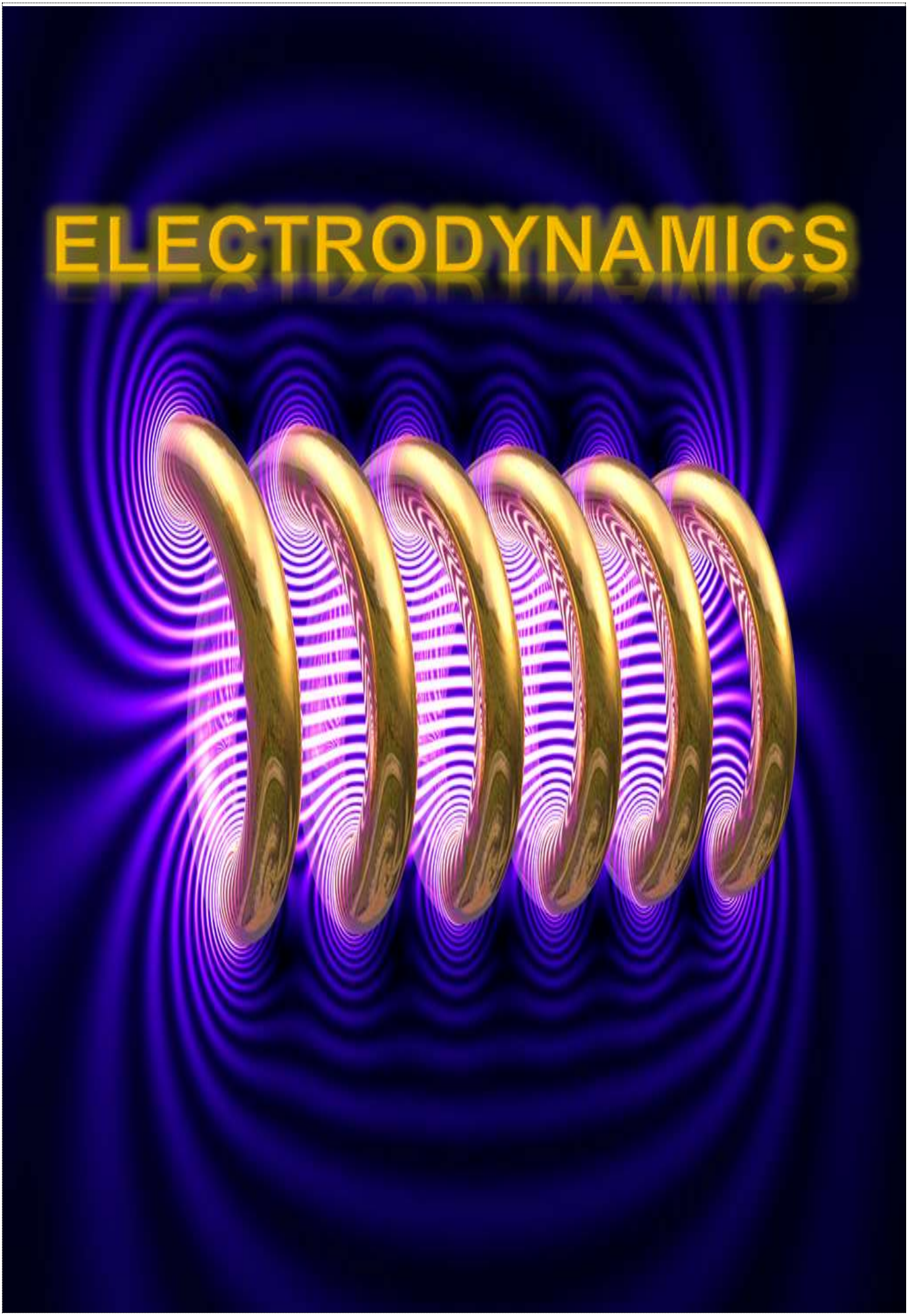
ELECTRODYNAMICS



Michael Faraday, James Clerk Maxwell, Nikola Tesla, Hans Christian Oersted and Heinrich Lenz to mention but a few of scientists who have since passed on and who have contributed to scientific developments that continue to make our civilization better. These are the names of top physicists and pioneers in the field of electromagnetism or electrodynamics. Now, two centuries after their departure, the importance of their discoveries is very clear and cannot be overemphasized. From the generation of electrical power to the storage of information in a computer hard disk drive and from the design and functioning of a loud speaker to the transmission of information over TV and radio, their discoveries and applications thereof live on. This topic aims to discuss the applications of the theories that underpin electromagnetism in electrical machines such as generators and motors. It also goes a step further to discuss two types of current i.e. direct current as well as alternating current. Lastly, this paper also brings forth to the attention of the learner, the various types of exam-type questions related to this topic in grade 12.

Chapter Outline

1. Electrical machines i.e. generators and motors.
2. Alternating current.

Chapter goals.

By the end of this chapter, you should be able to:

1. State the energy conversion that occurs in generators.
2. Use the principle of electromagnetic induction (Faraday's law) to explain how a generator works.
3. Explain the functions of the components of an AC and a DC generator using words and pictures.
4. Use words and pictures to explain how a DC generator works and how it differs from an AC generator.
5. Explain why a current-carrying conductor placed in a magnetic field will turn by referring to the force exerted on moving charges by a magnetic field and the torque on the coil.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

6. Use words and pictures to explain the basic principle of an electric motor.
7. State the energy conversion that occurs in motors.
8. Use the motor effect to explain how a motor works.
9. Explain the functions of the components of a motor.
10. State examples of the use of motors and generators.
11. State the advantages of alternating current over direct current.
12. Sketch graphs of voltage versus time and current versus time for an AC circuit.
13. Define the term rms for an alternating voltage or an alternating current.
14. Solve problems using $I_{rms} = \frac{I_{max}}{\sqrt{2}}$ and $V_{rms} = \frac{V_{max}}{\sqrt{2}}$
15. Solve problems using $P_{ave} = I_{rms}V_{rms}$, $P_{ave} = \frac{1}{2}I_{max}V_{max}$ (for a purely resistive circuit), $P_{ave} = {I_{rms}}^2 R$ and $P_{ave} = \frac{{V_{rms}}^2}{R}$

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

1. Electrical machines (Generators and motors)

In electrodynamics, a generator is a device that converts input mechanical energy from an external source into electrical energy as output.

The following figure shows a picture of a generator.

Figure 1: A picture of a generator

- **Energy conversion in generators (EXAMINABLE)**

A generator converts mechanical energy into electrical energy.

The mechanical energy can come from any mechanism that rotates the rotor or the arm of the generator. When the turbine (attached to the rotor of the generator) turns (a mechanical process), through principles such as what will be explained later, emf (electrical energy) is induced in the terminals of the generator.

Coal-fired power stations

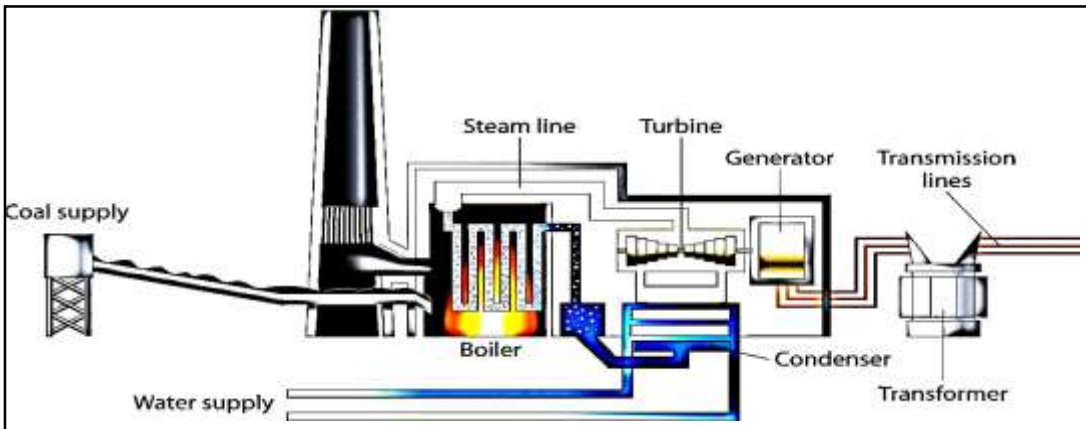


Figure 2: Picture that represents how electricity is generated at a coal-fired power plant. (NOT FOR EXAM PURPOSES)

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

In coal-fired power stations such as those used by Eskom, coal is used to heat up water which turns into steam moving at high speed. The steam turns the turbine which causes an emf to be induced in the generator.

The steam provides mechanical energy which turns the turbine and the generator turns the mechanical energy in electrical energy.

Hydroelectric power.

In a hydroelectric power plant, water that is placed at a relatively high altitude e.g. a dam on a mountain, is allowed to move down the steep slope and turn the turbine which causes the generator to produce emf.

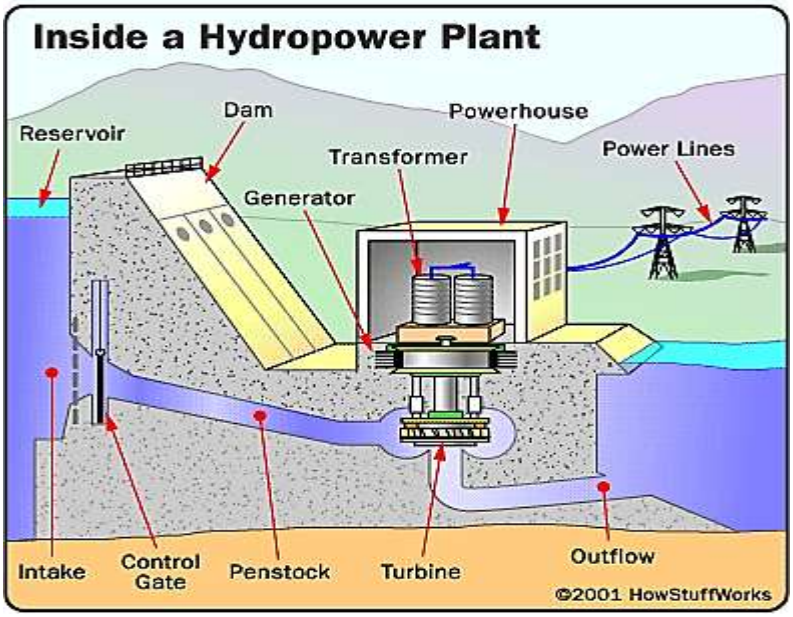


Figure 3: Hydroelectric power plant. (NOT FOR EXAM PURPOSES)

So, whether it **is hydroelectric power**, **nuclear power**, **coal power** or **geothermal power**, the principle is the same i.e. a certain mechanism turns the turbine of a generator which then produces emf as it rotates.

- **How generators work: Electromagnetic induction (EXAMINABLE)**

The principle behind the functioning of a generator is the principle of electromagnetic induction i.e. **Faraday's law.**

Faraday's law states: ***The emf induced in a coil of a conductor is directly proportional to the rate of change in magnetic flux linkage.***

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Mathematically:

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t}$$

Where:

- ε is the emf induced in the wire, in volts (V).
- N is the number of turns or loops of the wire.
- $\Delta\phi$ is the change in magnetic flux linkage in webers (Wb) and $\phi = BAcos\theta$
- Δt is the time taken for the change in magnetic flux in seconds.
- The minus sign (-) indicates that the emf produced leads to current with a magnetic field in a direction that tends to decrease the change in magnetic field. This is known as **Lenz's law**.

