 as part of your submitted assignment.

ELECTROMAGNETIC INDUCTION

PURPOSE:

This section introduces the generation of emf via electromagnetic induction.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Describe the principle of electromagnetic induction.
- Apply Fleming's Right Hand Rule to determine the relative motion, direction of induced emf or direction of magnetic field.
- State and describe Lenz's Law.
- Calculate the induced emf in a conductor given the coil turns, change in flux and change in time.
- Calculate the induced emf in a conductor given the conductor length, flux density and velocity of the conductor.
- Calculate the induced emf given the number of coil turns and rate of change of flux.
- List applications of electromagnetic induction.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 109-110 and 112-114.

1. INTRODUCTION

It has already been pointed out that an electromotive force can be produced by a primary or secondary cell and by a thermocouple. However, since the magnitudes of the emf's so produced are too small for the large scale commercial production of electricity, the electric generator is employed. In the electric generator the production of electricity is based on a process called electromagnetic induction.

The purpose of this section is to examine the operation of electromagnetic induction and the factors affecting the magnitude of the emf generated.

In 1831, the British scientist Michael Faraday succeeded in generating an emf by moving a bar magnet towards or from a coil of wire, as shown in figure 1.

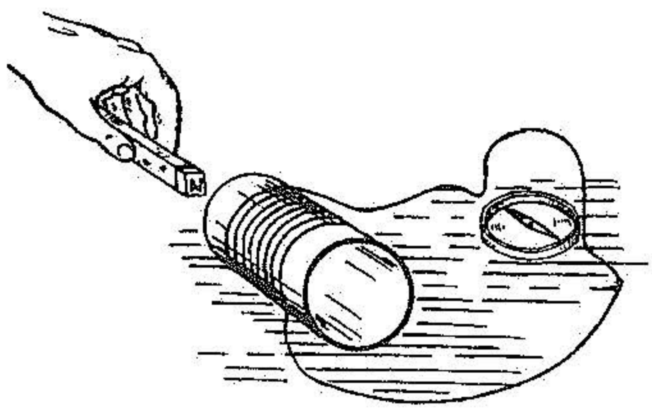


Figure 1

On moving the bar magnet into the coil, a momentary deflection of the compass needle was observed, and on removing the magnet from the coil the needle was deflected again, but in the opposite direction.

Faraday's experiments have led to countless applications of electricity in science and industry. The most common being -

- transformers
- generators.

2. ELECTROMAGNETIC INDUCTION

To investigate the principle of electromagnetic induction consider that a straight rigid conductor is connected to a sensitive galvanometer by flexible wires and that portion of the straight conductor is within the influence of a permanent magnet or an electromagnet. See figure 2.

Irrespective of the position of the conductor while ever it is stationary, there is no deflection of the galvanometer;

indicating zero

Commencing with the conditions shown in figure 2, if the conductor is moved downward past the North-pole of the magnet, an emf is induced in the conductor in an anti-clockwise direction.

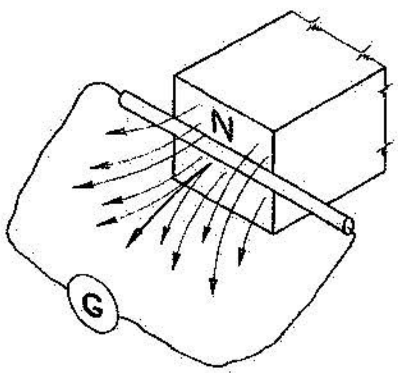


Figure 2

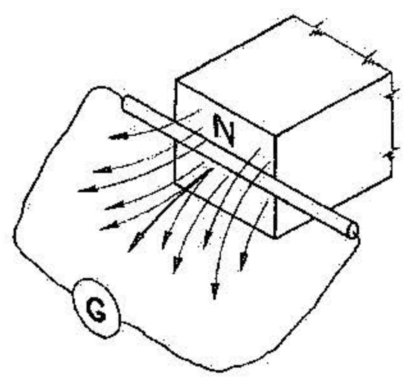


Figure 3

On reversing the movement as shown in figure 3 an emf is induced in a clockwise direction.

This shows that the direction of motion affects the direction of the induced emf.

Similarly it can be shown that if the magnet is rotated through 180°, that is the conductor under the influence of a south pole, and the two movements repeated, -

the directions of the induced emf will be the opposite of those shown in figures 2 and 3, respectively.

This shows that the direction of the magnetic field also affects the direction of the induced emf.

Using the same arrangement as before it can be shown that if the conductor is held stationary and the magnet moved upwards or downwards past the conductor an emf will be induced, as indicated in figures 4 and 5.

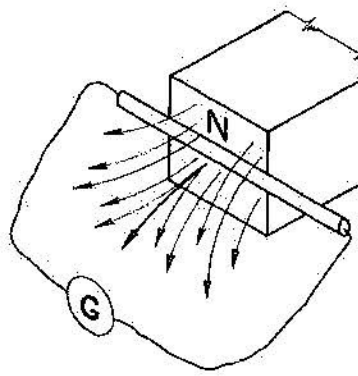


Figure 4

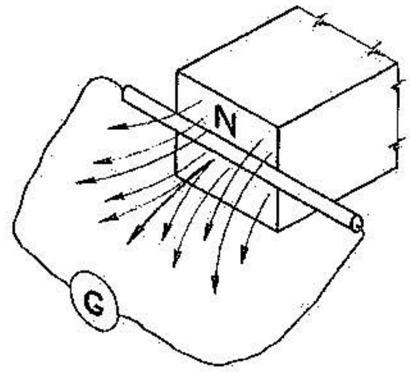


Figure 5

This shows that the induced emf. is dependent upon the -

____interaction____ between the conductor and field.

> No emf will be induced in a conductor unless a change of flux-linkages occurs between the conductor and the magnetic flux.

If the rate of movement of a conductor is reasonably constant and the angle at which the field is cut, is varied, then the emf -

- is a ____maximum____ when the lines of force are cut at right angles.
- becomes progressively ____decreased____ as the angle of cutting decreases
- is ____zero____ when the motion is parallel with the lines of force.

Thus we have shown that an emf is induced by relative motion between the conductor and the flux, such that a change of flux-linkages occurs between them. The maximum emf is obtained when the lines are cut at right angles.

Although we have only considered the emf induced in a single conductor in this section, for practical purposes a greater number of conductors usually would be necessary.

3. FLEMING'S RIGHT-HAND RULE

When studying the operation of electrical machinery it is often necessary to make use of the relationship that exists between -

- field polarity
- direction of motion
- direction of induced emf.

It is difficult to remember the results obtained in the set of diagrams considered in the previous section, but fortunately, a very simple rule has been developed by Professor J.A. Fleming which covers all possible combinations.

The rule is known as **Fleming's Right Hand Rule** and is applied as follows:

Clench the right hand and open the thumb and first two fingers mutually at right angles, as in figure 6, so that if applied to the corner of a cube they would lie along the three edges forming the corner.

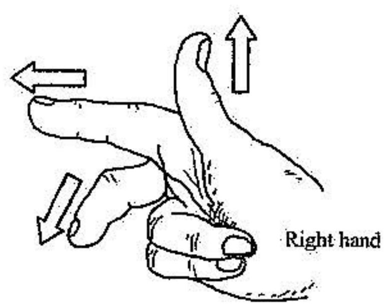


Figure 6

Then -

- the thumb represents direction of motion of conductor
- forefinger represents direction of lines of force
- second finger represents direction of induced emf.

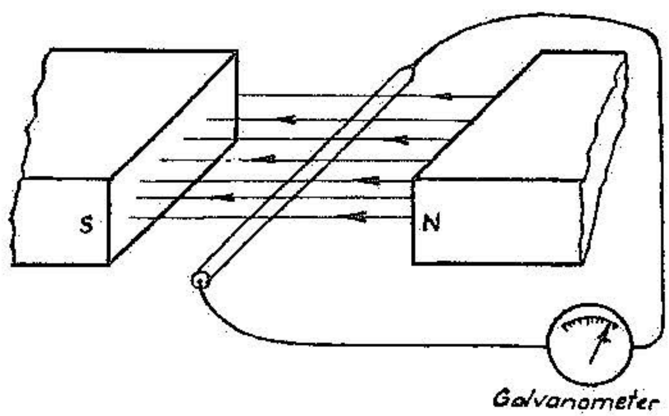


Figure 7

Please note:

- When applying the rule in a case where the flux moves past the conductor, the thumb represents the equivalent motion of the conductor, that is, we imagine the conductor to be moving in a direction opposite to the actual direction of the flux.
- If the conductor forms part of a closed circuit, the induced emf will produce a current, the direction of which also is represented by the second finger.
- The Right Hand Rule is not limited to finding the direction of emf, but may be used to obtain any one of the three related quantities when the other two are known.

Example: 1

Apply Fleming's Right Hand Rule to each of the diagrams shown in figure 8, to determine the -

(a) direction of the induced emf in diagrams (a) - (f)

(b) direction of conductor motion in diagram (g)

(c) magnetic polarities in diagram (h).

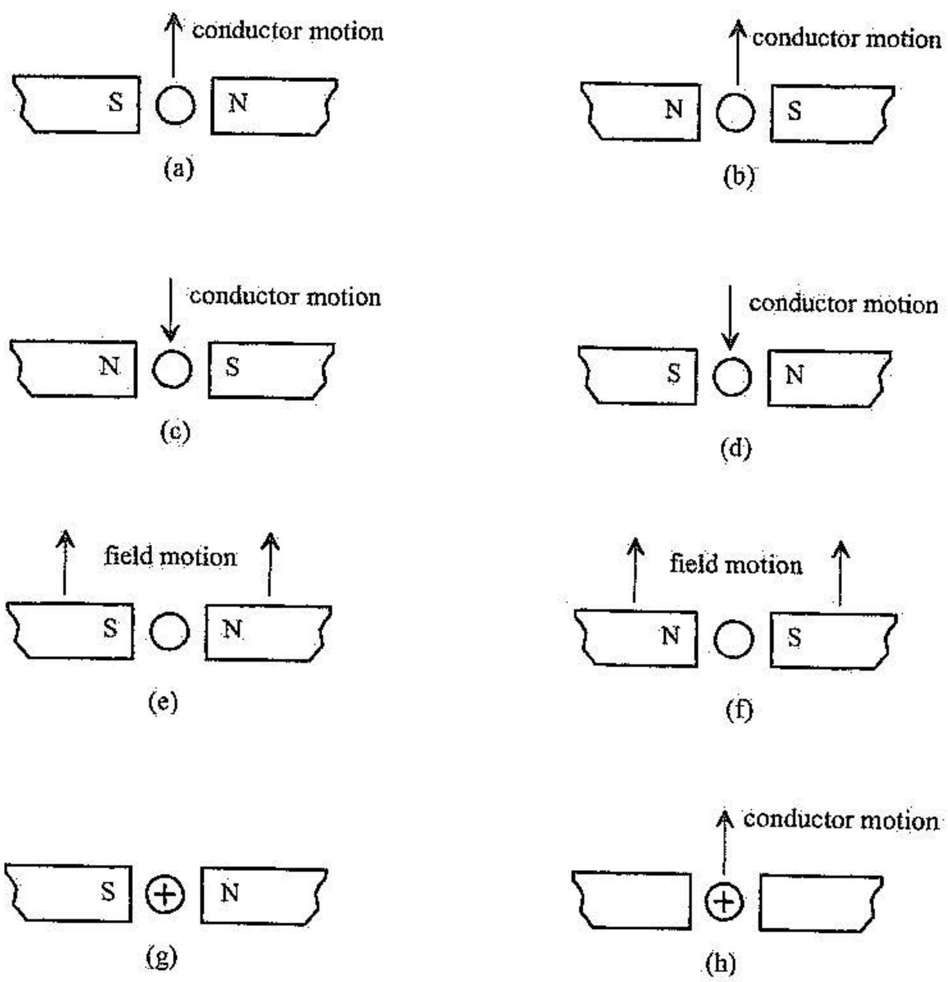


Figure 8

4. EMF INDUCED IN A STRAIGHT CONDUCTOR

It is possible to calculate the magnitude of the emf generated in a conductor moving through a magnetic field.

The value of the emf generated is dependent on the -

- ______________________ of the magnetic field
- ______________________ of the conductor within and at right angles to the field
- ______________________ at which the conductor cuts the field.

When these three factors are combined, the emf generated can be calculated using the equation -

$$e = B l v$$

where: e = induced emf in volts (V)
B = flux density in tesla (T)
l = length of conductor in metres (m)
v = velocity at which the conductor cuts the field in metres per second (m/s)

Example: 2

A conductor 250mm long moves at a velocity of 20m/s at right angles to a magnetic field with a flux density of 1.5 tesla. Determine the value of the emf generated in the conductor.

$e = B l v = 1.5 \times \frac{250}{1000} \times 20$

Example: 3

What would the velocity of a conductor be if it were 200mm long and moved at a uniform speed at right angles to a uniform magnetic field having a flux density of 0.25 tesla and the conductor has an emf of 1.5 volts induced in it?

$e = B l v$

$1.5 = 0.25 \times 200 \times 10^{-3} \times v$

$v =$

Example: 4

Determine the strength of the magnetic field if a conductor with a length of 25mm has an induced emf of 600μV in it when the conductor is moved at a speed of 15 m/s.

$e = B l v$

$600 \times 10^{-6} = B \times 250 \times 10^{-3} \times 15$

$B =$

5. VOLTAGE INDUCED IN A COIL & FARADAY'S LAW

Based on the foregoing, you can see that a voltage is induced in a conductor only if there is relative motion between the conductor and the magnetic field. When a conductor is wound into a coil, its length within the magnetic field is increased giving, as you'd expect, a higher induced voltage. The voltage induced in a coil depends on:

- the strength of the magnetic field
- the number of turns on the coil
- the speed of the cutting action

The equation e = Blv includes all these factors, but calculating the length of a conductor that's wound into a coil is rather difficult to do. Another way is to use the equation first described by Faraday, now known as Faraday's law which states -

> Induced emf is proportional to the rate of change of linkages between conductors and magnetic flux.

Faraday's law is summarised in the following equation -

$$e = N \frac{\Delta \phi}{\Delta t}$$

where:
e = induced emf in volts
N = number of turns on the coil
ΔΦ = change of flux in webers
Δt = time taken for flux change in seconds

Note : The Δ symbol (Greek letter delta) stands for 'change in'.

Example: 5

A coil of 15 turns has a flux linking it of 0.3Wb. If the flux is reduced to 0.1Wb in 100 milliseconds, calculate the induced emf in the coil.

$$e = N \frac{\Delta \phi}{\Delta t} = 15 \times \frac{0.3 - 0.1}{100 \times 10^{-6}} =$$

Example: 6

Calculate the number of turns required on a coil to induce an emf of 60V the coil if the flux linking the coil reduces from 0.4Wb to zero in 5 milliseconds.

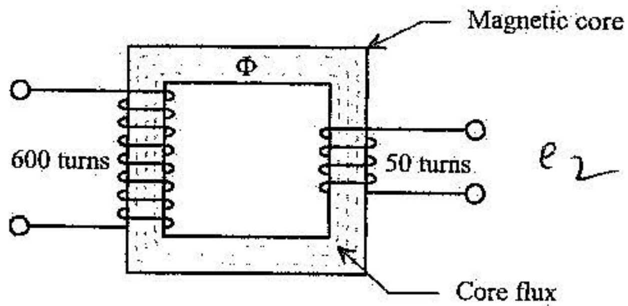
$$e = N \frac{\Delta \phi}{\Delta t}$$

$$60 = N \times \frac{0.4}{5 \times 10^{-3}}$$

Example: 7

A transformer has 600 turns on the primary and 50 turns on the secondary. If a flux of 0.25Wb is reduced to zero in 5 milliseconds, calculate the induced emf in each coil. See figure 9.

e_1



e_2

Figure 9

$$e_1 = N_1 \frac{\Delta \phi}{\Delta t} = 600 \times \frac{0.25}{5 \times 10^{-3}}$$

$$e_2 = N_2 \frac{\Delta \phi}{\Delta t} = 600\ 50 \times \frac{0.25}{5 \times 10^{-3}}$$

6. LENZ'S LAW

Newton's Third Law of Motion in physics states that for every action there is an equal and opposite reaction. That this is true not only in the sphere of mechanical physics but also in the field of electromagnetism was discovered in 1834 (a few years after the discovery of electromagnetic induction by Michael Faraday) by Heinrich Lenz, a Russian scientist of German descent.

Considering Faraday's and other experiments, he came to the conclusion that an induced emf is always of such a direction that its effect tends to oppose the motion or the change of flux which produces that emf. This is known as Lenz's law and is usually stated in the following way -

> The direction of an induced emf is such that the resulting current flow will produce a magnetic field which tends to oppose the original motion causing the induced emf.

The arrangement shown in figure 10 illustrates the application of Lenz's law.

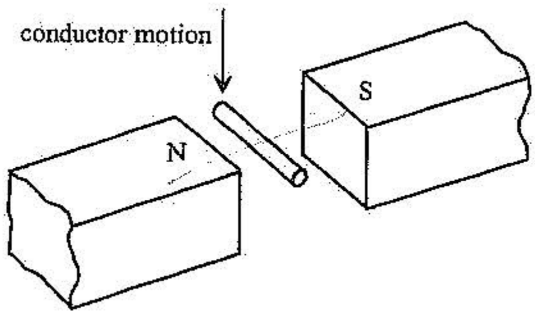


Figure 10

The conductor moving down through the field will induce an emf in the conductor and assuming the conductor is part of a closed loop, a current will flow. The direction of the induced emf and resultant current flow may be determined by applying Fleming's Right Hand Rule.

The current flowing in the conductor will establish a circular magnetic field around the conductor. The direction in which this field operates may be determined using the right hand conductor rule.

The combination of the two magnetic fields will result in -

- the main field being ________________ below the conductor and ______________ above it
- a force acting on the conductor in direct perpendicular to the original conductor movement.

Figures 11 and 12 also illustrate the application of Lenz's law.

In figure 11 a force is applied to the magnet pushing it into the coil. As a result of the emf induced in the coil and the resultant current flow, a force will be exerted opposing the movement of the magnet into the coil.

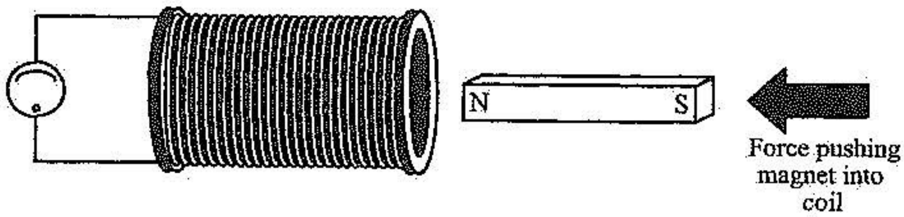


Figure 11

Figure 12 shows a force applied to the magnet such that it is withdrawn from the coil. As a result of the emf induced in the coil and the resultant current flow, a force will be exerted opposing the movement of the magnet out of the coil.

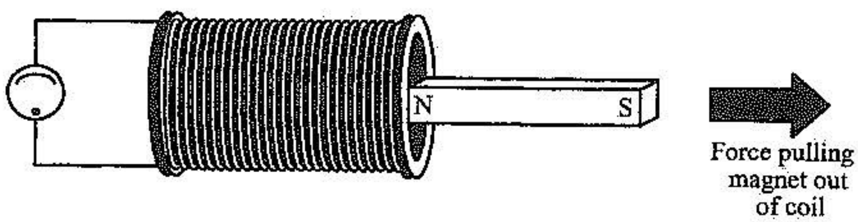


Figure 12

7. APPLICATIONS OF ELECTROMAGNETIC INDUCTION

Some common applications of electromagnetic induction include -

- generators and alternators
- transformers
- fluorescent lamp ballast
- car ignition systems
- magnetos
- damping the movement of a moving coil instruments.

****

ELECTROMAGNETIC INDUCTION & INDUCTANCE

PURPOSE:

This practical assignment will be used to examine electromagnetic induction and the factors affecting inductance and self induced emf.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Describe the factors affecting the magnitude of an emf produced via electromagnetic induction.
- Describe the factors affecting the inductance of a coil.
- Use an LCR meter to measure inductance values.
- Carry out a basic test to determine the presence of an emf of self induction.

EQUIPMENT:

- ☐ 1 x DC power supply
- ☐ 1 x digital multimeter
- ☐ 1 x dual coil panel and 1 x soft iron core
- ☐ 1 x terminal panel
- ☐ 3 x neon lamps (no series resistor)
- ☐ 1 x 60-0-60μA centre zero microammeter
- ☐ 2 x rectangular bar magnets
- ☐ 1 x LCR meter
- ☐ 4mm connecting leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

PROCEDURE :

1. ELECTROMAGNETIC INDUCTION

1. Arrange the equipment on the bench in a neat and logical manner.
2. Connect the circuit as shown in figure 1. **Do not** insert the iron core.

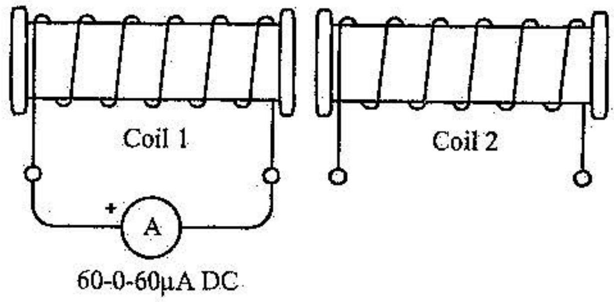


Figure 1

3. Hold the bar magnet at the side of the coil with the north pole pointing towards the centre line of the coil.
4. Slowly move the magnet along the side of the coil, noting both magnitude and polarity of the induced voltage.
   NOTE: Try to remember the speed at which you move the magnet past the coil so that this speed can be doubled at a later stage in this experiment.
5. Repeat step 4, moving the magnet in the opposite direction.

Observation:

6. What effect does reversing the relative direction of the magnetic field cutting the conductor have on the polarity of the induced voltage?

____

____

7. Insert the soft iron core in the coil.
8. Repeat steps 4 and 5 noting any change in magnitude of the induced voltage.

Observation:

9. What is the effect on the induced emf of inserting the soft iron core into the coil?

____

____

10. Hold the two bar magnets together with like poles adjacent to each other as shown in figure 2. (This will double the strength of the magnetic field).

Figure 2

11. Repeat steps 4 and 5 noting any change in the induced voltage.

Observation:

12. What is the effect on induced emf of increasing the strength of the magnetic field that cuts the conductors?

____

____

13. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

14. Connect the two coils in series as shown in figure 3. (This will double the number of turns cut by the magnetic field.

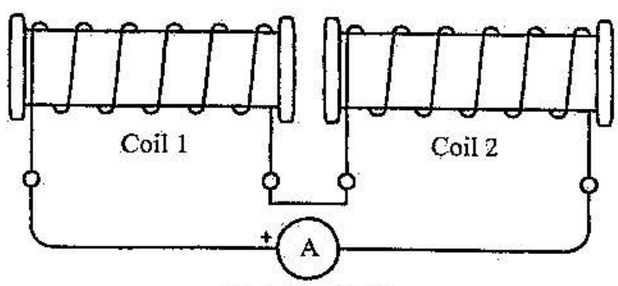


Figure 3

15. With the soft iron core inserted in the coils and the two magnets held together as in step 10, repeat steps 4 and 5 noting any change in the magnitude of the induced voltage.

Observation:

16. What is the effect on induced emf of increasing the number of conductors being cut by the magnetic field?

17. With the equipment set up as in step 15, double the velocity of the magnet when it is moved past the coil noting any change in induced voltage.

Observation:

18. What is the effect on the induced voltage of increasing the velocity of the magnetic field cutting the coil conductors?

19. Reconnect the circuit as shown in figure 4, with the soft iron core removed.

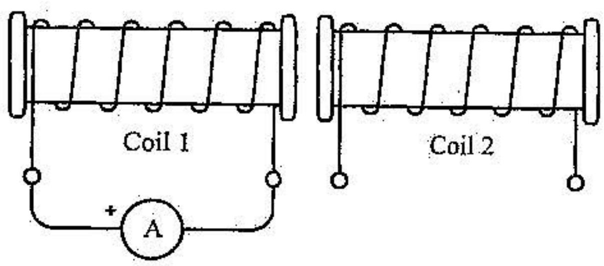


Figure 4

20. Place one magnet on the coil as shown in figure 5.

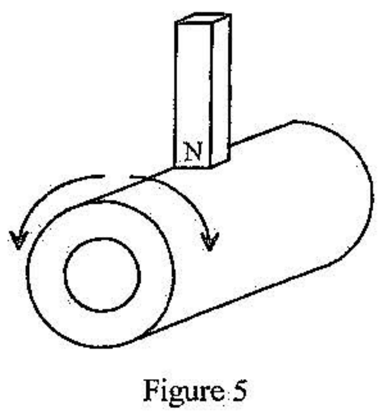


Figure 5

21. Slowly move the magnet around the outside of the coil, noting the value of the induced voltage.

Observation:

22. What was the value of induced voltage when the motion of the magnetic field was parallel to the conductors in the coil?

____

____

23. Insert the soft iron core into the coil. Ensure that circuit is connected as shown in figure 4.
24. Hold magnet stationary against one end of the iron core. Observe the meter deflection.
25. Move the magnet to and fro past the iron core. Observe the meter deflection.

Observation:

____

____

____

26. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

2. INDUCTANCE

1. Using the LCR meter measure the individual inductances of coil 1 and coil 2. Record your results in table 1.

Table 1

	Inductance Coil 1	Inductance Coil 2
Air Core		
Iron Core		

2. Insert the soft iron core and measure the individual inductances of the two coils. Record your results in table 1.
3. Remove the iron core.

4. Connect the two coils in series and measure the total inductance. Record your results in table 2.

Table 2

	Inductance of Coils 1 and 2 in Series
Air Core	
Iron Core	

5. Insert the iron core and measure the total inductance. Record in table 2.

6. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

3. EMF OF SELF INDUCTION

1. Connect three neon lamps to the terminal board.
2. Connect one neon lamp across the power supply as shown in figure 6.

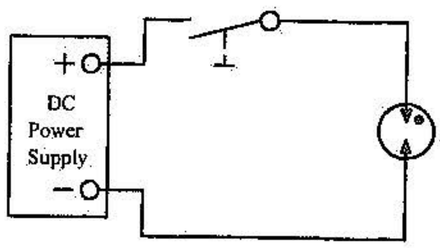


Figure 6

3. Close the circuit switch and adjust the power supply for maximum voltage.
4. Measure and record the lamp voltage and condition, that is, lit or not lit..

Lamp voltage = ______________

Lamp condition = ______________

5. Switch off the power supply.

6. Connect the circuit as shown in figure 7, using one coil and a neon lamp.

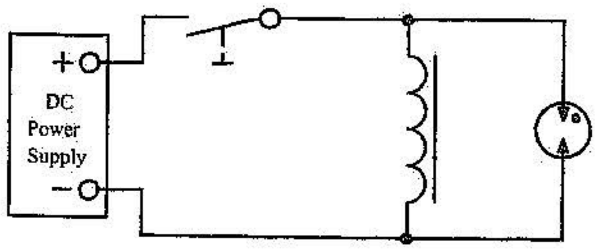


Figure 7

7. Insert the iron core into the centre of the coil.
8. With the circuit switch open, adjust the power supply for an applied voltage of 10V.
9. Close the circuit switch and note the effect on the lamp, that is, lit, not lit or flicked on.

---

10. Open the circuit switch and note the effect on the lamp.

---

11. Connect two lamps in series across the coil as shown in figure 8.

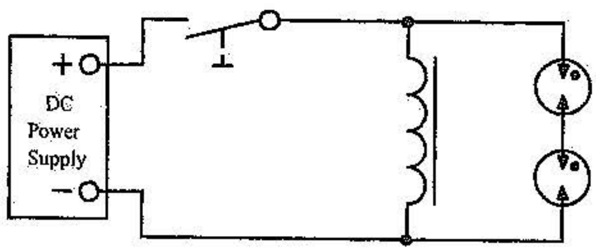


Figure 8

12. Close the circuit switch and note the effect on the lamps, that is, lit, not lit or flicked on.

---

13. Open the circuit switch and note the effect on the lamps.

---

14. Connect three lamps in series across the coil as shown in figure 9.

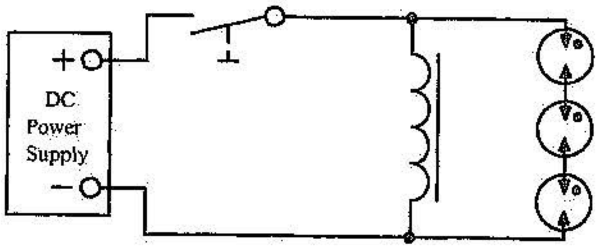


Figure 9

15. Close the circuit switch and note the effect on the lamps, that is, lit, not lit or flicked on.

____

16. Open the circuit switch and note the effect on the lamps.

____

17. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

18. Switch off the power supply, then disconnect the circuit.
19. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Answer true or false to each of the following statements. Base your answers on observations made during this practical assignment.

   An emf will be induced into a conductor:

   (a) when there is relative movement between the conductor and the magnetic field.

   ____

   (b) when a conductor is placed within a magnetic field, whether there is movement or not.

   ____

   (c) provided the conductor is moving, whether a magnetic field exists or not.

   ____

2. Answer true or false to each of the following statements. Base your answers on observations made during this practical assignment.

   The emf induced into a coil is:

   (a) directly proportional to the number of turns in the coil.

   ____

   (b) inversely proportional to the rate of cutting of the lines of force.

   ____

   (c) increased by a factor of 4 if the flux density of the magnetic field is doubled.

   ____

3. What factors determine the magnitude of the emf induced in a conductor?

   ____

   ____

   ____

4. Briefly explain the reason for the results when the magnet was moved around the coil as opposed to along the coil.

   ____

   ____

   ____

5. Based on your observations what factors affect the inductance of a coil?

   ____

   ____

   ____

6. Why did the inductance of the coils increase when the iron core was inserted?

   ____

   ____

   ____

7. What is the minimum voltage required to turn a neon lamp on?

   ____

   ____

8. What was the approximate self induced emf developed by the coil in the circuits of figures 7, 8 and 9?

9. If the iron core in the circuits of figures 7, 8 and 9 was removed, what would happen to the level of the self induced emf?

10. What is inductance and in what form does inductance provide opposition current?

****

Electromagnetic Induction

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. If a conductor in a magnetic field moves parallel to the magnetic field , the induced voltage will be ______ volts.
   (a) a maximum
   (b) alternating
   (c) an average
   (d) zero

2. Fleming's Right Hand rule is used to determine the direction of the:
   (a) magnetic field around a solenoid
   (b) induced currents in a conductor
   (c) magnetic field around a single conductor
   (d) force exerted on a current carrying conductor

3. The value of emf induced into a conductor is dependent upon the ______ density, ______ of conductor and ______ of the conductor.
   (a) conductor; length; velocity
   (b) flux; type; velocity
   (c) flux; length; velocity
   (d) flux; length; material

4. Maximum emf is induced in a conductor when it moves through a magnetic field at an angle of intersection of:
   (a) 0^0
   (b) 45^0
   (c) 90^0
   (d) 180^0

5. If the rate at which a conductor moves through a magnetic field is increased, the induced emf will:
   (a) decrease
   (b) remain the same
   (c) alternate
   (d) increase

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

6. In Flemings Right Hand Rule, the thumb indicates ___(a)___; the first finger indicates ___(b)___ and the middle finger indicates ___(c)___.

7. A cross shown in a cross sectional view of a conductor shows ___(a)___, whilst a dot shows ___(b)___.

8. The polarity of an emf induced into a conductor depends on the ___(a)___ of the magnetic field and the ___(b)___ of the conductor.

9. To find the emf induced into a conductor, the equation to use is ___(a)___, where e is the ___(b)___, measured in ___(c)___, B is the ___(d)___ measured in ___(e)___, l is the ___(f)___ measured in ___(g)___ and v is the ___(h)___ measured in ___(i)___.

10. If the rate at which a conductor cuts across a magnetic field is increased, the value of the ___(a)___ will ___(b)___.

11. **Neatly** reproduce (or cut and paste) the diagram of figure 1 on your answer sheet. For the diagram of figure 1,
    (a) draw the magnetic field pattern for the bar magnet;
    (b) determine the polarity for the terminals "**A**" and "**B**" if the bar magnet is moved into the coil in the direction as shown; and
    (c) describe the method you used to determine the polarity of the terminals.

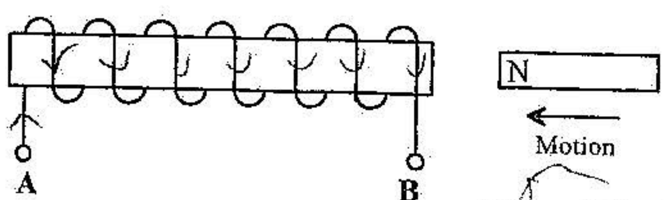


Figure 1

SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

12. A conductor 250mm long moves at right angles with a velocity of 20m/s through a magnetic field with a flux density of 1.5 tesla. Determine the emf induced in the conductor. (7.5V)

    $e = Blv = 1.5 \times 250\times10^{-3} \times 20$

13. For the conductor in question 1, what would need to be increase in flux density to increase the voltage to 12V? (0.9T)

    $12 = B \times 250\times10^{-3} \times 20 \quad B =$

14. Determine the velocity of a conductor of 200mm length which is moving at a uniform speed through a magnetic field of 1.25 tesla flux density at right angles to produce a voltage of:
    (a) 1.5V (6m/s)
    (b) 10V (40m/s)
    (c) 500mV (1m/s)

    $e = Blv$

    $1.5 = 1.25 \times 200\times10^{-3} \times v$

15. Determine the flux density of a magnetic field if a conductor 25mm long cuts through the flux at right angles with a velocity of 15m/s to produce a voltage of 6V. (20T)

    $e = Blv \rightarrow 6 = B \times 25\times10^{-3} \times 15$

16. A coil of 150 turns is lined by a flux of 300mWb. If the flux is reduced to 100mWb in 100mS, determine the voltage induced in the coil. (300V)

    $e = N\frac{\Delta\phi}{\Delta t} = 150 \times \frac{300\times10^{-3}}{100\times10^{-3}}$

17. The diagram of figure 2 represents a transformer with input (primary) and output (secondary) turns as shown. The coils are linked by a common core flux of 25mWb, which is reduced to zero in 5mS. Determine the voltage induced in both coils. (V_1=3kV;V_2=250V)

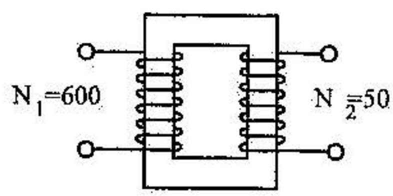


Figure 2

$$e_1 = N_1\frac{\Delta\phi}{\Delta t} = 600 \times \frac{25\times10^{-3}}{5\times10^{-3}}$$

$$e_2 = N_2\frac{\Delta\phi}{\Delta t} = 50 \times \frac{25\times10^{-3}}{5\times10^{-3}}$$

INDUCTORS & INDUCTANCE

PURPOSE:

This section introduces the physical properties of the inductor and its inductance.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- describe the meaning of the terms self induction and inductance.
- describe the construction of an inductor and draw the Australian Standard circuit diagram symbols for four types of inductor.
- calculate the inductance of a coil given the number of turns, change in flux and change in current.
- calculate the inductance of a coil given its physical parameters.
- identify the common types of inductor core and list applications for each.
- describe the construction of a coil wound using a bifilar winding.
- describe the testing procedures for inductors.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 111-114.

F $\frac{N^2 A}{l \mu}$

1. INTRODUCTION

In the previous section it was shown that a voltage could be developed by electromagnetic induction if there is -

moving between a conductor and a magnetic field.

This means that it doesn't matter whether the field moves or the conductor moves, just as long as one moves with respect to the other.

It was also shown that the induced voltage could be increased, if the conductor was wound into a coil.

The value of the voltage induced in a coil depends on three factors, the -

- strength of the magnetic field
- number of Turns on the coil
- speed of the conductor.

These concepts are described in Faraday's law which states -

> Induced emf is Proportional to the rate of change of linkages between conductors and magnetic flux.

