CHAPTER 7

Generators

Generators are used to provide large scale power production

7.1 Generators

- ***Describe the main components of a generator***
- ***Compare the structure and function of a generator to an electric motor***

So far we have discussed the principle of magnetic induction in which mechanical energy can be converted to electricity via a changing magnetic flux. In this chapter, we will look closely at a specialised device that does this, the **generator**.

Definition

An **electric generator** is one that converts mechanical energy to electrical energy using the principle of electromagnetic induction.

Generators are the key functional unit of power stations. In power stations, various energy sources, such as fossil fuels, are used as the source of energy for the generators to produce electricity.

To describe a generator in very simple terms, we can say a generator has essentially the same design as an electric motor; however, it functions in the opposite way compared to that of a motor. Just like a motor, there are DC and AC electric generators. A schematic diagram of a simple DC generator is shown in the diagram below:

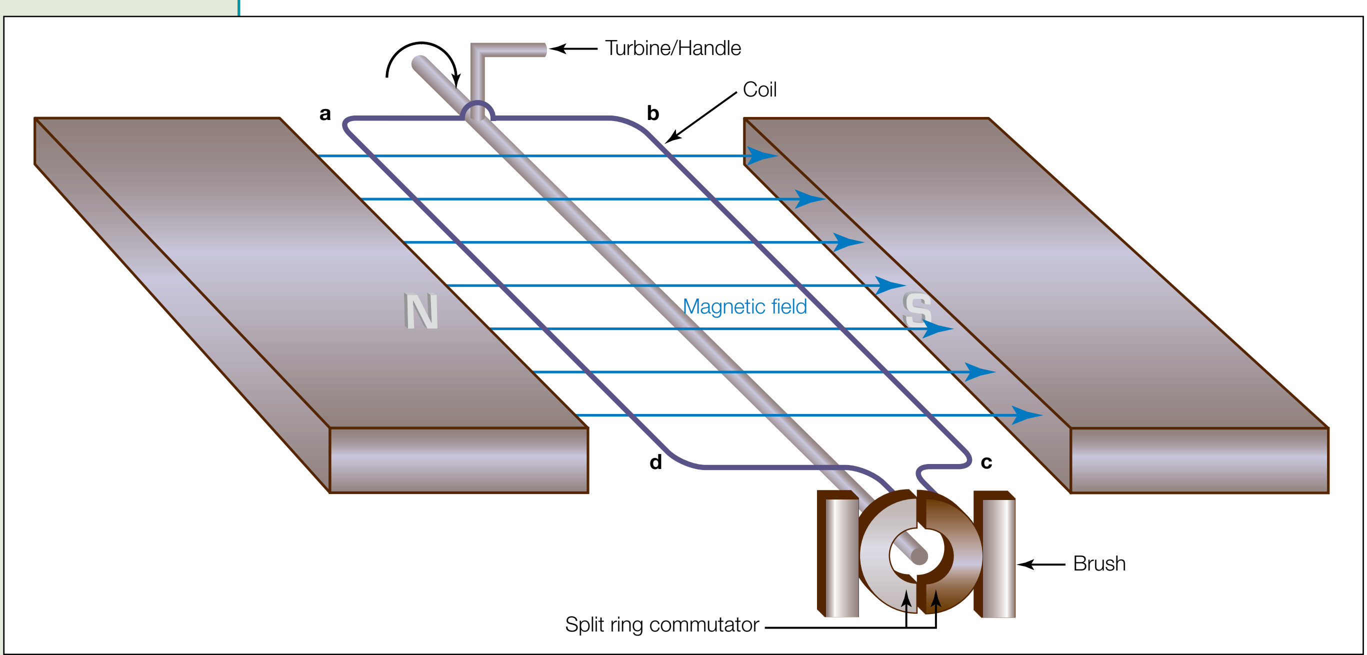


Figure 7.1 A simple DC generator

NOTE: In the context of this chapter, DC generators do not include galvanic cells (batteries).