Lenz's law states:

The emf induced in a coil of wire leads to current with a magnetic field that tends to decrease the change in magnetic flux.

Thus, a change in magnetic flux (caused by a moving magnet, or moving or rotating conductor or changing area) results in an emf induced in the wire.

- **<u>A simple AC generator (EXAMINABLE):</u>**

The following figure shows the basic (important components) of an AC generator. (AC stands for alternating current).

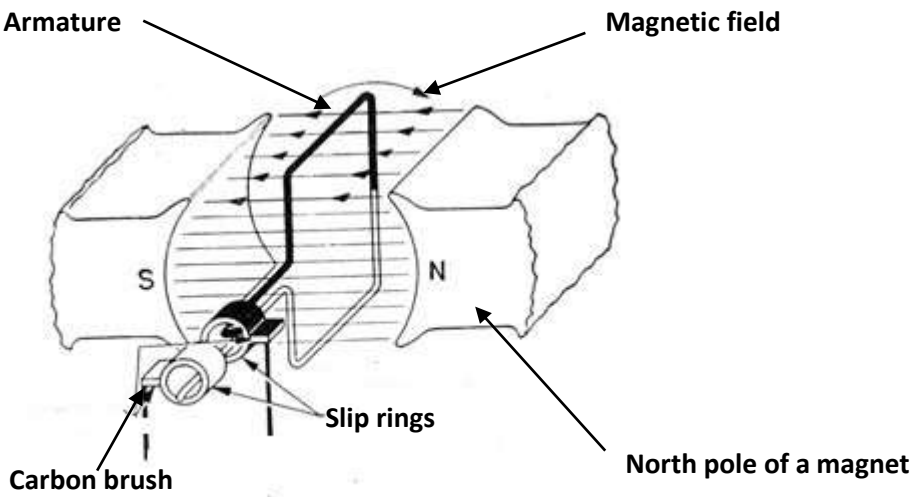


Figure 4: Basic components of an AC generator. Notice especially, the slip rings which is an important structural difference from a DC generator.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Functions of the basic components of a generator (EXAMINABLE)

1. **Armature** – Allows emf and current to be induced through it as it rotates in the magnetic field.
2. **Magnets** – provides magnetic field that passes through the armature (coil)
3. **Slip rings** –
    a. Allows current to change direction every half-revolution (half-rotation) of armature.
    b. Allows continuous contact with brushes so that current can be transmitted to terminals without breaking the circuit.
4. **Carbon- brushes**-
    a. Maintains electrical contact with the slip rings.
    b. Conducts or takes current out of the coil.

AC generator at work (EXAMINABLE)

Consider an AC generator with its armature turning clockwise by some mechanical force as shown in figure 5 below.

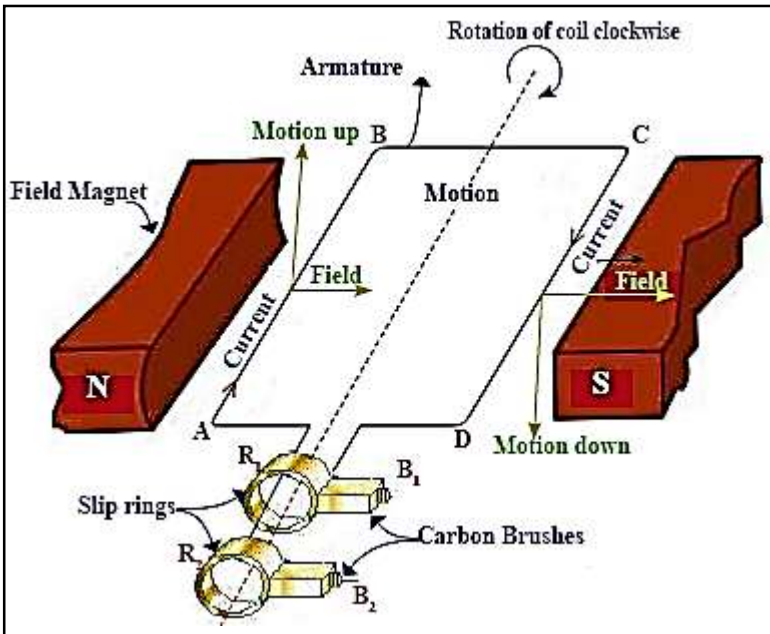


Figure 5: A generator rotated clockwise by a force.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Directions of movement of sides of the coil (force), magnetic field and current through the armature (EXAMINABLE).

1. Magnetic field is always directed from north pole to south pole. In the generator in figure 5, the magnetic field is from left to right.
2. Since the armature is rotating clockwise, part AB moves upwards whilst part CD moves downwards.
3. To determine the direction of the current through each part i.e. AB, BC, CD and AD, we use right hand rule (or generator rule). See the following figure.

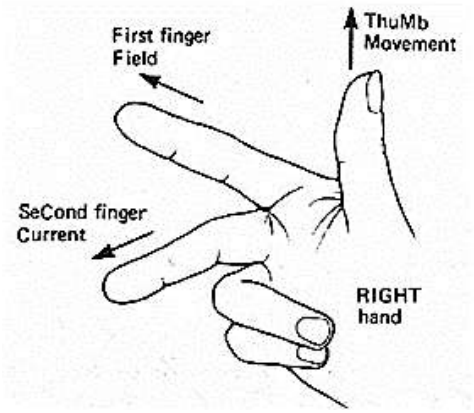


Figure 6: The right hand-rule is used to determine the direction of one variable if the other two are known out of the three i.e. magnetic field, force and current.

If we shape and orient (or "direct") our right hand so that the first finger (for finger or index finger) so that it points to the right, whilst our thumb points upwards, the second fingre points into the page.

The direction of the current at AB is from A to B.

We can use the right hand rule to determine the direction of the current at part CD of the armature.

Magnitude and direction of current and emf induced in an AC generator.

AC generators produce alternating current (AC).

Alternating current is current that changes direction periodically according to a specified frequency or period.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Alternating voltage is voltage that changes polarity periodically according to a specified frequency of period.

Example, In South Africa, Eskom generators in power plants produce alternating current that has a frequency of 50 Hz (f = 50 Hz) and changes direction according every 0,02 seconds (T = 1/f, T = 1/50, = 0,02 s).

The graphs of alternating current and alternating voltage are sinusoidal i.e. they are shaped like sine and cosine graphs:

The following figure shows a sketch graph of alternating voltage.

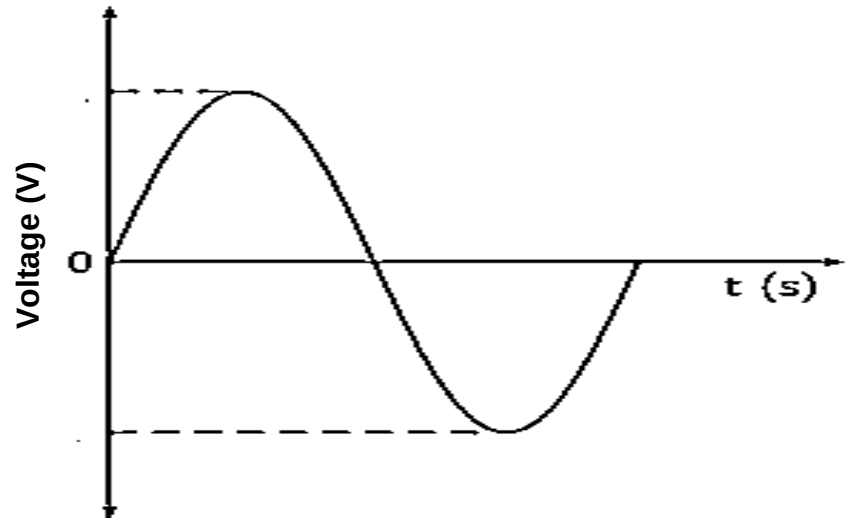


Figure 7: Graph of voltage versus time for alternating current.

The shape of the graph of current versus time for alternating current is the same as that of voltage versus time.

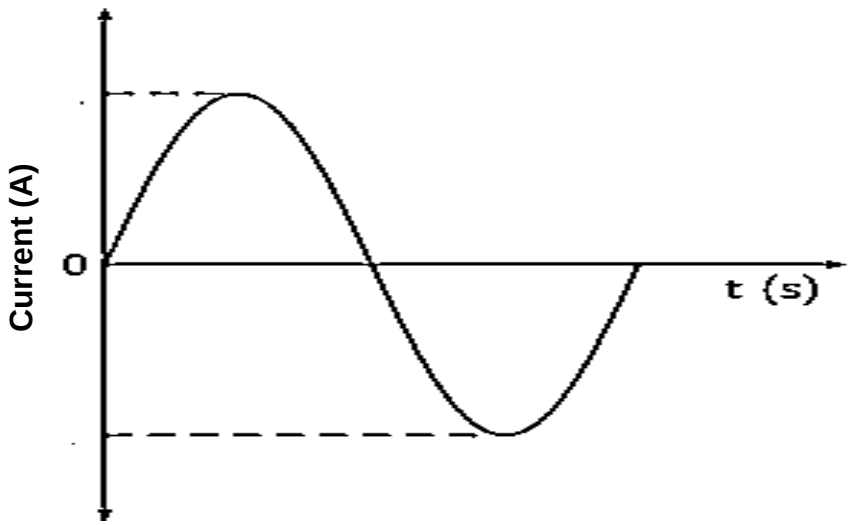


Figure 8: Graph of current versus time for alternating current.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

The magnitude and direction of emf (voltage) and current produced by an AC generator is directly linked to the rotation of the armature in the generator and its orientation in comparison to the magnetic field surrounding it.

Remember:

Magnetic flux is the product of the perpendicular component magnetic field passing through the coil and the area of the coil.

To understand better what is meant, one can draw a normal to the area as seen below:

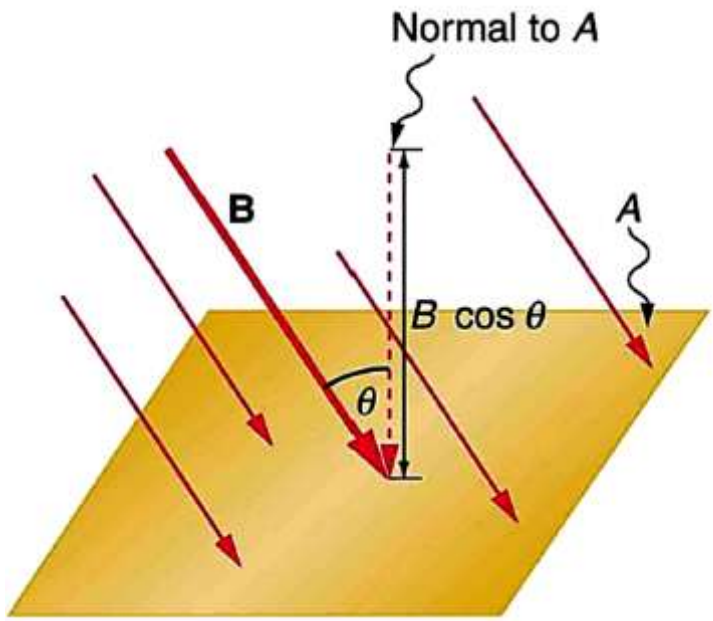


Figure 9: The perpendicular component of the magnetic field is along the normal to the surface or coil through which the magnetic field passes.