Faraday's law is summarised in the equation -

$$Emf = -\frac{d\phi}{dt}$$

Example: 1

A coil 150 turns has a flux linking it of 0.2Wb. If this flux changes from 0.2Wb to 0.1Wb in 0.1 seconds, calculate the induced emf in the coil.

$$e = 150 \times \frac{0.2 - 0.1}{0.1}$$

2. EMF OF SELF INDUCTION

If a coil is connected to a battery as in figure 1, then the energising current produces a magnetic flux which links the coil.

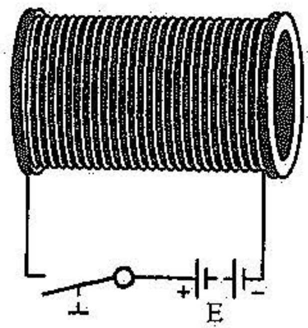


Figure 1

As the flux builds up whilst the current is being established an emf is induced in the coil the magnitude of which depends on the -

- number of turns in the coil
- the rate at which the flux increases.

The emf so induced is called an emf of Induction.

As stated in Lenz's law the direction of the emf of self induction must always be such that it tends to produce a current which would oppose the increase of flux.

When the switch is opened, the current falls to zero and consequently the flux produced by the current also falls to zero. During the time, in which the flux is falling, an emf is induced due to the cutting action of the flux falling through the coil conductors. Again, this emf is known as an emf of self induction.

By Lenz's law the direction of the emf of self induction must be such that it tends oppose the falling current and subsequent decrease of flux.

The emf of self induction will always have a polarity such that it ______________ an increase or decrease in current. For this reason, the emf of self induction is often known as the -

______________________________________.

Example: 2

A coil of 1000 turns carries a current which establishes a flux of 0.01Wb. If it takes 0.05 seconds for the current to reach its steady state value, determine the self induced emf of the coil.

$e = N \frac{d\phi}{dt} = 1000 \times \frac{0.01}{0.05}$

3. INDUCTANCE

It appears from above that any coil has certain properties opposing changes in current. The property of a coil to oppose changes in current is called the -

____________________ or ___________________________ of the coil.

Since inductance opposes changes only, it follows that inductance is effective only if there is a ______________ of current in the circuit.

As inductance is closely linked with a magnetic field, it means that not only a coil has an inductance, but also a straight piece of current carrying conductor has it as well because it is surrounded by a magnetic field. The difference being -

- an iron-cored coil has a higher inductance
- an air-cored coil has a Low inductance
- a straight conductor has a Low inductance.

The unit of inductance is the Henry (H).

It was named after an American physicist, Joseph Henry (1797-1878), who independently discovered magnetic induction at the same time as Michael Faraday.

The henry can be defined as follows:

> A circuit is said to possess an inductance of 1 henry when a current changing at the rate of 1 ampere per second induces in the circuit an opposing emf of 1 volt.

This means that if the current in a circuit having an inductance of 1 henry changes at the rate of 1 ampere per second, the induced voltage will be 1 volt.

This emf is the counter emf which acts to oppose any changes of current in the circuit.

If factors related to the coil are changed, the inductance changes, for example -

- if the number of turns on the coil are increased -

  the self induced emf is conductor of coil has a voltage

  this means the coil inductance has Induced by its own magnetic field

- if the value of flux change is increased -

  the self induced emf is Increased.

  this means the coil inductance has ~~reduced~~ Increased

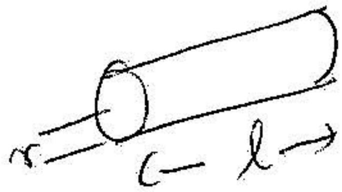
Expressed mathematically,

$$L = N\frac{\Delta \phi}{\Delta I}$$

where: L = the inductance of the circuit in henrys
N = the number of coil turns
$\Delta\Phi$ = the change of flux in for a given change in current in webers
ΔI = the change in current in amperes.

$$L = \frac{N^2 \mu A}{l}$$

4. FACTORS AFFECTING COIL INDUCTANCE



As previously shown the inductance of a coil is related to -

- the number of turns
- the change in flux.

The flux change within a coil is dependent on the -

$$\phi = \frac{NI}{}$$

- ______________________ of the flux path
- ______________________ of the flux path
- ______________________ within the coil.

Provided these four physical properties of a coil are known, the inductance of a coil may be calculated -

$$L = \frac{N^2 \mu A}{l}$$

where: L = inductance in henrys
N = the number of coil turns
μ = permeability of the core of the coil
A = cross-sectional area of the coil in metres squared
l = length of the flux path in metres

Example: 3

A coil of 200 turns is wound on a wooden cylinder 200mm long and having a cross-sectional area of 700mm^2. Calculate the inductance of the coil.

$$L = \frac{200^2 \times 4\pi \times 10^{-7} \times 700(10^{-3})^2}{200 \times 10^{-3}} \text{ H}$$

$$R_m = \frac{NI}{\phi} \qquad L = N\frac{\phi}{t} \qquad L = N\frac{\phi}{I}$$

Example: 4

The wooden core of the solenoid in example 3 is replaced with a magnetic material having a permeability of 33 x 10^{-4}. Calculate the new inductance.

$$L = \frac{200^2 \times 4\pi \times 10^{-7} \times 33 \times 10^{-4} \times 700 \left(10^{-3}\right)^2}{200 \times 10^{-3}}$$

5. NON-INDUCTIVE WINDINGS

Sometimes it will be necessary to accommodate a length of conductor (such as resistance wire) within a small space, a coiling the wire being the most convenient way of doing so. If the resultant inductance is unacceptable, the wire can be wound so that the magnetic effect is neutralised.

There are several methods of achieving such non-inductive windings. In one, the (insulated) wire is doubled back on itself at its centre and the two resulting conductors are wound simultaneously on the core or coil former as shown in figure 2.

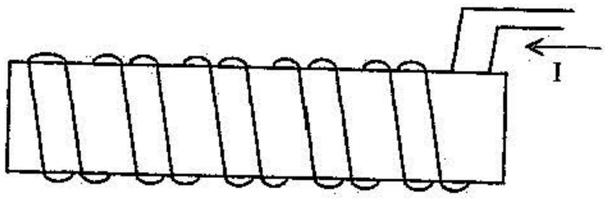


Figure 2

It is clear that the magnetising effect of one conductor is neutralised by the effect of the equal and opposite current flowing in the adjacent conductor, which results in a non-inductive winding. This type of winding, achieved by the simultaneous winding on to the former of two conductors, is called a -

~~Non inductive~~ winding.
Transformer

If the length of wire to be accommodated is excessive, an identical effect is obtained either by winding two identical, separate and adjacent coils in the same direction figure 3 or in the opposite directions figure 4 and connecting their ends in such a fashion that the direction of the current flowing through them produces equal and opposite magnetic fields, thus creating overall a non-inductive coil.

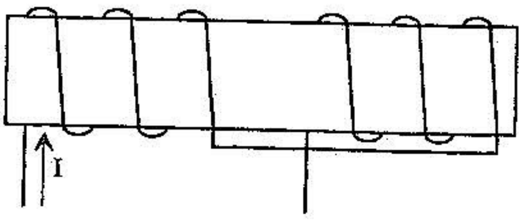


Figure 3

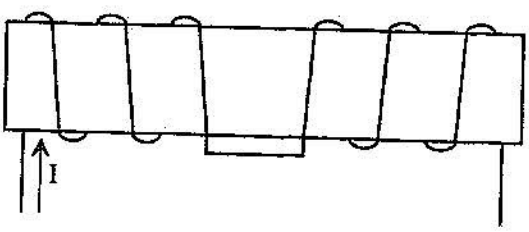


Figure 4

6. INDUCTORS

Although a conductor has inductance, it's generally too small to consider. However, a coil has quite a lot of inductance, so coils are often called inductors, depending on the use. For instance, an electromagnet is not usually called an inductor because it's used to produce a magnetic field, not for its inductance.

Inductors come in all shapes and sizes, and are called by various names, such as -

- ______________________
- ______________________

As stated earlier, the unit of inductance is the henry.

There are three main types of core materials used with inductors:

- air (or other non-magnetic materials)
- soft iron
- ferrite.

The Australian Standard drawing symbols for inductors are as shown in figure 5.

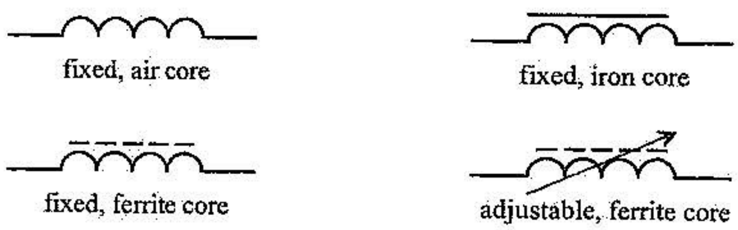


Figure 5

An inductor without a ferromagnetic core is assumed to have an air core. An air-cored coil has a low inductance, usually measured in microhenries.
These coils are used mainly in -

- radios
- communications equipment
- where high frequency signals are involved.

Small air-cored coils are usually wound on a former made of ceramic, phenolic, plastic or other non-magnetic materials. See figure 6.

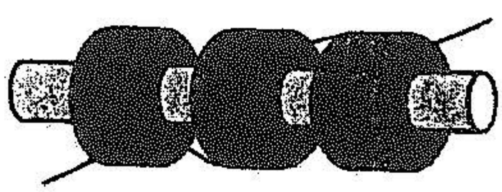


Figure 6

Large air-cored coils are used in transmitters where they might handle many kilowatts of power. Coils of this type often have windings that are thick enough to hold their shape without a former.

Small value inductors (a few μH) are sometimes etched on a printed circuit board, as in figure 7. Here the copper tracks form the windings, and the core is the material from which the printed circuit board is made - usually either fibreglass or phenolic.

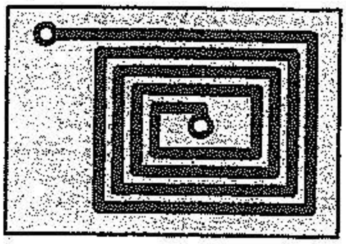


Figure 7

Soft silicon steel is used as the core in inductors that work with low frequencies, such as mains power (50 hertz) and audio frequencies. These cores are made by stacking thin laminations, as below. Each lamination is covered with a thin layer of insulation to stop induced currents flowing in the core. Steel inductors have a large inductance value - often several henries.

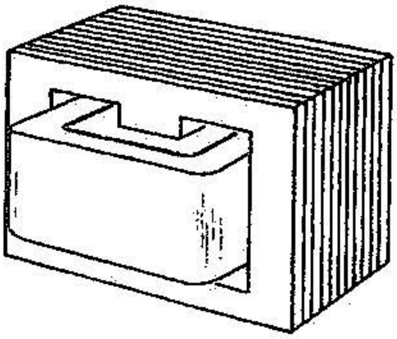


Figure 8

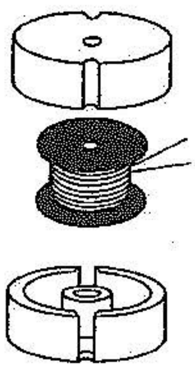


Figure 9

Ferrite cores are used in inductors that operate at relatively high frequencies.

Ferrite is a type of ceramic with the same magnetic properties as soft iron, but being a ceramic it doesn't conduct electricity. The inductance of a coil with a ferrite core can range from millihenries to several henries. As shown in figure 9, ferrite cores are made by clamping preformed sections together. Specially shaped cores such as toroids and cup-cores are usually made of ferrite.

7. TESTING INDUCTORS

The primary reasons for inductor failure are -

- open circuits in the windings due to factors such as -
  - excessive current
  - overheating
  - age
- shorts that develop between the winding and core
- shorts that develop between turns of the winding.

The open-circuit condition can be checked easily with an ohmmeter. If the resistance of the inductor is infinite the coil is open circuit.

The short-circuit condition is harder to check because the resistance of many good inductors is relatively small and the shorting of a few windings will not adversely affect the total resistance. Of course, if one is aware of the typical resistance of the coil, it can be compared to the measured value.

A short between the windings and the core can be checked by simply placing one lead of the meter on one wire (terminal) and the other on the core itself. An indication of zero ohms reflects a short between the two because the wire that makes up the winding has an insulation jacket throughout.

The universal LCR meter, shown in figure 10, can be used to check the inductance level.

Figure 10

****

Inductors & Inductance

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. The unit of inductance is the:
   (a) Farad
   (b) Ohm
   (c) Watt
   (d) henry

2. Compared to the inductance of a straight conductor, the inductance of an air cored coil will be:
   (a) equal
   (b) greater
   (c) less
   (d) zero

3. To increase the inductance of an iron cored coil, you would ______ the _____.
   (a) decrease; CSA of the core
   (b) increase; length of the core
   (c) decrease; number of coil turns
   (d) increase; number of coil turns

4. If a mild steel core is inserted into an air cored coil, the inductance will _______ due to an increase in the _______.
   (a) decrease; reluctance of the flux path
   (b) increase; magnetomotive force of the flux path
   / (c) increase; permeability of the flux path
   (d) decrease; length of the iron core

5. The ideal size/shape of the core of an inductor will be:
   (a) long with a small CSA
   (b) short with a small CSA
   (c) long with a large CSA
   / (d) short with a large CSA

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

iron eddy current hysteresis

6. Most inductor cores are made from laminated ___(a)___ to reduce ___(b)___ and ___(c)___ losses.

7. A non-inductive coil (as used in some wire wound resistors) is produced by _______. Accompany your answer with a diagram.

8. To increase the inductance of a coil, you would: [**NOTE:** Show (i) as either an *increase* or a *decrease*!]
   (a) ___(i)___ the number of coil ___(ii)___
   (b) ___(i)___ the length of the ___(ii)___
   (c) ___(i)___ the cross sectional area of the ___(ii)___
   (d) ___(i)___ the ___(ii)___ of the core

CSA

9. To increase the self induced voltage of a coil, increase either the ___(a)__ of the coil, or the ___(b)___ of the flux linking the coil.

improve

10. An inductor opposes _______ in current. built up

~~induced voltage~~

11. A voltage of self inductance is an example of ___(a)___ Law in action, which states ___(b)___.

12. When determining the voltage of self inductance of a coil, the expression $\Delta\Phi/\Delta t$ can be stated as the ___e___.

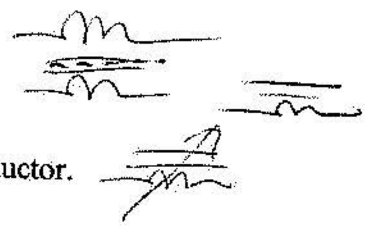
induced increased

13. If the flux change linking a coil is increased, the ___(a)___ voltage will be ___(b)___.

14. If the rate of change of current flowing through a coil is ___(a)___ the ___(b)___ voltage will decrease.

decreased induced

15. Draw the Australian Standard symbols for the following, and give an example of an application for each one:
    (a) an air cored inductor;
    (b) an iron cored inductor;
    (c) a fixed ferrite cored inductor;
    (d) an adjustable ferrite cored inductor.



SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

16. Determine the inductance of a 100m length of straight 2.5mm^2 single cored conductor. Assume that the number of turns equals 1, and the permeability of air is 12.57×10^{-7} H/m (31.4×10^{-15}H)

$L = \frac{N^2\mu A}{l} = \frac{1^2\times12.57\times10^{-7}\times2.5(10^{-3})^2}{100}$

17. If the conductor in question 1 is now wound to produce an air cored coil of 3000 turns with a cross sectional core area of 400mm^2 and an overall length of 50mm, determined the new inductance. (90.5mH)

$= \frac{3000^2\times12.57\times10^{-7}\times400(10^{-3})^2}{100}$

18. An aired cored coil of 400 turns has a cross sectional area of 1000mm^2 and a length of 125.7mm. If the permeability of free air is 12.57×10^{-7} H/m, determine the the inductance of the coil. (1.6mH)

$L = \frac{N^2\mu A}{l} = \frac{400^2\times12.57\times10^{-7}\,1000(10^{-3})^2}{125.7\times10^{-3}}$

19. If an iron core with a relative permeability of 1400 is inserted into the centre of the coil in question 18 above, determine the new inductance of the coil. (2.24mH)

$= \frac{400^2\times1400\times12.57\times10^{-7}\times1000(10^{-3})^2}{125.7\times10^{-3}}$

20. A coil of 354 turns and a length of 350mm has a cross sectional area of 50mm^2. Determine the inductance of the coil with:
    (a) an air core ($\mu = 12.57\times10^{-7}$ H/m) (22.5μH)
    (b) an iron core ($\mu r = 180$) (4.05mH)
    (c) a mu-metal core ($\mu r = 100\times10^3$) (2.25H)

$L = \frac{N^2\mu A}{l} = \frac{354^2\times12.57\times10^{-7}\times50(10^{-3})^2}{350\times10^{-3}}$

21. An inductor with 600 turns has a flux linking it of 25mWb. If this flux is reduced to zero in 5 milliseconds, determine the voltage induced in the coil (3kV)

$e = N\frac{d\phi}{dt} = 600\times\frac{25\times10^{-3}}{5\times10^{-3}}$

22. Determine the flux change required to generate 240V in an inductor of 150 turns if the flux changes in 10 milliseconds. (16mWb)

$e = N\frac{d\phi}{dt} \rightarrow 240 = 150\times\frac{d\phi}{10\times10^{-3}}$

23. Determine the inductance of a coil of 120 turns when a reduction of the coil current from 2.0A to 0.4A produces a reduction of the core flux from 25mWb to 9mWb. (1.2H)

$L = N\,d\phi/dt \Rightarrow L = 120\times(25-9)\times10^{-3}/2-0.4$

24. An inductor of 1.5H has a flux change of 20mWb when the current changes by 5A. For these conditions, determine the number of coil turns of the inductor. (375)

$L = N\frac{d\phi}{dI}$

$1.5 = N\times\frac{20\times10^{-3}}{5}$

MUTUAL INDUCTANCE & R-L CIRCUITS

PURPOSE:

This section introduces mutual inductance and the time constant of the resistive-inductive DC circuit.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- describe what is meant by the term mutual inductance
- list practical applications for mutual inductance
- define the term 'time constant' as applied to a series circuit containing an inductor and a resistor (R-L circuit)
- calculate the value of the time constant for an R-L circuit given the values of the components
- state the number of time constants required for the current in an R-L circuit to reach its final value
- calculate the instantaneous values of voltage and current in an R-L circuit using a universal time constant chart.

REFERENCES:

Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R.
Pages 114-118.

1. SELF INDUCTANCE

As shown in section 6, if a coil is connected to a battery as in figure 1, then the energising current produces a magnetic flux which links the coil.

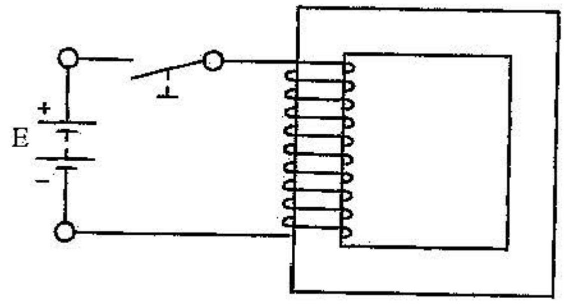


Figure 1

As the flux builds up whilst the current is being established an emf is induced in the coil the magnitude of which depends on the -

- number of turns in the coil
- the rate at which the flux increases.

The emf so induced is called an emf of self induced voltage

According to Lenz's law -

- the direction of the emf of self induction must always be such that it tends to produce a current which would opposes the increase of flux.

Lenz law $e = -\frac{d\phi}{dt}$

When the switch is opened -

- the current falls to zero
- consequently the flux produced by the current also falls to zero.
- during the time, in which the flux is falling, an emf is induced due to the cutting action of the flux falling through the coil conductors.

  Again, this emf is known as an emf of self induced.
- by Lenz's law the direction of the emf of self induction must be such that it tends ________________ the falling current and subsequent decrease of flux.

The emf of self induction will always have a polarity such that it ______________ an increase or decrease in current. For this reason, the emf of self induction is often known as the -

____.

The property of a conductor or coil to produce an emf of self induction and its subsequent opposition to a change in current is known as the -

______ fm ______ or ________________________ of the coil.

Example: 1

A coil of 1500 turns carries a current which establishes a flux of 0.01Wb. If it takes 0.05 seconds for the current to reach its steady state value, determine the self induced emf of the coil.

____

____

____

2. MUTUAL INDUCTANCE

Consider the two coils A and B in figure 2. The galvanometer connected across the terminals of coil B is used to detect the presence and direction of any induced emf in coil B.

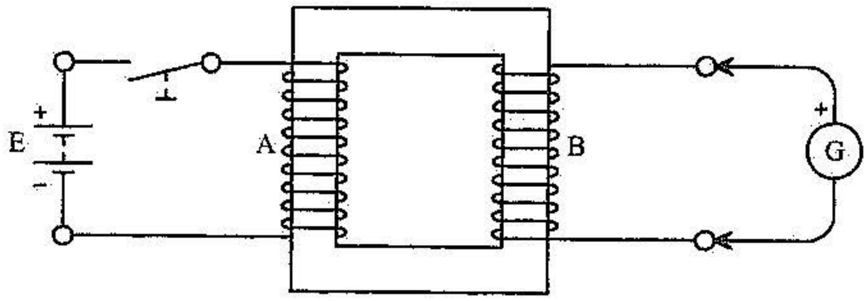


Figure 2

When the switch is closed -

- the current in coil A builds up a magnetic field, a considerable part of which links coil B
- an emf is induced in coil B
- the galvanometer will deflect momentarily and then return to zero.

If the current in coil A is interrupted by opening the switch, or if it is altered in magnitude -

- the magnitude of the flux linking B is changed
- thereby inducing an emf in B
- the deflection will reverse and the galvanometer pointer again returns to zero.

The reversal of the direction of induced emf is due to the reversal of the direction of motion of the flux. Because coil B is in such a position with relation to A that an emf is induced in B, due to a change of current in A, these two coils are said to possess the -

property of______________________________.

The induced emf in coil B is therefore referred to -

as an ______________________________________.

If two electric circuits possess the property of mutual inductance they are said -

to be ______________________.

The two coils are ____________ or ____________ coupled depending on whether all, or only a part, of the magnetic flux links with both coils. The tightness of the coupling is increased by the use of an iron core through both coils.

The unit of mutual inductance is the ______________ (   ).

Mutual inductance is defined in the following way -

> Two coils have a mutual inductance of one henry when an emf of one volt is induced in one coil by a current changing at the rate of one ampere per second in the other coil.

Applications for mutual inductance include -

- the transformer
- car ignition systems
- switch mode power supplies
- clip-on ammeter (tong tester).

3. R-L CIRCUIT

When power is first applied to a resistive DC circuit the current rises instantly from zero to its steady state value, as shown in figure 3.

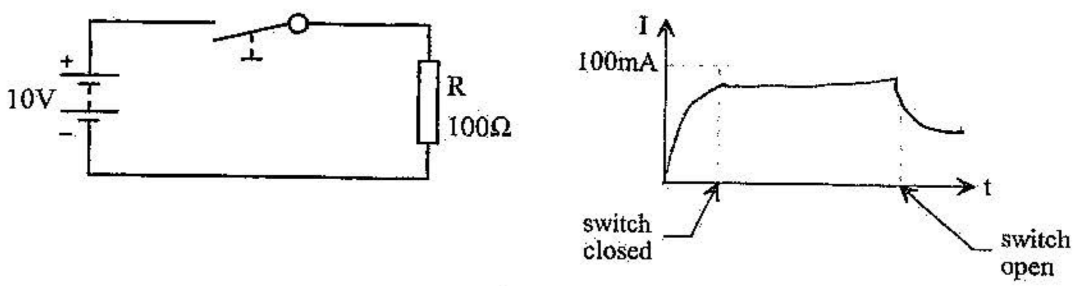


Figure 3

The value of the steady state current can be determined by applying Ohm's law:

When an inductor is connected in series with the resistor, forming an 'R-L circuit' -

- the ___induced voltage___ of the inductor opposes any change in current.

That is, when current is -

- increasing the self-induced emf opposes the ___increase___ of current
- decreasing the self-induced emf opposes the current ___direction___.

Figure 4 shows the effect of the inductor self-induced emf on the growth of current at switch on and switch off.

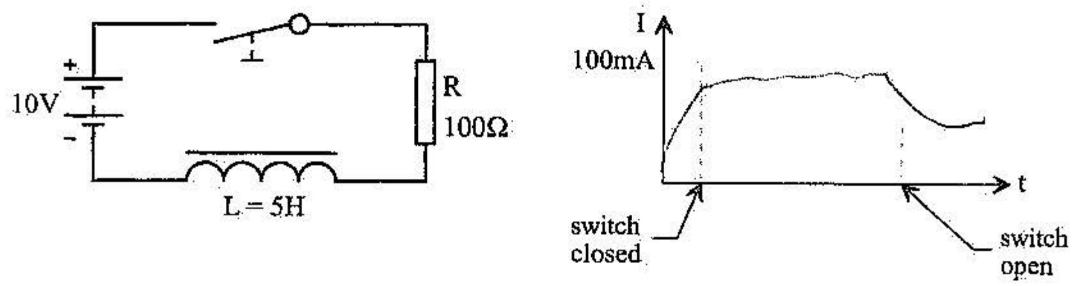


Figure 4

The time taken for the current to increase from zero to its maximum or steady state value is -

- ___RL___ circuit inductance
- ___RL___ circuit resistance.

The ratio of the inductance (L) to the resistance (R) is referred to as the -

___time constant___ for the circuit.

Where, by definition, the time constant is the time taken for the current to:

- increase to 63.2% of its final or steady state value after switch on
- decrease to 36.8% of its maximum or steady state value after switch off.

The time constant for the R-L circuit can be determined provided the resistance and inductance values are known -

$$T = \frac{L}{R}$$

where:
T = time constant in seconds (S)
L = circuit inductance in henries (H)
R = circuit resistance in ohms (Ω)

Example: 2:

For the circuit of figure 5, calculate:

(a) the circuit time constant

(b) the final or steady state value of current.

$\tau = \frac{L}{R} = \frac{4}{2} = 2$

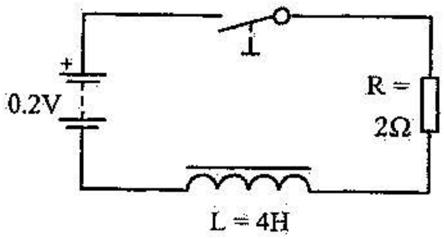


Figure 5

The curve shown in figure 6 illustrates how the current increases in an R-L circuit at switch on. It should be noted that the shape of the curve is the same for all R-L circuits.

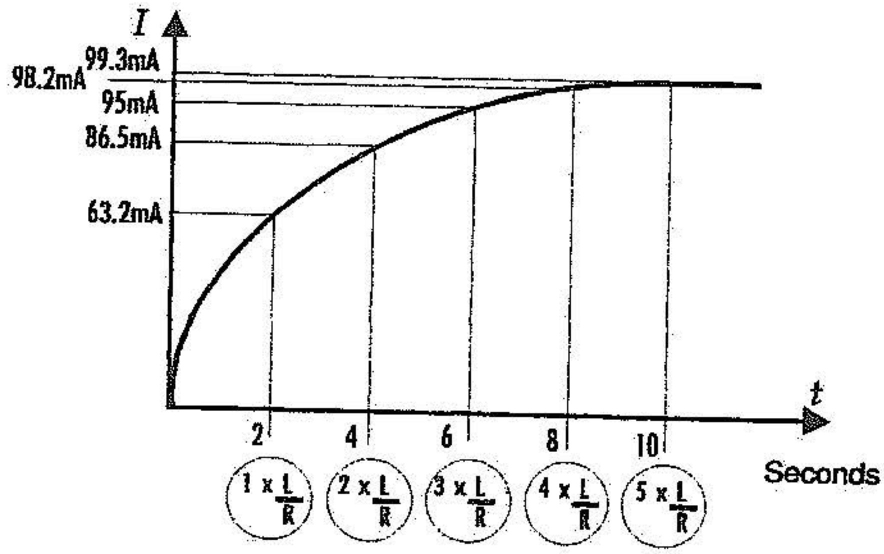


Figure 6

Reference to the curve of figure 6 shows the time taken for the current to reach its final or steady state value is equal to -

10sec ____________________.

When the DC supply is removed and the inductor is shorted across the resistor, as shown in figure 7 -

- the magnetic field of the inductor will collapse, inducing a voltage which opposes the current decay.

That is, the induced voltage does not allow the current to drop instantly to zero, but maintains the current flow in the same direction as the original current for a period of time.

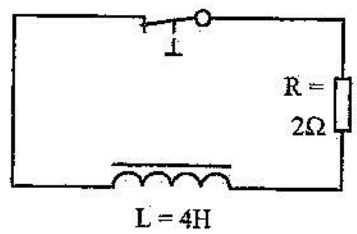


Figure 7

The time taken for the current to fall from its steady state value to zero is 5 time constants, as shown in figure 8.

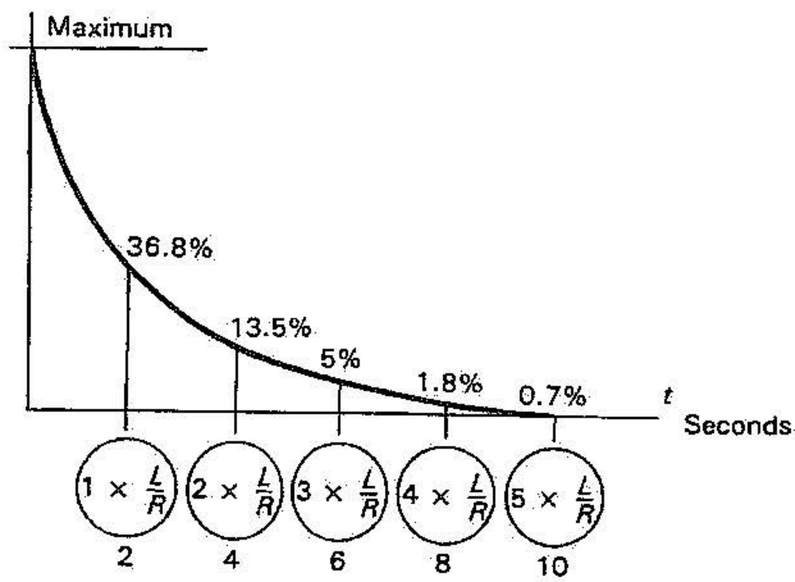


Figure 8

With reference to the curve of figure 8, it can be seen that after one time constant the current drops to 36.8% of its steady state value.

Again it should be noted that the shape of the current decay curve is the same for all R-L circuits.

Example: 3

For the circuit of figure 9, calculate:

(a) the circuit time constant
(b) the circuit steady state current
(c) the circuit current one time constant after switch on
(d) the circuit current one time constant after switch off.

a $T = \frac{L}{R} = \frac{0.8}{47}$

b $I = \frac{25}{47}$

c $I = \frac{25}{47}$

d $I = 0$

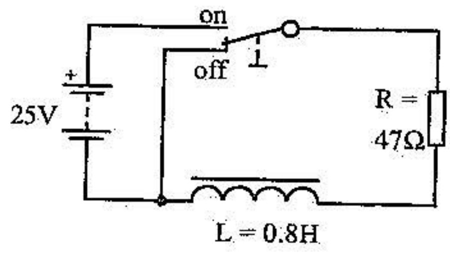


Figure 9

4. UNIVERSAL TIME CONSTANT CHART

The graph presented in figure 10 are known is the '***universal time constant chart***'.

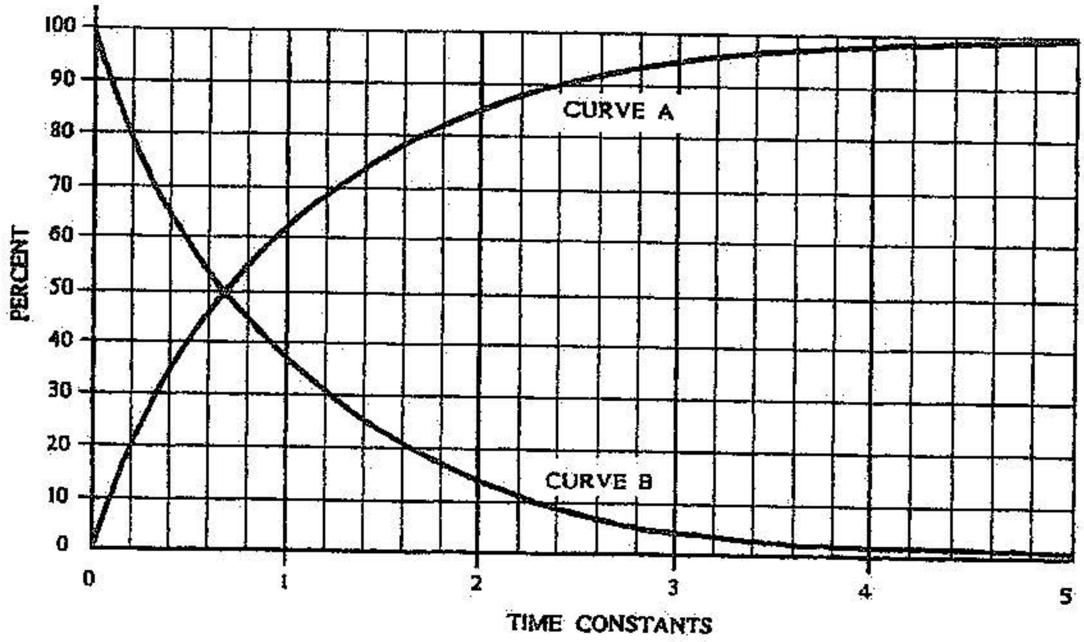


Figure 10

The curves A and B are applied in the following way to an R-L circuit.

At switch on -

- curve A represents the - circuit current
  voltage across the resistor
- curve B represents the - voltage across the inductor

At switch off -

- curve B represents the - circuit current
  voltage across the resistor
  voltage across the inductor.

Example: 4

For the circuit of figure 11, calculate the current flowing in the inductor 1mS after the initial application of power.

$$I = I(0)\, e^{-t/\tau} \qquad \tau = \frac{L}{R}$$

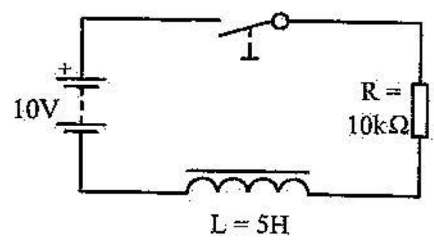


Figure 11

$$I = I(0)\, e^{\frac{Rt}{L}}$$

$$= 10\, e^{10 \times \frac{10\times10^{3}\,(1\times10^{-3})}{5}}$$

$$= 10\, e^{20} =$$

Example: 5

For the circuit of figure 12, calculate the current flowing in the inductor -

(a) 0.9mS after the initial application of power.

(b) 6mS after the initial application of power.

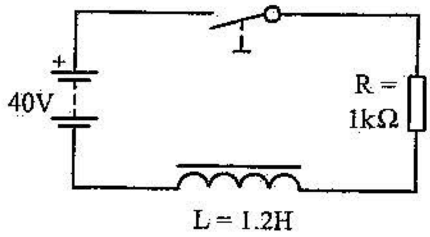


Figure 12

$I_{(ss)} \; \frac{40}{10 \times 10^3}$

$I = I(0)\, e^{-t/\tau}$

$= \frac{40 \times 10^{-3}}{10}\, e^{-0.9 \times \frac{10^3}{1.2}}$

$=$

****

Name: ____________________ Practical 6

MUTUAL INDUCTANCE

PURPOSE:

This practical assignment will be used to examine mutual inductance and the degree of coupling that exists between two mutually coupled coils.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Describe the operation of mutual induction when one of two mutually coupled coils is supplied from a DC source.
- Describe the operation of mutual induction when one of two mutually coupled coils is supplied from an AC source.
- Explain the effects of varying the coupling between mutually coupled coils.

EQUIPMENT:

- ☐ 1 x 24V, 50Hz AC power supply
- ☐ 1 x digital multimeter
- ☐ 1 x dual coil panel
- ☐ 3 x soft iron cores - 1 of each 6mm, 12mm and 15mm
- ☐ 1 x 1.5V cell
- ☐ 1 x 60-0-60μA centre zero microammeter
- ☐ 4mm connecting leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

PROCEDURE :

1. MUTUAL INDUCTION WITH A DC SUPPLY

1. Arrange the equipment on the bench in a neat and logical manner.
2. Connect the circuit as shown in figure 1. **Do not** insert an iron core.