The main functional components of an electric generator

The main components of a generator are:

- the magnetic field
- an armature
- a commutator
- the carbon brushes

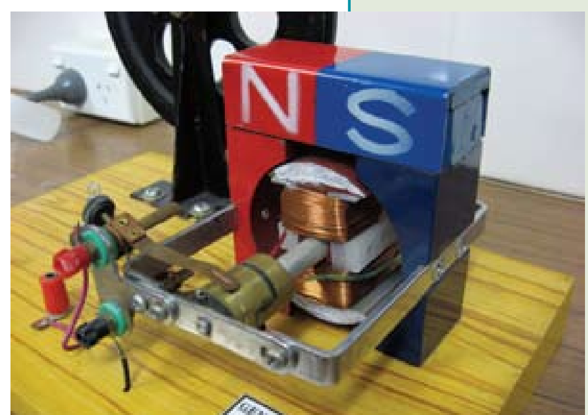
Magnetic field

As noted before, a changing magnetic flux is essential for the generation of electricity. Hence a magnetic field is essential for the function of a generator. The magnetic field can be provided by either permanent ferromagnets or electromagnets, as with motors. The changing magnetic flux is often created by creating a relative motion between the magnetic field and coil. The magnets are usually the stator in simple generators such as those described in this chapter, but in industrial motors, they are often the rotor. The relative motion, for instance, rotating the coil inside a magnetic field, is often achieved by the turning motion of a turbine, which is in turn powered by steam generated by burning of fossil fuels, or from hydropower or wind.

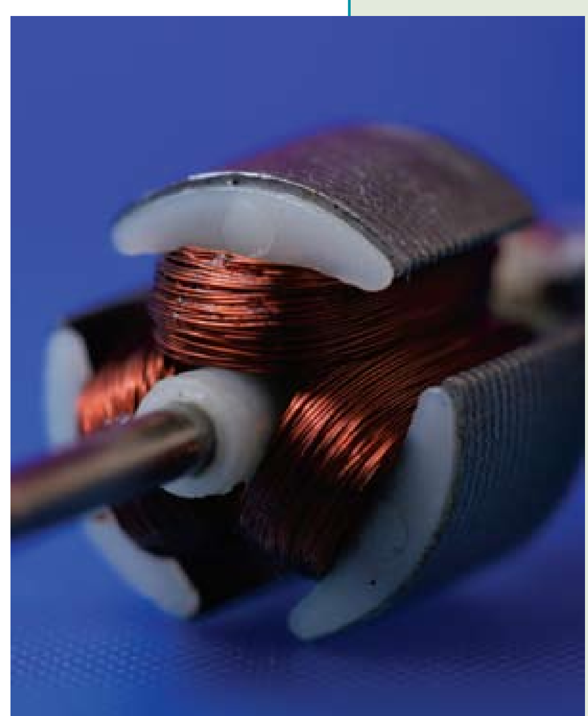
Armature

An armature refers to the coil of wire wound around a soft iron core. It can be a stator or rotor depending on the design of the generator. Multiple coil armatures are common for large scale electric generators.

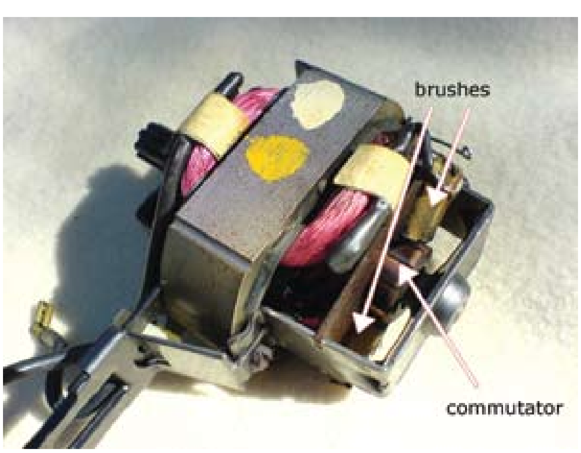
A generator at a power station



Magnets



An armature



Commutators and brushes

Commutator

The structure of commutators in generators is similar to that of motors. As in motors, DC generators have **split ring commutators**, whereas AC generators have **slip ring commutators**.

Carbon brushes

The carbon brushes in generators have the same structures, and are used for the same purpose as in electric motors. Refer to Chapter 5.