Therefore, from the equation $\phi = BAcos\theta$, we see that:

1. When the coil is perpendicular to the magnetic field, the normal is perpendicular to the surface and parallel to the magnetic field and the magnetic flux is at its maximum value (BA) since $\cos 0^o = 1$.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

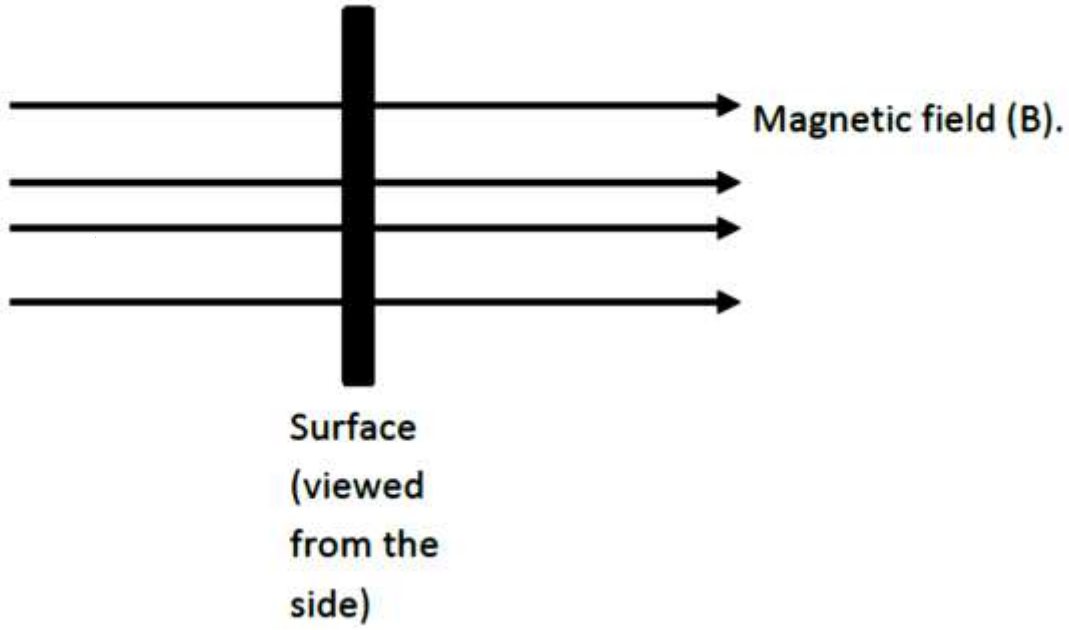


Figure 10: When **the coil is perpendicular** to the magnetic field (B), the magnetic flux ϕ **is at its maximum value**.

2. When the coil is parallel to the magnetic field, the normal is perpendicular to the surface and magnetic field and the magnetic flux is minimum i.e. zero since $\cos 90^o = 0$.

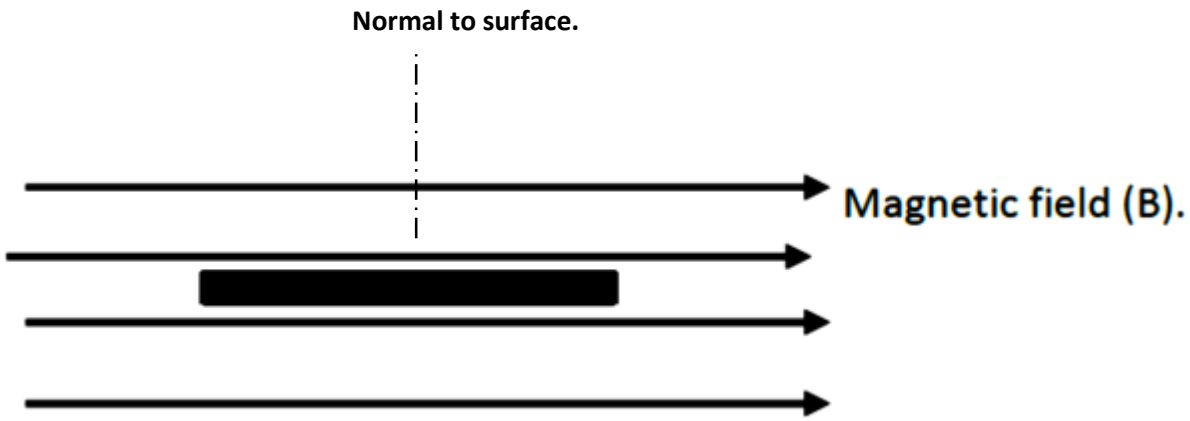


Figure 11: When **the coil is parallel to the magnetic field** (B), the magnetic flux ϕ is at its **minimum value** i.e. 0 since $\cos 90^o = 0$

Now, consider a generator with its armature perpendicular to the magnetic field, as shown below:

1. **Position 1 to 2**: Since the conductor starts off as perpendicular to the magnetic field (position 1 on the diagram to your right), the **magnetic flux is maximum** and the armature rotates to the horizontal position, **the magnetic**

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

flux decreases to minimum whilst the emf increases to maximum. See figure 12.

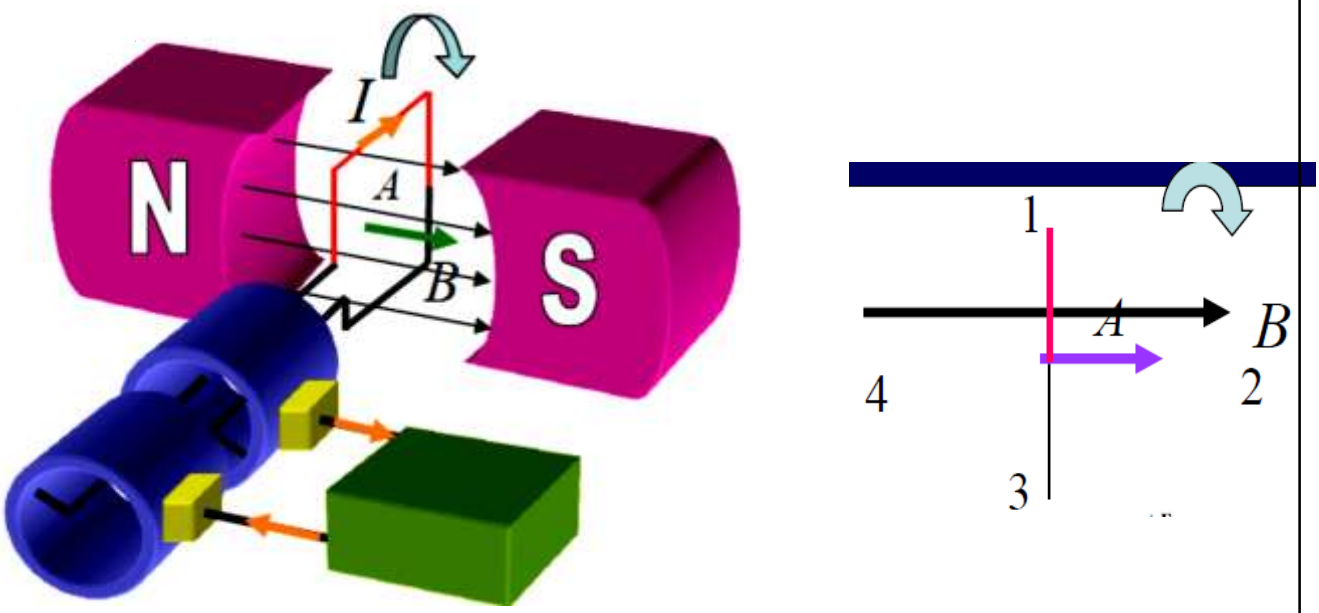


Figure 12: Armature rotates from perpendicular position (1, $\theta = 0^o$) to parallel position (2, $\theta = 90^o$). Magnetic flux is positive and decreasing and emf is positive and is increasing to its maximum from zero.

2. **Position 2 to 3**: As the coil rotates from position 2 to 3, the magnetic flux is negative and increases from minimum to maximum whilst the emf decreases from maximum to zero. See figure 13.

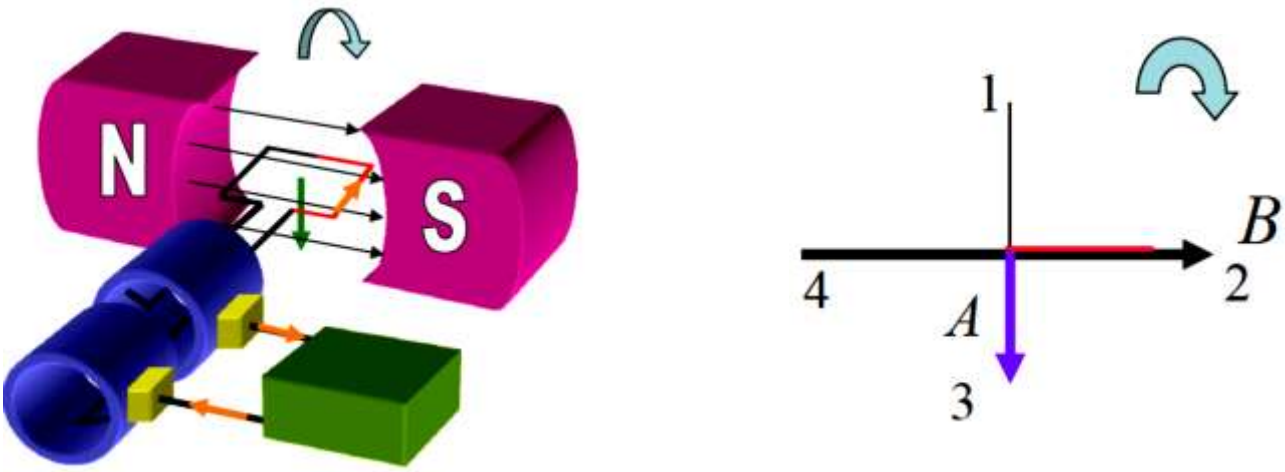


Figure 13: Armature rotates from parallel position (2, $\theta = 90^o$) to perpendicular position (3, $\theta = 180^o$). Magnetic flux is negative and increasing and emf is positive and is decreasing from maximum to zero.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

3. **Position 3 to 4:** The coil is perpendicular to the magnetic field but it rotates to position 4 where it becomes parallel to the magnetic field. The magnetic flux is negative and decreases from maximum to minimum whilst the emf is negative and increases from zero to maximum. See figure 14.