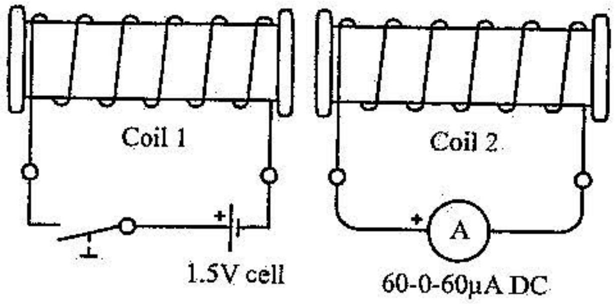


Figure 1

3. Close the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

4. Open the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

5. Insert the **6mm iron core** into the centre of the two coils.
6. Close the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

7. Open the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

8. Repeat each procedure, if necessary, to obtain your results.

9. Remove the 6mm iron core and insert the **12mm iron core** into the centre of the two coils.

10. Close the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

11. Open the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

12. Repeat if necessary.

13. Remove the 12mm iron core and insert the **15mm iron core** into the centre of the two coils.

14. Close the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

15. Open the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

16. Repeat the procedure if necessary.

17. Close the circuit switch and leave closed, then note the polarity and magnitude of any deflection on the microammeter.

____

18. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

19. Reconnect the circuit as shown in figure 2.

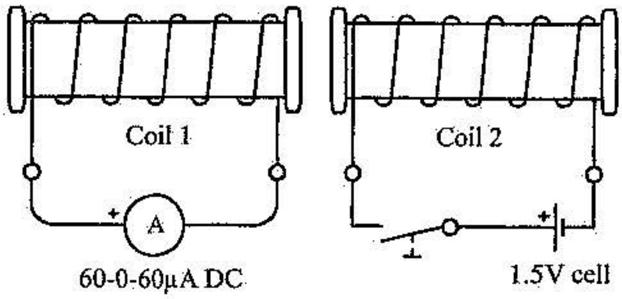


Figure 2

20. Insert the **15mm iron core.**

21. Close the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

22. Open the circuit switch and note the polarity and magnitude of any deflection on the microammeter.

____

23. Repeat the procedure if necessary.

24. Close the circuit switch and leave closed, then note the polarity and magnitude of any deflection on the microammeter.

____

25. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

2. MUTUAL INDUCTION WITH AN AC SUPPLY

1. Connect the circuit as shown in figure 3. **Do not** insert a soft iron core.

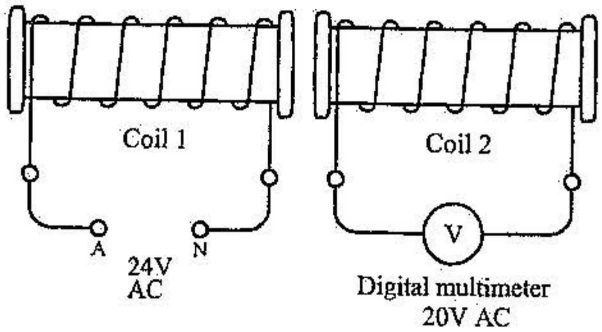


Figure 3

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

3. Switch on the 24V AC supply, then measure and record the value of voltage induced into coil 2. Record in table 1.

Table 1

	Voltage Applied to Coil 1	Voltage Induced in Coil 2
Air Core	24V	
6 mm Iron Core		
12 mm Iron Core		
15 mm Iron Core		

4. Insert the 6mm soft iron core, then measure and record the value of voltage induced into coil 2. Record in table 1.

5. Insert the 12mm soft iron core, then measure and record the value of voltage induced into coil 2. Record in table 1.

6. Insert the 15mm soft iron core, then measure and record the value of voltage induced into coil 2. Record in table 1.

7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

8. Switch off the power supply, then disconnect the circuit.
9. Please return all equipment to its proper place, safely and carefully.

3. OBSERVATIONS:

1. What is mutual inductance?

____

____

____

2. When is an emf of mutual inductance produced, when one of two mutually coupled coils is supplied from a DC source?

____

____

____

3. When is an emf of mutual inductance produced, when one of two mutually coupled coils is supplied from a AC source?

____

____

____

4. What is meant by the term coupling, as applied to two mutually coupled coils?

____

____

____

5. Of the four cores used in this assignment, which provided the tightest coupling between the coils?

____

____

____

6. How could the coupling between the two coils used in this assignment be improved?

____

____

____

7. Will two mutually coupled coils work either way round?

____

____

____

8. What factors affect the level of induced voltage produced in a coil as a result of mutual inductance?

____

____

____

****

Mutual Inductance

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. Mutual inductance is defined as the magnetic linkage between:
   (a) a single coil and its' flux
   (b) any number of adjacent coils
   (c) an inductor and a resistor
   (d) the flux and the magnetic core

2. A transformer operates on the principle of:
   (a) self inductance
   (b) core inductance
   (c) mutual inductance
   (d) coil inductance

3. If a current change occurs in a coil, an emf of self induction is induced in the coil. This induced emf is commonly known as a ______ and is explained by ______.
   (a) back emf; Lenze's Law
   (b) back emf, Ohm's Law
   (c) mutually induced emf; Faradays Law
   (d) mutually induced emf; Lenze's Law

4. The unit of mutual inductance is the:
   (a) Farad
   (b) Henry
   (c) Ohm
   (d) Teslas

5. To increase the time constant of an LR circuit, either ______ the inductance value or ______ the resistance value.
   (a) increase, increase
   (b) decrease, increase
   (c) increase, decrease
   (d) decrease, decrease

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

6. If two or more coils are joined by the same magnetic flux, the coils are said to be ___(a)___ by___(b)___
7. Two common applications employing mutual inductance are ___(a)___ and ___(b)___.
8. When installing power cables and ___(a)___ cables adjacent to each other, the cables are segregated to avoid problems associated with ___(b)___ induced into the data cables due to ___(c)___
9. An LR circuit is set up when a resistor is connected in ___(a)___ with an ___(b)___.
10. Increasing the resistance of an LR circuit will cause the ___(a)___ to ___(b)___, whilst increasing the ___(b)___ of an LR circuit will cause the time constant to ___(c)___.
11. For voltages of self inductance or mutual inductance to occur, there must be ___(a)___ between the ___(b)___ and the ___(c)___.
12. If an inductive circuit is open circuited, the rapidly ___(a)___ magnetic field can ___(b)___ dangerously high ___(c)___.
13. Any circuit circuit capable of producing magnetic ___(a)___ has the property of ___(b)___
14. Cut and paste the diagram of figure 1 to your answer sheet.

    Identify and label the following:
    (a) the input or primary winding
    (b) the output or secondary winding
    (c) the magnetic core
    (d) show and label the core flux

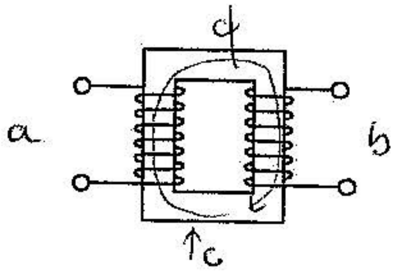


Figure 1

SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

15. Determine the voltage induced in two adjacent coils of 250 turns & 600 turns respectively if they are cut by a magnetic flux with a rate of change of flux of 10mWb/5mSec. (500V & 1200V)

$V = N\frac{d\phi}{dt} = 250 \times \frac{10\times10^{-3}}{5\times10^{-3}} =$ $V = 600 \times \frac{10\times10^{-3}}{5\times10^{-3}}$

16. Determine the change in flux of a coil with 1200 turns if 240V is induced into the coil in 10mSecs. (2mWb)

$V = N\frac{d\phi}{dt} \rightarrow 240 = 1200 \times \frac{d\phi}{10\times10^{-3}}$ $d\phi = \frac{240}{1200} \times 10\times10^{-3}$

17. For the coil in question 17., determine the voltage that is induced if the flux of 2mWb collapses in 2mSec. (1.2kV)

$V = 1200 \times \frac{2\times10^{-3}}{2\times10^{-3}}$

18. A coil of 30mH is connected in series with a resistance of 120Ω. When connected to a 36V DC supply, determine:
    (a) the time constant of the circuit; (250μSec)
    (b) the circuit current after one time constant; (189.6mA)
    (c) the steady state circuit current. (300mA)

$\tau = \frac{L}{R} = \frac{30\times10^{-3}}{120}$

$I(t) = I(0)\, e^{-t/\tau}$ $t > 5\tau$

$I(0) = \frac{36}{120} = 300mA$ $= 300 \times e^{-5} =$

19. For the circuit of figure 2, determine:
    (a) the time constant of the circuit (6.81mSec)
    (b) the current after one time constant with the switch in position "A" (34.5mA)
    (c) the steady state current with the switch in position "A" (54.5mA)
    (d) the current after one time constant with the switch in position "B" (20mA)
    X (e) the time taken for the current to fall to zero (34mSec)
    X (f) if the flux in the coil at steady current is 140mWb, determine the voltage induced in the coil as the current collapses to zero. (1kV)

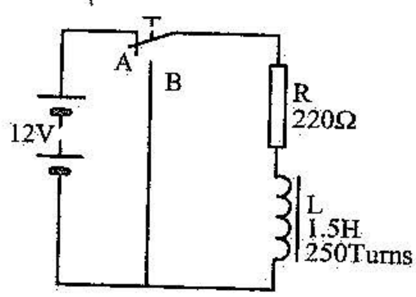


Figure 2

(a) $\tau = \frac{L}{R} = \frac{1.5}{220} = 6.81$ m sec

(b) $I(t) = I(0)\, e^{-t/\tau} = \frac{12}{220} \times e^{-T/\tau} = \frac{12}{220} \times e^{-1} =$

(c) $I(0) = \frac{12}{220} = 54.5mA$ (e) = e = H

(d) $I(t) = \frac{12}{220} \times e^{-T/\tau} = \frac{12}{220} \times e^{-1} =$

(d) $I(t) = I(0)\, e^{-t/\tau}$

$e^{-t/\tau} = 0$

$-\frac{t}{\tau} = \ln 0$

$5\tau \Rightarrow I(0) = 5\times6.81 = 34ms$

NOTES

THE DC GENERATOR

PURPOSE:

This section introduces the principle of operation of the DC generator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- state the basic operating principle of a generator.
- apply Fleming's right hand rule for generators.
- calculate the emf produced by a simple generator.
- identify the main components of a dc rotating machine.
- draw the connections and equivalent circuit of a separately-excited generator.

REFERENCES:

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.
Pages 267-272, 268, 272-274 and 278-282.

1. INTRODUCTION

Electric machines, motors and generators, have electric circuits and magnetic circuits interlinked through the medium of a magnetic field. Electric currents flow through the electric circuits which are made up of windings and magnetic fluxes "flow" through the magnetic circuits which are made up of iron cores.

Interaction between the currents and fluxes is the basis of the electromechanical energy conversion process that takes place in both generators and motors.

Thus magnetic circuits play an essential role in electric machines and transformers. In this section we examine the basic principles as applied to generators.

2. THE DC GENERATOR

The purpose of a DC generator is to convert ____________ energy to ____________ energy. The output energy from the generator appearing in the form of a DC voltage and current.

This concept is illustrated in figure 1.

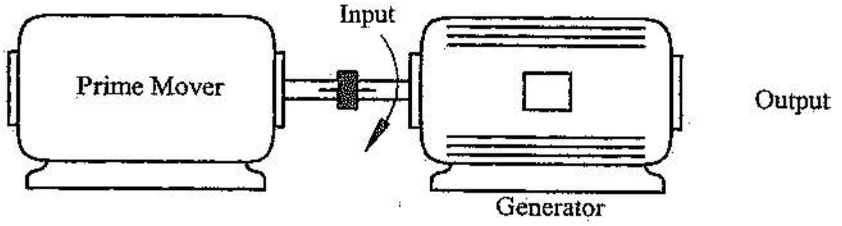


Figure 1

Note, the generator must be driven by a prime mover - that is, the prime mover provides the mechanical input energy.

The action of the generator depends on the principle of ______________________________.
According to this principle, a conductor moving with its length perpendicularly across a magnetic field has an emf induced in it, the magnitude of which is proportional to the flux cut by the conductor per second.

In order to apply this principle to the practical conversion of mechanical energy into electrical energy, it is necessary to provide:

- a ______________________________ in which the motion can take place
- a system of ________________________ in which the emf's are induced by the motion
- suitable arrangements for maintaining contact between the system of moving conductors and the external circuit in which the current is utilised.

3. GENERATOR OPERATION

The general arrangement of a generator, reduced to its simplest form, is illustrated in figure 2.

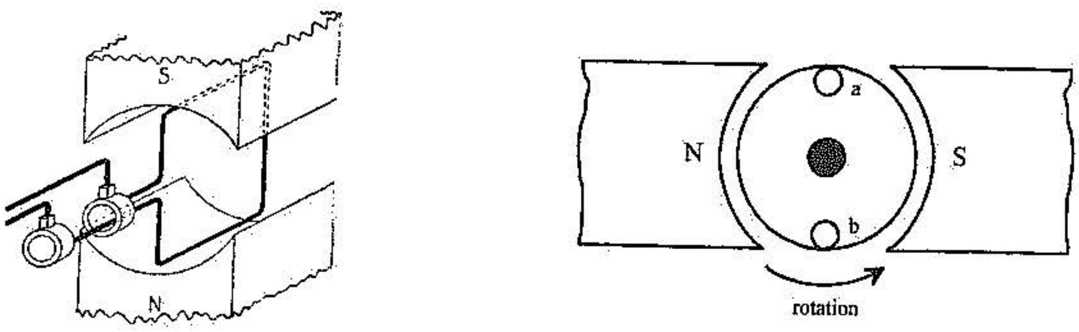


Figure 2

In this arrangement we have a simple loop of wire rotating in the magnetic field between two magnetic poles N and S. The single loop of wire is embedded in a cylindrical iron core called the armature.

With the armature in position, the flux is concentrated where it is needed, namely, across the narrow gaps between the pole faces and the armature surface. Figure 2 shows approximately the shape of the flux path in the generator.

Consider one full rotation of the armature, starting with the loop in the position shown in figure 3. Application of Fleming's Right Hand Rule allows the direction of the induced emf to be determined.

At 0°:
The sides of the loop a and b are running parallel to the lines of magnetic flux.

The induced emf = ____________________.

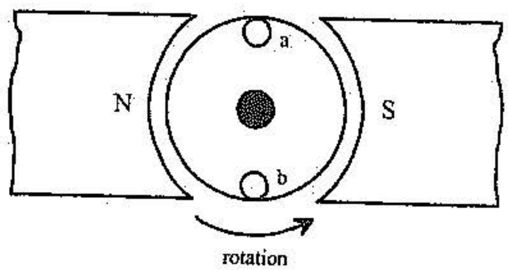


Figure 3

At 90°:
The sides of the loop are cutting across the lines of flux at right angles.

The induced emf = ____________________.

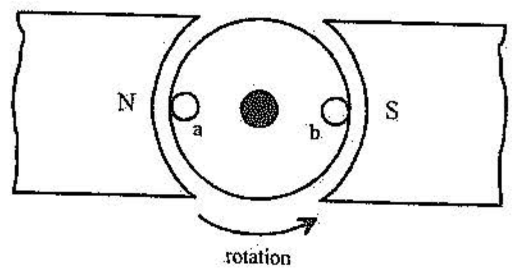


Figure 4

At 180°:
Again the sides of the loop are moving parallel to the lines of magnetic flux.

The induced emf = ____________________.

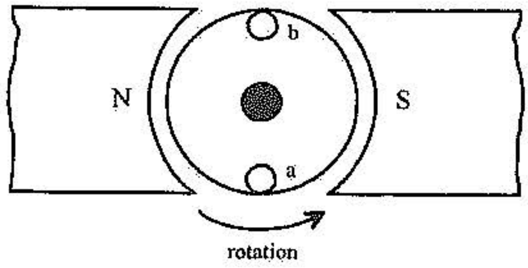


Figure 5

At 270°:
The sides of the loop are cutting across the lines of flux at right angles.

The induced emf = ____________________.

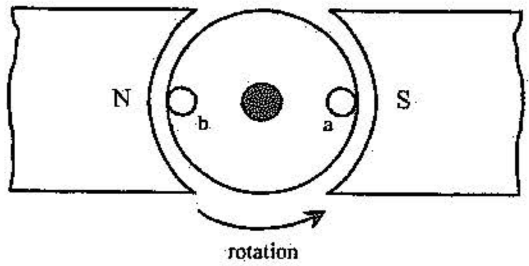


Figure 6

As can be seen in figures 3, 4, 5 and 6, the emf within the loop has undergone a complete series of changes during the revolution of the armature, as represented graphically in figure 7.

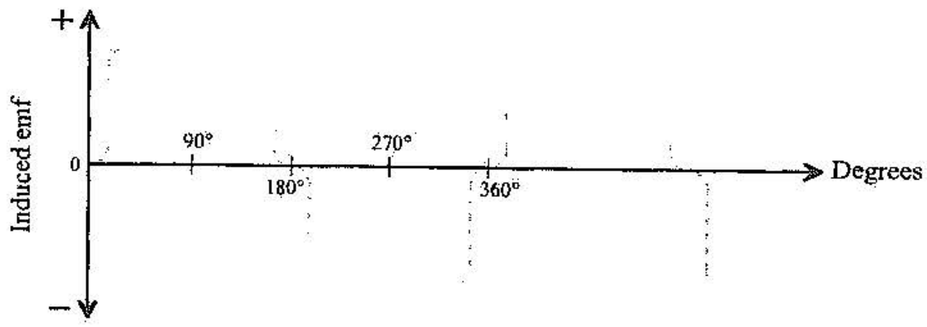


Figure 7

The complete series of changes is termed an alternating emf, and the graph represents one complete cycle.

If the emf when acting in any given direction around the circuit is regarded as positive, and is represented by drawing the graph above the horizontal zero line, then the emf after reversal is distinguished by the negative sign, and when represented graphically is shown below the zero line.

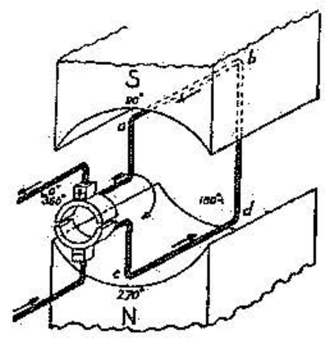
Continuous rotation of the armature would produce a regular succession of complete waves or cycles of emf at the rate of one cycle per revolution.

If the circuit were closed, the resulting current would follow the variations of emf and there would be an alternating current in both the armature winding and the external circuit. Thus the machine we have been studying is an elementary form of alternating current generator, that is, a simple alternator.

Alternating currents are suitable for many purposes, but there are some applications in electrical work which require currents in one direction only.

The modern type of machine for producing unidirectional current is essentially an alternator, as described above, which is fitted with a commutator that automatically changes over the connections between the armature winding and the external circuit, whenever the polarity of the generated emf is reversed.

In its simplest form, the commutator is merely a short length of metal tube, split lengthwise into halves and mounted on a cylinder of insulating material which is keyed to the shaft. See figure 8.

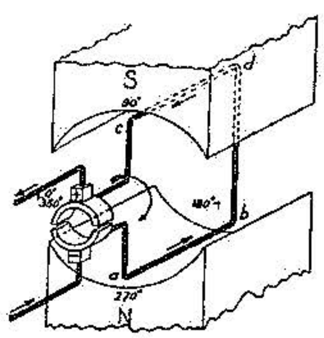


(a) Loop at 90°

Figure 8

During rotation of the armature, the conductors ab and cd have an emf induced in each exactly as occurs in the simple alternator. While ab passes between 0° and 180° the upper brush is of positive polarity and the lower brush is negative.

While ab is passing between 180° and 360°, its emf is reversed, compared with that generated during the first half revolution.



(b) Loop at 270°

Figure 9

Consequently the polarity of the upper brush would be negative if it were still connected to ab; however the commutator has automatically changed the connections of the coils to the brushes so that the top brush is now connected to cd. The commutator thus ensures that the brushes maintain the same polarity.

Figure 10 is a graphical representation of the emf obtained at the terminals of the simple DC generator. Notice that the graph is simply the wave of figure 7 with its negative half inverted, or rectified.

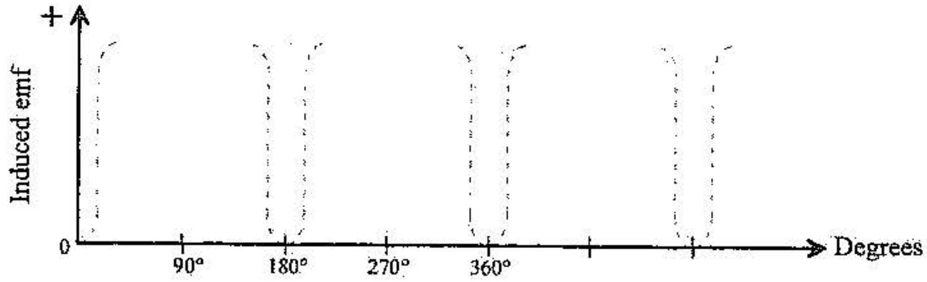


Figure 10

4. VALUE OF GENERATED EMF

It has already been established that when a conductor cuts flux at the rate of one weber per second, an emf of one volt is induced in the conductor.

It is a simple matter therefore to calculate the value of generated emf in a generator, provided the following values are known -

- ____________________ of the magnetic field
- ____________________ of the conductor within and at right angles to the field
- ____________________ at which the armature conductors cut the magnetic field.

As before, the combination of these three factors gives the equation -

Example: 1

A single conductor having a length of 200mm is moved through a magnetic field with a flux density of 0.5T at a velocity of 12m/s. Calculate the emf induced in the conductor.

____

____

____

Example: 2

A single loop of wire is moved through a magnetic field with a flux density of 0.5T at a velocity of 12m/s. If each side of the loop has a length of 200mm within the field, calculate the emf induced in -

(a) one side of the loop

(b) the loop.

Example: 3

A DC generator armature is wound using 6 series connected coils of copper wire. Each coil has 40 turns and each side of a coil is 250mm long. If the armature is rotated in a magnetic field of 0.8T at a velocity of 10m/s, determine the emf induced in -

(a) one half turn

(b) one turn

(c) one coil

(d) the entire armature.

5. EXCITATION OF DC GENERATORS

The magnetic field, required in a generator, can be provided by -

- permanent magnets
  or
- electromagnets - always used as field systems in dc machines of appreciable size.

Since the emf induced in the armature conductors depends upon the strength of the magnetic field in the air-gap, the emf generated by a generator having an electromagnetic field system is easily controlled by varying the current in the field coils.

Generators are classified according to the source of the current for field excitation as being:

- ________________ -excited
- ________________ -excited.

6. CONSTRUCTION OF DC MACHINES

Figure 11 shows the general construction of a dismantled dc machine with the main parts identified.

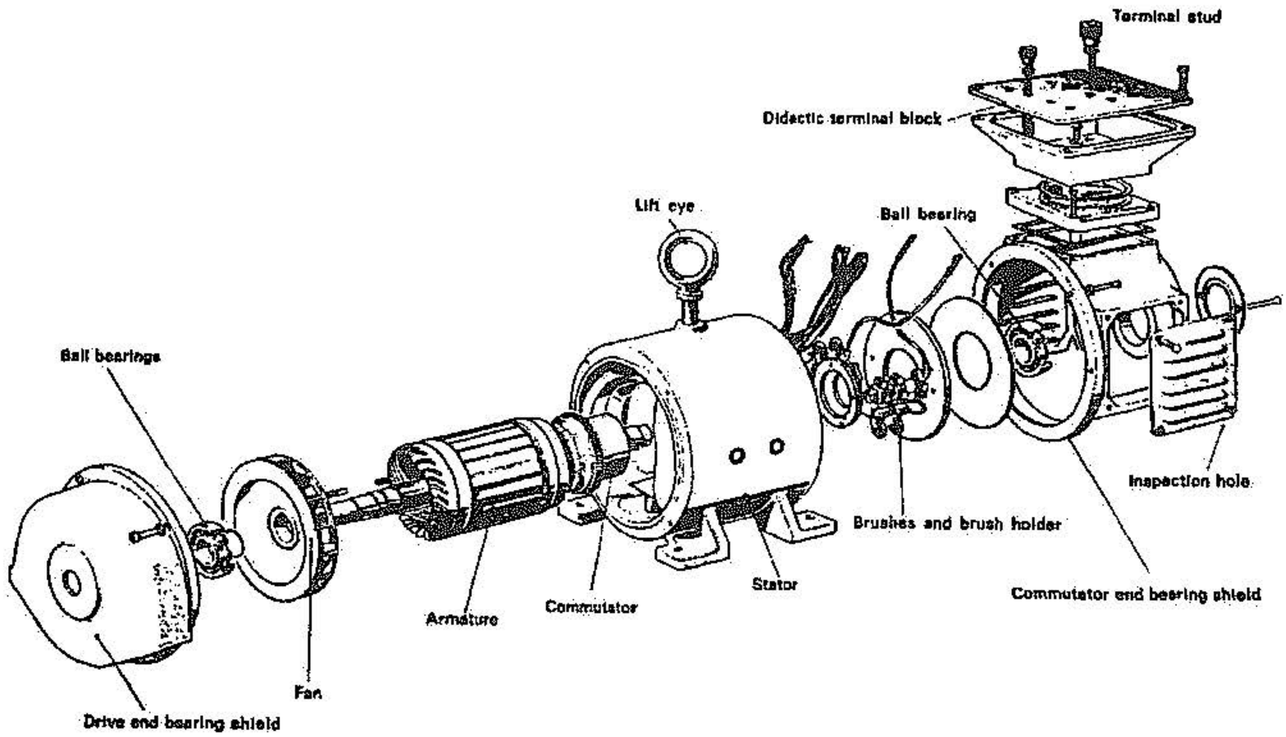


Figure 11

The main components of a dc machine are -

- frame or yoke -
  - completes the magnetic circuit
  - made of a material of high permeability, such as cast steel or fabricated rolled steel
  - acts as a rigid frame to which the poles and end shields are bolted and to which mounting feet are welded or cast.

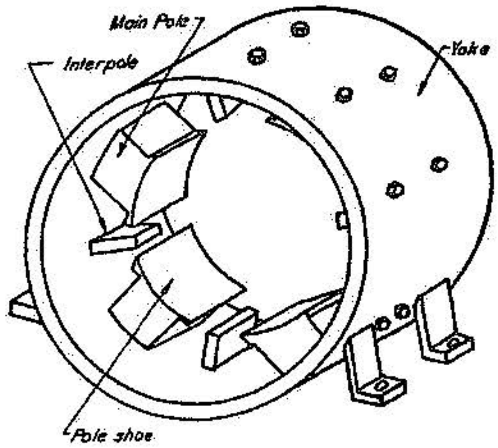


Figure 12

- field poles and field coils -
  - each main pole is an assembly of steel laminations 1 to 1.5mm thick riveted together and of the same length as the armature core
  - the field pole provides a seat to support the field coil
  - generally a given number of poles (eg. 2, 4, 6) covers a given output range - the larger the output the greater the number of poles
  - the field coils magnetise the pole cores
  - the connections of the field coils are such that the magnetic polarity of consecutive pole shoes is alternately north and south.

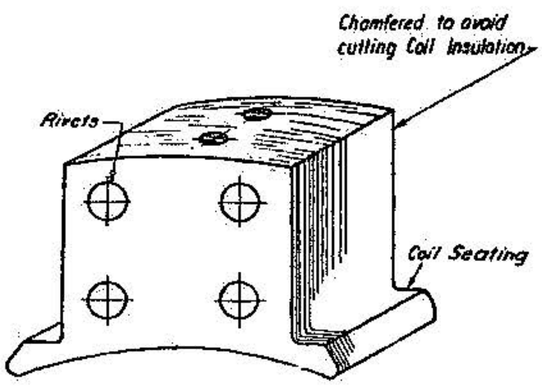


Figure 13

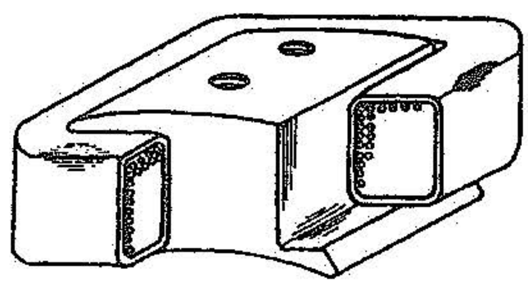


Figure 14

- armature core -
  - made up of iron laminations, with very good magnetic characteristics and low iron loss
  - each lamination is insulated to reduce eddy current losses
  - slots are notched on the periphery - the armature coils are fitted into these slots
  - clamped between two end plates and keyed to the shaft
  - holes are provided in the core to allow cooling air to pass through
  - the shaft is usually made from steel of a high tensile strength.
  - the bearings are generally ball or roller bearings.

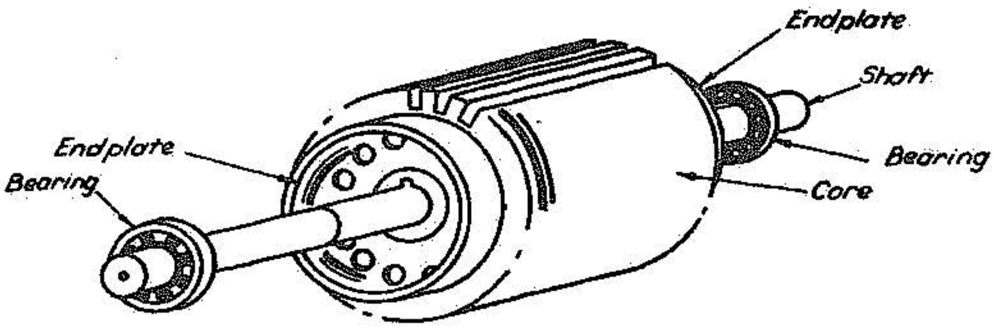


Figure 15

- commutator -
  - the commutator which consists of a number of hard-drawn copper segments or bars insulated from one another by strips of mica
  - the leads from the armature coils are soldered to the segments
  - must be machined to a high degree of accuracy to ensure a smooth true surface for brushes to run on at all speeds.

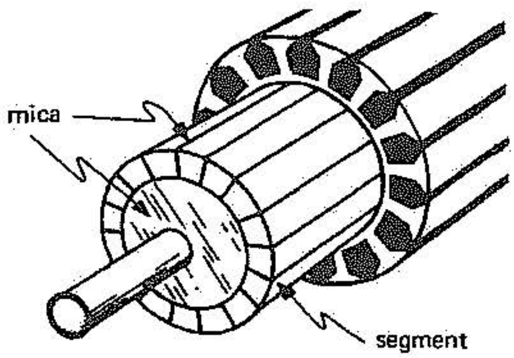


Figure 16

- brush gear and brushes -
  - collect current from, or supply current to, the armature
  - the brushes are usually made of carbon or graphite and held in brush-holders
  - the brush holder holds the brush in position, allowing it to slide up and down but preventing side movement
  - a spring presses the brush firmly on the commutator

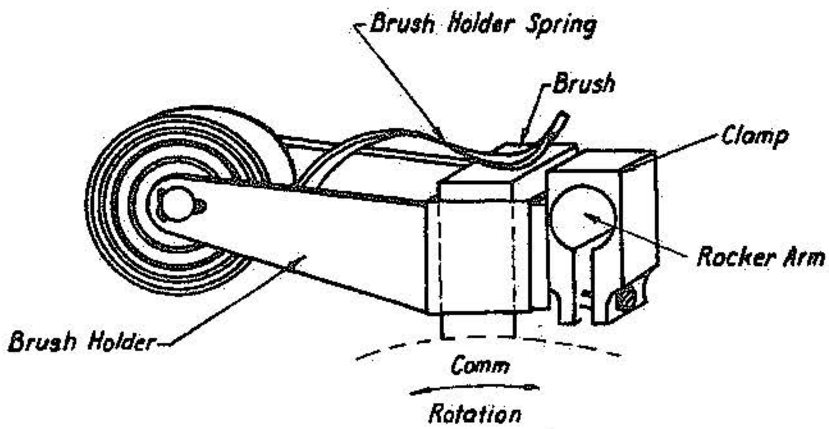


Figure 17

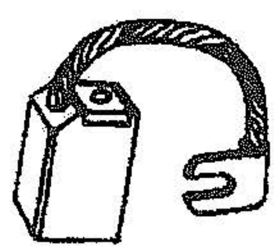


Figure 18

The arrangement of a fully assembled machine is shown in figure 19.

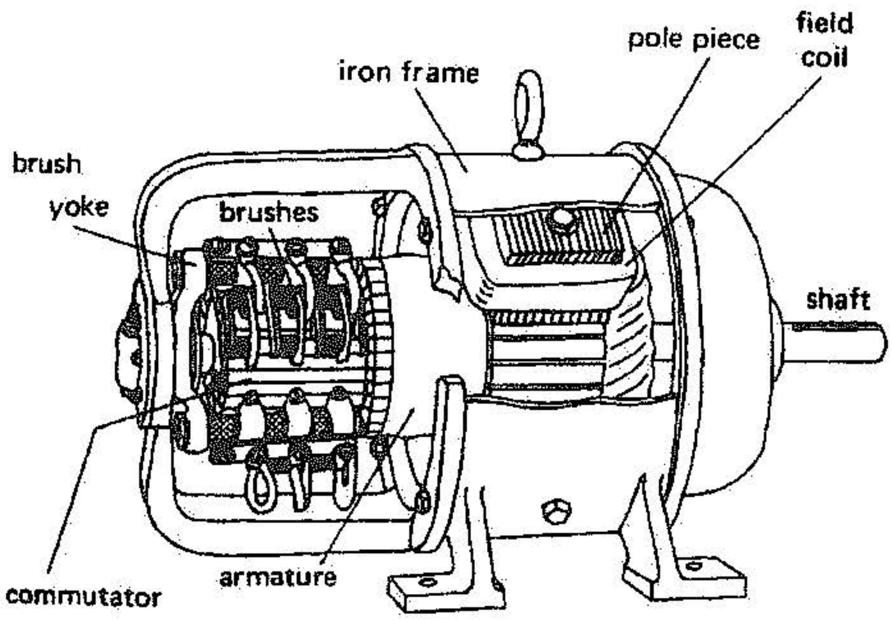


Figure 19

7. SEPARATELY-EXCITED GENERATOR

A simple method of exciting the field coils of a dc generator is to connect them to an external source of dc supply, as shown in figure 20.

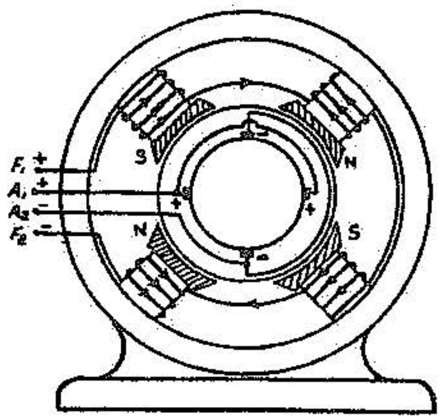


Figure 20

The field coils of the four-pole machine are shown connected in series with one another and to the terminals F_1 and F_2, located in the terminal box.

The brushes are connected to the terminals A_1 and A_2, also located in the terminal box.

If the field coils are connected to an external supply, as shown in figure 21, the generator is said to be separately-excited.

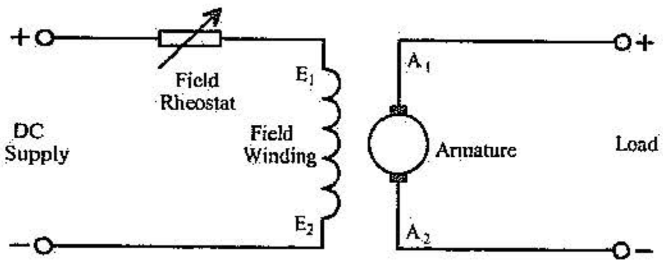


Figure 21

As shown in the diagram a variable resistor or **"field rheostat"** is usually connected in series with the field winding to control the value of generated emf by varying the field current.

The equivalent circuit of the separately excited generator is shown in figure 22.