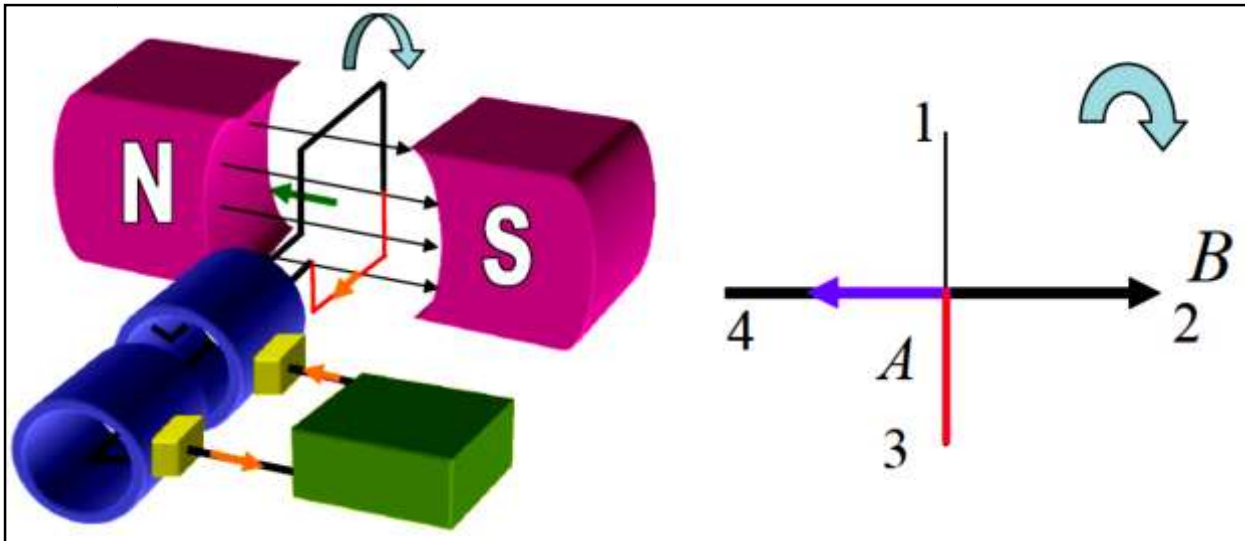


Figure 14: Armature rotates from perpendicular position (3, $\theta = 180^o$) to parallel position (4, $\theta = 270^o$). Magnetic flux is negative and decreasing and emf is negative and is increasing from zero to maximum.

1. **Position 4 to 1:** The coil is parallel to the magnetic field (position 4, $\theta = 270^o$) but it rotates to position 1 where it becomes perpendicular to the magnetic field. The magnetic flux is positive and increases from minimum to maximum whilst the emf is negative and decreases from maximum to zero. See figure 15 below.

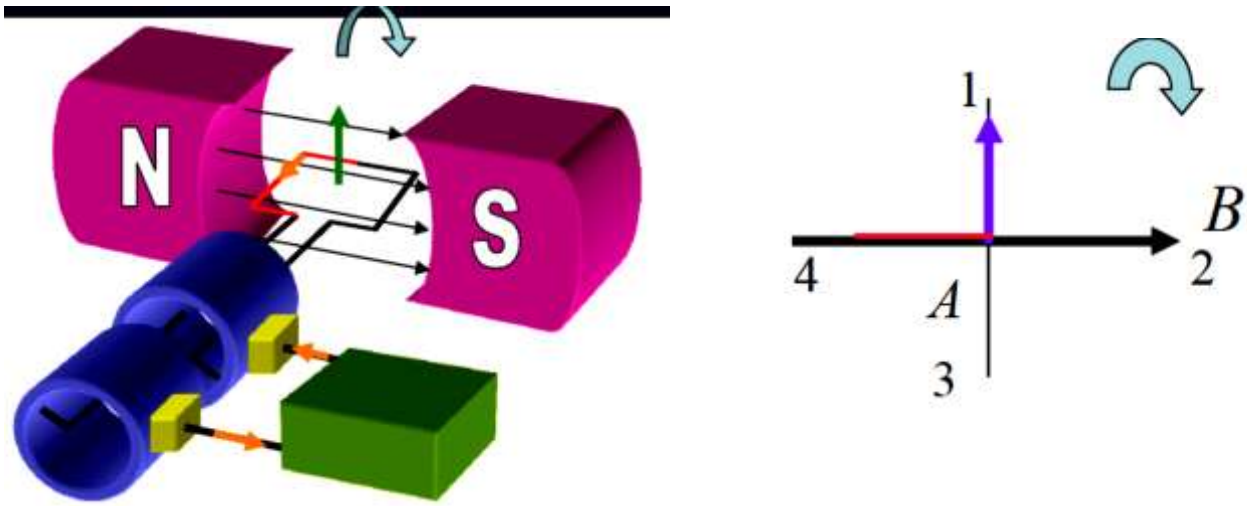


Figure 15: Armature rotates from parallel position (4, $\theta = 270^o$) to perpendicular position (1, $\theta = 0^o$). Magnetic flux is positive and increases and emf is negative and is decreasing from maximum to zero.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

The following diagram (figure 16) summarizes the above points. A graph of emf versus time is also included to show how various positions of the armature (coil) compare to the magnitude and direction of the emf induced.

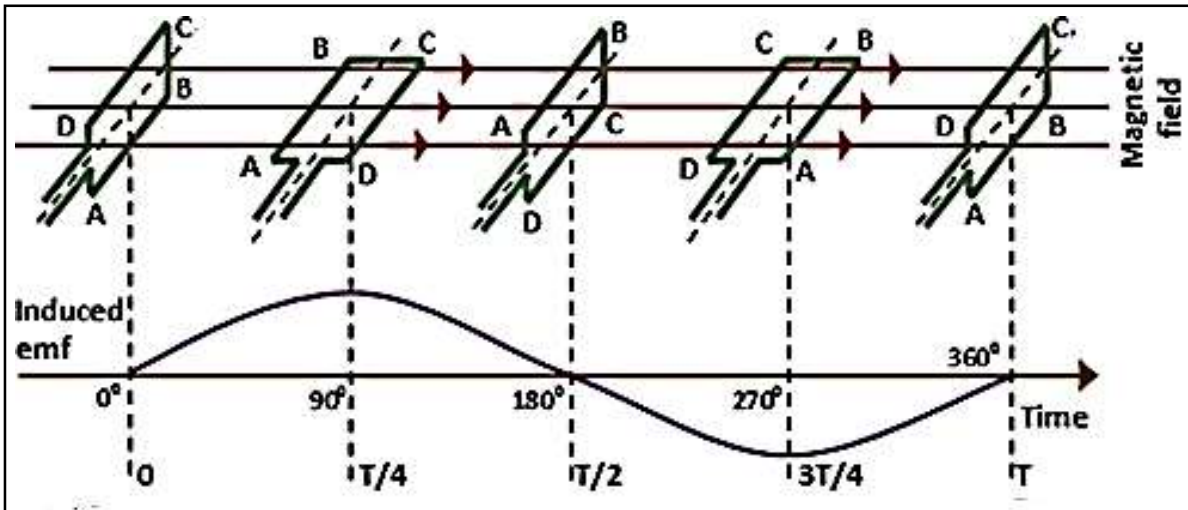


Figure 16: Relationship between the position of the armature and the magnitude of the emf induced. T stands for period. N.B. One period is the inverse of frequency (T = 1/f)

DC generator

A DC generator produces direct current.

Direct current is current is current that maintains its direction.

The direction of current is that of conventional current which flows from positive to negative.

As you can see in the following figure, a DC generator is similar in many respects to an AC generator. One major difference between the two is that a DC generator has a split ring or commutator instead of two slip rings.

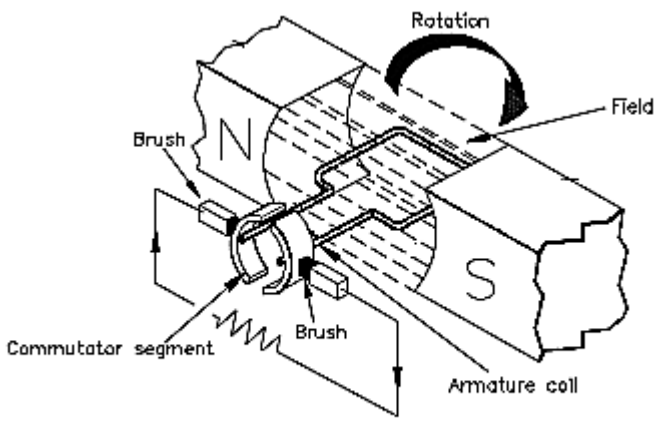


Figure 17: Basic components of a DC generator. It is similar in many respects to the AC generator except that the DC generator has a commutator (or split rings) instead of the two slip rings found in an AC generator.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Functions of the basic components of a DC generator.

1. **Armature** – Allows emf and current to be induced through it as it rotates in the magnetic field.
2. **Magnets** – provides magnetic field that passes through the armature (coil)
3. **Split rings** (or commutator) –
    a. Allows induced current to flow in one direction
    b. Allows continuous contact with brushes so that current can be transmitted to terminals without breaking the circuit.
4. **Carbon brushes** –
    a. Maintains electrical contact with the split rings (or commutators)
    b. Conducts/ takes current out of the coil.

DC generator at work (EXAMINABLE)

Consider a DC generator with its armature that is made to turn in the anticlockwise direction by some mechanical effort as shown in figure 18 below.

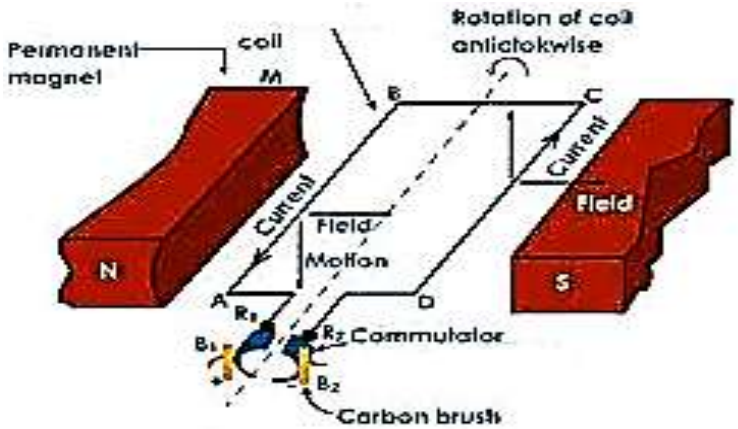


Figure 18. A DC generator with its armature turning in an anticlockwise direction by mechanical efforts. Take note of the commutator because it is the main structural difference between a DC generator and an AC generator.

Directions of movement of sides of the coil (force), magnetic field and current through the armature (EXAMINABLE).

1. Magnetic field: Magnetic field is always directed from north to south. In this case, the magnetic field is to the right.
2. Armature movement: Since the armature is rotated anticlockwise, part AB moves downwards whilst CD moves upwards.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

3. Direction of current through armature: WE can use the right hand rule to determine the direction of the current through the armature as follows:
   For part AB on the armature:
5. The first finger points to the right to indicate the direction of the magnetic field.
6. The thumb points downwards to indicate the movement of this part as the armature rotates anticlockwise.
7. The second finger shows that the current flows from B to A.

Using the same right hand rule, we can show that the current through CD flows from D to C

Consider the following diagram representing a DC generator with its armature rotating due to some mechanical effort.