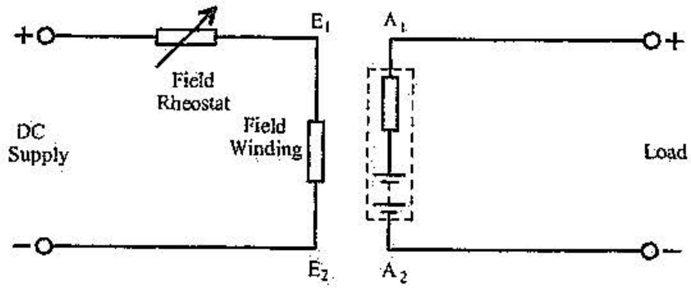


Figure 22

The equivalent circuit consists of the following -

R_F = field winding resistance, measured in ohms
R_A = armature resistance, measured in ohms
Eg = generated armature voltage, measured in volts
V_T = load terminal voltage, measured in volts

Separately-excited generators are used in situations where it is more convenient to operate the generator fields at a different voltage from that generated by the armature. Separate excitation permits accurate and wide-range control of the armature output voltage; the excitation is not affected by changes in speed and load.

8. GENERATOR OUTPUT VOLTAGE

The output voltage of the generator is dependent upon three factors -

- the field ____________ in webers
- the ______________ at which the generator is driven in rpm
- constructional features of the machine, particularly the armature. These features are beyond the scope of this module and will not be covered.

The product of these three values allows the value of the generated voltage to be calculated -

where: Eg = generated emf in volts
k = machine constant based on constructional features
ϕ = field flux in webers
n = armature speed in rpm

Example: 4

A separately-excited generator has an effective field flux of 0.08Wb and is operated at a speed of 360rpm. Determine the generated voltage if the machine constant is 15.

Example: 5

If the field flux for the generator in example 4 was increased to 0.1Wb, what would be the value of the generated voltage. The speed and machine constant are unchanged.

Example: 6

The generator in example 4 is operated with an effective field flux of 0.08Wb and a speed of 500rpm, what is the generated emf.

****

THE DC GENERATOR

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. A DC generator converts ______ energy to ______ energy.
   (a) electrical, mechanical
   (b) electrical, electrical
   (c) chemical, electrical
   (d) mechanical, electrical

2. The principle by which emf's are generated in a DC generator is:
   (a) electromagnetic induction.
   (b) Lenz's law .
   (c) self inductance.
   (d) chemical reaction.

3. The function of the commutator in a DC generator is to:
   (a) connect the AC generated in the windings directly to an external circuit.
   (b) convert the AC generated in the windings to DC when connecting to an external circuit.
   (c) supply an external current to the armature to drive the generator.
   (d) allow the generator to be converted to a motor.

4. The windings for the magnetic field system are mounted on the:
   (a) armature.
   (b) commutator.
   (c) frame.

(d) pole cores.

5. The value of the generated emf's in the armature conductors is ______ to the field flux, and ______ to the armature speed.
   (a) proportional, proportional
   (b) proportional, inversely proportional
   (c) inversely proportional, proportional
   (d) inversely proportional, inversely proportional

6. To increase the output of a generator you could either ______ the field current or ______ the armature speed.
   (a) decrease, decrease
   (b) increase, decrease
   (c) increase, increase
   (d) decrease, increase

7. The relationship between current, magnetic flux and the force applied to a conductor within a generator can be determined by:
   (a) Fleming's right hand rule.
   (b) Fleming's left hand rule.
   (c) Faraday's right hand rule.
   (d) Faraday's left hand rule.

SECTION B

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

The conductors for the field system of a generator are located in the ___(1)___.

To connect the generated emf's to an external circuit, a ___(2)___ and carbon ___(3)___ are employed.

The function of the ___(4)___ is to convert the ___(5)___ voltage generated within the armature conductors to the ___(6)___ voltage available at the generator terminals.

The generator field is either ___(7)___ excited or ___(8)___ excited.

To determine the polarity of the induced emf's within the armature conductors you would use ___(9)___.

Maximum emf will be induced in the armature ___(10)___ when cutting the field flux at ___(11)___.

If more turns are added to the armature conductors, the generated voltage will ___(12)___.

The emf induced into a conductor is proportional to the ___(13)___ of the magnetic field, the ___(14)___ of the conductor and the ___(15)___ of the conductor through the magnetic field.

SECTION C

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A single conductor of 150mm length is rotated through a field flux of 0.8T at a velocity of 10m/s. Determine the emf induced in the conductor. (1.2V)

2. Determine the flux density of the magnetic field required to generate 12.6V in a conductor with an effective length of 2m which moves through the magnetic field at 90^0 with a uniform velocity of 10.5m/s. (0.6T)

3. A generator is wound with 6 series connected coils, each wound with 40 turns. If the length of the armature is 200mm, the density of the flux is 1.25 Tesla and the armature rotates with a velocity of 2m/s, determine the generated output voltage of the generator. (240V)

4. A separately excited generator has an effective field flux of 0.02T, and is spins at 400 rpm. If the machine constant is 12, determine the generated voltage. (96V)

5. For the diagram of figure 1, label the following:
   (a) the frame
   (b) the field coil
   (c) the armature
   (d) the field pole

Include the diagram with your answer sheet.

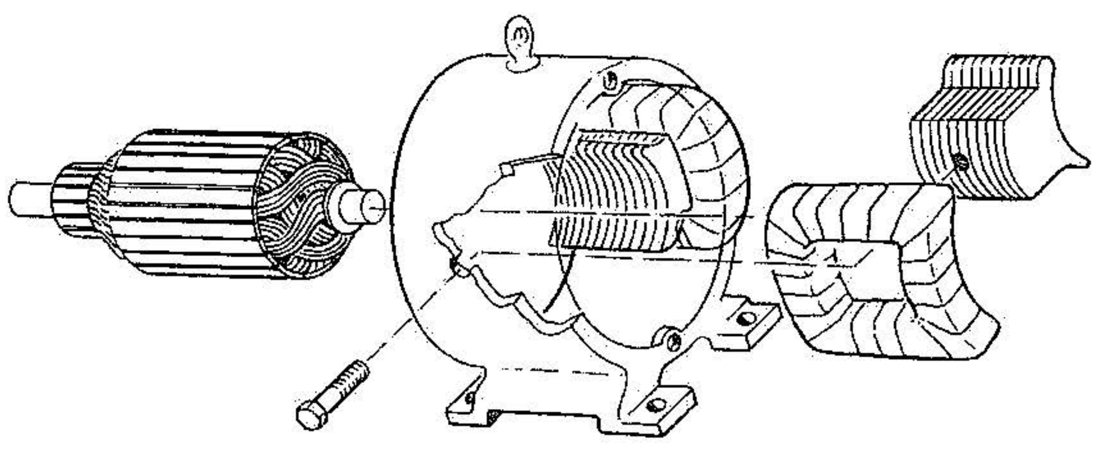


Figure 1

6. For the diagrams of figure 2(a) to 2(e), determine the direction of current flow through the conductors "a" and "b", and show the currents on the diagrams.

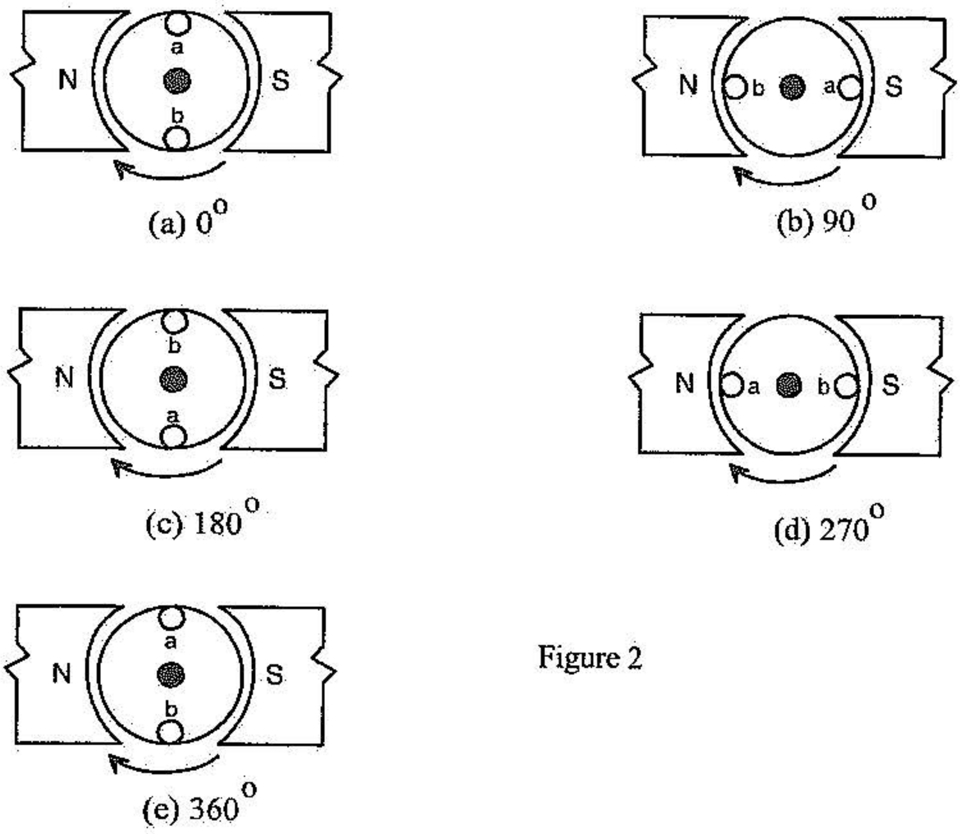


Figure 2

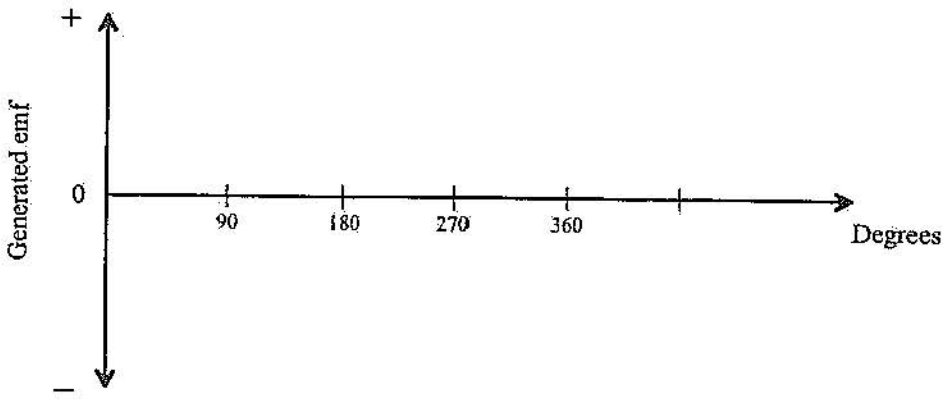


Figure 3

7. State the method used to determine the direction of the induced currents in the conductors.

8. On the axis of figure 3, neatly draw the output waveform if the generated emf is connected to an external circuit via a commutator and brushes.

Add this sheet to your answer sheets

****

DC GENERATORS - PART 2

PURPOSE:

This section introduces the load and no-load characteristics of the separately excited DC generator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- describe and interpret the no-load characteristic of a dc generator.
- describe the effects of armature reaction on the operation of a dc generator.
- describe and interpret the load characteristic of a separately excited dc generator.
- calculate voltages and currents associated with separately excited dc generators.

REFERENCES:

Electrical Principles for the Electrical Trades, 5th Edition. Jenneson J.R.
Pages 270-276 and 277.

1. GENERATOR OPEN-CIRCUIT CHARACTERISTIC

The open-circuit characteristic is often referred to as the "saturation" or "magnetization curve", since it indicates the degree of magnetization of the magnetic circuit of the machine. This follows from the fact that the generated emf varies with the flux per pole of the generator, when all other quantities affecting the generated emf are constant.

The curve is obtained by driving the generator at a constant speed, while the field current (obtained from a separate source) is increased in steps from zero to its maximum value. At each value of field current the open-circuit voltage is measured. Figure 1 shows the circuit arrangement for determination of the open-circuit characteristic.

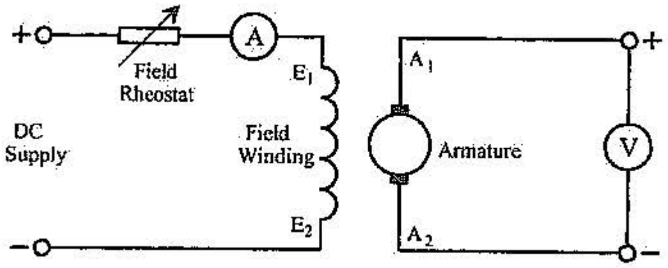


Figure 1

Reference to the equivalent circuit of the generator reveals that when the generator is unloaded, the terminal voltage equals the generated emf. See figure 2.

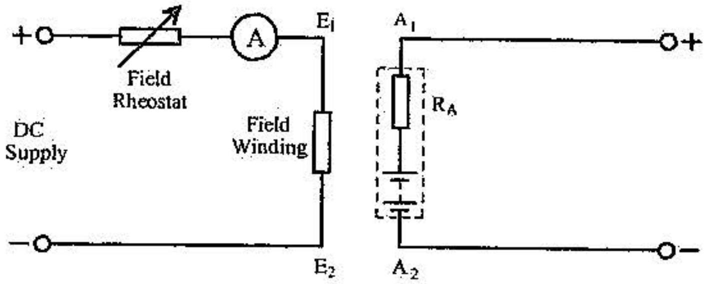


Figure 2

where: V_T = generator terminal voltage in volts
Eg = armature generated voltage in volts

Values of terminal voltage are then plotted against field current values and a curve obtained similar to that in figure 3.

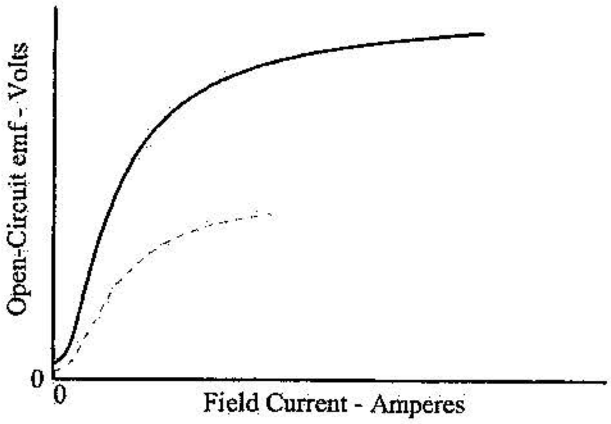


Figure 3

As the generated emf is directly proportional to the effective flux, the curve shows the relationship between the field current and the flux which this field current produces. It follows, that there is no difference between this curve and the magnetization curve of a ferro-magnetic material. The straight part of the curve shows that over this range the generated emf is directly proportional to the field current. Beyond this range the curve "flattens out", showing that the iron parts of the magnetic circuit are becoming "saturated".

It should be noted that when the field current is zero the generated emf is not zero, but has a value between 1% and 5% of the normal voltage. This is due to the percentage of magnetism (residual) remaining in the magnetic circuit after it has once been magnetized.

If the open-circuit characteristic of a generator is plotted for a particular speed, then its characteristic at any other speed can be readily determined. The emf, generated for a given value of field current, is directly proportional to the speed. For example, if the full-line curve in figure 1 is obtained at a speed of 1000 rpm then a curve, having half the height for any particular value of field current, as shown by the broken line, will be obtained at a speed of 500 rpm.

Example: 1

A separately-excited generator has an effective field flux of 0.08Wb and is operated at a speed of 500rpm. If the machine constant is 15, determine the -

(a) generated voltage

(b) no-load terminal voltage.

2. ARMATURE REACTION

When a generator supplies current to a load, as illustrated in figure 4, the terminal voltage will no longer equal the generated emf.

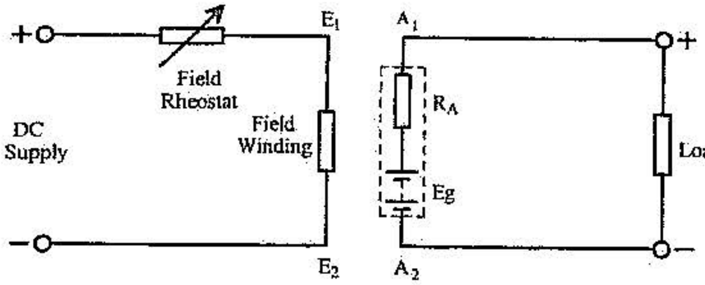


Figure 4

One of the reasons for this change in terminal voltage is an effect within the generator called ______________________________.

Armature reaction may be divided into two principle effects -

- ______________________________ effect, causing distortion of the main field
- ______________________________ effect, causing a weakening of the main field.

Consider the simplified diagram of a generator shown in figure 5.

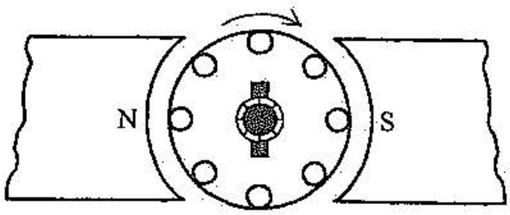


Figure 5

Assuming the armature rotates in a clockwise direction, the direction of the induced armature emfs will be -

- under the influence of the north pole - ________________ the page
- under the influence of the south pole - ________________ the page.

With a load connected, the induced armature emfs cause armature current to flow in the same direction as the induced emf. As a result, there are as many magnetic poles formed around the armature as there are main poles in the field system. The axis of each armature field is midway between the main poles, that is, coinciding with the **'neutral axis'** of the main field. See figure 6.

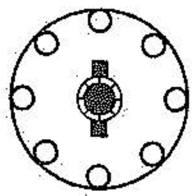


Figure 6

The right-hand solenoid rule shows the direction of the field to be as indicated in the diagram and the axis of the armature field coincides with the brush axis. If the armature was removed from the field magnets the maximum intensity of the armature field would be at the brush axis, as shown

With the armature in position between the poles, as shown in figure 7, the maximum intensity of the armature field will be at the tips of the pole shoes, being a minimum at the midpoint of the pole shoe, that is, the neutral axis of the armature field.

The intensity of the armature field, in the vicinity of the brush axis, will be very small owing to the length and reluctance of the path in the air, compared with that across the air-gap and the iron of the main pole.

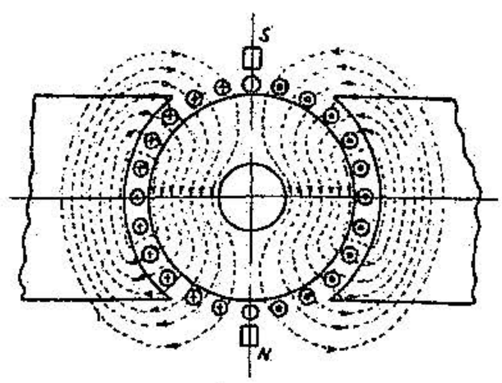


Figure 7

The same effect occurs in a multipolar armature; there will be as many armature magnetic poles formed as there are main poles; the axes of the armature poles will coincide with the brush axes.

As the armature rotates the conductors pass successively from one armature circuit to the next and the direction of current in them is reversed; the number of conductors carrying current in the same direction, on each side of the brush axis, remains fixed in space. The armature field remains stationary and unchanging.

Since the axis of the armature field always coincides with the brush axis it is evident that when the brushes are in the geometric neutral position, the armature field will be displaced 90 electrical degrees from the main field.

It is on account of this displacement in relation to the main field, that the armature ampere-turns which produce this field at 90 electrical degrees to the main field, are called ______________________________ turns.

When both the main field winding and the armature winding are carrying current there will be a resultant distribution of the flux due to the action of the main field and armature ampere-turns in combination.

Figure 8 illustrates this effect in the case of a two-pole generator.

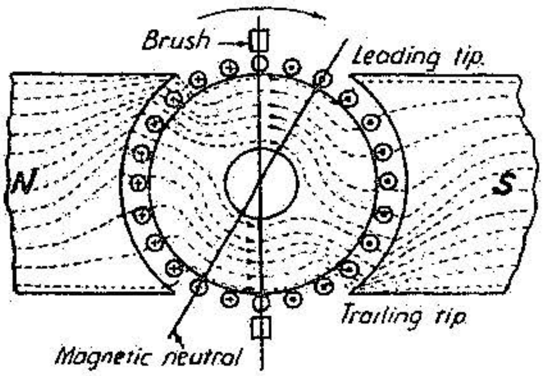


Figure 8

From the centre of each pole to the "leading" pole tip, the action of the armature ampere-turns is ______________________ to the main field ampere-turns; the opposition being greater at the tips.

For the other half of the pole shoe, the flux caused by the armature current ______________ that of the main fields.

Thus, in the case of a generator, the effect of the armature current is to shift the magnetic field forward in the direction of rotation. The greater the armature current, the greater will be the displacement of the field and the neutral zone. It is shown in figure 8 that the magnetic neutral axis has moved-forward from the geometric neutral axis in the direction of rotation.

The brushes are now in the ________________________ position for good commutation.

The distribution of flux over the pole face is altered by the armature field; the flux density at the -

- leading pole tip is ______________________
  and
- at the trailing tip it is ______________________.

The extent of this main field distortion varies with the armature current.

For a given machine the distortion is -

- slight for small loads
- increasing with increase of load current.

The fact that the cross-magnetizing ampere-turns weaken the leading pole tip in a generator, is an additional reason why the brushes require a different "lead" for different load currents.

When the brushes of a machine are given a lead for good commutation, the armature field, whose axis is parallel with the brush axis, is now at some angle less than 90 electrical degrees to the main field.

The armature field can be resolved into two component fields at right angles to each other; one at right angles to the axis of the main field, the other parallel to it but acting in the other direction. This may be seen by reference to figure 9.

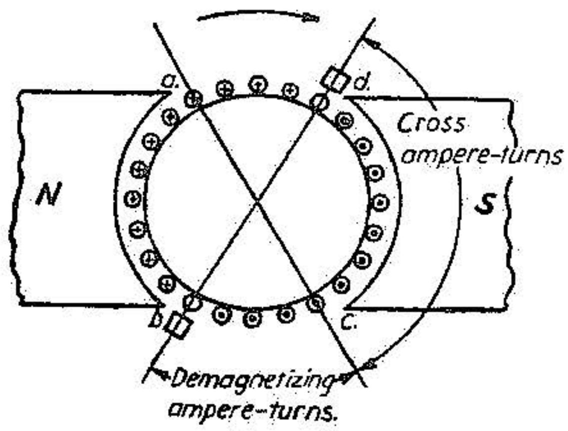


Figure 9

Consider the current-carrying conductors between "a-d" and "b-c", and determine the direction of the flux set up by them.

This flux acts along the same axis as the main field flux, but in the opposite direction. This component of the armature field will produce a direct demagnetizing effect upon the main field. The remaining conductors, between "a-b" and "c-d", produce a cross magnetizing component tending to distort the main field.

Thus, when the brushes are given a lead, armature reaction will cause the useful flux to decrease as the load on the machine is increased which results in a reduction in generated emf. The effect is greater as the angle of lead is increased.

3. SEPARATELY-EXCITED GENERATOR EXTERNAL CHARACTERISTIC

The external characteristic of a generator is a curve showing the relationship between the terminal voltage and the load current. It is usually obtained by carrying out a load test on the generator, which is operated at its rated speed, while the load current is increased in steps from zero to approximately 125 per cent of its full-load value. Terminal voltages are then plotted against the corresponding current value and the curve is obtained.

Figure 10 shows the external characteristic for a separately excited generator.

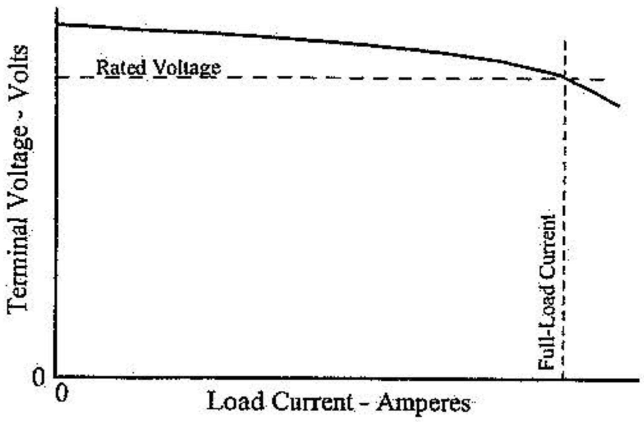


Figure 10

Reference to the equivalent circuit of the generator reveals that when the generator is unloaded, the terminal voltage equals the generated emf. When the generator is delivering current to a load the terminal voltage is less than the generated voltage. See figure 11.

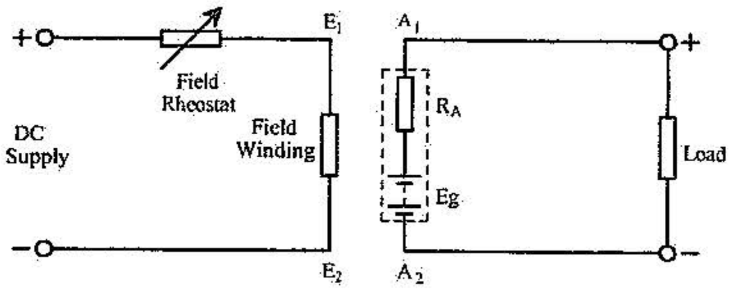


Figure 11

This voltage decrease is due to two reasons:

- as the flux per pole is reduced by the armature reaction, the emf generated by cutting this flux is also reduced.
- the terminal voltage is less than the generated emf by an amount equal to the voltage drop across the armature circuit resistance.

Thus, when the load on a separately-excited generator increases, its terminal voltage decreases slightly and steadily as shown by its characteristic curve.

Under load conditions, the armature circuit is a series circuit and all the characteristics of such a circuit apply.

where: V_T = generator terminal voltage in volts
Eg = armature generated voltage in volts
I_A = armature current in amperes
R_A = armature circuit resistance in ohms

Example: 2

A separately excited generator has a field resistance of 125Ω and is supplied from a 125V dc supply. If the generator has an open-circuit terminal voltage of 500V, an armature circuit resistance of 0.25Ω and an armature current of 35A, determine the -

(a) field current

(b) generator terminal voltage

(c) load resistance

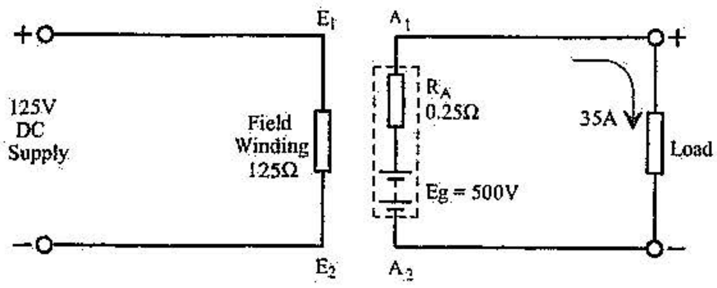


Figure 12

4. EFFECT OF LOAD ON PRIME MOVER

When load is applied to a generator, the generator is required to deliver energy to the load. This additional energy must come from the prime mover. The mechanism through which this is achieved is shown in figure 13.

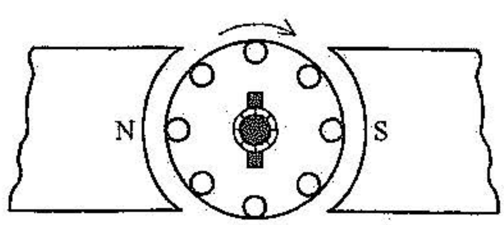


Figure 13

When load is applied, armature current flows and as discussed previously the armature establishes a magnetic field. According to Lenz's law, the polarity of this magnetic field acts to oppose the motion that caused the generation of the armature induced voltage. That is, a counter or reverse torque.

As load is increased the counter torque also increases, making the prime mover work harder to drive the generator. The prime mover applies a greater level of mechanical energy to the input of the generator. Therefore, an increased input energy provides the required output energy. The generator carrying out the conversion of mechanical to electrical energy via electromagnetic induction.

Example: 3

A separately excited generator has a field resistance of 200Ω and is supplied from a 250V dc supply. The armature circuit resistance is 0.2Ω and the load has a resistance of 10Ω. Given the generator operates with a field flux of 0.1Wb, a speed of 1000rpm and has a machine constant of 5 determine the -

(a) field current
(b) generated emf
(c) load current
(d) generator terminal voltage when delivering load current
(e) voltage drop across the armature circuit resistance.

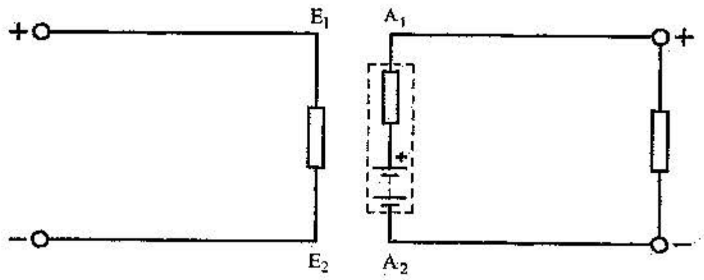


Figure 14

Example: 4

If the load on the generator in example 3 was increased, such that the load resistance was 8Ω and the effective flux per pole was reduced to 0.098Wb. Determine the -

(a) field current

(b) generated emf

(c) load current

(d) generator terminal voltage when delivering load current

(e) voltage drop across the armature circuit resistance.

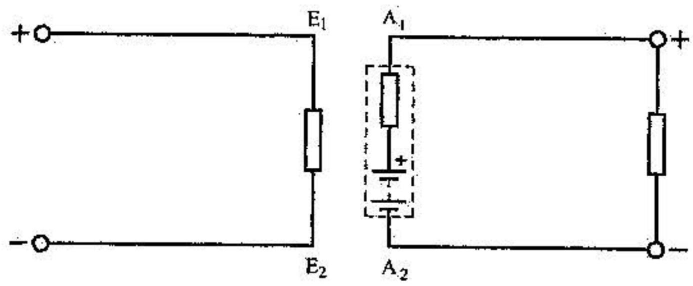


Figure 14

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NOTES:

THE SEPARATELY EXCITED GENERATOR

PURPOSE:

This practical assignment will be used to examine the no-load and load characteristics of the separately excited dc generator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect a separately excited generator using a circuit diagram as a guide
- Carry out a no-load test on a dc generator and plot the no-load characteristic.
- Carry out a load test on a dc generator and plot the load characteristic.
- Using test results, draw the equivalent circuit of the armature circuit of a dc generator.

EQUIPMENT:

- ☐ 1 x variable dc power supply
- ☐ 1 x three phase 41.5/24V, 50Hz supply
- ☐ 1 x Betts dc compound machine
- ☐ 1 x Betts three phase, squirrel cage induction motor
- ☐ 1 x Betts machine bed to accommodate two machines
- ☐ 1 x variable speed ac drive
- ☐ 1 x digital multimeter
- ☐ 2 x 0-2A analogue dc ammeter
- ☐ 1 x optical tachometer
- ☐ 1 x alternator load panel
- ☐ 4mm connecting leads

- REMEMBER -
- WORK SAFELY AT ALL TIMES -
observe correct isolation procedures

PROCEDURE 1: THE PRIME MOVER

1. The generator must be driven by a prime mover, in this case a delta connected, three phase motor controlled via a variable speed drive.
2. Connect the prime mover as shown in figure 1. This arrangement will be used throughout the practical assignment.

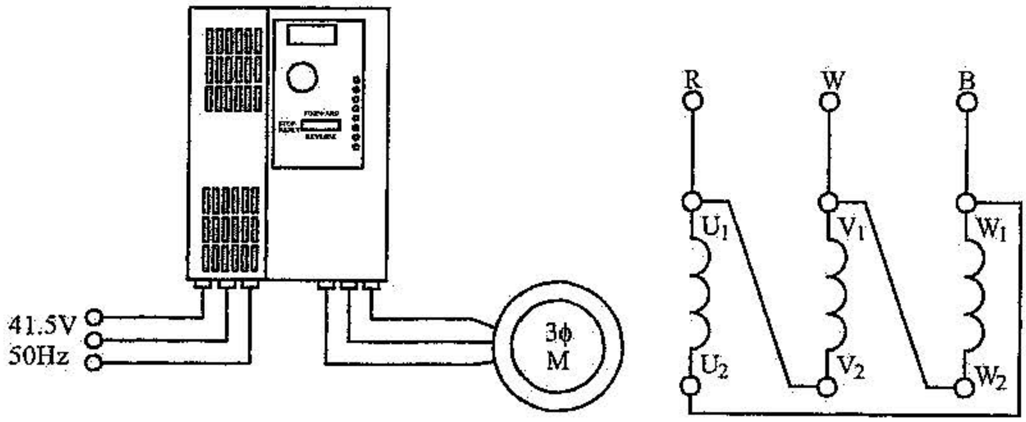

Figure 1

PROCEDURE 2: NO-LOAD CHARACTERISTIC

1. Connect the generator as shown in figure 2.

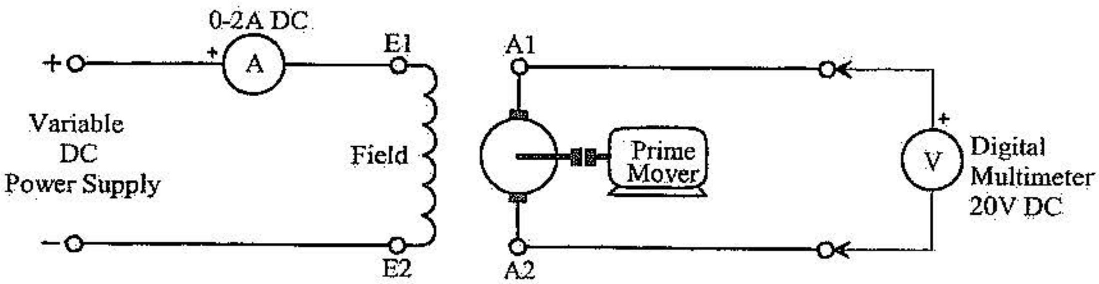

Figure 2

2. **<u>Do not proceed</u>** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

3. Ensure the DC power supply is switched off.
4. Start the prime mover and via the variable speed drive adjust its speed to **1400rpm**.

5. Measure the generator output voltage using the digital multimeter and record in the space provided in table 1.

Table 1

Field Current amperes	0	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
Output Voltage volts												

6. Turn on the DC power supply, slowly adjust to give a field current of 0.1A, then measure the generator output voltage. Record the voltage value in table 1.
7. Repeat the procedure for each of the values of field current shown in table 1.
8. Reduce the field current to 0A and turn off the field supply.
9. Adjust the variable speed drive to provide a prime mover speed of **700rpm.**
10. Measure the generator output voltage using the digital multimeter and record in the space provided in table 2.
11. Turn on the DC power supply, slowly adjust to give a field current of 0.1A, then measure the generator output voltage. Record the voltage value in table 2.

Table 2

Field Current amperes	0	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2
Output Voltage volts												

12. Repeat the procedure for each of the values of field current shown in table 2.
13. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

14. Turn the DC power supply and the prime mover off.

PROCEDURE 3: LOAD CHARACTERISTIC

1. Connect the circuit as shown in figure 3.

   Note: The load is a lamp panel that consists of a series of lamps that may be switched into circuit via a load switch. The load panel is to be connected as shown in figure 3.

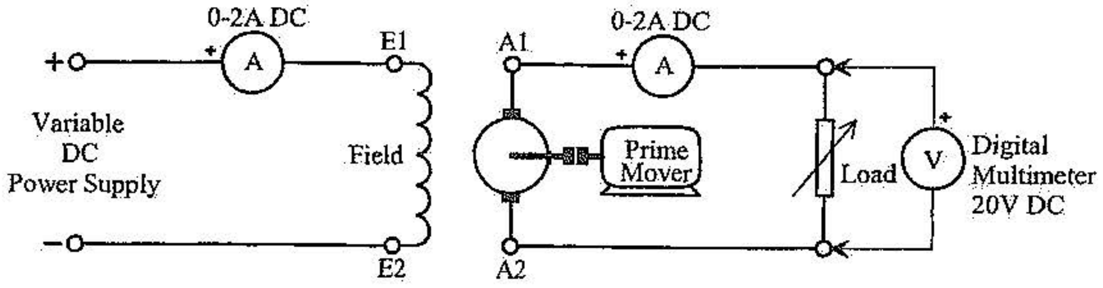

Figure 2

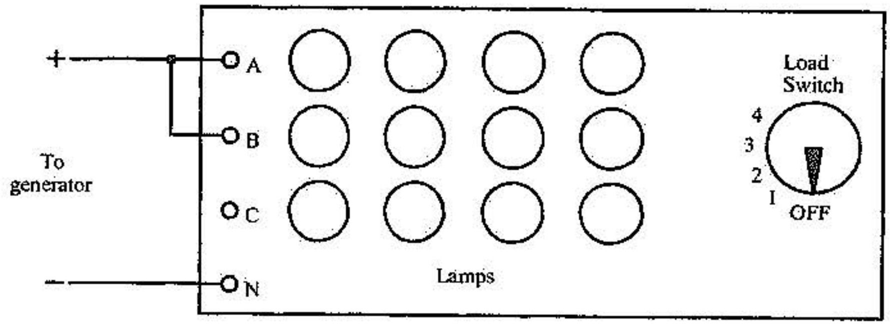

Figure 3

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

3. Ensure the DC power supply is switched off and the load switch is in the off position.
4. Start the prime mover and via the variable speed drive adjust its speed to **1400rpm**.
5. Turn on the DC power supply, slowly adjust to give a field current of 2A, then measure the generator terminal voltage.
6. Record the value of the terminal voltage in table 3.

Table 3

Field Current amperes	**Load Switch Setting**	**Terminal Voltage volts**	**Load Current amperes**
2A at all loads	Off		0A
	1		
	2		
	3		
	4		

7. Set the switch on the load panel to position 1.
8. Check that the generator speed is 1400rpm and the field current is 2A. Adjust if necessary.
9. Measure and record, in table 3, the generator terminal voltage and load current.
10. Repeat the procedure with load switch settings of 2, 3 and 4.

    Note: Be sure to keep the generator speed at 1400rpm and field current at 2A throughout the load test.

11. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

12. Turn the load switch to the off position and if necessary re-adjust the field current to 2A.
13. Using the tachometer measure the generator shaft speed.

    Shaft speed = ____________

    What happened to the generator speed when load was removed?

    ____

14. Switch of both power supplies, then disconnect the circuit.
15. Please return all equipment to its proper place, safely and carefully.

OBSERVATIONS:

1. Using the axis of figure 4, draw the no-load characteristics of the generator at both 1400rpm and 700rpm.

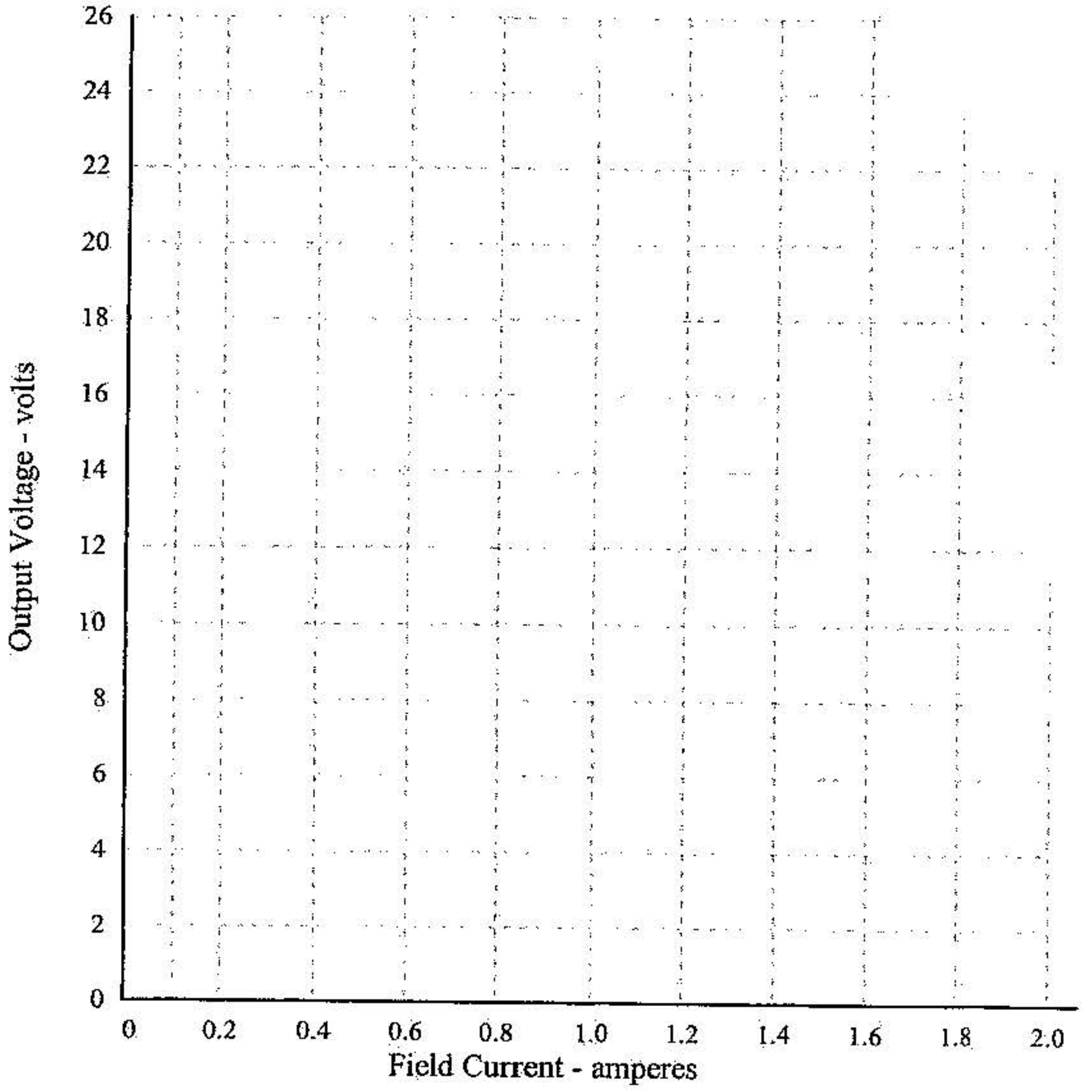

Figure 4

2. Based on your results, what is the relationship between generator speed and the generated emf?

3. Based on your results, what is the relationship between generated voltage and field current?

4. Using the axis of figure 5, draw the load characteristic for the generator?

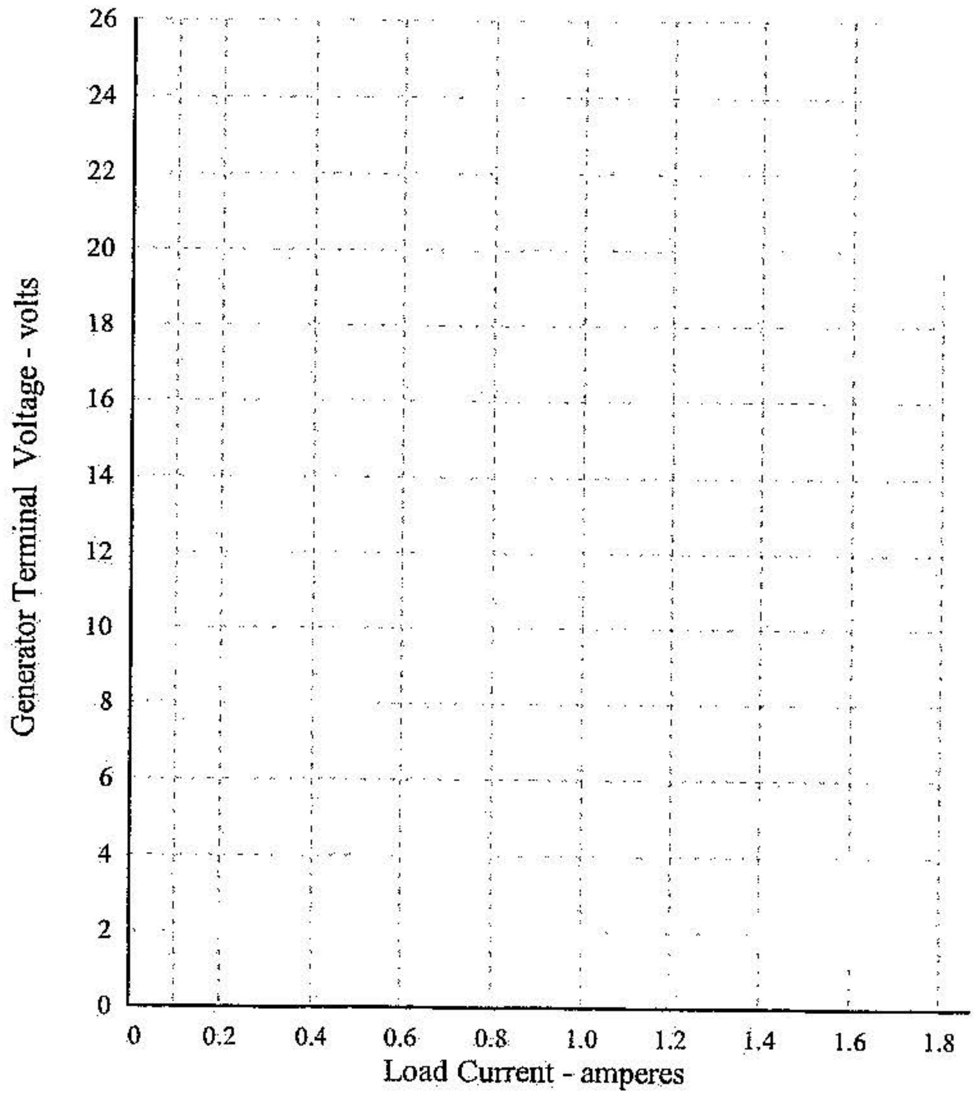

Figure 5

5. What causes the terminal voltage of the generator to decrease with an increase of load?

____

____

____

6. Using the results obtained with maximum load on the generator, determine the resistance of the armature circuit.

$$R_A = \frac{E_g - V_T}{I_A}$$

____

____

7. Based on the results of this assignment, draw the equivalent circuit of the generator armature circuit.

8. What is the effect of increased generator load on the speed of the prime mover?

****

THE DC GENERATOR (PART 2)

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

When the field current in a separately excited generator is zero, the output voltage is not zero due to ___(1)___.

If the speed of the prime mover driving a generator is reduced, the output voltage will ___(2)___

Increasing the load on a generator causes the prime mover speed to ___(3)___ due to the ___(4)___ developed by the armature current.

Armature reaction is due to ___(5)___ effect which distorts the main flux, and ___(6)___ effect which weakens the main flux.

Armature reaction will shift the ___(7)___ axis in the ___(8)___ direction as the direction of rotation.

As the load on a generator increases, the effect of armature reaction ___(9)___, which results in the brushes being in the ___(10)___ position for good commutation.

As the load on a generator increases, the concentration of flux on the trailing edge of the pole face ___(11)___, and the concentration of flux on the leading edge of the pole face ___(12)___.

As the load on a generator increases, the terminal voltage ___(13)___. This is due to ___(14)___ and the ___(15)___ voltage drop.

The terminal voltage of a generator is the ___(16)___ between the generated voltage and the ___(17)___ voltage drop.

The open circuit characteristic of a separately excited generator shows the ___(18)___ of the magnetic material used in core.

SECTION B

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A separately excited generator has an effective flux of 8mWb and is operated at a speed of 292 rpm. If the machine constant is 12, determine the:
   (a) generated voltage; (28V)
   (b) no-load terminal voltage. (28V)

2. Determine the field flux required to produce a no-load voltage of 240V in a separately excited generator rotating at 600rpm with a machine constant of 15. (26.7mWb)

3. Determine the speed a prime mover must drive a generator under no load to produce a terminal voltage of 300V. The generator has an effective flux of 20mWb and a machine constant of 15. (1000rpm)

4. A generator has an armature resistance of 0.15Ω and a full load resistance of 25Ω. If the open circuit voltage is 250V, determine the terminal voltage at full load. (248.5V)

5. A separately excited generator has an effective field flux of 0.02Wb, a machine constant of 12 and spins at 400 rpm. If the generator has an armature circuit resistance of 0.15Ω and an armature current of 20A, determine the load voltage for this condition. (93V)

6. The generator shown in figure 1 has a machine constant of 10, and effective flux of 25mWb and is driven at 1000rpm.

   Determine the:
   (a) field current; (667mA)
   (b) generated voltage; (250V)
   (c) armature current; (16.54A)
   (d) terminal voltage (248V)
   (e) armature circuit voltage drop. (2V)

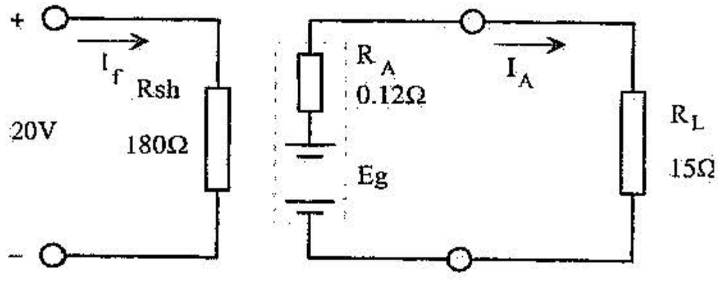

Figure 1

SECTION C

1. The diagram of figure 2 represents the armature and field of a separately excited generator.
   (a) In the diagram of figure 2(a), determine the direction of the currents flowing in the armature conductors.
   (b) In the diagram of figure 2(a) neatly draw the field patterns of the main field flux and the armature field flux.
   (c) In the diagram of figure 2(b), neatly draw the resultant field produced by the two fluxes shown in figure 2(a).

Attach this page to your written tutorial assignment for marking.

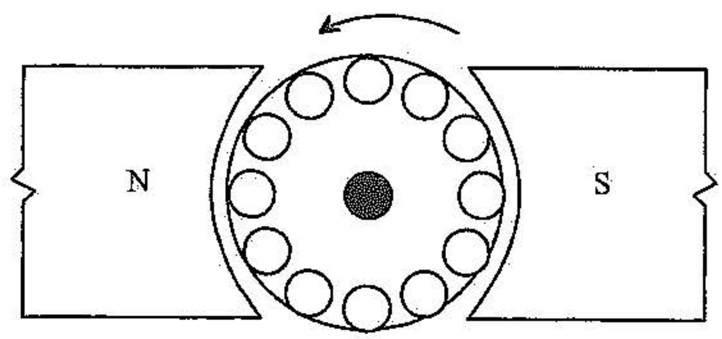

Figure 2(a)

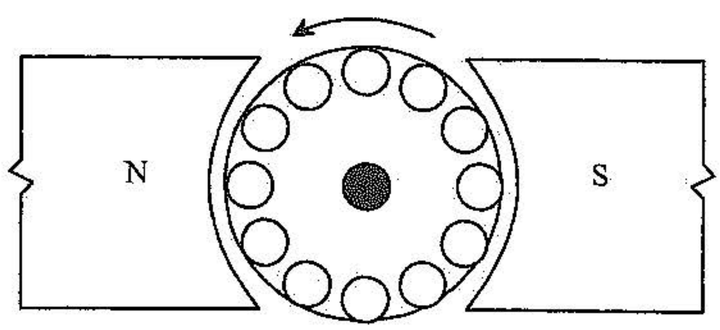

Figure 2(b)

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NOTES

SELF EXCITED GENERATORS

PURPOSE:

This section describes the operating principles and characteristics of self-excited dc generators.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- draw the circuit arrangement and connect various types of self-excited dc generator.
- list the characteristics and applications of various types of self-excited dc generator.
- list and describe the methods of excitation used for dc generators.
- describe the methods used to regulate the output voltage of dc generators.

REFERENCES:

Electrical Principles for the Electrical Trades, 5th Edition. Jenneson J.R.
Pages 270-276 and 277.

1. SELF-EXCITED GENERATORS

A self-excited generator is one whose exciting current is obtained from the generator itself. The way in which the field coils are connected, in relation to the armature, determines the type of generator. The types are:

- ________________ connected - the field winding is connected in "shunt" or "parallel" with the armature.
- ________________ connected - the field winding is connected in series with the armature.
- ________________ connected - has a combination of shunt and series field windings.

In order that a self-excited generator may "build up" its emf.:

- there must be residual magnetism in the magnetic circuits of the machine to initiate the generated emf
- the resistance of the exciting circuit must not be too high and prevent the building up of field current due to the emf generated from the residual flux
- the speed must not be too low; the emf generated from the residual flux must be sufficient to cause the necessary current in the field winding to build up.

2. SHUNT GENERATORS

In this type of generator the field winding -

- consists of a relatively large number of turns of small csa conductor
- is connected across the terminals of the armature (parallel with the armature)
- has a comparatively high resistance and being connected across the armature it carries a current directly proportional to the terminal voltage and inversely proportional to the resistance of the field circuit.

Figure 6 shows the arragement of one shunt field coil and its associated pole core.

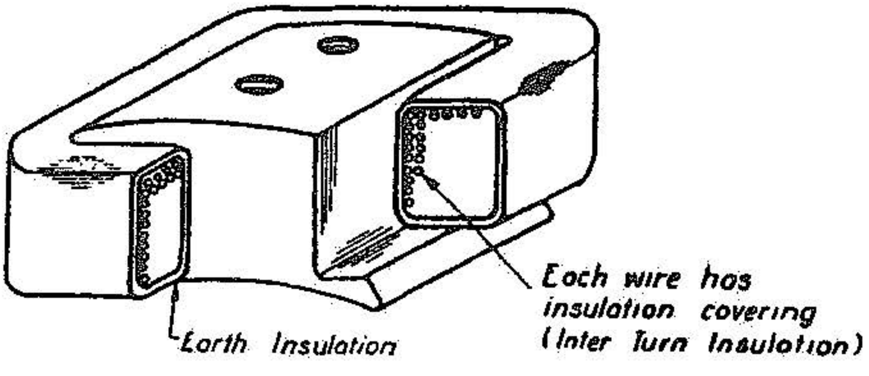

Figure 6

The internal connections of the shunt generator are shown in figure 7.

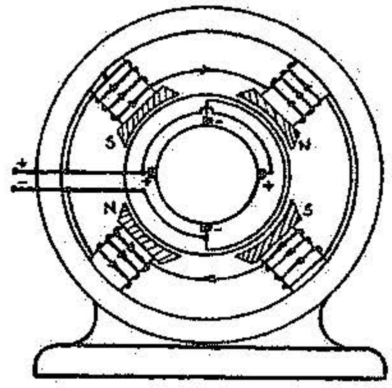

Figure 7

The field current, although supplied by the armature, is independent of the load current. The exciting current varies only with the terminal potential difference (tpd) of the machine. The armature current divides and flows partly around the shunt field circuit and partly around the external circuit. The field current varies between 1% and 3% of the total current supplied by the armature, depending upon the size of the machine. Figure 7 is the basic circuit diagram.

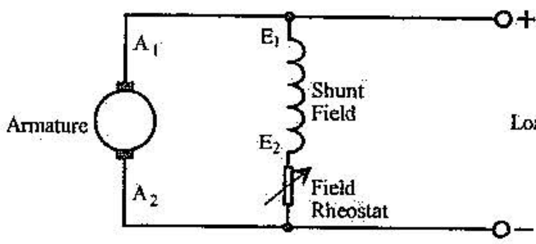

Figure 8

When the armature of a shunt generator begins to rotate -

- the armature conductors cut the lines of force resulting from the residual magnetism of the poles and generate a small emf
- the armature consequently produces a small current in the shunt field circuit which increases the magnetization of the iron
- this strengthened field then produces a larger emf in the armature, so that in a short time the field is built up and the emf attains its full value
- the final steady value is such that the potential difference applied to the field winding is just equal to the voltage drop in the ohmic resistance of the field circuit.

The external characteristic of a shunt generator is shown in figure 9.

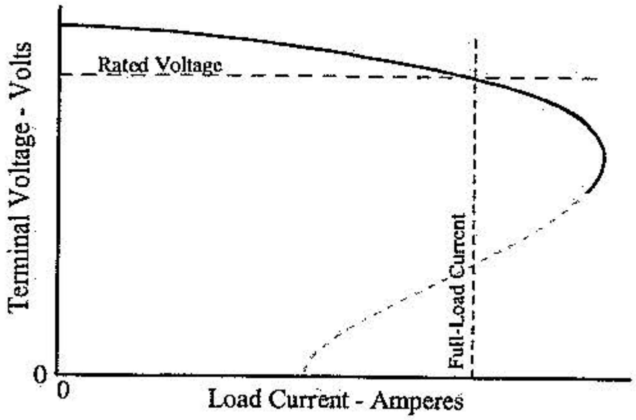

Figure 9

The terminal voltage -

- equals the generated voltage when the machine is unloaded
- as the load current is increased the terminal voltage decreases from the no-load value, decreasing at a greater rate than in the case of a separately-excited machine.

The decrease in terminal voltage, with increase of load, of a shunt generator is due to three reasons:

- the demagnetizing effect of armature reaction
- the voltage drop in the armature circuit
- the combined effects of demagnetization and armature circuit voltage drop causes a decrease in the shunt-field current and as a result less flux is produced.

There is a limit beyond which the current supplied by the generator cannot be increased. If there is an attempt to increase the load current beyond this limit by further reducing the resistance of the external circuit, the terminal voltage decreases rapidly and the load current actually decreases. This is shown in the diagram by the broken part of the curve. The generator is unstable under these conditions.

This rapid decrease in the tpd is due to the reduction of field current to such a value that the flux induced in the field magnets is below the "knee" of the magnetization curve. Further decreases in field current produce large reductions in flux.

Thus, it is evident that a shunt-wound generator may have its armature short circuited and the shunt circuit **"closed"** later without any excessive current flowing in the armature. There would be only current, due to the emf induced by interaction with the residual magnetism, passing around the armature circuit. If the armature were short circuited, while the generator was fully excited, the current would increase to its maximum value and then decrease towards zero. The current value, in a short circuited generator, will follow the path of the external characteristic curve provided that the sparking at the brushes is insufficient to cause a flash-over from brush to brush at the commutator.

With modern generators it is difficult to obtain the complete external characteristic curve, as the heating and sparking limits are attained before maximum value of current is obtained.

3. SERIES GENERATORS

The field excitation is obtained by passing the armature current through the field winding in this type of generator.

As shown in figure 10, the field coils are wound with a small number of turns of heavy-gauge wire.

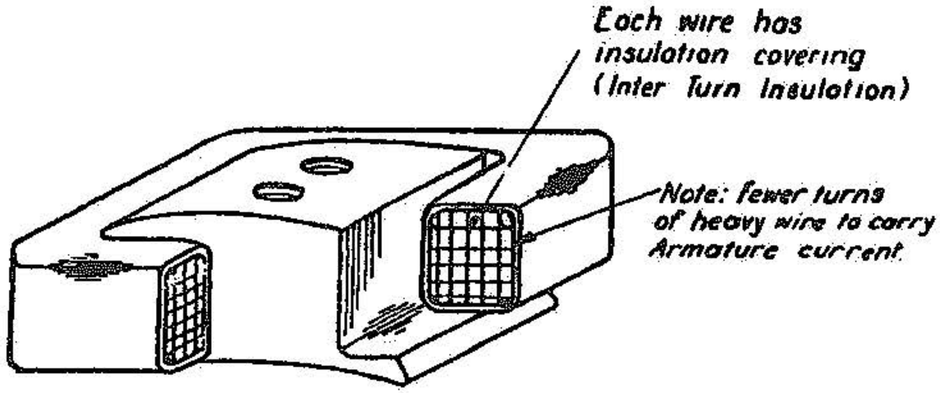

Figure 10

The field strength produced by a winding depends upon the number of turns and a current in the fields of the series generator. It can be arranged to produce the equivalent field strength of a large number of turns and a small current in the fields of a shunt generator.

Figure 11 shows the internal connections of the series generator.

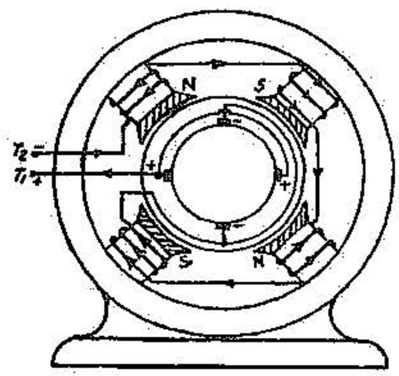

Figure 11

Generally with a shunt generator the machine is allowed to build up its emf to the normal value before the load is applied, but with a series generator self-excitation is not possible until the load circuit is completed; the load circuit is also the exciting circuit.

The basic diagram of figure 12 shows this arrangement.

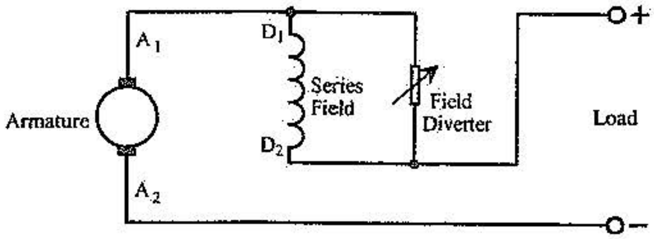

Figure 12

So far as the main principles are concerned the action of the series generator differs only in minor detail from that of the shunt machine. Appreciable building up will not occur until the resistance of the exciting circuit is reduced to a certain critical value, determined by the speed of operation and the magnetic characteristics of the machine. The final voltage attained for any speed of operation is determined by the resistance of the exciting circuit and in this case the exciting circuit consists of the complete field windings, armature circuit and the load resistance.

The load characteristic for a series generator is shown in figure 13.

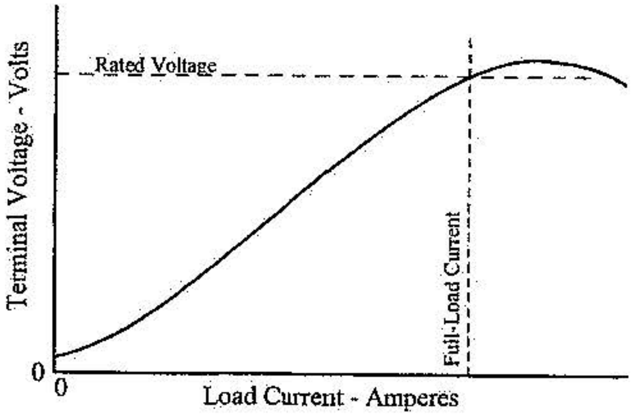

Figure 13

As the field winding is in series with the armature and the external load, at no load the terminal voltage is that due to residual magnetism. As the load current is increased the field strength and terminal voltage increase. The tpd is less than the generated emf, because of the voltage drops in the armature and field windings and because of armature reaction. When the curve is at a maximum value any attempt to increase the load current will cause the armature reaction to decrease the terminal voltage.

4. COMPOUND GENERATORS

Since the effect of increase of load is to diminish the voltage of a shunt-wound generator and to increase the voltage of a series-wound generator (except with very large currents), it is possible by combining the two methods to have the terminal voltage at full load the same as that at no load.

Figure 14 illustrates the arrangement of a single pole from a compound generator.

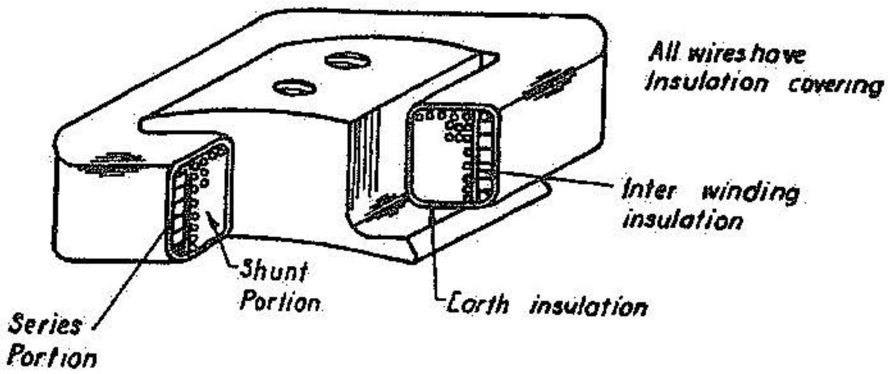

Figure 14

The internal connections of the compound generator are shown in figure 15.

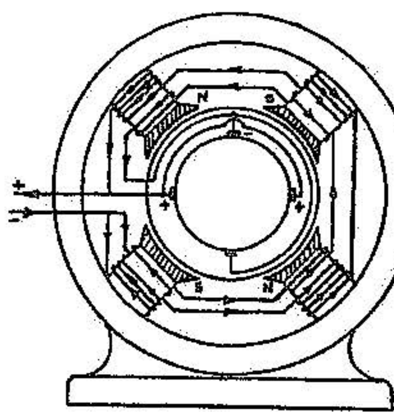

Figure 15

The field magnets are provided with a composite winding, consisting of shunt and series coils on each pole, arranged to carry current in the same direction so that the total mmf developed is the sum of the mmfs developed by the two coils; an approximately uniform tpd may be obtained at all loads.

On open-circuit the compound-wound generator builds up its voltage as a shunt generator. As the load is increased the effect of the load current in the series winding is to increase the excitation.

Such machines are often called ________________________ compound generators. Generally, the series winding on full load develops about 25% of the ampere-turns of the shunt winding.

For certain applications the series winding of a compound generator is reversed, so that its mmf opposes the mmf. of the shunt winding. This causes the tpd of the machine to diminish rapidly as the load current is increased.

These machines are referred to as ______________________-compounded generators.

Figure 16, shows the diagram of connections of a compound generator. The shunt field is connected across the output terminals of the machine.

This is known as the ____________________________ connection.

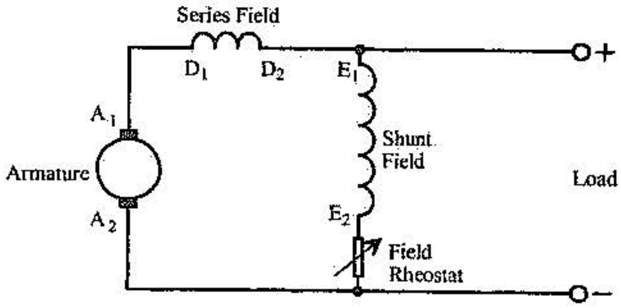

Figure 16

If the shunt field were connected directly across the brushes, figure 17, instead of across the terminals of the machine, the connection would be called

_________________________________.

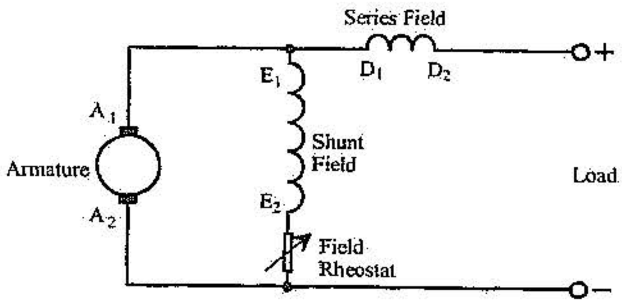

Figure 17

It is of little importance whether the long or short shunt method of connection be employed.

A short shunt machine will generate a slightly higher voltage at heavy loads compared to a long shunt.

When using compound generators, voltage regulation can be obtained automatically.

The curves shown in figure 18 are typical characteristics that may be obtained from compound generators.

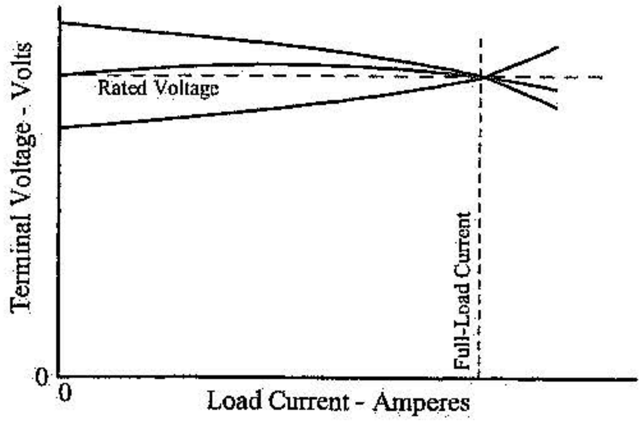

Figure 18

The load characteristic of the machine depends upon the ampere-turns in the series field. By adjusting these ampere-turns the increase in tpd, due to the series field, compensates for the internal voltage drop caused by the load current. There are basically three possibilities -

- ____________________ compounded - if the strength of the series field is such as to cause the generator to deliver the same value of tpd at both no load and full load.
- ____________________ compounded - when the series ampere-turns are adjusted so that the tpd of the generator is greater at full load than at no load.
- ____________________ compounded - a lower value of ampere turns will allow the full-load voltage to fall below the no-load voltage.

Except those supplying power for welding, generators are seldom under compounded. They are usually designed to be over compounded, according to the service for which the machine is intended.

For generators near the point of power consumption, the degree of over compounding may be as low as 3% while for traction generators, with long feeder systems, it may be as high as 10% to compensate for the voltage drop in the feeder.

Figure 18 shows the shape of the load characteristics of generators with different amounts of compounding.

The characteristic of a differentially-compounded generator is shown in figure 19.

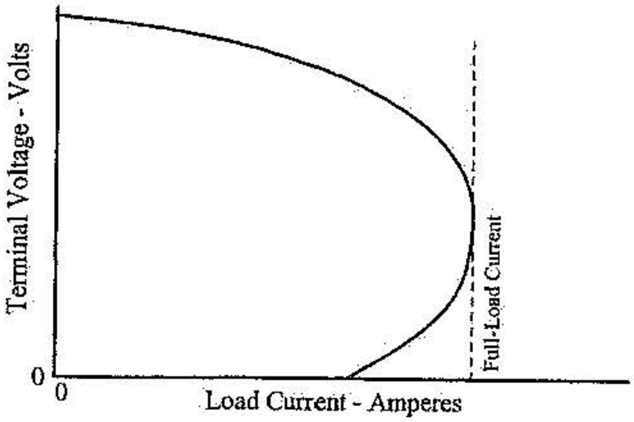

Figure 19

In this type of generator, the series field winding is connected in opposition to the shunt field winding, with the result that the normal voltage drop in the generator is very much increased by the demagnetizing effect of the series field winding.

Differentially-compounded generators are used for applications where it is desirable to limit the output from the machine automatically. For example, certain welding systems require a constant current at variable voltage or electrically-driven excavators have motors which are likely to be "stalled" under certain conditions. The characteristic curve shows how the generator is protected from overloads by its rapidly decreasing terminal voltage.

****

Name: ________________ **Practical 8**

SELF-EXCITED GENERATORS

PURPOSE:

This practical assignment will be used to examine the load characteristics of the shunt and compound self-excited dc generators.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect a shunt generator using a circuit diagram as a guide.
- Carry out a load test on a shunt generator and plot the load characteristic.
- Connect a compound generator using a circuit diagram as a guide.
- Carry out a load test on a compound generator and plot the load characteristic.
- Compare the performance of shunt and compound dc generators.

EQUIPMENT:

- ☐ 1 x variable dc power supply
- ☐ 1 x Betts dc compound machine
- ☐ 1 x Betts single phase, 240V drive unit
- ☐ 1 x Betts machine bed to accommodate two machines
- ☐ 1 x digital multimeter
- ☐ 1 x 0-2A analogue dc ammeter
- ☐ 1 x alternator load panel
- ☐ 4mm connecting leads

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

PROCEDURE 1: SHUNT GENERATOR

1. Connect the generator as shown in figure 1.

   Note: The load is a lamp panel that consists of a series of lamps that may be switched into circuit via a load switch. The load panel is to be connected as shown in figure 2.