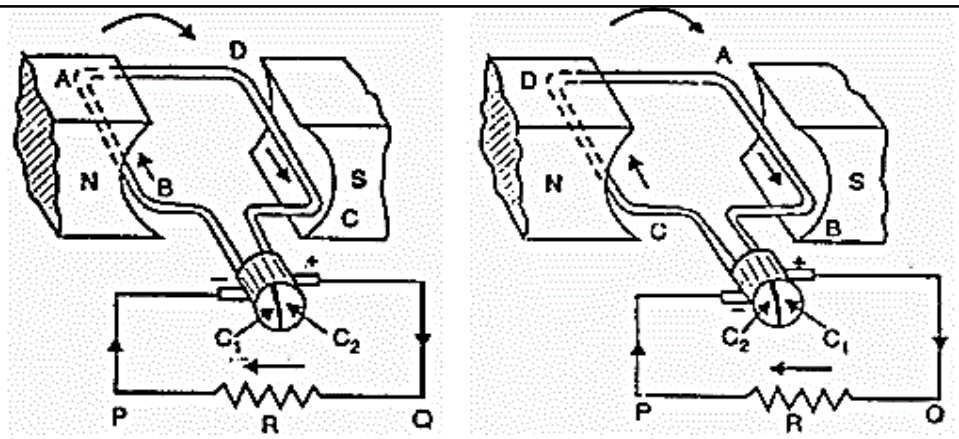


Figure 19. The two diagrams shown here both represent one DC generator that rotates clockwise due to some mechanical effort. It shows that the current maintains its polarity throughout the rotation of the armature.

<u>Points to consider:</u>

1. The type of current induced in the generator is taken as conventional current.

   Conventional current refers to current that flows from the positive terminal to the negative terminal. Thus, the terminal where the current flows from is the negative terminal and the terminal it flows to is the negative terminal.

2. As long as the armature rotates in the same direction (e.g. clockwise), the current on the left will always have the same direction just as the current on the right will maintain its direction.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

3. This is true because the force (or movement) of the part of the wire on that side will always have the same direction. The magnetic field will also maintain its direction i.e. from north pole to south pole.
4. The commutators are fixed and rotate as the armature rotates.
5. The carbon brushes are just connectors and have no effect on the polarity of the emf or current induced.

How the commutators maintain polarity of emf produced.

In figure 19 (left diagram), for the left part of the armature, the right hand rule predicts that current will flow from B to A. This makes commutator 1 (C1) and the carbon brush connected to it the negative whilst C2 and its brush positive.

For the diagram on the right, the armature has rotated such that CD is now on the left. The right hand rule predicts that the current flows from C to D. This makes commutator C2 positive along with its carbon brush. This way the polarity of the emf induced by a DC generator is maintained.

In short: The emf and current induced in a DC generator has the same polarity (positive terminal and negative terminals do not change or swap) through the rotation of the armature. This is achieved by the use of the commutator.

Every half cycle, the induced emf changes direction whilst at the same time, the two segments of the commutator swap the brushes that are connected to them. This way, the emf across the terminals of the DC generator maintains its polarity.

Magnitude and direction of induced emf as armature rotates:

The magnetic flux in a dc generator changes in the same way that it changes in an AC generator. The current induced, however maintains the same direction because the part of the armature and split-ring connected to one brush always has current flowing in the same direction. Thus the graph of emf versus time for a dc generator looks as follows.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

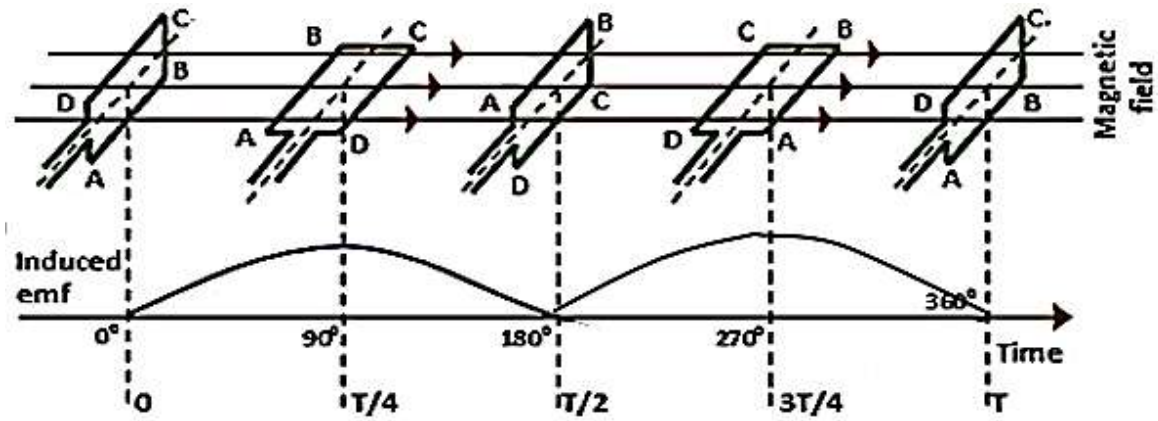


Figure 20: Graph of emf versus time for a dc generator with the corresponding orientation of armature at interval angles.

Motors.

A motor is a device that converts input electrical energy into output mechanical energy.

Energy conversion in motors (EXAMINABLE).

Motors convert electrical energy into mechanical energy.

Thus, a motor does the exact opposite of what a generator does.

A motor can be used as a generator if its shaft (or rotor) is turned mechanically and a generator can be used as a motor if it is connected to a source of energy e.g. a battery.

Principle of motor operation (EXAMINABLE)

- **The motor effect**

Electric motors operate on the motor effect.

The motor effect is the phenomenon whereby a current-carrying conductor placed in a magnetic field experiences a magnetic force perpendicular to the current in the conductor and magnetic field through it.

The motor effect can also be defined as the interaction between the magnetic field due to the current in the conductor and the external magnetic field.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

It was discovered when a current-carrying conductor is placed in a magnetic field, the moving charges in the conductor will experience a force which is perpendicular to the magnetic field through the conductor and the current inside the conductor.

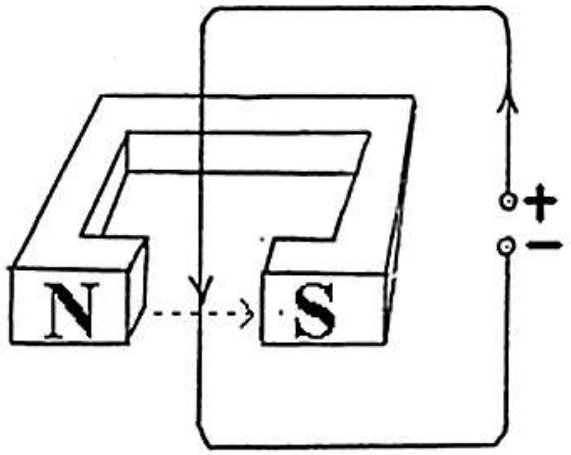


Figure 21: Current-carrying conductor placed inside a magnetic field.

Due to the force exerted on the charges, the conductor will move in the direction of the force exerted on it.

The direction of the force exerted on the current-carrying conductor is given by **Fleming's left hand rule** where:

1. The thumb indicates the direction of force (and movement) of the conductor.
2. The first finger indicates the direction of the magnetic field through the conductor.
3. The second finger indicates the direction of the current inside the conductor.

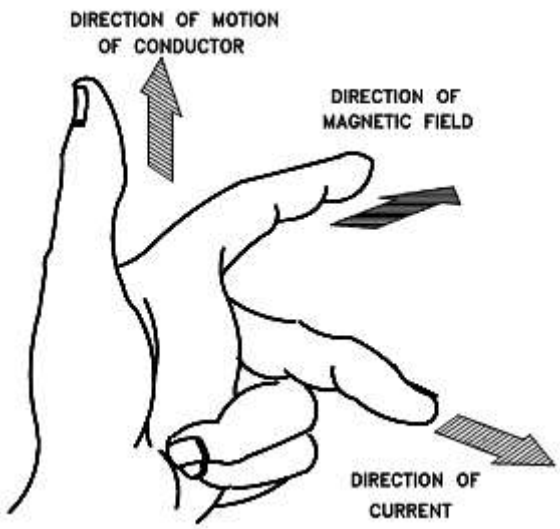


Figure 22: Fleming's left hand rule for current-carrying conductor inside a magnetic field.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

The magnitude of the force depends on:

1. The magnitude of the current (I) inside the wire, measured in amperes (A).
2. The length (l) of the part of the conductor inside the magnetic field, measured in meters.
3. The strength of the perpendicular component of the magnetic field ($B_{\perp}$) passing through the conductor.

So, mathematically:

$$\boldsymbol{F = IlB_{\perp}}$$

Now, consider the armature of a coil of a dc motor connected to a battery as shown below:

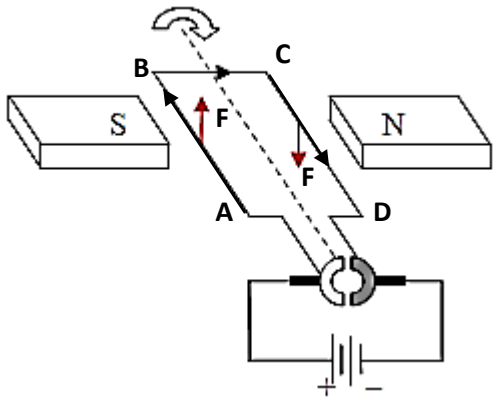


Figure 23: DC generator. The conductor experiences a force inside the magnetic field. The current flowing through the circuit is conventional

The maximum force is exerted on the conductor when it is perpendicular to the magnetic field and zero when it is parallel to it.

For the armature in figure 23, AB and CD experience a maximum force since they are perpendicular to the magnetic field.

BC and AD experience no force because they are parallel to the magnetic field.

A force that tends to rotate an object is called torque.

Torque is defined as the moment of a force or the rotational effect of a force.

There is maximum torque exerted on the conductor when the force is perpendicular to the distance that connects the point of rotation to the point where the force acts.

The **torque** exerted on the coil is given by:

$$\boldsymbol{\tau_{max} = NIAB}$$

Where:

- N is the number of turns of the coil.
- I is the current inside the coil in amperes (A)

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- A is the area of the coil in square meters (m^2)
- B is magnetic field through the coil (in tesla, T).

Therefore:

The torque on (and speed of rotation of) the armature can be increased by:

- Increasing the number of turns of the coil.
- Increasing the current through the coil.
- Increasing the area of the coil.
- Increasing the strength of the magnetic field i.e. using stronger magnets.

Inertia of the coil (EXAMINABLE).

Since the DC motor has split-rings which are separated from each other, there is a point (when the coil is perpendicular to the magnetic field) during the rotation of the armature where the carbon brushes are not in contact with the split rings. At this point, there is no current flowing in the armature.

What keeps the armature rotating at this point, is the inertia of the coil.

Inertia is the tendency of an object to resist any change in its state of motion.

<u>Use of AC generators</u>

1. Generation of electric power in power plants (e.g. hydroelectric power plants, wind power plants, nuclear power plants, coal-fired power plants and geothermal power plants). (See figure 2 and 3).
    - Alternating current is easy to step-up (increase by using a step-up transformer) and step-down (decrease by using a step-down transformer).
    - Most household appliances (appliances found at 'home') work on alternating current.