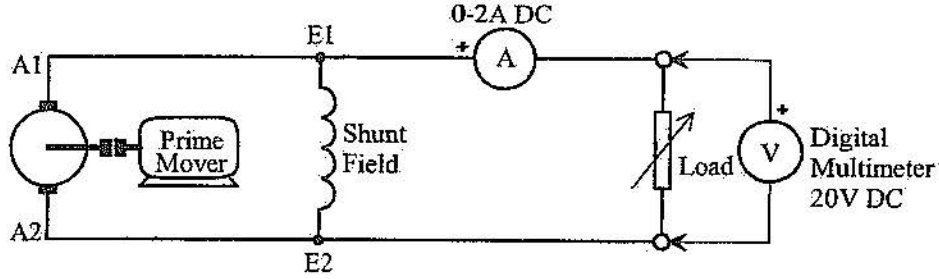

Figure 1

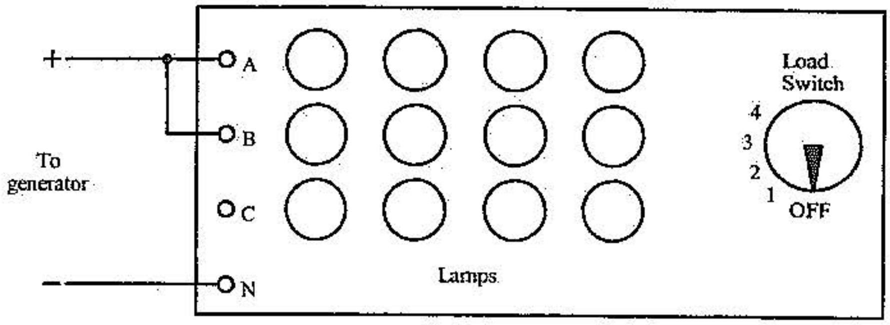

Figure 2

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

3. Ensure the load switch is in the '**off position**'.
4. Turn the prime mover on.
5. Measure, and record in table 1, the generator terminal voltage.
6. Set the switch on the load panel to position 1.
7. Measure and record, in table 1, the generator terminal voltage and load current.
8. Repeat the procedure with load switch settings of 2, 3 and 4

Table 1

Load Switch Setting	Terminal Voltage volts	Load Current amperes
Off		0A
1		
2		
3		
4		

9. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

10. Turn prime mover off.

PROCEDURE 2: COMPOUND GENERATOR

1. Connect the circuit as shown in figure 4.

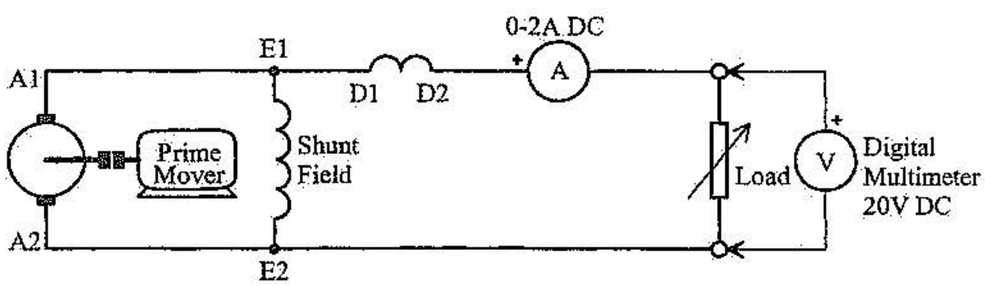

Figure 4

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

3. Ensure the load switch is in the '**off position**'.
4. Turn the prime mover on.
5. Measure the generator terminal voltage and record the value in table 2.
6. Record the value of the terminal voltage in table 3.

Table 2

Load Switch Setting	**Terminal Voltage volts**	**Load Current amperes**
Off		0A
1		
2		
3		
4		

7. Set the switch on the load panel to position 1.
8. Measure and record, in table 2, the generator terminal voltage and load current.
9. Repeat the procedure with load switch settings of 2, 3 and 4.
10. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

11. Turn the load switch to the off position.
12. Turn the prime mover off and allow to come to rest.
13. Disconnect the circuit.
14. Please return all equipment to its proper place, safely and carefully.

OBSERVATIONS:

1. Using the axis of figure 5, draw the load characteristics for the shunt generator.

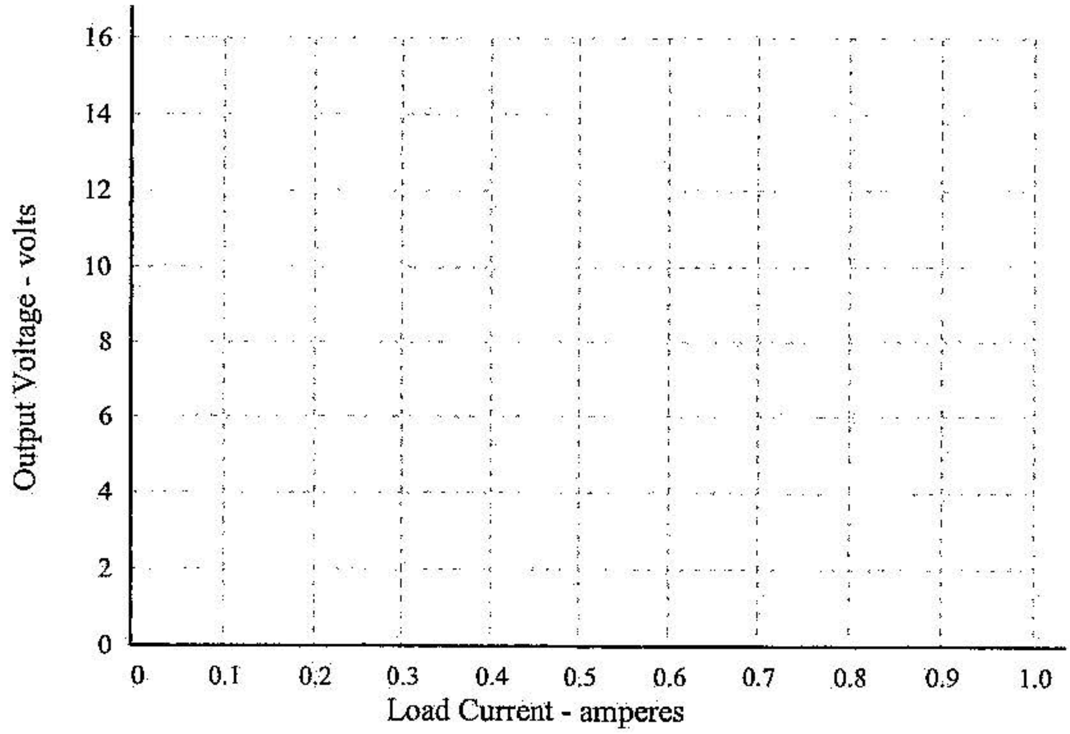

Figure 5

2. What are the factors that cause the terminal voltage of a shunt generator to decease with an increase of load?

____

____

____

3. Why is a shunt generator considered to be short circuit proof? Use your results to verify your answer.

____

____

____

4. Using the axis of figure 5, draw the load characteristic for the compound generator?

5. Why were the load characteristics for the compound generator better than those of the shunt generator?

____

____

____

6. Of the two generators tested, which would be better for suppling a high current load?

____

____

____

7. What could have been done during construction, to improve the load characteristics of the compound generator?

____

____

____

****

Self Excited Generators

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. If a generator is connected for a shunt configuration, the field connections would be a ______ resistance field connected in ______ with the armature.
   (a) high, series
   (b) high, parallel
   (c) low, series
   (d) low, parallel

2. If a generator is connected for a compound configuration, the field connections would be a ______ resistance field connected in series with the armature and a ______ resistance field connected in ______ with the armature.
   (a) high, high, parallel
   (b) high, low, parallel
   (c) low, high, series
   (d) low, high, parallel

3. A self excited shunt generator relies on ____________ for its initial magnetic flux.
   (a) separate excitation
   (b) residual magnetism
   (c) field flashing
   (d) good luck

4. The generator type which is used for certain welding applications would be a_______ type.
   (a) differentially compounded
   (b) cumulatively compounded
   (c) shunt
   (d) series

5. The type of compound generator which would have the load current flowing through the series winding would be connected as:
   (a) long shunt.
   (b) short shunt.
   (c) differentially shunted.
   (d) series compounded.

6. If a generator is connected for a series configuration, the field connections would be a ______ resistance field connected in ______ with the armature.
   (a) high, series
   (b) high, parallel
   (c) low, series
   (d) low, parallel

7. If a the full load voltage of a compound generator is the same as the no load voltage, the generator would be:
   (a) flat compounded.
   (b) over compounded.
   (c) under compounded.
   (d) differentially compounded.

8. If a the full load voltage of a compound generator is the less than the no load voltage, the generator would be:
   (a) flat compounded.
   (b) over compounded.
   (c) under compounded.
   (d) differentially compounded.

SECTION B

For a self excited generator to build up a generated emf, there must be ___(1)___ in the magnetic circuits of the machine.

Three types of self excited generators are ___(2)___ connected, ___(3)___ connected and ___(4)___ connected.

A shunt connected generator will have a ___(5)___ terminal voltage at full load than at no load. This is due to the ___(6)___ effect of ___(7)___ and the ___(8)___ in the armature circuit.

If a compound generator is ___(9)___ excited, the voltage at full load will be greater than the voltage at ___(10)___ .

If the speed of the prime mover driving a self excited generator is ___(11)___, then the small emf generated by ___(12)___ will not increase sufficiently to build up the required magnetic flux.

The two methods of connecting a compound generator are ___(13)___ where the shunt field is connected in parallel with both the armature and the ___(14)___ , and ___(15)___ where the shunt field is in parallel with the ___(16)___ only.

If a compound generator is wound as ___(17)___ compounded, then both the ___(18)___ field and shunt field fluxes will act in the same direction to assist each other.

SECTION C

1. The diagram of figure 1 represents the armature and fields symbols for self excited generators. Attach the diagram of figure to your answer sheet, and complete the diagrams 1(a) to 1(d) as follows:
   (a) Series generator;
   (b) Shunt generator;
   (c) Short shunt compound generator; and
   (d) Long shunt compound generator.

****

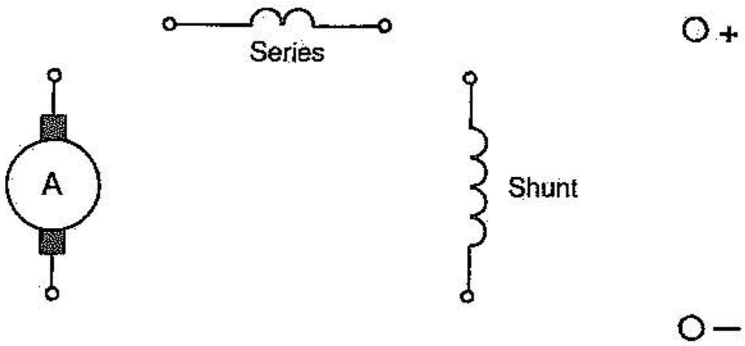

Figure 1(a)

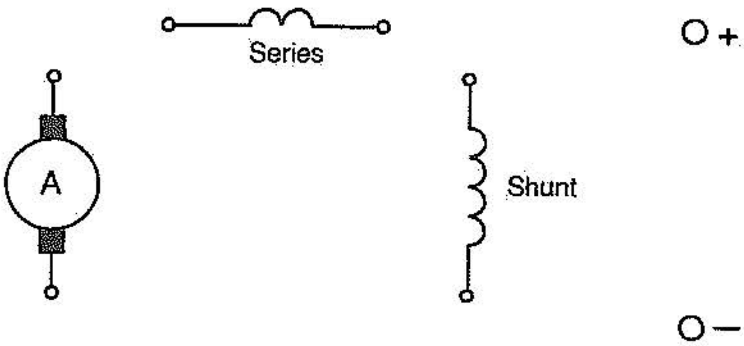

Figure 1(b)

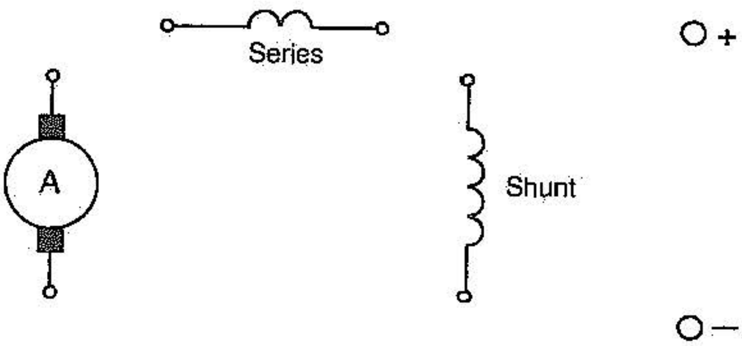

Figure 1(c)

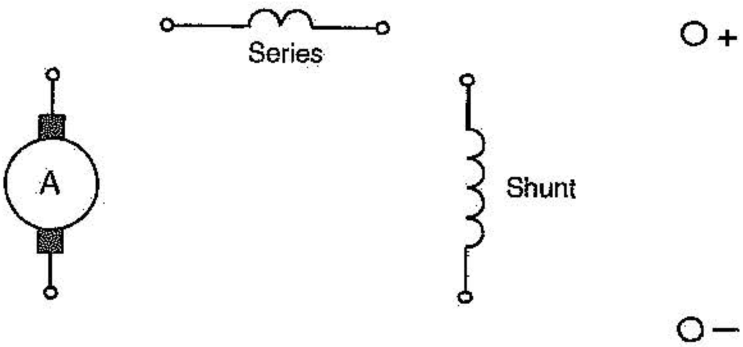

Figure 1(d)

THE DC MOTOR

PURPOSE:

This section introduces the principle of operation of the DC motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- state the basic operating principle of a motor.
- apply Fleming's left hand rule for motors.
- describe how a motor develops a back emf and its effect on armature current.
- describe how the motor effect is produced by an electric current, including the development of torque.
- calculate values of voltage, current and torque associated with dc motors.

REFERENCES:

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.
Pages 276-278 and 282-284.

1. THE DC MOTOR

A dc motor is similar in principle and construction to a dc generator. Overall, the construction can be broken down into two major parts -

- ______________________
- ______________________

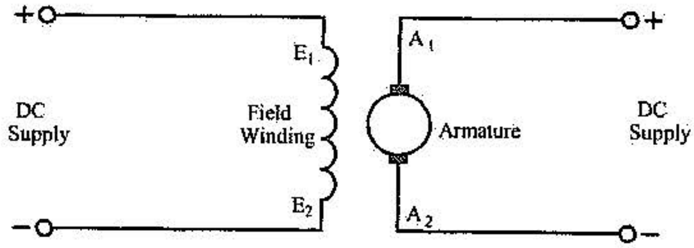

Figure 1

In simple terms, the only difference between a motor and a generator is their application.

The purpose of a dc motor is to convert ____________ energy to ____________ energy.

The output power from the motor is delivered to the load via a rotating shaft. This concept is illustrated in figure 2.

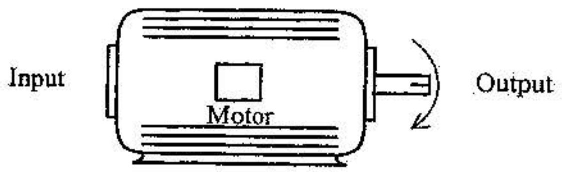

Figure 2

A dc generator, when supplied with a potential difference from an external source, will operate satisfactorily as a motor and drive a load, that is, it will convert electrical energy to mechanical energy.

Similarly, a machine which is classified as a DC motor, when driven by a suitable prime mover, will generate an emf and supply a tpd and current to an external load; thus, converting mechanical energy to electrical energy.

2. PRODUCTION OF ROTATION

The action of a motor depends upon the fact, that a conductor carrying current in a magnetic field is acted upon by a force which is perpendicular to the conductor, and to the positive direction of the magnetic field.

The relationship which exists between the direction of the magnetic field, the current and the resulting force is shown in figure 2.

Figure 2

The relationship that exists between field polarity, direction of current and direction of motion for any conductor carrying current and free to move in a magnetic field, is summed up in a simple rule developed by Professor J A Fleming. This resembles the right hand rule for generators (as detailed earlier in this module) except that the left hand is used instead.

'Fleming's left hand rule' for a motor is applied as follows - clench the left hand and open the thumb and first two fingers mutually at right angles, so that if applied to the corner of a cube they would lie along the three edges forming the corner.

Then -

- the thumb represents the direction of motion of____________________
- the forefinger represents the direction of________________________
- the second finger represents the direction of______________________.

Figure 3 illustrates the application of the Fleming's left hand rule for motors.

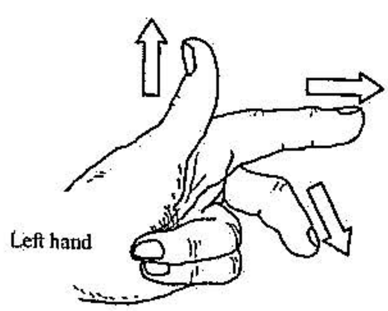

Figure 3

The direction in which the force acts upon the conductor, depends upon the positive direction of the magnetic field and the positive direction of the current in the conductor. A change in either of these, with relation to the other, will reverse the direction in which the force acts; a change in both will not produce any alteration. Fleming's Left-hand Rule, a convenient method of determining the direction of the force is again illustrated in figure 4.

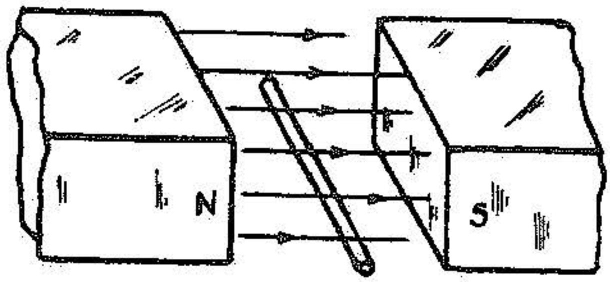

Figure 4

Example: 1

Apply Fleming's Left Hand Rule to each of the diagrams shown in figure 5, to determine -

(a) direction of the force acting on conductor in diagrams (a) - (d)

(b) direction of conductor current in diagrams (e) and (f)

(c) magnetic polarities in diagrams (g) and (h).

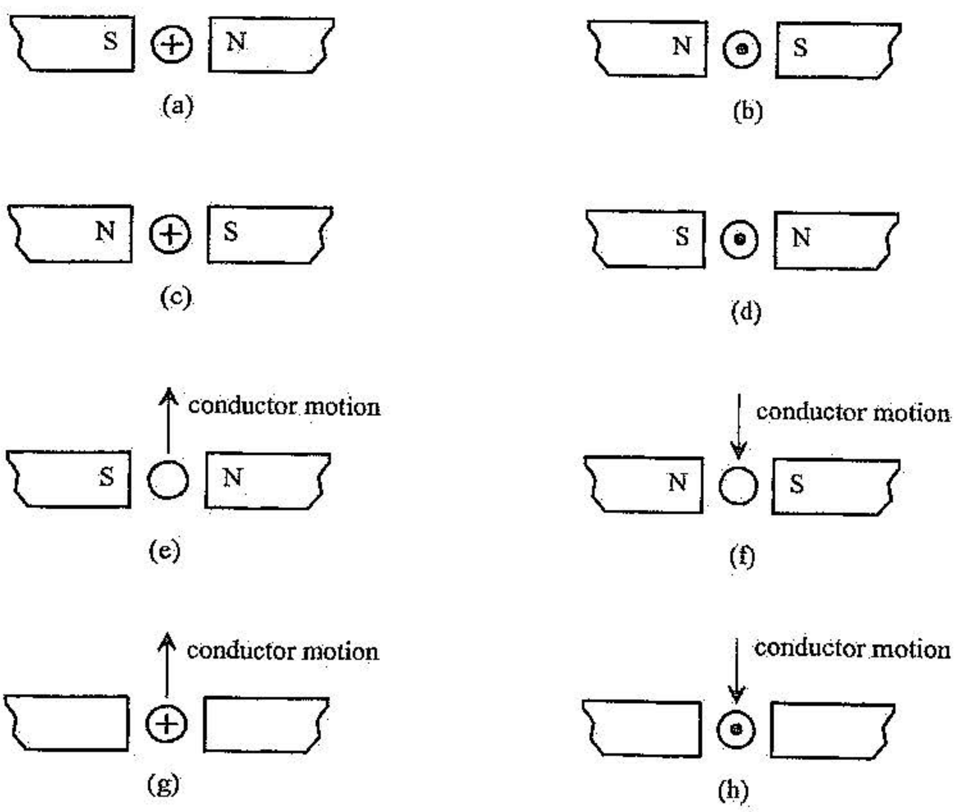

Figure 5

The magnitude of the force acting upon a current carrying conductor in a magnetic field depends on the -

- ______________________ of the magnetic field
- ______________________ flowing in the conductor
- ______________________ of the conductor within and at right angles to the field.

When these three factors are combined, the force exerted on current carrying conductor can be calculated -

where: F = force acting on the conductor in newtons
B = flux density of the magnetic field in tesla
I = current flowing in the conductor in amperes
l = length of the conductor within and at right angles to the field, in metres

Example: 2

A 200mm long conductor carries a current of 30A at right angles to a magnetic field of 0.4T. Calculate the force acting on the conductor.

____

____

3. TORQUE DEVELOPED BY A MOTOR

The torque or turning effort, developed by the armature of a motor, is due to the electromagnetic reaction set up between -

- current-carrying conductors arranged upon the armature core and
- the magnetic flux in the air gap under the fixed poles of the motor.

Figure 6 represents a bipolar armature, with its conductors carrying current in the directions indicated in a magnetic field. The positive direction of the magnetic field is from N to S.

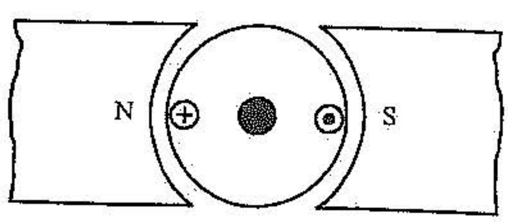

Figure 6

Applying the Left hand Rule to each conductor shows that a force will be exerted upon each of these conductors in the direction shown by the arrows, that is, at right angles to the diameter. It will be noticed that there is a continuous force acting round the armature tending to produce rotation in the direction shown.

When the armature rotates, the current carrying conductors pass under the N and S poles in succession. In order that rotation will be maintained in the same direction, for a fixed field polarity, it is essential that the direction of current in the conductors shall be reversed when passing under pole faces of different polarities.

This reversal of current in the coils is effected by the commutator and brushes.

The torque or turning effort developed by the motor depends on the -

- ______________________ exerted on the conductor
- ______________________ of the armature.

Combining these factors allows the torque to be calculated -

where: T = torque developed in Newton metres
F = force exerted on conductor in newtons
r = armature radius in metres

Example: 3

A single loop armature winding in a DC motor carries a current of 15A and operates in a magnetic field of 1.1T. If the armature has a radius of 260mm and a length of 180mm, determine the -

(a) force developed on one half of the loop
(b) torque developed by one half of the loop
(c) torque developed by the armature.

____

____

____

____

____

____

Example: 4

If the armature in the previous example was rewound and carries 160 turns, that is 160 conductors on each side of the armature, determine the torque developed assuming all other factors remain constant.

____

____

____

4. GENERATED OR BACK EMF

Immediately the armature conductors have motion imparted to them, they cut the flux of the field, thereby having an emf induced in them.

The induced armature emf always acts in such a direction as to __________ the applied pd.

As a result the induced armature emf in a motor armature is called a -

- ______________________

  or

- ______________________,

since it always tends to oppose the applied pd, and in doing so, tends to establish a current which in turn, will tend to stop the motion which gives rise to it (Lenz's Law).

In figure 7, "a" and "b" represent the same armature and field of a two pole motor.

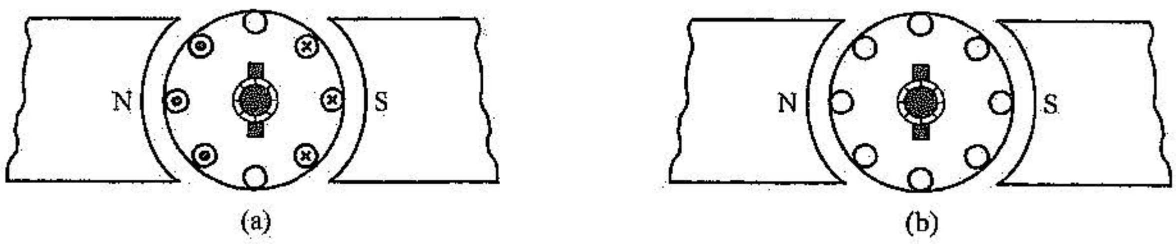

Figure 7

In "a" the conductors carry current in the direction indicated due to the applied pd, thus producing rotation of the armature in a clockwise direction (check by Left-hand Rule).

Owing to this clockwise direction of rotation, these same armature conductors will have an emf induced in them in the direction indicated in "b" (check by Right-hand Rule).

The back emf of a motor has precisely the same value as would be established if the armature of the machine were driven at the same speed as a generator and with the same conditions of field magnetization.

Thus, back emf can be determined in the same way as the generated emf of a generator -

where: Eg = back emf in volts
k = machine constant
ϕ = field flux in webers
n = armature speed in rpm

Since the applied pd and the back emf in the motor armature act in opposition to each other, the resultant voltage will be the difference between the applied pd and the back emf and will act in the direction of the greater value, which is the applied pd. The current, which will flow in the motor armature, will be directly proportional to the difference between the applied pd and the back emf and inversely proportional to the armature circuit resistance.

Normally in a motor, the current flows in the direction of the applied pd; hence, the magnitude of the current to produce the driving torque is:

where: I_A = armature current in amperes
V = applied voltage in volts
Eg = back emf in volts
R_A = armature circuit resistance in ohms

Consequently, any decrease in back emf must produce an increase in armature current. Similarly, any increase in back emf is always followed by a decrease in armature current.

The "volts drop" in the armature is always equal to the difference between the applied pd and the back emf, because:

Normal values for the $I_A R_A$ drop are, from approximately 1.5% of tpd for large machines, to approximately 5% for small machines.

If the armature of a dc motor is rotated at such a speed that the back emf is exactly equal to the applied pd, there will not be any current flowing in the conductors and consequently there will not be any turning effort or torque developed. If operating below this critical speed, the machine is a motor. When driven at a speed higher than the critical speed, the machine becomes a generator.

5. EFFECT OF LOAD

For a given field flux, the torque exerted on the motor shaft is proportional to the armature current; this armature current must increase or decrease according to the demands of the load driven by the motor.

In a given motor, the torque is proportional to the product of the -

- ______________________________

  and the

- ______________________________.

The adjustment of the armature current is achieved automatically in the following manner:

An increase of load on the shaft of the motor causes the -

- armature speed to ______________________
- back emf to ______________________
- armature current to ______________________
- torque to ______________________, to drive the additional load.

The armature speed will adjust itself so that the difference between the applied pd and the back emf is just sufficient to cause the current required (to produce the driving torque for the new load) to flow through the armature conductors.

Similarly if the load is reduced, the -

- armature speed is ______________________
- back emf is ______________________
- armature current is ______________________
- torque is ______________________, to meet the needs of the smaller load.

For large machines, having a constant field flux, the variation in speed is from 3% to 4 % of the full-load value; for small machines the variation is from 9% to 10%.

6. TORQUE DEVELOPED

The torque developed by the armature of a dc motor is dependent upon three factors, -

- ____________________
- ____________________
- machine construction, known as the ____________________.

Combining these three factors allows the calculation of the torque developed -

where: T = torque developed in Newton metres
k = machine constant
ϕ = field flux in webers
I_A = armature current in amperes

Example: 5

A 4 pole dc motor carries an armature current of 25A and operates with a field flux of 0.016Wb/pole. Determine the torque developed if the motor has a machine constant of 80.

____

____

____

Example: 6

If the motor in example 5 had additional load applied, such that the armature current increased to 35A, determine the torque developed. Note, all other factors remain constant.

____

____

____

Example: 7

A 650V, separately-excited motor has an effective field flux of 0.08Wb and operates at a speed of 500rpm. If the motor has a machine constant of 15 and an armature circuit resistance of 0.25Ω, determine the -

(a) back emf

(b) armature current

(c) torque developed.

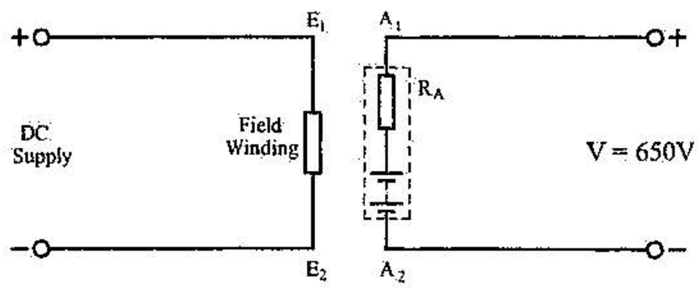

Figure 8

NOTES:

THE DC MOTOR

PURPOSE:

This practical assignment will be used to examine the operation of the dc motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect a dc motor using a circuit diagram as a guide.
- Test a dc motor to determine the effect of variable armature current on torque.
- Test a dc motor to determine the effect of variable field current on torque.
- Carry out a load test on a dc motor.

EQUIPMENT:

- ☐ 1 x dual variable dc power supply
- ☐ 1 x single variable dc power supply
- ☐ 1 x Betts dc compound machine
- ☐ 1 x inertia wheel
- ☐ 1 x eddy current load
- ☐ 1 x Betts machine bed to accommodate two machines
- ☐ 1 x digital multimeter
- ☐ 2 x 0-2A analogue dc ammeter
- ☐ 1 x 0-10A analogue dc ammeter (AVO8)
- ☐ 1 x tachometer
- ☐ 4mm connecting leads

- REMEMBER -
- WORK SAFELY AT ALL TIMES -
observe correct isolation procedures

PROCEDURE 1: VARIABLE ARMATURE CURRENT

1. Connect the motor as shown in figure 1.

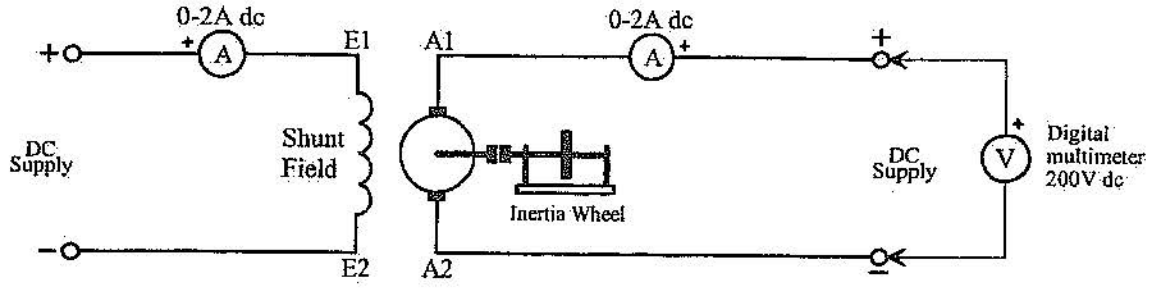

Figure 1

2. Ensure both power supplies are adjusted for minimum output.
3. Adjust the field power supply for a field current of 1A.
4. Adjust the armature supply for an armature voltage of 10V, then measure and record in table 1 the armature current and motor shaft speed.

Table 1

Field Current amperes	**Armature Voltage** volts	**Armature Current** amperes	**Shaft Speed** rpm
1A	10		
	12		
	14		
	16		
	18		
	20		
	22		
	24		

5. Repeat the procedure for each value of armature voltage shown in table 1.
6. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

PROCEDURE 2: VARIABLE FIELD CURRENT

1. Use the same circuit arrangement as that shown in figure 1.
2. Ensure both power supplies are adjusted for minimum output.
3. Adjust the field power supply for a field current of 1A.
4. Adjust the armature supply for an armature voltage of 24V, then measure and record in table 2 the motor shaft speed.

Table 2

Armature Voltage volts	Field Current amperes	Shaft Speed rpm
24V	0.4	
	0.6	
	0.8	
	1	
	1.2	
	1.4	
	1.6	

5. Repeat the procedure for each value of field current shown in table 2 by firstly reducing the field current below 1A, then subsequently above 1A.
6. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

PROCEDURE 3: EFFECT OF LOAD

1. Connect the circuit as shown in figure 2.

   Note: Three dc power supplies are required -
   1. field supply
   2. armature supply
   3. eddy current load.

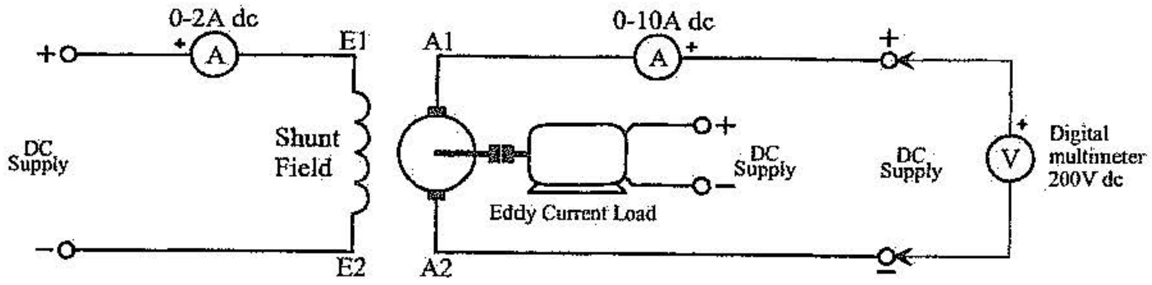

Figure 2

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

3. Ensure the armature and eddy current power supplies are switched off.
4. Adjust the field current to 2A.
5. Adjust the armature supply to 24V. The motor should accelerate up to speed of approximately 1500rpm.
6. Measure and record, in table 1, the armature current and motor speed.

Table 3

Field Current amperes	**Load Torque** Nm	**Armature Current** amperes	**Shaft Speed** rpm
2A	0		
	0.1		
	0.2		
	0.3		
	0.4		
	0.5		

7. Switch on the supply to the eddy current load and adjust for a load torque of 0.1Nm. Ensure the field current is set to 2A, adjust if necessary.
8. Measure and record, in table 1, the armature current and motor speed.
9. Repeat the procedure for each value of load torque shown in table 1. In doing so, be sure to maintain the field current constant at 2A.

10. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

11. Switch off the dc power supplies in the following sequence -
    1. eddy current load
    2. armature
    3. field.

12. Disconnect the circuit.

13. Please return all equipment to its proper place, safely and carefully.

OBSERVATIONS:

1. What is the effect on the force exerted on the armature as a result of increased armature current?

____

____

____

2. If the force exerted on the armature is increased, what is the effect on the torque developed by the motor.

____

____

____

3. What is the relationship between field current and armature speed?

____

____

____

4. Assuming constant field current, what is the effect of increased load on the speed of a dc motor?

____

____

____

5. Assuming constant field current, what is the effect of increased load on the armature current taken by a dc motor?

____

____

____

****

THE DC MOTOR

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. A DC motor converts ______ energy to ______ energy.
   (a) electrical, mechanical
   (b) electrical, electrical
   (c) chemical, electrical
   (d) mechanical, electrical

2. To determine the forces acting on a current carrying conductor within a magnetic field, you would use:
   (a) Flemmings right hand
   (b) Lenz's law
   (c) right hand conductor rule
   (d) Flemmings left hand rule

3. The torque produced in a DC motor is ______ to the armature current and ______ to the main field flux.
   (a) inversely proportional, proportional
   (b) proportional, proportional
   (c) inversely proportional, inversely proportional
   (d) proportional, inversely proportional

4. An increase in the load applied to a DC motor will cause the motor speed to _______ and the motor torque to _______ .
   (a) increase, increase
   (b) decrease, decrease
   (c) decrease, increase
   (d) increase, decrease

5. Whilst driving a load, a _______ is generated in the armature conductors which _______ the applied motor voltage.
   (a) counter emf, opposes
   (b) counter emf, increases
   (c) mutual emf, opposes
   (d) mutual emf, increases

SECTION B

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

The force acting upon a current carrying conductor depends on the ___(1)___ of the magnetic field, the ___(2)___ flowing in the conductor and the ___(3)___ of the conductor within the magnetic field.

The torque developed within a DC motor is proportional to the ___(4)___ acting on the conductor and the ___(5)___ of the armature.

If the load applied to a DC motor is decreased, the:
speed will ___(6)___ ,
the back emf will ___(7)___ ,
the armature current will ___(8)___ and
the torque developed by the motor will ___(9)___ .

The emf generated within the armature conductors ___(10)___ the applied voltage, and is known as a ___(11)___ .

The field system of a DC motor is mounted on the ___(12)___ and the current in the armature conductors is transferred from the supply via the ___(13)___ and ___(14)___ .

The current flowing in the armature conductors is dependant on the ___(15)___ generated within the armature conductors.

If the load applied to a DC motor is increased, the:
speed will ___(16)___ ,
the back emf will ___(17)___ ,
the armature current will ___(18)___ and
the torque developed by the motor will ___(19)___ .

Motor torque is produced when the main ___(20)___ reacts with the armature ___(21)___ .

SECTION C

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A 150mm long conductor carries a current of 40A at right angles to a magnetic field with a flux density of 0.5T. Determine the force acting on the conductor. (3N)

2. Determine the increase in flux density required in question 1 to increase the force acting on the conductor to 7N. (0.667T)

3. An armature has a radius of 125mm, and an effective conductor length of 150mm under the field pole. If the main flux is 0.4T and the armature current is 100A, determine
   (a) the force acting on the conductor; (6N) and
   (b) the torque developed on the conductor under the field poles. (0.75Nm)

4. An armature with a radius of 125mm is wound with 4 coils each of 100 turns. If the effective length of one half of a loop under the field poles is 200mm, the current in the conductors is 250A and the flux is 0.2T, determine the torque developed within the armature. (1000Nm)

5. A DC motor has a machine constant of 20, a main flux of 0.015Wb and runs at 750rpm. Determine the emf generated within the armature conductors. (225V)

6. If the motor in question 5 is connected to a 250V supply and has an armature circuit resistance of 0.15Ω, determine the amount of current flowing in the armature. (167A)

7. The motor shown in figure 1 has a field flux of 0.0125Wb, runs at 250rpm, and has a machine constant of 8. For these conditions, determine the:
   (a) back emf; (25V)
   (b) armature current; (30A)
   (c) developed torque; (3Nm) and
   (d) armature circuit voltage drop. (3V)

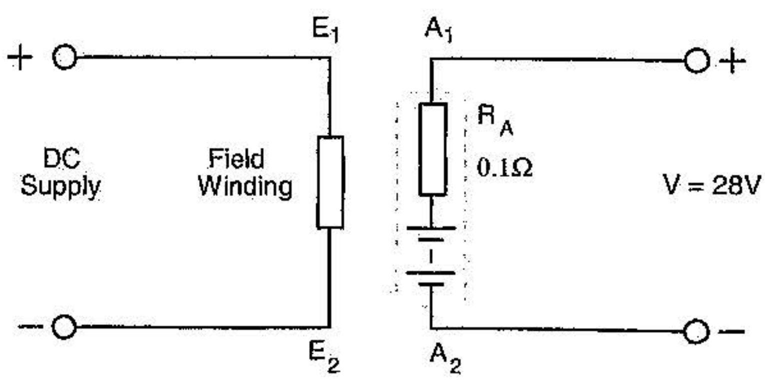

Figure1

SECTION D

1. Complete figure 2 as follows:
   (a) Figures 2(a) and 2(b) show the force acting on the conductors;
   (b) Figures 2(c) and 2(d) show the currents flowing in the conductors;
   (c) Figures 2(e) and 2(f) show the magnetic field polarities.

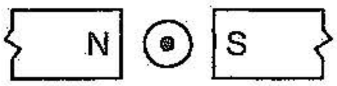

Figure 2(a)

Figure 2(b)

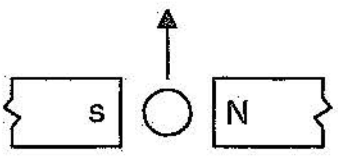

Figure 2(c)

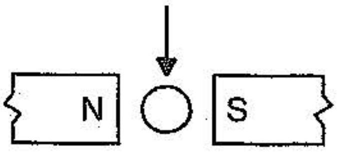

Figure 2(d)

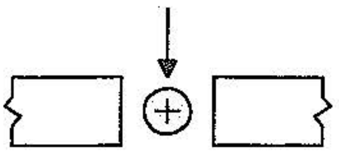

Figure 2(e)

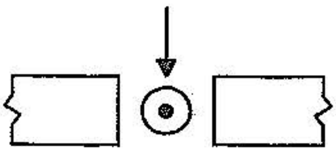

Figure 2(f)

2. State and describe the method you used to complete figure 2.

Add this completed sheet to your tutorial assignment for assessmant.

****

DC MOTOR CHARACTERISTICS

PURPOSE:

This section introduces the types, operating characteristics and reversal of rotation of DC motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- list the three main types of dc motor.
- draw circuit arrangements and connect various dc motors.
- state typical applications of various types of dc motor.
- describe the operating characteristics of the various types of dc motor.
- reverse the direction of rotation of a dc motor.
- calculate values of voltage, current and torque associated with dc motors.

REFERENCES:

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.
Pages 276-284.

1. TYPES OF DIRECT-CURRENT MOTOR

The structure of a dc motor is essentially the same as that of a dc generator.

The same machine may operate either as a generator or a motor.

Direct-current motors, as well as generators, are classified according to the way the field winding is connected relative to the armature as:

- ______________________ wound
- ______________________ wound
- ______________________ wound.

2. SHUNT WOUND MOTORS

In a shunt motor the field is connected directly across the line and since the line voltage is constant -

- field current
  and
- field flux.

Figure 1 shows the circuit diagram of the shunt motor and figure 2 the equivalent circuit. Also included are the voltages and currents associated with the motor.

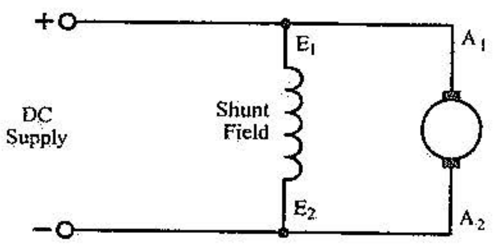

Figure 1

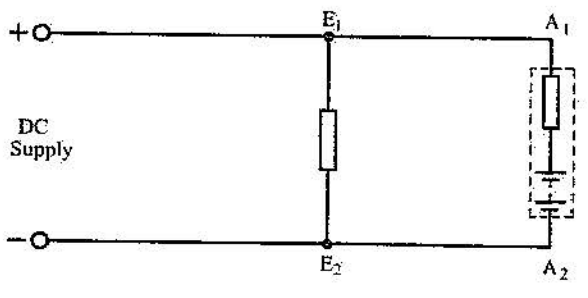

Figure 2

If such a motor is unloaded the retarding torque is small being due only to windage and friction. The armature will develop a back emf that will restrict the armature current to a value that will cause the motor to develop a torque equal to the resisting torque.

When a load is applied to the motor -

- motor speed ________________ - because the small no-load current is just sufficient to produce a torque to overcome friction.
- generated back emf ________________, since the field flux is constant
- armature current ________________.
- torque is ________________ until it is equal to that required by the load.

When this point is attained, the armature current and speed will remain constant until the load is again changed.

If the load is decreased, the torque developed will be greater than that of the external load. Then the -

- speed will ________________
- back emf will ________________
- the armature current will ________________.

From the last explanation it can be seen that the armature current required by a shunt motor is regulated automatically by the load placed upon it. This is true for all types of dc motors - shunt, series and compound.

> The industrial application for which a motor is best suited depends upon the variation of the speed and the torque with the load.

The reduction in speed of the motor, caused by load, is reduced slightly by armature reaction; which causes the flux to be less and the speed to increase correspondingly. In some cases armature reaction is sufficient to cause the speed to remain nearly constant or even increase with an increase in load.

For these reasons a shunt motor is considered a ________________ speed motor, even though the speed usually decreases slightly with an increase in the load.

Characteristics of a typical shunt motor are shown in figure 3, where speed, torque, and efficiency are plotted against armature current.

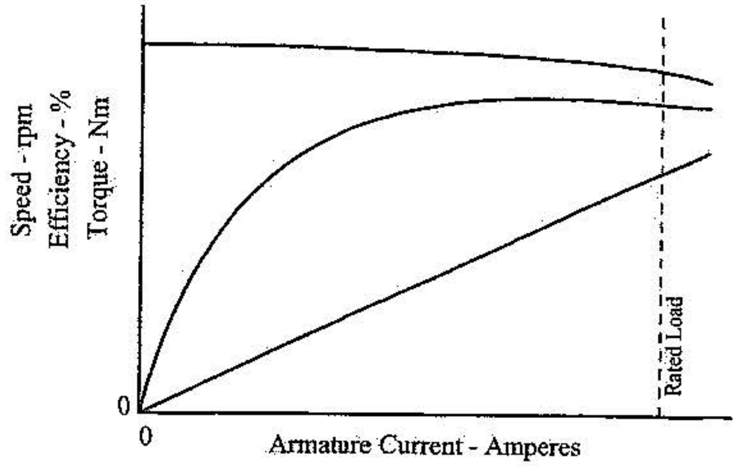

Figure 3

The characteristic curves for the shunt motor show -

- small speed variation from no-load to full-load.
- torque is almost linear over a reasonable range of load currents.
- efficiency increases rapidly at light loads, reaches a maximum at rated load value and decreases gradually. This is due to the fact that at light loads the friction and copper losses are high when compared with the external load. Above full-load the copper losses in the armature cause the efficiency to decrease gradually.

The shunt motor is best suited for ______________________ speed drives.

It meets the requirements of a large range of industrial applications, such as the driving of machine tools, blowers and fans.

Example: 1

A 250V shunt motor takes a line current of 20A. Determine the back emf at this load, given the resistance of the shunt field is 200Ω and that of the armature circuit is 0.2Ω.

____

____

____

Example: 2

If the load on the motor in example 1 is increased such that the line current increases to 25A, determine the motor back emf.

____

____

____

3. SERIES WOUND MOTORS

The field coils of series wound motors are connected in series with the armature and carry the load current, as shown in figure 4. The cross-sectional area of the copper used in the field windings must be large enough to carry the load current; there are comparatively few turns in the field coils.

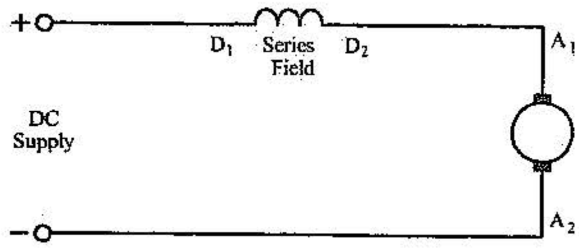

Figure 4

The equivalent circuit of the series motor is shown in figure 5.

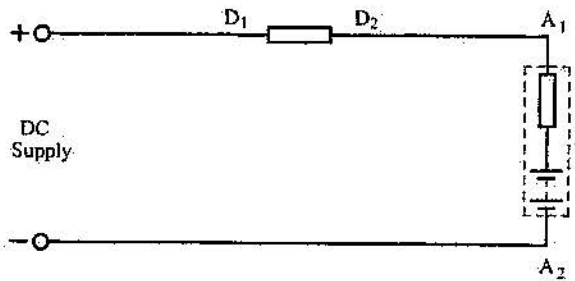

Figure 5

In the series motor the field strength depends upon the value of the armature current.

When the motor is operating on no-load -

- the only torque the motor has to develop is that required to overcome friction and windage.
- consequently the armature and field current is small, and the field strength is _______.
- the motor must run at a _________________ speed to generate the back emf required to limit the armature current to the required value.

> Centrifugal forces set up by this very high no-load speed, which is a characteristic of the series motor, may tear the armature conductors from the slots and destroy the motor. For this reason series wound motors should never drive a load through belting; they should always be direct-coupled to the load to drive fans or blowers, or drive through gearing in the cases of trains, trams and cranes.

In very small series wound motors, friction, windage and armature resistance are relatively high and are usually sufficient to ensure a safe no-load speed.

As the load on the motor is increased -

- armature current must ________________.
- the increased armature current flows through the series field coils and ____________ the field flux since the magnetic circuit of the motor is unsaturated at light loads.
- the back emf required to limit armature current is ________________
- the back emf can be generated at a much ________________ speed at the increased field strength.

If the load is increased above full load the magnetic circuit becomes saturated and the field strength remains fairly constant. This means that the decrease in speed, for a given increase in load, becomes less.

The overall result of changes in load current and flux is that at light loads the speed of a series wound motor decreases considerably as the load increases. As the load is further increased the speed continues to decrease but less rapidly than at light loads.

The series motor is essentially a ________________ speed machine.

The torque developed by a series motor increases rapidly as the load current is increased, since the torque developed by any dc motor depends upon the product of flux and armature current. During the time the field is only moderately magnetized the flux will be almost directly proportional to current and the torque is therefore almost directly proportional to current squared. This relationship is shown in figure 6, where speed, torque and efficiency of a typical series motor are plotted against load current (armature current).

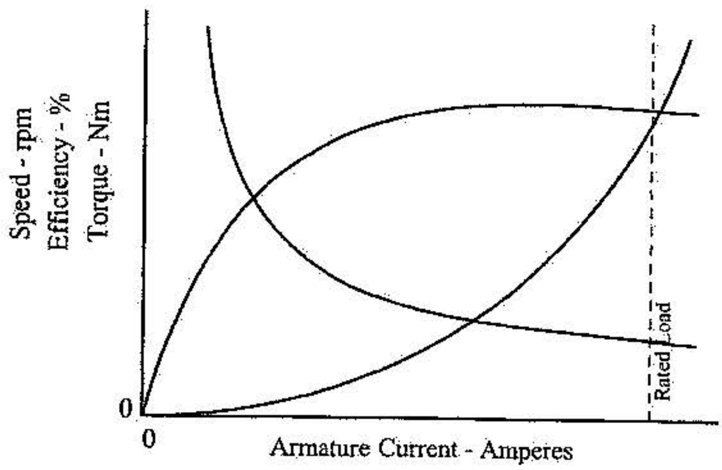

Figure 6

The characteristic curves highlight the following -

- torque increases rapidly with increased load. Such characteristics make the use of the series motor desirable where it is necessary to supply a large torque with a moderate increase in current. For this reason a series motor is ideal where high starting torques are required.
- wide variation in speed with change in load.
- although the efficiency of a series motor varies approximately the same as that of a shunt motor, the actual operating values of efficiency are usually much lower. This is due to the fact that a series motor seldom operates at its rated load; it is continually accelerating and decelerating.

Series motors are used chiefly for widely varying loads where extreme speed changes are not objectionable. They are used extensively for -

- cranes and hoists
- traction purposes.

The large torque developed by series motors is very suitable for work demanding frequent acceleration under heavy loads.

Example: 3

A 400V series motor has an armature circuit resistance of 0.4Ω and the back emf is 360V. Calculate the armature current.

Example: 4

The load on the series motor in example 3 is increased causing the armature current to increase to 125A. Determine the back emf of the motor.

4. COMPOUND WOUND MOTORS

Based on what has been considered so far, the speed of a -

- shunt motor is nearly constant at all loads, normally decreasing slightly with increasing load.
- series motor varies considerably, decreasing in a marked manner as the load is increased.

Figure 7 shows the connections for the compound motor and figure 8 the equivalent circuit.

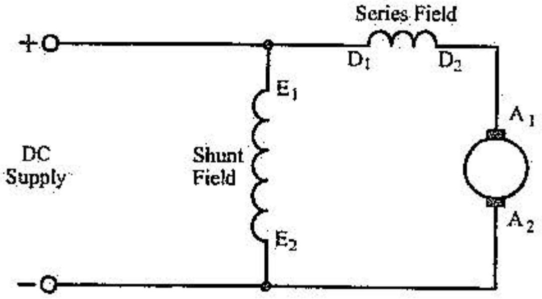

Figure 7

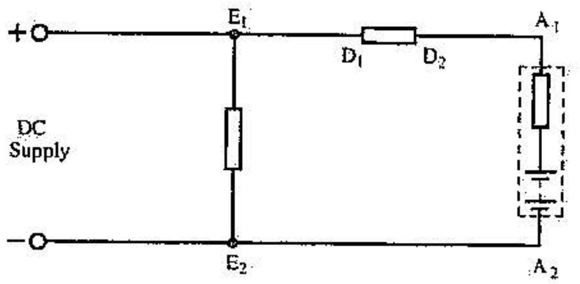

Figure 8

When using compound windings, that is, both shunt and series coils connected in such a manner that the series winding assists the shunt, the motor speed characteristic can be intermediate to those of the shunt and series motors -

- the shunt winding suffices to limit the no-load speed to a safe value
- the series winding increases the flux as the load increases and so causes the speed to decrease considerably with heavy loads.

This method of connection is called **"cumulative compound"** and in figure 9, speed and torque of a typical machine are plotted against armature current.

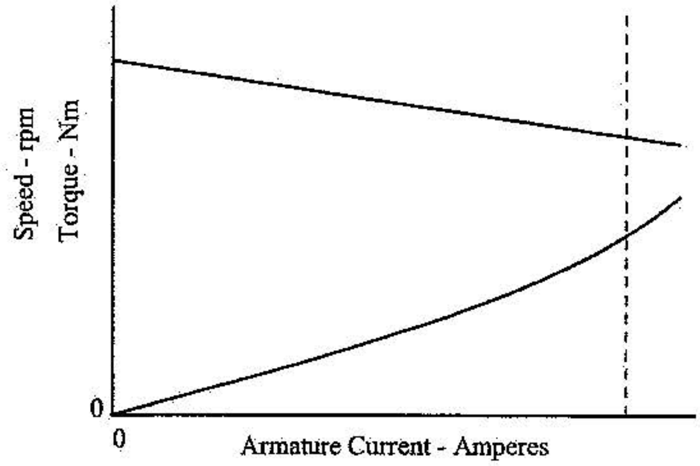

Figure 9

The speed and torque characteristics of a cumulatively-compounded motor may approach those of shunt or series motors as limits, depending upon the strength of the two fields -

- if the motor contains a **"light series winding"** it will have better torque characteristics than a shunt motor, but will retain most of the good speed regulation of the shunt motor.
- if the motor has a light shunt winding sufficient to maintain the no-load speed within certain limits and a **"heavy series winding"**, it will have the characteristics of a series motor, but will not operate at a dangerous speed at light load.

Compound motors are used for driving machines that require fairly constant speed and are subject to irregular loads or sudden applications of heavy loads, such as -

- presses
- planers
- compressors
- lifts.
- they are also used in situations where it is desirable to give the motor some protection from the effects of intermittent overloads. The provision of a heavy series field winding causes a decrease in speed under heavy loads and reduces slightly the output from the motor.

Another method of connecting the field coils in a compound-wound motor is known as **"differential compound"**.

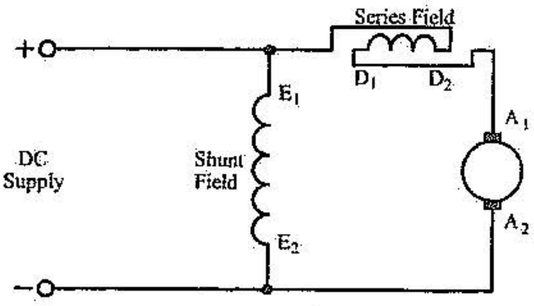

Figure 9

The series coils are arranged to oppose the shunt coils so that their effect is to reduce the useful flux progressively as the load on the motor increases.

As a result of the reduced flux the motor tends to __________ its speed with increased load. According to the strength of the series fields the speed may be maintained practically constant at all values of load or it may be allowed to increase slightly as the load increases. In either case only a relatively weak series field is needed.

Differentially-compounded motors have very little application. Their only advantage is that it is possible to arrange the proportion of shunt and series ampere-turns to provide a constant speed over their load range. Consequently they are only used for special cases where the constancy of speed is of the utmost importance.

Sudden fluctuations of load will cause the speed of the differentially-compounded motor to fluctuate. Heavy overloads may so weaken the field that the motor will race, then stop and reverse. Starting devices must be so arranged that the series winding is short circuited until the motor is up to speed; otherwise the series field is likely to overpower the shunt field and cause the motor to start in the incorrect direction.

In practice differentially-compounded motors have been almost superseded by shunt motors which can be designed to give a constant speed, over a large range of load, without any of the disadvantages caused by the opposing field fluxes of the differentially-compounded machine.

Example: 5

A 240V compound motor has a shunt field resistance of 120Ω, a series field resistance of 0.3Ω and an armature resistance of 0.5Ω. What is the line current if the back emf is 220V?

Example: 6

If the load on the compound motor in figure 5 is increased such that the line current is 32A, determine the motor back emf.

5. REVERSAL OF ROTATION

In practice, it often becomes necessary to reverse the direction of rotation of a motor. In some applications, such as cranes, hoists, lifts and winches, the reversal of rotation is frequent and must occur in the shortest possible time.

To reverse the direction of rotation of a motor, the direction of flow of "either" the field or the armature current must be reversed.

If the supply cables to the motor are interchanged the motor will operate in the same direction as previously, because both the field current and the armature current are reversed in direction. There will be no change in the direction in which the magnetic forces act on the conductors carrying current in the magnetic fields of the machine.

A shunt motor is shown in figure 10.

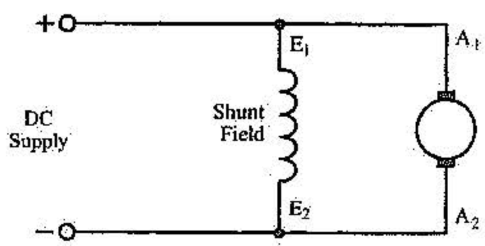

Figure 10

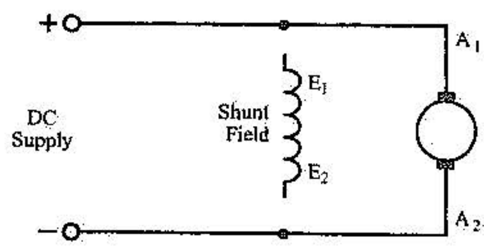

Figure 11

For the field and armature currents shown, assume the direction of rotation is __________.

In figure 11, the shunt field connections only are interchanged thus reversing the direction of rotation. There is no alteration to the armature circuit.

The armature circuit connections only are interchanged in figure 12 and again the direction of rotation is reversed.

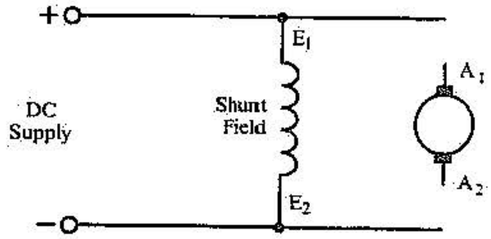

Figure 12

Figure 13 shows a series motor.

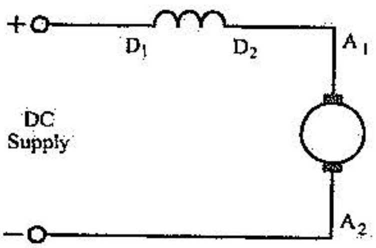

Figure 13

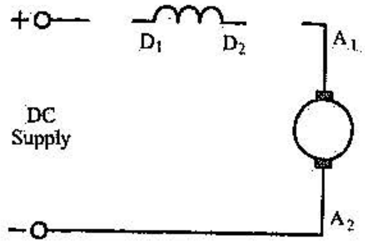

Figure 14

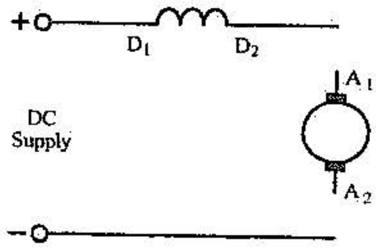

Figure 15

In figure 13, assume the direction of rotation is clockwise.

In figure 14 the connections to the series field winding are interchanged, thus reversing the direction of rotation.

In figure 15 the connections to the armature circuit are interchanged and the direction of rotation is reversed.

Almost all compound motors have the field windings connected so that the currents flow in the same direction in both shunt and series field coils, that is, they are "cumulatively compounded". The diagram of figure 16 shows a machine of this type.

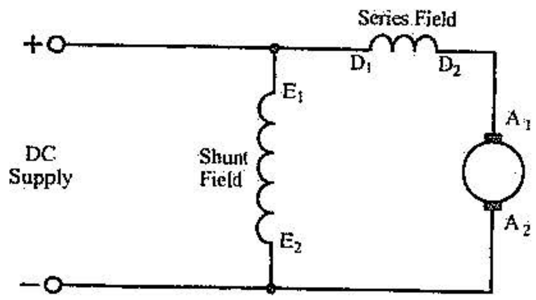

Figure 16

For the field polarity and direction of armature current shown in figure 16, assume the direction of rotation to be clockwise.

In figure 17, the connections to both the shunt and series field windings are interchanged; this reverses the direction of rotation. It is necessary to interchange both the shunt and series field connections. If only one change were effected the motor would be differentially compounded.

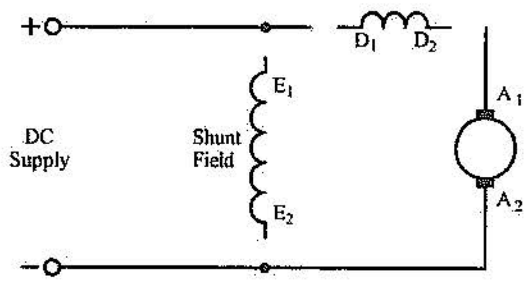

Figure 17

The connections to the armature circuit only are interchanged in figure 18; this reverses the direction of rotation. This is the simplest method of reversing a compound motor since only one reconnection is necessary. If the fields are reversed, two reconnection's are necessary.

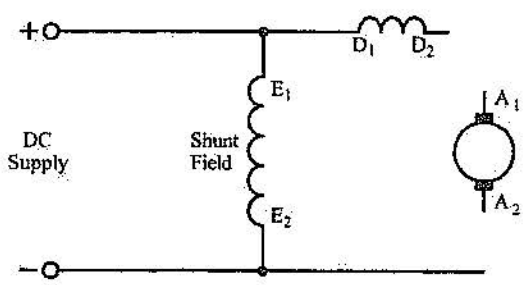

Figure 18

Caution:

Separately-excited and self-excited shunt and compound machines have highly-inductive field circuits if opened suddenly whilst full field current is flowing, the emf of self-induction may be high enough to puncture the insulation of the field windings, thus resulting in a breakdown.

****

Name: ____________________ Practical 10

DC MOTOR CHARACTERISTICS & REVERSAL

PURPOSE:

This practical assignment will be used to examine the characteristics and reversal of dc motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect shunt, series and compound motors.
- Plot the characteristics of shunt, series and compound motors.
- Reverse the direction of rotation of shunt, series and compound motors.

EQUIPMENT:

- ☐ 1 x dual variable dc power supply (0-6A output)
- ☐ 1 x Betts dc compound machine
- ☐ 1 x Betts eddy current load
- ☐ 1 x Betts double machine bed
- ☐ 1 x digital multimeter
- ☐ 2 x 0-5A analogue dc ammeter
- ☐ 1 x tachometer
- ☐ 4mm connecting leads

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

PROCEDURE 1: SHUNT MOTOR

1. Connect the shunt motor, with eddy current load attached, as shown in figure 1.

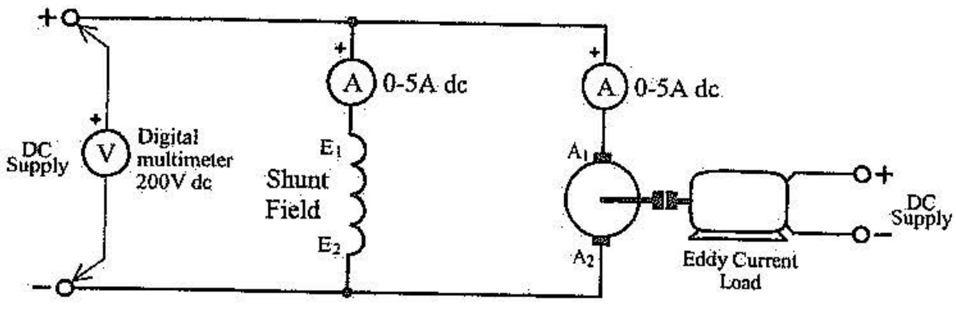

Figure 1

2. Ensure both power supplies are adjusted for minimum output.
3. Switch on and slowly adjust the motor power supply for a supply voltage of 24V. The motor should start and accelerate up to speed.
4. Measure and record, in table 1, the shaft speed, field current and armature current.

Table 1

Voltage volts	**Motor Torque** Nm	**Shaft Speed** rpm	**Field Current** amperes	**Armature Current** amperes	**Line Current** amperes
24V	0				
	0.1				
	0.2				
	0.3				
	0.4				

5. Adjust the supply to the eddy current load for a torque of 0.1Nm. Then measure and record, in table 1, the shaft speed, field current and armature current.
6. Repeat the procedure for each value of torque shown in table 1.
7. Complete table 1 by determining the line current for each load condition. $I_L = I_F + I_A$
8. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

9. With the motor operating under no-load, note the direction of rotation of the motor shaft looking at the drive end.

Direction of rotation = ________________________

10. Switch the motor off.

11. Reverse the connections to the shunt field.

12. Switch the motor on and note the direction of rotation of the motor shaft looking at the drive end.

Direction of rotation = ________________________

13. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

PROCEDURE 2: SERIES MOTOR

1. Connect the series motor as shown in figure 2.

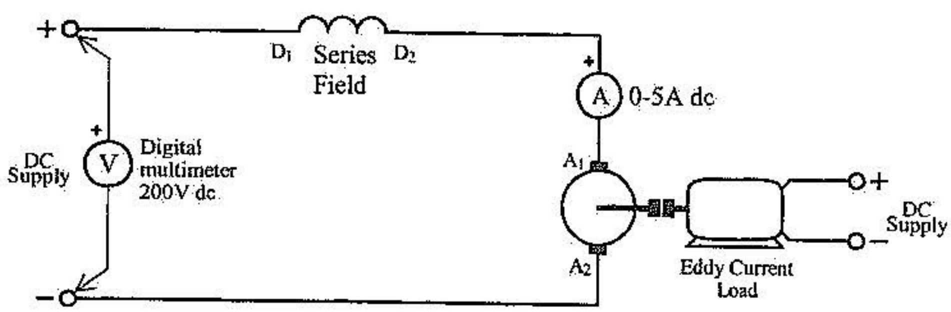

Figure 2

2. Ensure both power supplies are adjusted for minimum output.

3. Switch on and slowly adjust the motor power supply for a supply voltage of 24V. The motor should start and accelerate up to speed.

4. Measure and record, in table 2, the shaft speed and armature current.

5. Adjust the supply to the eddy current load for a torque of 0.1Nm. Then measure and record, in table 1, the shaft speed, field current and armature current.

6. Repeat the procedure for each value of torque shown in table 2.

Table 2

Voltage volts	**Motor Torque** Nm	**Shaft Speed** rpm	**Armature Current** amperes
24V	0		
	0.1		
	0.2		
	0.3		
	0.4		

7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
A	B	C

8. With the motor operating under no-load, note the direction of rotation of the motor shaft looking at the drive end.

Direction of rotation = ______________________

9. Switch the motor off.
10. Reverse the connections to the series field.
11. Switch the motor on and note the direction of rotation of the motor shaft looking at the drive end.

Direction of rotation = ______________________

12. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

PROCEDURE 3: COMPOUND MOTOR

1. Connect the compound motor as shown in figure 3.

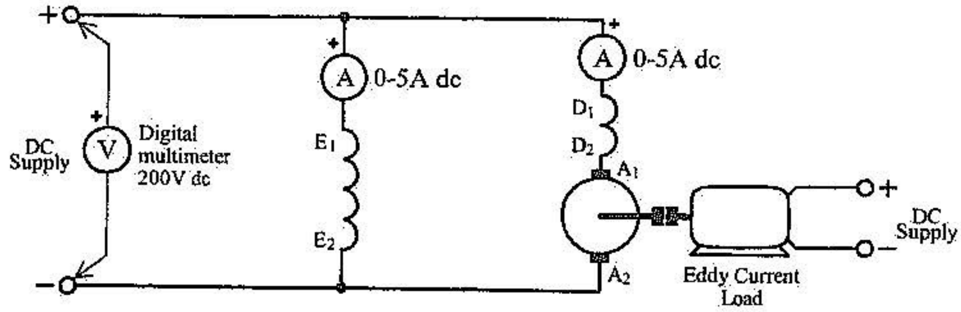

Figure 3

2. Ensure both power supplies are adjusted for minimum output.
3. Switch on and slowly adjust the motor power supply for a supply voltage of 24V. The motor should start and accelerate up to speed.
4. Measure and record, in table 3, the shaft speed, field current and armature current.

Table 3

Voltage volts	**Motor Torque** Nm	**Shaft Speed** rpm	**Field Current** amperes	**Armature Current** amperes	**Line Current** amperes
24V	0				
	0.1				
	0.2				
	0.3				
	0.4				

5. Adjust the supply to the eddy current load for a torque of 0.1Nm. Then measure and record, in table 1, the shaft speed, field current and armature current.
6. Repeat the procedure for each value of torque shown in table 1.
7. Complete table 1 by determining the line current for each load condition. $I_L = I_F + I_A$
8. **<u>Do not proceed</u>** until the teacher checks your circuit and completes the progress table.

Progress Table 6

attempt 1	attempt 2	attempt 3
A	B	C

9. With the motor operating under no-load, note the direction of rotation of the motor shaft looking at the drive end.

   Direction of rotation = ______________________

10. Switch the motor off.

11. Reverse the connections to the armature.

12. Switch the motor on and note the direction of rotation of the motor shaft looking at the drive end.

   Direction of rotation = ______________________

13. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
A	B	C

14. Disconnect the circuit.

15. Please return all equipment to its proper place, safely and carefully.

OBSERVATIONS:

1. Of the three types of motor tested, which had the highest no-load speed? Why was this the case.

   ____

   ____

   ____

2. Of the three types of motor tested, which had the greatest variation in speed from no-load to full-load?

   ____

   ____

   ____

3. Of the three types of motor tested, which produced the highest torque for the least line current?

   ____

   ____

   ____

4. On the axes of figure 4, plot the speed-torque characteristics for each of the motors tested.

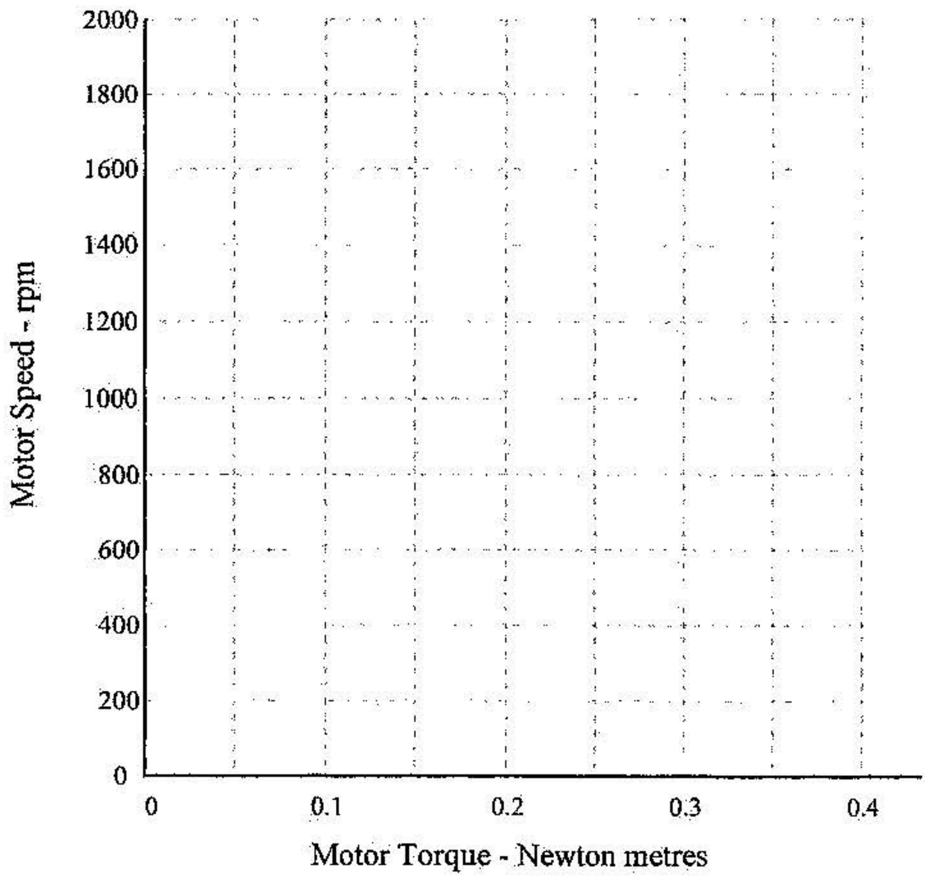

Figure 4

5. Of the three types of motor tested, which required the least armature current to produce a torque of 0.4Nm? Explain why this was the case.

6. Which motor would be best for driving a near constant speed load that did not require a large value of driving torque?