<u>Uses of DC generators.</u>

1. In factories that do electroplating (covering a metal with another metal).
2. In factories that produce chemicals such as chlorine and aluminium through electrolysis (use of electricity to make a chemical reaction occur).
3. In locomotives that are driven by diesel-electric motors.

N.B. Due to the use of commutators (which are expensive), many DC generators are being replaced by AC generators.

<u>Uses of electric motors</u>

1. Escalators (lifts) and elevators.
2. Cars e.g. starter, windscreen wipers.
3. CD players.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Alternating current.

Alternating current is current that changes direction periodically according to a specified frequency.

Alternating emf (or voltage) is voltage that changes polarity periodically according to a specified frequency.

In South Africa, power stations produce current and voltage with a frequency of 50 Hz.

The graph of voltage versus time for alternating current is sinusoidal as can be seen in figure 24:

The output voltage (V) varies as the armature of an AC generator rotates. The crests and troughs of the graph represent the **maximum or peak voltage (V_{max}).**

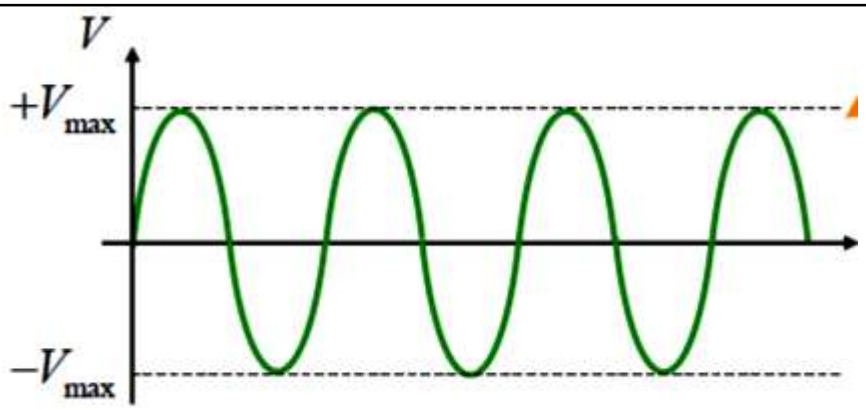


Figure 25: Output voltage of an AC generator varies with time as the armature rotates. Note that the average voltage is zero. (**V_{av} = 0 V**)

The graph of current versus time for alternating current is also sinusoidal as can be seen in figure 25:

The output current (I) also varies with time as the armature rotates. The crests and troughs of the graph represent **maximum or peak current (I_{max})**

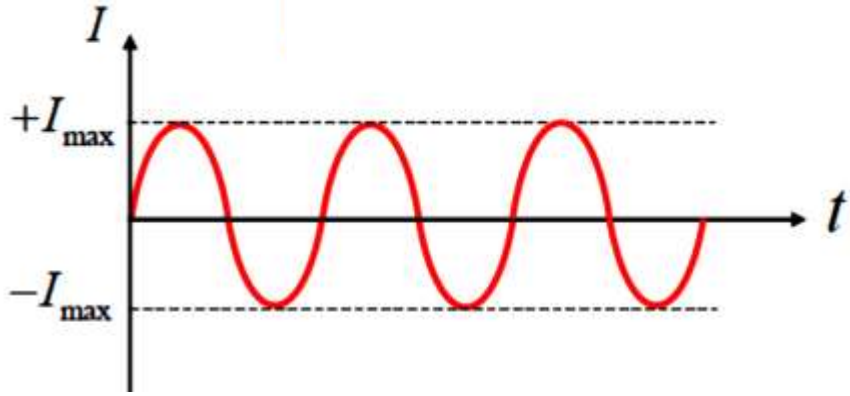


Figure 26: Output current (I) of an AC generator varies with time as the armature rotates. Note that the average current is zero. (**I_{av} = 0 A**)

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

The root-mean-square (RMS) values for AC current and voltage.

Since the output voltage and current varies for AC generators, there is no one single value that can be used to calculate, for example, the power dissipated in an electric kettle over time.

The average current and average voltage for alternating current, also gives us nothing to work with since it is equal to zero.

Scientists have found a way to work around this problem using the root-mean square values of the current and voltage for AC current and voltage.

The root-mean-square value is the square root of the average of the square of the AC current or voltage.

RMS voltage is the value of the voltage in a DC circuit that will have the same heating effect as an AC circuit.

RMS current is the value of the current in a DC circuit that will have the same heating effect as an AC circuit.

If every output value of voltage is squared in figure 24, every value becomes positive and the average can be found.

A graph of V^2 versus time is shown below.

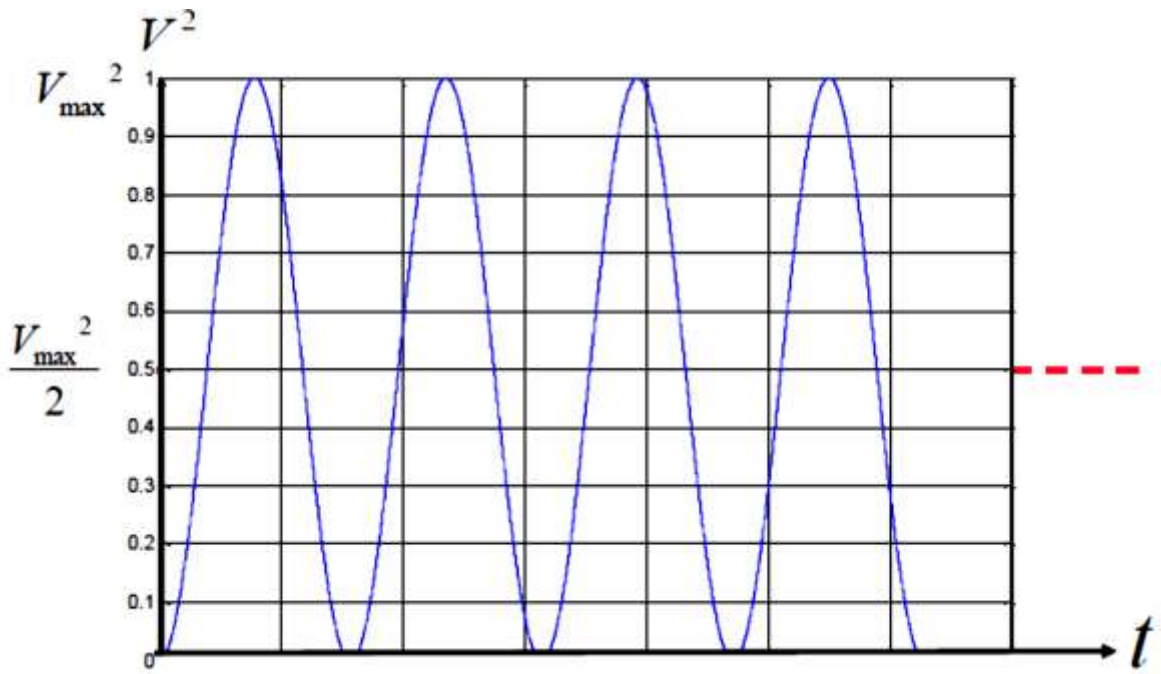


Figure 26: Graph of V2 versus time for AC current. Note the average value.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

$$V^2{}_{av} = \frac{V_{max}{}^2}{2}$$

V_{av} is called the root-mean-square (**rms value**) value of the voltage (**V_{rms}**). To get the average voltage, we obtain the square root of both sides of the equation:

$$V_{rms} = \frac{V_{max}}{\sqrt{2}}$$

Where

- **V_{rms}** is the root-mean-square value of the ac voltage in volts (V)
- **V_{max}** is the maximum voltage in volts (V)
- In the same manner, the rms value of current (**I_{rms}**) is:

$$I_{rms} = \frac{I_{max}}{\sqrt{2}}$$

Where:

- **I_{rms}** is the root-mean-square value of the **ac** current in amperes (A).
- **I_{max}** is the maximum current of the **ac** current in amperes (A)

Calculating average power in AC circuits (purely resistive).

For a purely resistive circuit, we use the following equations to calculate average power dissipated.

$$P_{ave} = \frac{1}{2} I_{max} \times V_{max}$$

$$P_{ave} = I_{rms} \times V_{rms}$$

$$P_{ave} = I_{rms}{}^2 R$$

$$P_{ave} = \frac{V_{rms}{}^2}{R}$$

Where:

- P_{ave} is the average power dissipated in watts (W).
- I_{max} is the maximum ac current in amperes (A).
- V_{max} is the maximum output ac voltage in volts (V)

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- I_{rms} is the rms current in amperes (A).
- V_{rms} is the rms voltage in volts (V).
- R is the resistance of the resistor (or an electrical appliance e.g. kettle) in ohms.

N.B.:

- V_{max} is always greater than V_{rms}.
- I_{max} is always greater than I_{rms}.

Advantages of AC over DC

1. Alternating current can be stepped-down or stepped-up (using transformers)
2. It can be transferred over long distances with minimal or no loss of power.
3. AC can be generated in much higher voltages than DC.
4. AC generators are easier and cheaper to construct than DC generators as they do not consist of commutator.

Problem-solving of common exam-type questions based on electrodynamics

1. Multiple-choice questions.

General approach:

Try to answer the question (where possible) without looking into the given options. Otherwise, scribble some information that you have regarding the question on the question paper.

1.1. (Taken from Feb/March Physics supplementary exam, grade 12, 2015).

Question:

The speed of rotation of coils in an AC generator is increased. Which ONE of the following combinations of frequency and output voltage for the generator will occur as a result of the change?

	Frequency	**Output voltage**
A	Increases	Increases
B	No change	Increases

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

C	Decrease	Decreases
D	Increases	No change.

Approach:

Recall that one way of increasing the induced emf of a generator (according to Faraday's law) is to **increase the rate of change in magnetic flux** (page 1 in this paper) which can be done by **rotating the coil faster**.

Also recall that **the faster the rotation, the more revolutions** are completed in a short time.

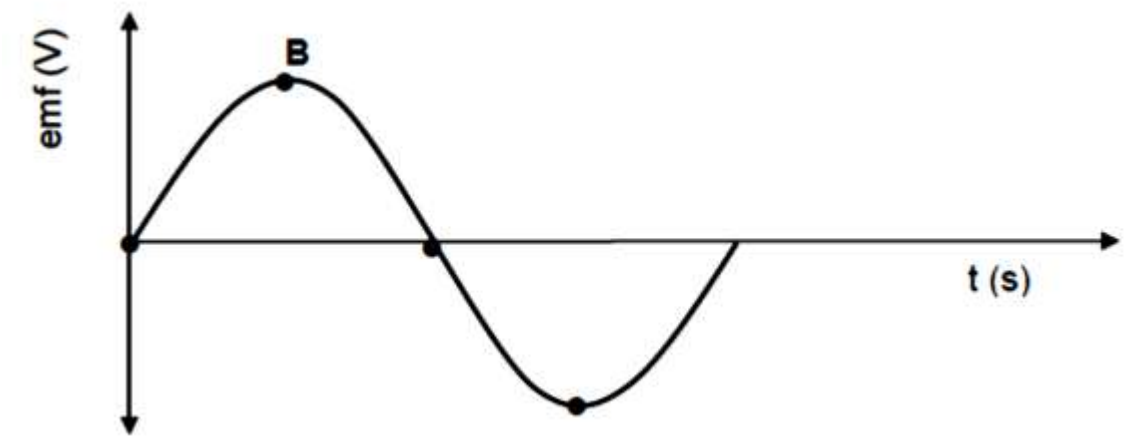
Thus by increasing the speed of rotation of the coil, the output voltage and the frequency of the ac voltage increase.

Answer:

A.

1.2. (Taken from November Physics final exam, grade 12, 2014).

The coils of an AC generator make one complete rotation. The resulting graph for the output emf is shown below.



The position **B** on the graph is obtained when the plane of the coil is at an angle of … to the magnetic field.

A 0°

B 60°

C 90°

D 120°

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

Approach:

Recall that the emf induced (or output voltage) in an AC generator is maximum when the magnetic flux is minimum and vice versa.

- The emf is maximum at the crest and trough.
- The emf is minimum (zero) at the origin and anywhere else where the graph intersects (cuts) the time (or x) axis.
- The magnetic flux is minimum when the coil is parallel to the magnetic field ($\theta = 0^o$)
- The magnetic flux is maximum when the coil is perpendicular to the magnetic field ($\theta = 90^o$)

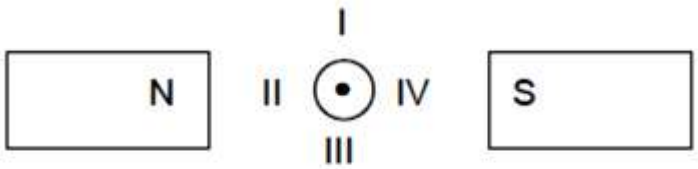
Since, an angle of zero means, minimum magnetic flux, it represents the maximum emf (point B on the graph).

Answer:

A.

1.3. (Taken from Exemplar Physics exam, grade 12, 2014).

In the diagram below, a conductor placed between tow magnets is carrying current out of the page.



The direction of the force exerted on the conductor is towards:

A I
B II
C III
D V

Approach:

Recall the motor effect i.e. a current-carrying conductor experiences a magnetic force with a direction that is perpendicular to the direction of the current and the magnetic field through it. (Page 17 of this paper).

Also recall the left-hand motor rule (or Fleming's left hand rule) in which, the thu**m**b, **f**irst finger and se**c**ond finger represent the force (or **m**ovement of conductor), **f**ield and **c**urrent when outstretched:

- Thu**m**b – direction **m**ovement of conductor (unknown yet).
- **F**irst finger – direction of magnetic **f**ield.
- Se**c**ond finger – direction of **c**urrent

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

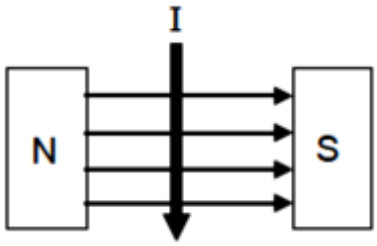
Thus, the direction of the movement (or force) on conductor is upwards, towards I.

Answer:

A.

1.4. (Taken from November Physics final exam, grade 12, 2013).

In the sketch below, a conductor carrying conventional current, I, is placed in a magnetic field.



Which ONE of the following best describes the direction of the magnetic force experienced by the conductor?

A	Parallel to the direction of the magnetic field
B	Opposite to the direction of the magnetic field
C	Into the page perpendicular to the direction of the magnetic field
D	Out of the page perpendicular to the direction of the magnetic field

Approach:

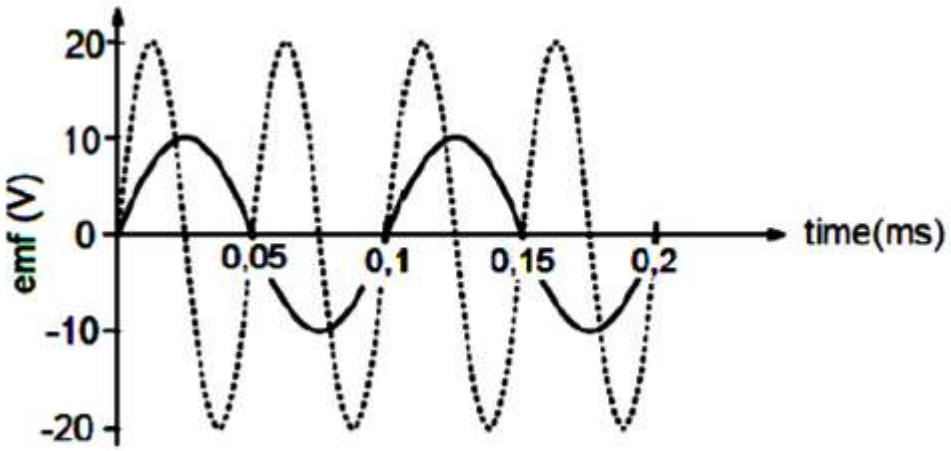
Same as the one in question 1.3. above i.e. use the left-hand motor rule to determine the direction of the magnetic force exerted on the conductor.

Answer:

D

1.5. (Taken from September Physics trial exam, grade 12, Western Cape, 2014).
In the graph shown, the solid curve shows how the emf produced by a simple generator varies with time. The dashed curve is the output from the generator after a change was made to the generator.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO



What change was made to produce the result shown?

A The area of the coil was doubled

B A commutator was added

C The number of turns in the coil was doubled

D The speed of rotation of the coil was doubled.

Approach:

Try to understand what the shape of the graph indicates.

- For the solid curve, the maximum emf is 10 V and it is 20 V for the dashed curve.
- The solid curve shows 2 complete "waves" which represents 2 revolutions whilst the dashed curve shows 4 complete "waves" which represents 4 revolutions.
- Therefore, the dashed curve represents a higher frequency and therefore faster or double the rotation represented by the solid curve.

Furthermore:

- Increasing area of coil and number of turns will increase emf induced but will have no effect on the frequency of graph.
- Replacing slip rings with commutators changes type of current (and emf) induced and shape of graph, not the magnitude.

Answer:

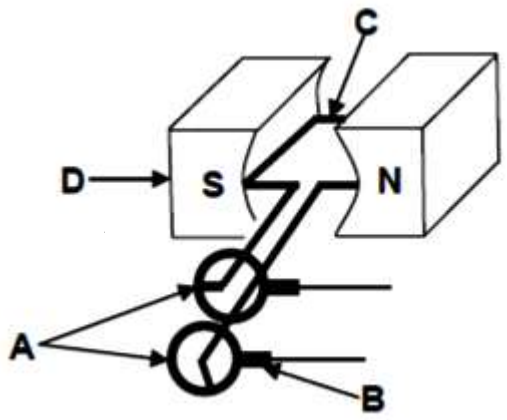
D

Long questions

- **Question 10: (Taken from November Physics final exam, grade 12, 2013).**

The simplified sketch represents an AC generator. The main components are labelled **A**, **B**, **C** and **D**.

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO



10.1 Write down the name of component:

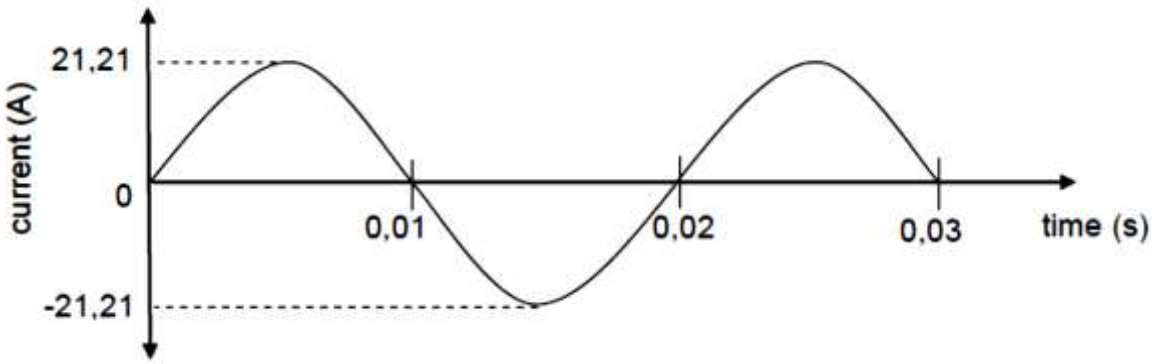
10.1.1 A (1)

10.1.2 B (1)

10.2 Write down the function of component B. (1)

10.3 State the energy conversion which takes place in an AC generator. (1)

A similar coil is rotated in a magnetic field. The graph below shows how the alternating current produced by the AC generator varies with time.



10.4 How many rotations are made by the coil in 0,03 seconds? (1)

10.5 Calculate the frequency of the alternating current. (3)

10.6 Will the plane of the coil be PERPENDICULAR TO or PARALLEL TO the magnetic field at t = 0,015 s? (5)

10.7 If the generator produces a maximum potential difference of 311 V, calculate its average power output. (5)

Solutions:

10.1 **Approach:**

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- Consult page 6 of this paper:
- Identify the device as an AC generator and try to label all the components of the generator. This will ensure that you don't label the components incorrectly.

Answers:

10.1.1. Slip rings.✓

10.1.2. Carbon brush✓

10.2 **Approach:**

- Same as in number 10.1 i.e. consult and revise **page 6** of this paper i.e. the functions of an AC generator.

Answer:

Maintains electrical contact with slip rings. ✓

OR:

Takes/ conducts current out of the coil. ✓

10.3 **Approach:**

- Identify the device as an AC **generator. (stated in the statement above the sketch)**
- Consult **page 3** of this paper i.e. the energy conversion that takes place in a generator.

Answer:

Mechanical energy is converted to electrical energy. ✓

10.4 **Approach:**

- Revise **pages: 10 to 13** and **figure 12 to figure 16** in this paper.
- Look at the sketch. Notice that "one wave" on the graph represents one complete rotation of the coil.
- Count the number of "waves" in the graph.

Answer:

1,5 rotations✓

OR One and a half rotation.

10.5 **Approach:**

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- Recall that **frequency is equal the inverse of the period of a wave. ($f = \frac{1}{T}$)**
- ***Period is the time taken to complete one wave or cycle***.
- In this case, the time taken to complete one cycle (or one "wave") is 0,02 seconds. (**period (T) = 0,02 s**).
- List your known and unknown variables:
  $f = ?, T = 0{,}02\ s$.
- Look for a suitable equation in the formula sheet under "ALTERNATING CURRENT". If it is not available, try to think of one learnt in earlier grades i.e. $f = \frac{1}{T}$
- Do the calculations. Do not forget to write the **answer with** the **correct SI unit.**

Answer:

$f = \frac{1}{T}$ ✓

$= \frac{1}{0{,}02}$ ✓

$= 50\ Hz$ ✓

10.6 **Approach:**

- Revise **pages: 10 to 13** and **figure 12 to figure 16** in this paper.
- Recall that **when the emf (and current) induced is maximum (crest and trough or highest point and lowest point on the graph), the magnetic flux is minimum** and the **plane of the coil is parallel to the magnetic field** and **when the emf (and current) induced is minimum (zero, x-intercept or when graph cuts x-axis or time-axis), the magnetic flux is maximum and the plane of the coil is perpendicular to the magnetic field**.
- **Find the time value** on the graph where **t = 0,015 s** which is **half-way between 0,01 s and 0,02 s** and at this point the

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

current is maximum, so the **magnetic flux is minimum** and the **coil is parallel to** the magnetic field.