7. On the axes of figure 5, plot the torque-armature current characteristics for the three motors.

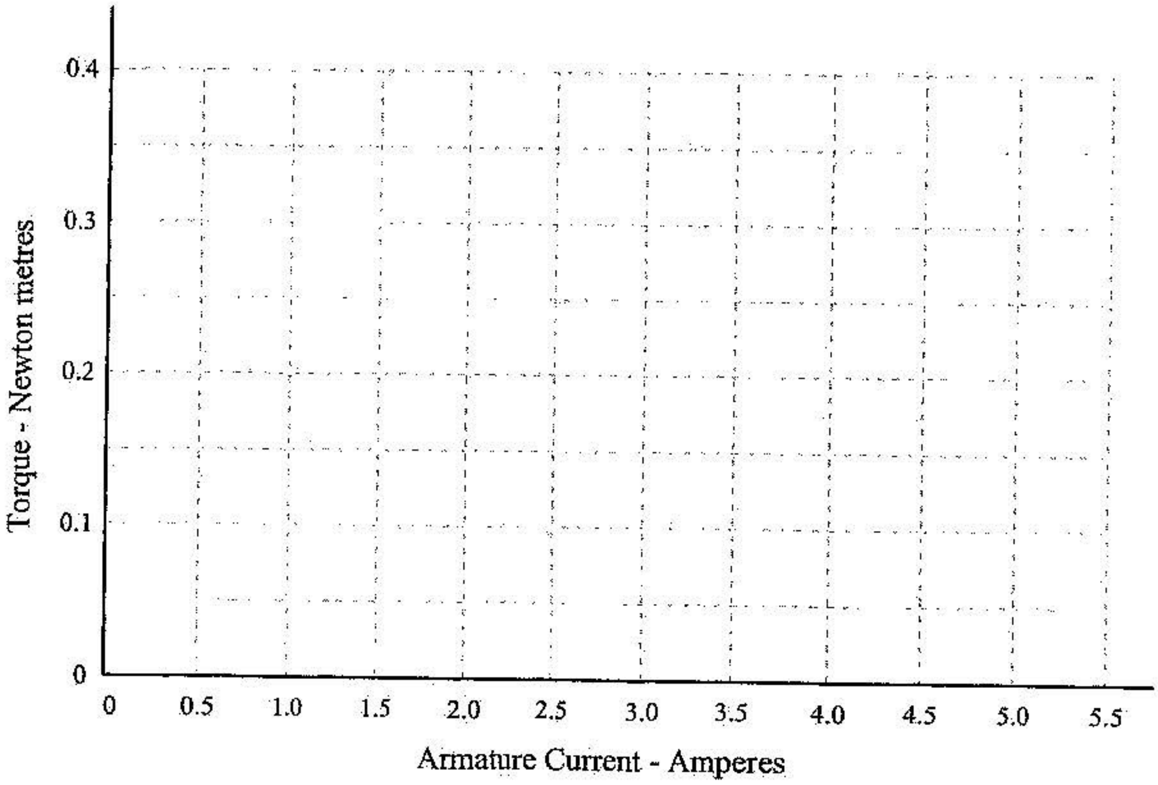

Figure 5

8. Of the three types of motor tested, which would be best for driving a load requiring a high torque?

____

____

____

****

DC Motor Characteristics

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- For calculations questions all relevant equations and working are to be shown.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. In a dc shunt motor, the __________ and __________ are constant.
   (a) field current, armature flux
   (b) field flux, armature flux
   (c) field flux, armature current
   (d) field current, field flux

2. A dc series motor should never be run unloaded, as this will cause the motor to:
   (a) overheat
   (b) overspeed
   (c) overload
   (d) slow down

3. DC compound motors are usually connected to be __________ compounded.
   (a) cumulatively
   (b) differentially
   (c) shunt
   (d) series

4. To reverse the direction of rotation of a compound motor by field reversal, you would reverse the connection to:
   (a) the series field only
   (b) either the shunt or series field
   (c) both the shunt and series fields
   (d) the shunt field only

5. Whilst driving a load, a ______ is generated in the armature conductors which ______ the applied motor voltage.
   (a) counter emf, increases
   (b) mutual emf, opposes
   (c) mutual emf, increases
   (d) counter emf, opposes

SECTION B

For the following questions, complete the statements on your answer sheet with the word or phrase you think fits best.

Three methods of connecting a DC motor are ___(1)___, ___(2)___ and ___(3)___ .

If the load connected to a shunt connected DC motor is increased, the motor speed will ___(4)___, the back emf will ___(5)___ , the armature current will ___(6)___ , and the motor torque will ___(7)___ .

A shunt connected DC motor is considered to be a ___(8)___ speed motor, and a series connected DC motor is considered to be a ___(9)___ speed motor.

When unloaded, the speed of a series connected DC motor is ___(10)___ due to the ___(11)___ field strength.

Over speeding of a series connected DC motor is prevented by having a ___(12)___ connected to the motor, or by having a light ___(13)___ connected across the supply.

If the load connected to a series connected DC motor is increased, the motor speed will ___(14)___, the back emf will ___(15)___, the armature current will ___(16)___ , and the motor torque will ___(17)___ .

Series connected DC motors are commonly used for ___(18)___ and ___(19)___ .

Compound connected DC motors are used for ___(20)___ speed applications where sudden changes in ___(21)___ may occur. Two examples are ___(22)___ and ___(23)___

Reversal of DOR in a DC motor is achieved by reversing the ___(24)___ connections or the ___(25)___ connections, but NOT both.

If reversing the DOR of a compound motor is required, reversing the ___(26)___ connections is the simplest and preferred method as only ___(27)___ reconnection is required.

A common application of shunt connected DC motors is ___(28)___ .

SECTION C

The following problems are to be solved with the aid of a calculator. Any working for a problem is to be fully shown. Where a problem involves calculating for circuit conditions, a neat and fully labelled circuit diagram (if not provided) is to accompany the question. Answers are to be expressed in the appropriate multiple or sub-multiple.

1. A 28V shunt connected motor draws a line current of 50A. Determine the back emf for these load conditions of the armature resistance is 0.0505Ω, and the shunt field resistance is 56Ω. (25.5V)

2. If the back emf in question decreases to 25V, determine the current drawn form the supply. (59.9A)

3. A 240V series connected motor has a line current of 40A. If the series field resistance is 0.4Ω and the armature resistance is 0.6Ω, determine the back emf generated within the armature. (200V)

4. If the back emf in question 3 increases to 215V, determine the new value of line current drawn from the supply. (25A)

5. A 250V compound motor has a shunt field resistance of 100Ω, a series field resistance of 0.5Ω and an armature resistance of 0.8Ω.
   (a) draw an equivalent circuit for the motor, being sure to fully label the circuit and show all motor currents;
   (b) if the back emf is 216V, determine the current drawn from the supply; (21.73A)
   (c) if the load current increases to 45A, determine the back emf now generated within the armature (194.75V)

SECTION D

Add this sheet to your tutorial answer sheets.

1. For the diagram of figure 1(a), assume the motor's DOR is clockwise. In the diagram of figure 1(b), show how you would reverse the DOR by reversing the field connections.

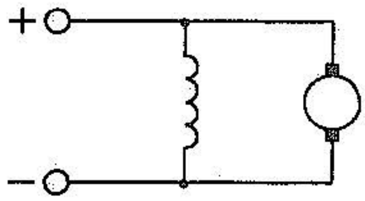

Figure 1(a)

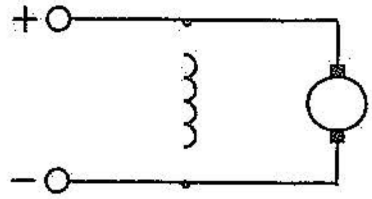

Figure 1(b)

2. For the diagram of figure 2(a), assume the motor's DOR is clockwise. In the diagram of figure 2(b), show how you would reverse the DOR by reversing the field connections.

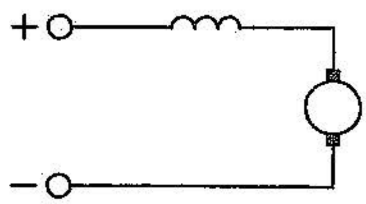

Figure 2(a)

Figure 2(b)

3. For the diagram of figure 3(a), assume the motor's DOR is clockwise. In the diagram of figure 3(b), show how you would reverse the DOR by reversing the field connections.

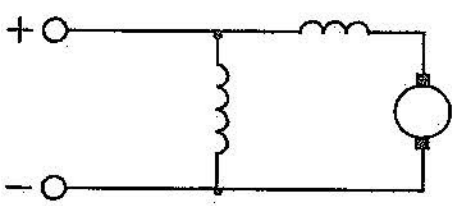

Figure 3(a)

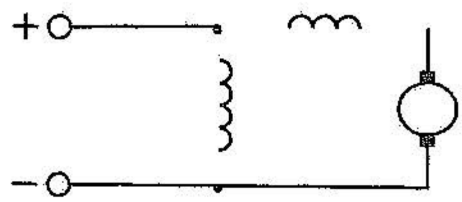

Figure3(b)

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DC MOTOR STARTING & SPECIALIST MACHINES

PURPOSE:

This section examines the need for starters in conjunction with dc motors and introduces specialist dc machines.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- explain the need for current limiting dc motor starters.
- calculate the value of starting resistance required for a given dc motor.
- describe the construction of tachogenerators, servomotors and stepper motors.
- explain the operating principles of tachogenerators, servomotors and stepper motors.
- list applications of tachogenerators, servomotors and stepper motors.

REFERENCES:

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.
Pages 278-279, 291-293 and 319-320.

1. FUNCTION OF A MOTOR STARTER

The value of current required by a dc motor armature depends mainly upon the value of the ______________________________ induced in the armature.

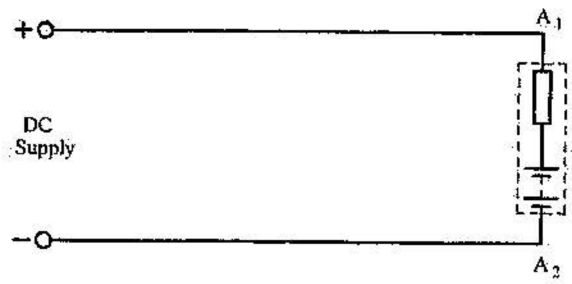

Figure 1

Motor back emf is proportional to the product of the -

- ______________________

  and

- ______________________ and will be ________ when the armature is at standstill.

If the motor were connected to the supply while the armature was at standstill or "rest", the strength of the armature current would be limited by only the - ______________________.

Due to the comparatively low resistance of armatures, the current would be ____________ and would result in damage to the brushgear and commutator.

It is invariably the practice to start dc motors from standstill by means of a special starter which is so arranged that, on starting, the armature is firstly connected to the supply through a resistance sufficiently high to reduce the current to a safe value.

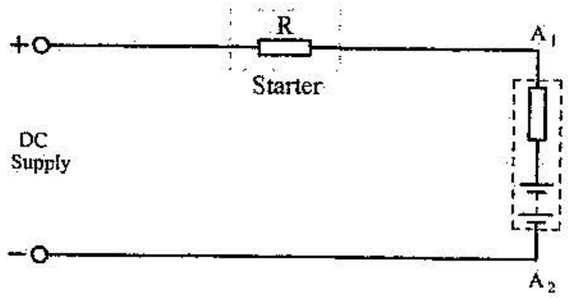

Figure 2

The resistance in series with the armature is gradually diminished by operation of the starter as the speed and back emf of the armature increase.

In the final or "running" position of the starter, the resistance is entirely "cut out", so that the armature current then depends upon the back emf of the armature only. This is the function of the motor starter.

In order that shunt and compound motors may develop their correct torque when starting, it is essential that the current in the shunt-field circuit should be the normal value. Therefore, the starter resistance is connected in series with the armature circuit and the shunt field is supplied with the normal supply voltage. See figures 3 and 4.

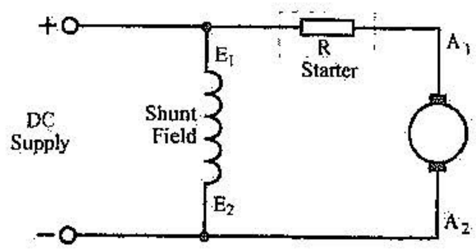

Figure 3

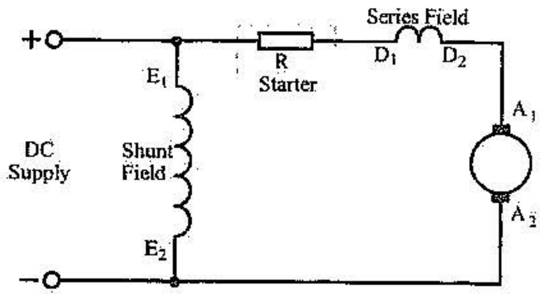

Figure 4

The current required by a motor, at starting, is usually limited to approximately __________ of the full-load armature current. This value of current enables the motor to -

- start under full load
  and
- accelerate to full speed fairly rapidly.

The following example shows the method of calculating the value of resistance required in a starter to limit the armature current to a specified value at standstill.

Example: 1

A 600V, compound-wound, dc motor requires a line current of 23A at full load. Its shunt field resistance is 1200Ω, and its armature circuit resistance is 1Ω. Determine the starter resistance required to limit the starting current to 150% of the full-load armature current.

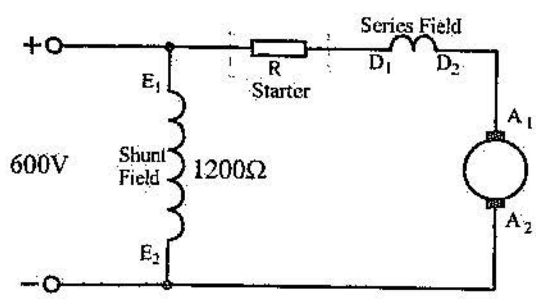

Figure 5

____

____

____

____

____

Example: 2

A dc motor operates on 240V, and takes a full-load current of 45A. Given the resistance of the shunt field is 480Ω and the resistance of the armature is 0.5Ω, calculate the resistance of a starter to limit the armature current to 150% of full-load armature current.

Example: 3

A 250V dc series motor takes a full-load current of 100A. The resistance of the series field winding is 0.1Ω and that of the armature 0.067Ω. Determine the starting resistance required to limit the starting current to 150% of full-load armature current.

2. STARTER RESISTORS

The material and form of resistance elements for a starter depend upon the current-carrying capacity required.

For currents up to approximately 20A they consist of resistance wire, usually a high-resistance alloy such as Eureka, wound on insulated bobbins.

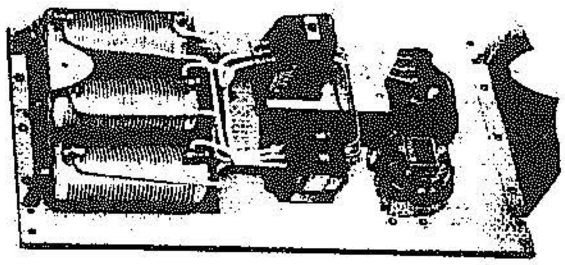

Figure 6

For very heavy currents the resistance sections may be in the form of cast-iron grids. Alternatively, they may be made of resistance material of rectangular cross-section, wound on edge. The starter resistors of electric trains, for example, are these types.

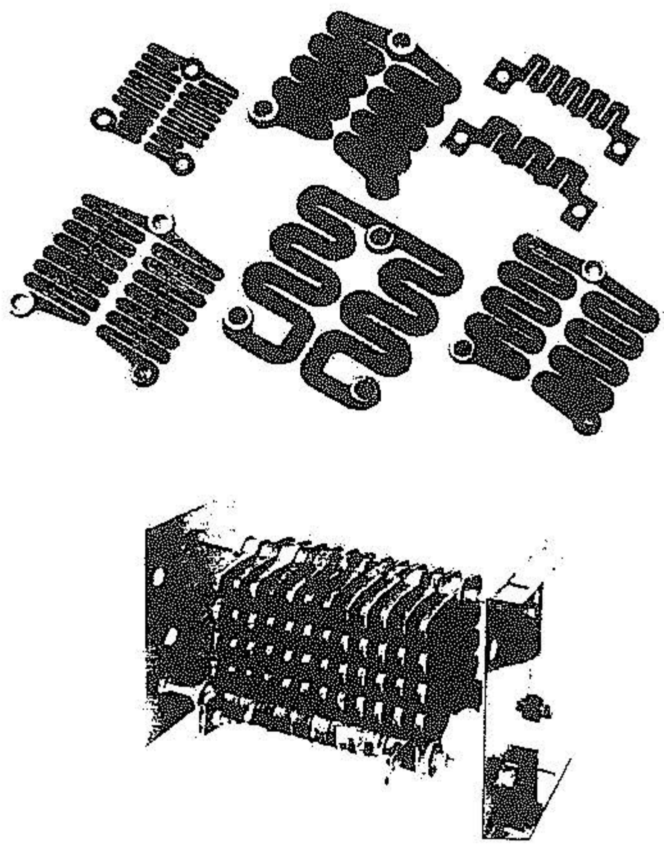

Figure 7

Starter resistors are designed to carry the heavy starting current "**intermittently**". If they are in circuit too long, they are liable to become overheated.

3. THE TACHOGENERATOR

The tachogenerator, is a generator that utilises permanent magnets to establish the field flux. Two examples of small tachogenerators are shown in figure 7.

Figure 7

Earlier it was shown that the voltage induced in the armature of a generator could be determined using the equation -

As the field flux of the tachogenerator is produced by permanent magnets, the flux will be constant. Therefore, the voltage produced will be proportional to the speed of rotation.

Figure 8 shows the voltage speed characteristic for the tachogenerator.

Figure 8

Because of its characteristics, the tachogenerator is used -

- directly for the measurement of speed
- to provide feedback as part of a speed control system.

4. THE STEPPER MOTOR

Up to this point, we have discussed devices that are basically analog in nature. By analog, we mean that the motor armature turns at a speed proportional to the input voltage. For example, in a permanent-magnet motor, if we increase the input voltage, the armature speed will also increase. The speed of the permanent-magnet motor can also be continuously varied. The speed does not have to he adjusted in steps.

> A motor that takes electrical pulses and changes them into mechanical movement is called a stepper (or stepping) motor.

Conventional motors, as we have seen, rotate continuously when power is applied to them. The stepper motor, when pulsed, rotates or steps in fixed angles. The output shaft (or rotor) rotates through a specific number of degrees for each input pulse. For example, with one input pulse, the rotor may move an angle of 7°. After the pulse is applied, the rotor steps, then waits for the next controlling pulse. The angle is repeated precisely with each following pulse. All stepper motors work in this fashion.

The basic operation of a stepper motor is shown in Figure 9.

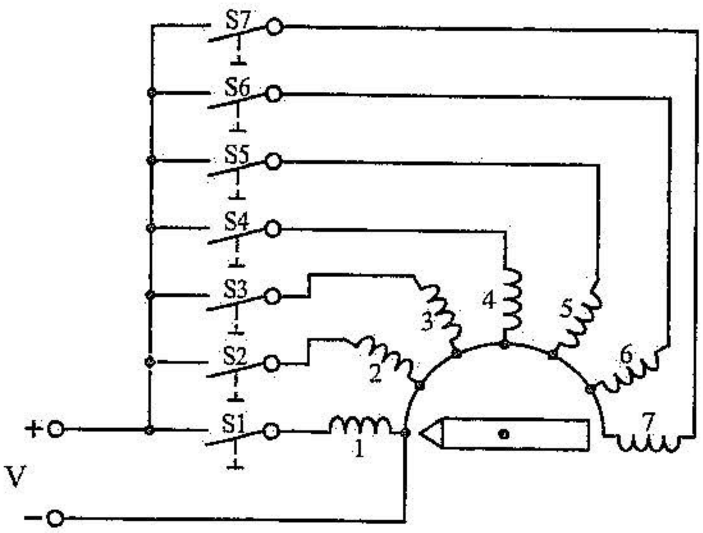

Figure 9

The stepper can be compared to a series of electromagnets arranged in a circle. When switch 1 is closed, the permanent magnet will align itself with electromagnet 1. If that switch is then opened and switch 2 is closed, the permanent magnet will be attracted to electromagnet 2. If the correct switches are closed in the correct sequence, the permanent magnet will revolve in a complete circle.

There are two basic types of stepper motor -

- permanent-magnet
- variable-reluctance.

Only the operation of the permanent magnet stepper motor will be considered in this module.

The permanent magnet stepper operates on the reaction between an electromagnetic field and permanent magnet rotor, in its simplest form, the permanent magnet unit consists of a two-pole permanent magnet rotor revolving within a four-pole slotted stator. The basic elements of the permanent magnet stepper are illustrated in figure 10.

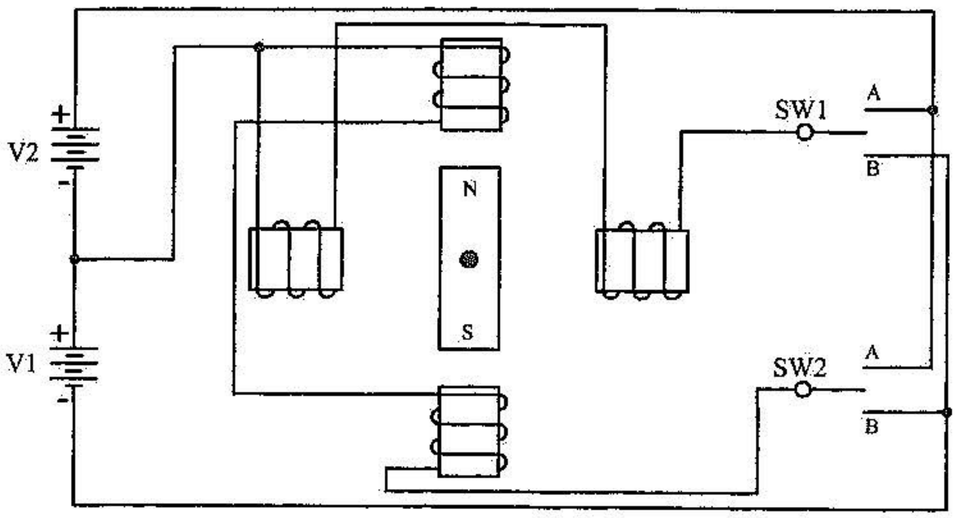

Figure 11

If the switches are operated in a set sequence the rotor can be made to step in a particular direction. Table 1 shows the switch sequences for the four step motor of figure 11.

Table 1

	Clockwise Rotation		Rotor North Position	Anticlockwise Rotation		Rotor North Position
	Switch 1	Switch 2		Switch 1	Switch 2	
Step 1	off	B	↑	off	B	↑
Step 2	B	off	→	A	off	←
Step 3	off	A	↓	off	A	↓
Step 4	A	off	←	B	off	→
Step 5	off	B	↑	off	B	↑

One significant difference between stepper motors and conventional dc motors is that the stepper motor may hold a stationary position by keeping a stator coil energised. To hold a conventional motor a brake must be applied.

The rotor is actually cylindrical and toothed. The teeth concentrate the magnetic flux. If the flux were evenly distributed, the motor would not have its characteristic and repeatable steps. Figure 12 shows the constructional features of a practical permanent magnet motor.

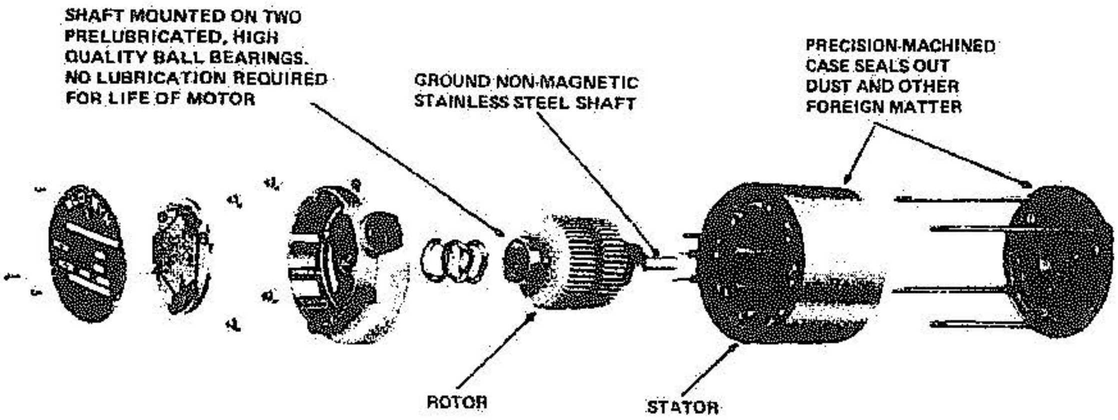

Figure 12

When assembled the motor takes the form of that shown in figure 13.

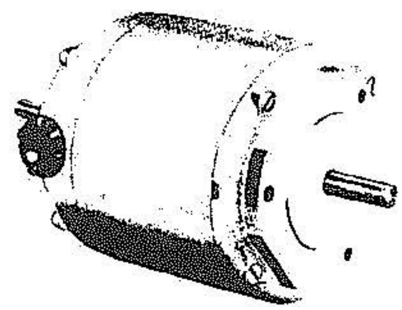

Figure 12

The rotor of the permanent magnet stepper motor must be large in order to produce enough field strength to interact with the stator field. This large rotor construction gives the motor a large inertia. The large inertia means that the motor will react slowly. This limits the motor's maximum stepping rate.

Figure 13 shows another variation to the construction of the permanent magnet stepper.

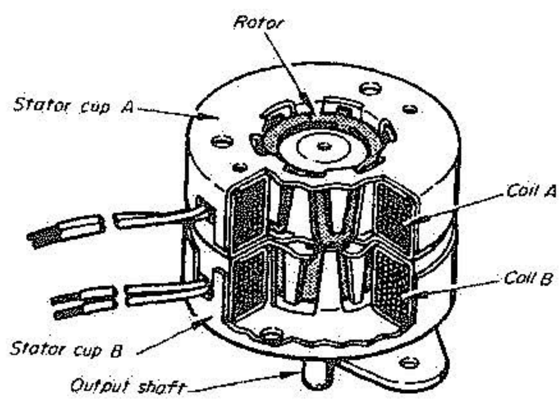

Figure 13

A low inertia stepper motor, shown in figure 14, has a rotor which is a thin disk which can be magnetized with up to 100 individual tiny magnets, evenly spaced around the edge of the disk and giving step angles down to 1.8°, or 200 steps per revolution. Conventional permanent magnet stepper motors are generally limited to a minimum full step angle of 30° (with a 12 pole stator) or maximum of 12 full steps per revolution. The thin disk motors are generally half the size and weigh 60% less.

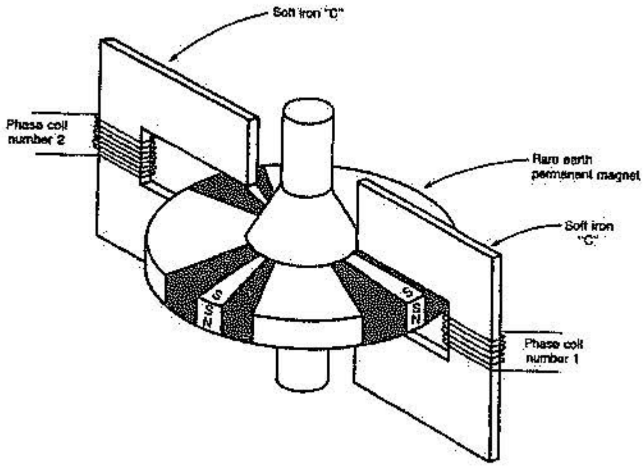

Figure 14

The disk is supported on a non-magnetic hub, making up the rotor. The disk magnet is polarized with alternating north and south poles as shown. A simple C-shaped electromagnetic field pole forms one phase of the motor. A second, identical field pole, offset by half a rotor pole, forms the second phase.

When one of the phases is energized, the rotor will align itself with the electromagnetic field generated. Then, when the first phase is turned off and the second is turned on, the rotor will turn by one-half of a rotor pole to align itself with the field from the second phase. To keep the rotor turning in the same direction, the second phase is turned off and the first phase is turned on again with opposite polarity.

Stepper motors are used in a wide variety of "**positioning tasks**", for example -

- the read/write head on a computer disk drive
- to position the joints of some lightweight robotic arms
- in X-Y plotters
- in X-Y positioning tables for heavy machinery.

5. THE SERVO MOTOR

Some industrial control systems are responsible for the positioning of objects. Examples include the positioning of -

- the rolls in a steel rolling mill
- valves
- mechanical mechanisms
- remote positioning devices.

The control system that is used for this type of control is called a "**servomechanism**", or "**servo system**" for short.

A servomechanism is a closed-loop system that moves or changes the position of the controlled object so that it will follow or coincide with the position of a control device. A servo system requires motors to cause mechanical movement. Such motors are known as "**servo motors**" and all have high response speed. The servomotor is a specially designed permanent-magnet or shunt wound dc motor.

Of the two dc servomotors, the permanent-magnet motor is the more popular. It is able to provide -

- a two-wire connection that simplifies installation connection
- exceptionally high torques for frequent starts and stops
- between 10-15% more efficiency than other types of motors.

Figure 15 shows one type of permanent magnet servo motor, known as the "**printed circuit motor**".

The field structure is an 8-pole permanent magnet with the magnetic circuit completed through a flux return plate, which also provides the additional function of supporting the brushes. The armature contains no iron, and armature conductors are produced using printed circuit board techniques. Brushes bear directly on the armature conductors. Because of its overall construction the printed circuit motor has a very low inertia and as a result a very fast response time.

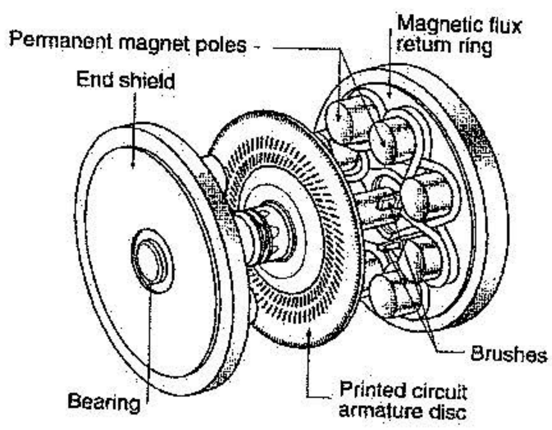

Figure 15

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DC MOTOR STARTING

PURPOSE:

This practical assignment will be used to examine the locked armature characteristics of a shunt motor and the determination of starting resistance to limit starting current to a prescribed value.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect shunt motor.
- Carry out a locked armature test.
- Determine the value of added resistance required to limit armature starting current to a specified value.

EQUIPMENT:

- ☐ 1 x dual variable dc power supply (0-6A output)
- ☐ 1 x Betts dc compound machine
- ☐ 1 x Betts eddy current load
- ☐ 1 x Betts double machine bed
- ☐ 1 x digital multimeter
- ☐ 2 x 0-5A analogue dc ammeter
- ☐ 1 x TES 3020 ac/dc clamp meter
- ☐ 3 x 6.8Ω, 10W resistors in parallel on a single mounting block with s/b terminals
- ☐ 4mm connecting leads

- REMEMBER -

- WORK SAFELY AT ALL TIMES -

observe correct isolation procedures

PROCEDURE 1: ARMATURE RESISTANCE

1. Using a digital multimeter measure the resistance of the armature of the dc motor.

Armature resistance = ____________ ohms

PROCEDURE 2: LOCKED ARMATURE TEST

1. Connect the shunt motor, with eddy current load attached, as shown in figure 1. Ensure the eddy current load is **"locked"** to prevent rotation.

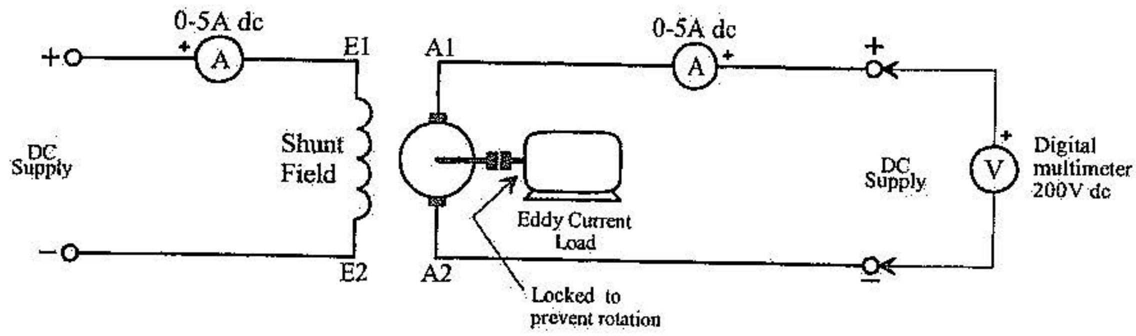

Figure 1

2. Ensure both power supplies are adjusted for minimum output.
3. Switch on and slowly adjust the power supply for a shunt field voltage of 24V. Measure and record the field current in table 1.
4. Adjust the armature voltage to 8V.
5. Measure and record, in table 1, the armature current and torque developed.

Table 1

Armature Voltage = 8V			Armature Voltage = 24V		
Field Current amperes	Armature Current amperes	Torque Developed Nm	Field Current amperes	Armature Current amperes	Torque Developed Nm

6. From your measured results, calculate the expected values of field current, armature current and torque for armature and field voltages of 24V. Record your answers in the appropriate columns of table 1.

Armature current = $\frac{24}{8}$ x I_A =

Torque = $\frac{24}{8}$ x T =

Field current =

7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
A	B	C

PROCEDURE 3: DETERMINATION OF STARTING RESISTANCE

1. Determine the value of starting resistance required to limit the armature starting current to 5A. Assume the armature is to be supplied at the normal rated voltage of 24V and use your measured value of armature resistance from procedure 1.

$$R_{ST} = \frac{V}{I_{ST}} - R_A \quad =$$

2. Turn on the power supply and pre-set both the field and armature supplies to 24V.
3. Turn the power supply off.
4. Connect the motor and starting resistance as shown in figure 2.
   Note: The eddy current load is to be uncoupled from the motor, so that the motor is free to rotate.

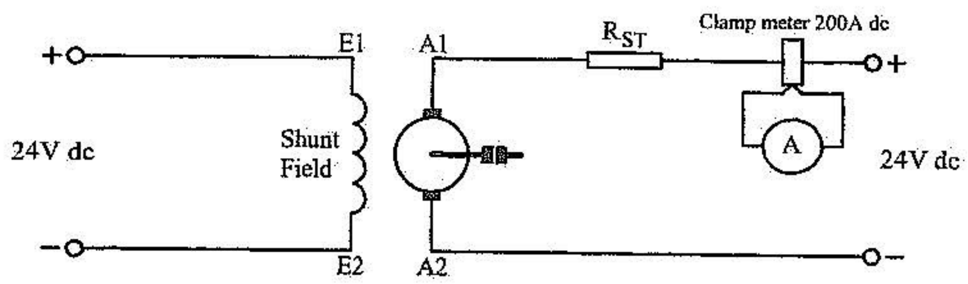

Figure 3

5. Set the clamp ammeter to the 200A dc range, zero and then press the peak hold pushbutton.
6. Turn on the power supply, then measure and record the starting current taken by the motor.

Starting current = ______________ amperes

7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
A	B	C

8. Adjust the armature supply for minimum output, then do the same with the field supply.
9. Turn the power supply off then disconnect the circuit.
10. Please return all equipment to its proper place, safely and carefully.

OBSERVATIONS:

1. Was the armature starting current of the motor close to the nominated value of 5A?

2. What do the results obtained indicate about the method used for the determination of starting resistance?

3. What effect does the limitation of starting current have on motor starting torque?

4. If a higher value starting resistance were used in conjunction with the motor tested, what would be the effect on armature starting current and starting torque?

5. What effect did the starting resistance have on the current taken by the shunt field?

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Starting & Specialised DC Machines

Please note the following requirements in relation to tutorial work -

- All tutorial work is to be completed on ruled A4 pad paper, with multiple pages stapled together. Write on one side only of the answer sheets, and all work is to be completed in ink.
- In the case of multiple choice type questions, the question number and corresponding answer letter are to be written on the answer sheet.
- In the case of short answer type questions, the question and part number with your word or phrase choice is to be written on the answer sheet.
- All relevant equations and working are to be shown in the case of calculation type questions.

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter of your choice on your answer sheet.

1. A ______ is used to limit starting current to approximately ______ of full load current.
   (a) tacho-generator, 500%
   (b) stepper motor, 150%
   (c) motor starter, 150%
   (d) motor starter, 500%

2. At the instant of starting, armature current is limited by:
   (a) back emf and armature circuit resistance.
   (b) armature circuit resistance only.
   (c) back emf only.
   (d) shunt field resistance.

3. A stepper motor converts ______ pulses into precise ______ movements.
   (a) mechanical, electrical
   (b) electrical, electrical
   (c) electrical, mechanical
   (d) mechanical, mechanical

4. The DC machine used to measure the speed of rotating machines is a/an:
   (a) permanent magnet tacho-generator.
   (b) low inertia stepper motor.
   (c) shunt limited series generator.
   (d) differentially compounded motor.