Answer:

Parallel to✓

10.7 **Approach:**

- List your variables i.e. known and unknown:

  $V_{max} = 311\ V$, $P_{ave} = ?$

  The maximum current can be read from the graph (take the value that corresponds with the highest point on the graph).

  $I_{max} = 21{,}21\ A$

- Find a **suitable equation** from the formula sheet under "**ALTERNATING CURRENT**"

Answer:

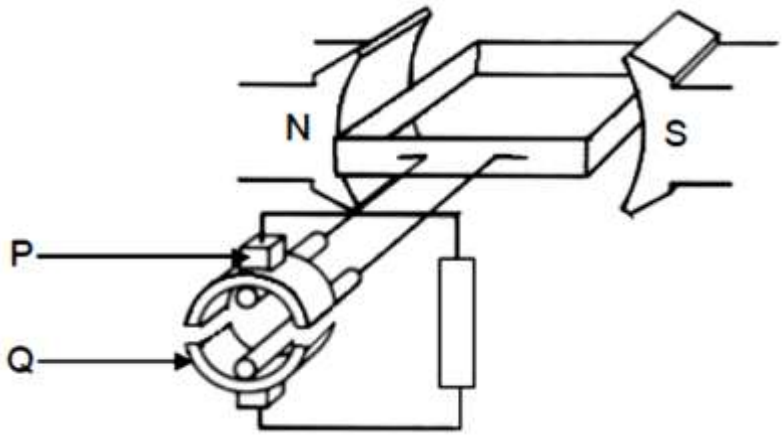
$P_{ave} = \frac{1}{2} I_{max} \times V_{max}$ ✓✓

$= \frac{1}{2} \times 21{,}21$ ✓ $\times 311$ ✓

$= 3298{,}16\ W$ ✓

- **Question 10: (Taken from Feb/March Physics supplementary exam, grade 12, 2013).**

AC generators and DC generators differ in their construction and the type of current they deliver. The simplified sketch below represents a DC generator.



10.1 Which components (**P** or **Q**) enables this generator to produce DC? (1)

10.2 What structural change must be made to this generator to change it to an AC generator? (1)

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

10.3 Briefly explain why ESKOM prefers using AC instead of DC for long distance transmission of electricity. (2)

10.4 An AC generator delivers 240 V_{rms} to a 60 W light bulb. The peak current in the light bulb is 0,35 A.

Calculate the:

10.4.1 rms current in the light bulb. (3)

10.4.2 Resistance of the light bulb. (3)

Solutions:

10.1 **Approach:**

- Understand that the sketch represents a DC generator (statement above sketch also indicates).
- Revise the functions of the basic components of a DC generator in this paper.
- Notice that component P represents the carbon brush whilst component Q represents a commutator (or split ring).
- The commutator allows the current to only flow in one direction, enabling the generator to work as a DC generator by doing so.

Answer:

Q. ✓

10.2 **Approach:**

- Recall the main structural differences between an AC generator and a DC generator, pages 5 and 14 of this paper.

Answer:

Replace the split rings (or commutators) with slip rings. ✓

10.3 **Approach:**

- Revise advantages of AC over DC on page 24 of this paper.
- The question specifically refers to transmission of electricity over long distances thus the answer should also refer to **long distance**

Answer:

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

AC can be transmitted over long distances with minimal or no loss of power. ✓✓

10.4.1 **Approach:**

- List your variables:

  $V_{rms} = 240\ V$, $I_{max} = 0{,}35\ A$

  Recall that the power specified for AC appliances is the average power dissipated:

  Thus: $P_{ave} = 60\ W$

- Find a suitable formula in the formula sheet under the section "ALTERNATING CURRENT"

Answer:

$I_{rms} = \frac{I_{max}}{\sqrt{2}}$ ✓

$= \frac{0{,}35}{\sqrt{2}}$ ✓

$= 0{,}25\ A$ ✓

10.4.2 **Approach:**

- Same as in question 10.4.1.

Answer:

$P_{ave} = \frac{{V_{rms}}^2}{R}$ ✓

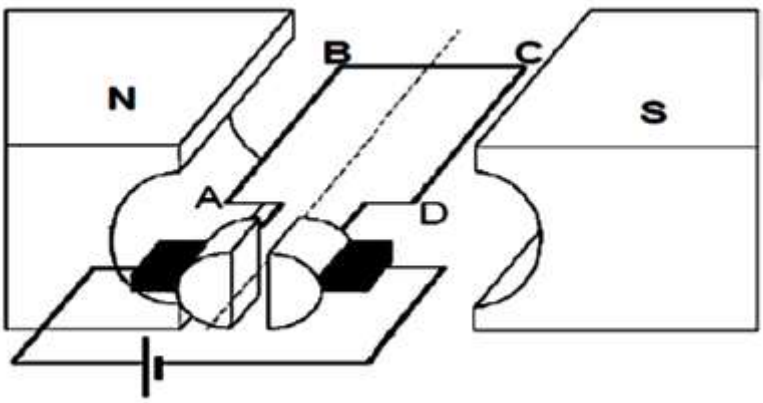
$60 = \frac{(240)^2}{R}$ ✓

$60 \times R = 57600$

$= 960\ \Omega$ ✓

- **Question 8: (Taken from September Physics trial exam, grade 12, 2014, Eastern Cape).**

The simplified sketch below represents a DC motor.



© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

8.1 Name the principle on which the motor operates (1)

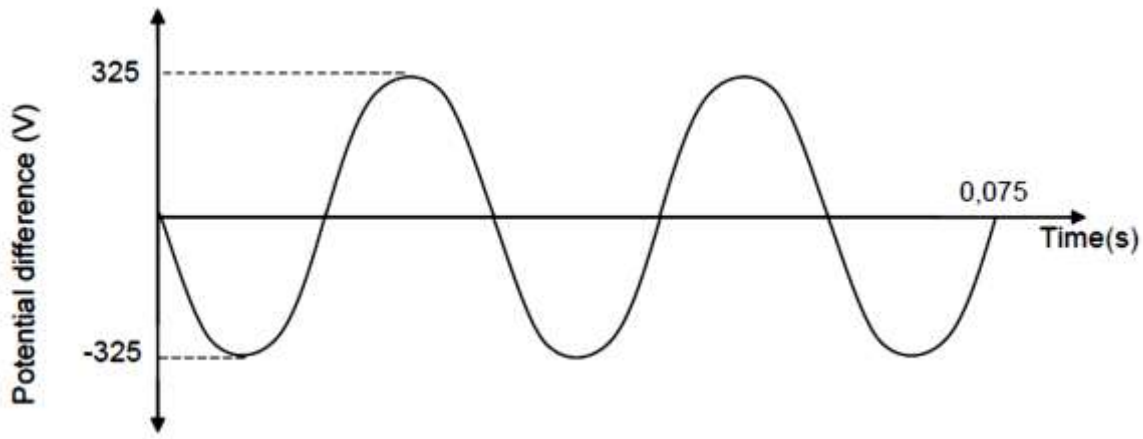
8.2 State the energy conversion which takes place in a DC motor. (1)

8.3 Give a reason why section BC in the above diagram does NOT experience a magnetic force whilst in the position as shown. (2)

8.4 In which direction will the coil rotate, CLOCKWISE or ANTI-CLOCKWISE? (1)

8.5 Write down one way in which the turning effect (torque) can be increased (1)

8.5 The generator below shows how the alternating voltage, produced by the AC generator, varies with time.



8.6.1 Calculate the frequency of the alternating voltage. (3)

8.6.2 The generator's average power output is 2,7 kW. Calculate the maximum current that the generator produces. (5)

Solutions:

8.1 **Approach:**

- Revise the section of this paper on principle of operation of a motor on **pages 17 to 19**.

Answer:

The motor effect. ✓

8.2 **Approach:**

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- Recall the energy conversion that takes place in motors in **page 17** of this paper.
- Understand that a motor uses electrical energy to do mechanical work.

Answer:

Electrical energy is converted to mechanical energy. ✓

8.3 **Approach:**

- Understand that the maximum force is exerted on the current carrying conductor when it is perpendicular to the magnetic field and minimum force (F = 0) is exerted when the conductor is parallel to the magnetic field. (**Page 19**)

Answer:

Because the conductor is parallel to the magnetic field. ✓✓

8.4 **Approach:**

- Find the direction of current by recalling that conventional current flows from positive terminal to negative terminal of battery (or cell). In this case, the **direction of the current is from A to B. (into the page). Page 18.**
- Apply Fleming's left-hand motor rule **(Page 18).**
  Where the thumb, first finger and second finger represent the following when outstretched:
  - ✓ Thu**M**b: **M**ovement of conductor.
  - ✓ **F**irst finger: magnetic **F**ield.
  - ✓ Se**C**ond finger: **C**urrent.
- In this case, for section AB of the armature:
  Thumb: points downwards:
  First finger: points to the right.
  Second finger: points into the page (A to B).
  So, AB will move downwards whilst CD will move upwards.

Answer:

Anti-clockwise. ✓

8.5 **Approach:**

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

- Consult page 19 of this paper on torque and the factors that it depends on for a motor. i.e.

  Torque depends on:

  - ✓ number of turns (N) in the coil. The greater the number of turns, the greater the torque.
  - ✓ the current (I) in the coil. The greater the current, the greater the torque.
  - ✓ the area (A) of the coil. The greater the area through which the magnetic field passes, the greater the torque.
  - ✓ the strength of the magnetic field (B). the stronger the external magnetic field, the greater the torque.

Thus, the torque can be increased by increasing any of the 4 quantities.

Answer:

- ✓ Increase the number of turns in the coil. ✓
- ✓ Increase the current in the coil. ✓
- ✓ Increase the area of the coil. ✓
- ✓ Increase the strength of the magnetic field by using stronger magnets. ✓

(any of the 4)

8.6.1 **Approach:**

- Recall that frequency is equal to the inverse of period of a wave or the number of complete cycles per second.
- Count the number of complete rotations using the complete "waves" on the graph i.e. 2,5.
- Read the total time as 0,075 s.
- Find the period and use it to find the frequency:

Answer:

$$T = \frac{total\ time}{total\ number\ of\ complete\ rotations}$$

$$= \frac{0{,}075}{2{,}5}$$

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO

$= 0{,}03\ s$✓

$f = \frac{1}{T}$

$= \frac{1}{0{,}03}$✓

$= 33{,}33\ Hz$✓

8.6.2 **Approach:**

- List your variables:

  $V_{max} = 325\ V\ read\ from\ the\ graph,\ P_{ave} = 2{,}7\ kW$ (k stands for kilo which means "1000"

Convert the power to the correct SI unit:

$P_{ave} = 2{,}7 \times 1000$

$= 2700\ W$

$I_{max} = ?$

- Find a suitable formula in the formula sheet under the section "ALTERNATING CURRENT"

Answer:

$P_{ave} = \frac{1}{2} I_{max} \times V_{max}$✓✓

2700✓ $= \frac{1}{2} \times I_{max} \times 325$✓

$2700 = 162{,}5 \times I_{max}$

$I_{max} = 16{,}62\ A$✓

© O.F. MAHLOMBE, 2015. Download notes from onedrive: http://1drv.ms/1gYCyQO