7.2 Magnetic flux, changing of flux and induced EMF

A few rules must be clarified before we move on. Figures 7.2 and 7.3 illustrate the different positions of the coil in a DC generator rotating clockwise inside the magnetic field.

In Figure 7.2, the coil is at a position that is parallel to the magnetic field. At this position the magnetic flux linked with the coil is zero as we have discussed before. However, it is very important to note that side 'ad' and 'bc' of the coil are 'cutting' the magnetic field lines perpendicularly, that is a maximum cut, so it follows that the changing flux at this position is the greatest. Consequently, the EMF induced when the coil is at this position is the greatest.

NOTE: Recall that a maximal 'cutting' of the magnetic field by convention means a maximum change in flux.

NOTE: Side 'ab' and 'dc' will not cut the magnetic field lines at any position during the course of rotation, therefore they do not participate in electromagnetic induction.

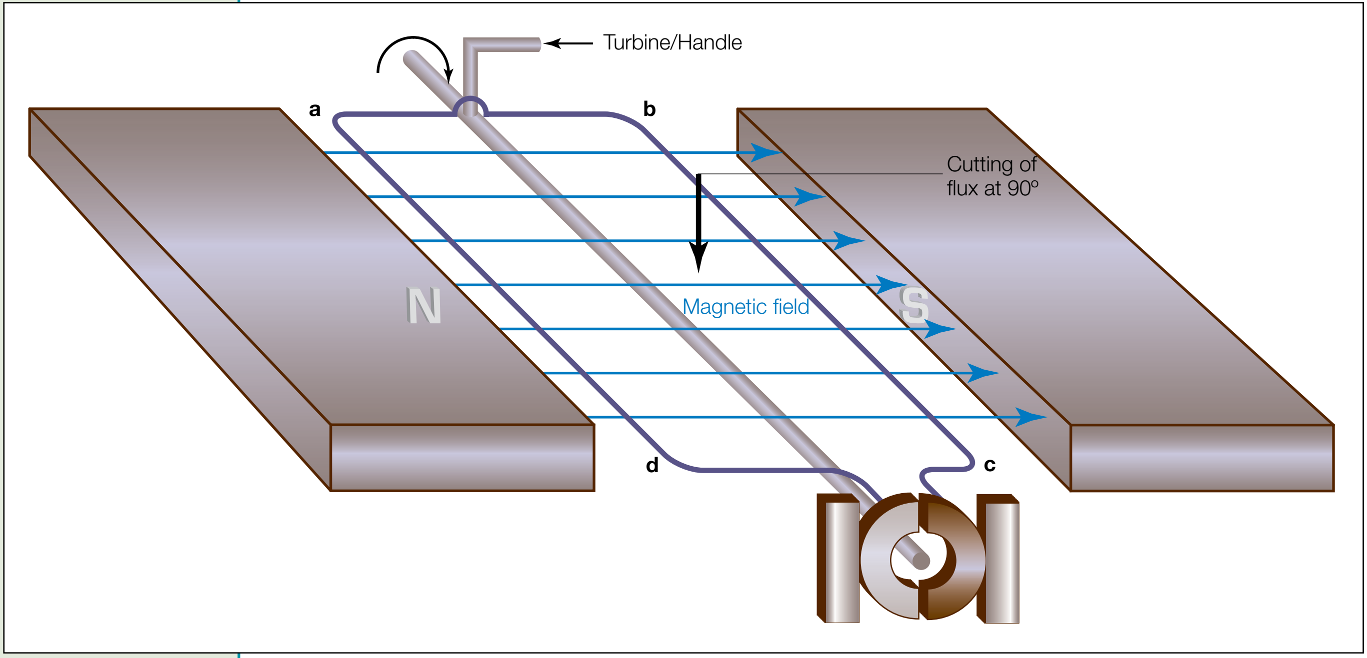


Figure 7.2 When the coil is parallel to the magnetic field

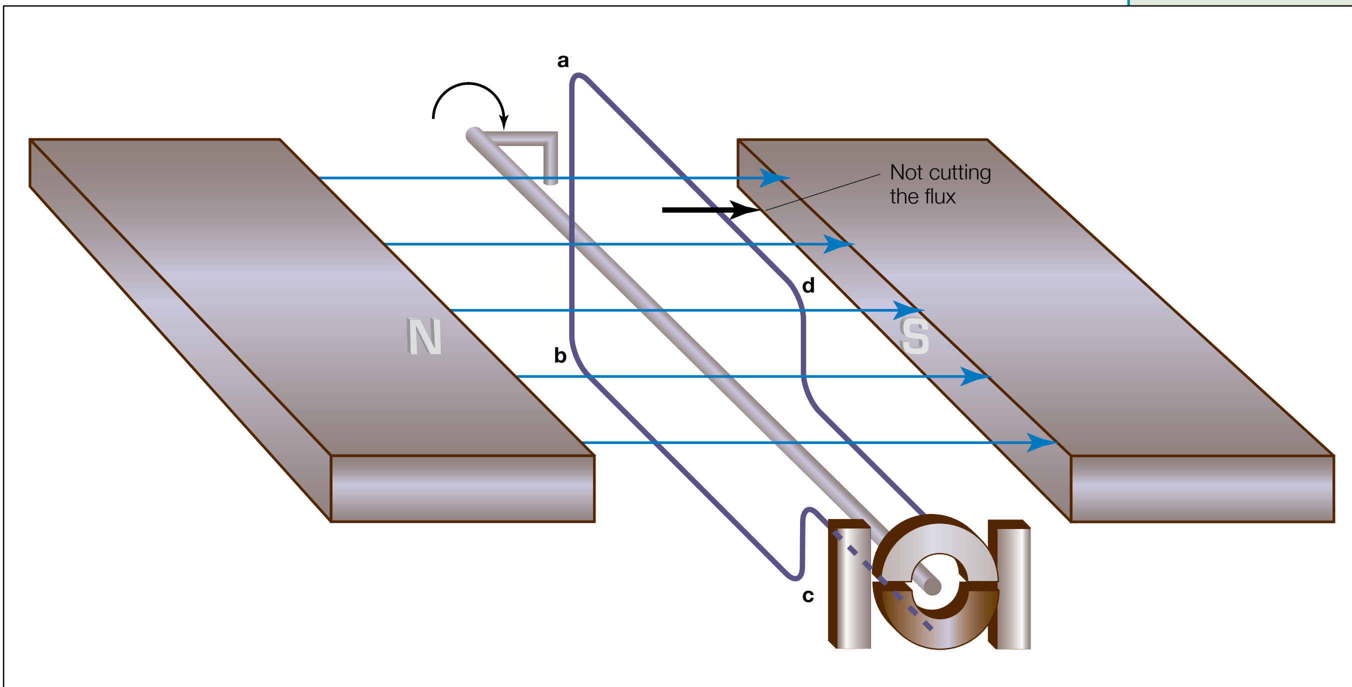


Figure 7.3
When the coil is perpendicular to the magnetic field

As the coil rotates, the amount of the magnetic flux through the coil gradually increases, and the change of magnetic flux (the cutting), and hence the size of induced EMF, gradually decreases.

Eventually, when the coil reaches a vertical position, as shown in Figure 7.3, the magnetic flux linked with the coil increases to a maximum. However, at this position, the side 'ad' and 'bc' are moving parallel to the magnetic field lines so there is no cutting of the field lines. Under this circumstance, the changing of magnetic flux is zero, therefore the size of the induced EMF drops to zero.

7.3 The difference between a DC generator and an AC generator

■ ***Describe the differences between AC and DC generators***

The major difference between a DC generator and an AC generator is the commutator used.

DC generator and split ring commutator

To understand the role and function of a split ring commutator in a DC generator, we need to look at it in conjunction with the nature of DC, as well as the way electricity is induced in the generator. Direct current (DC) by definition is one that flows in one direction only.

Consider the generator in Figure 7.4. The coil is at a position that is parallel to the magnetic field and is rotating clockwise between the poles of the permanent magnets.

As explained before, at this position, the EMF generated is a maximum. The direction can be determined by using the 'right-hand palm rule'. For example, for

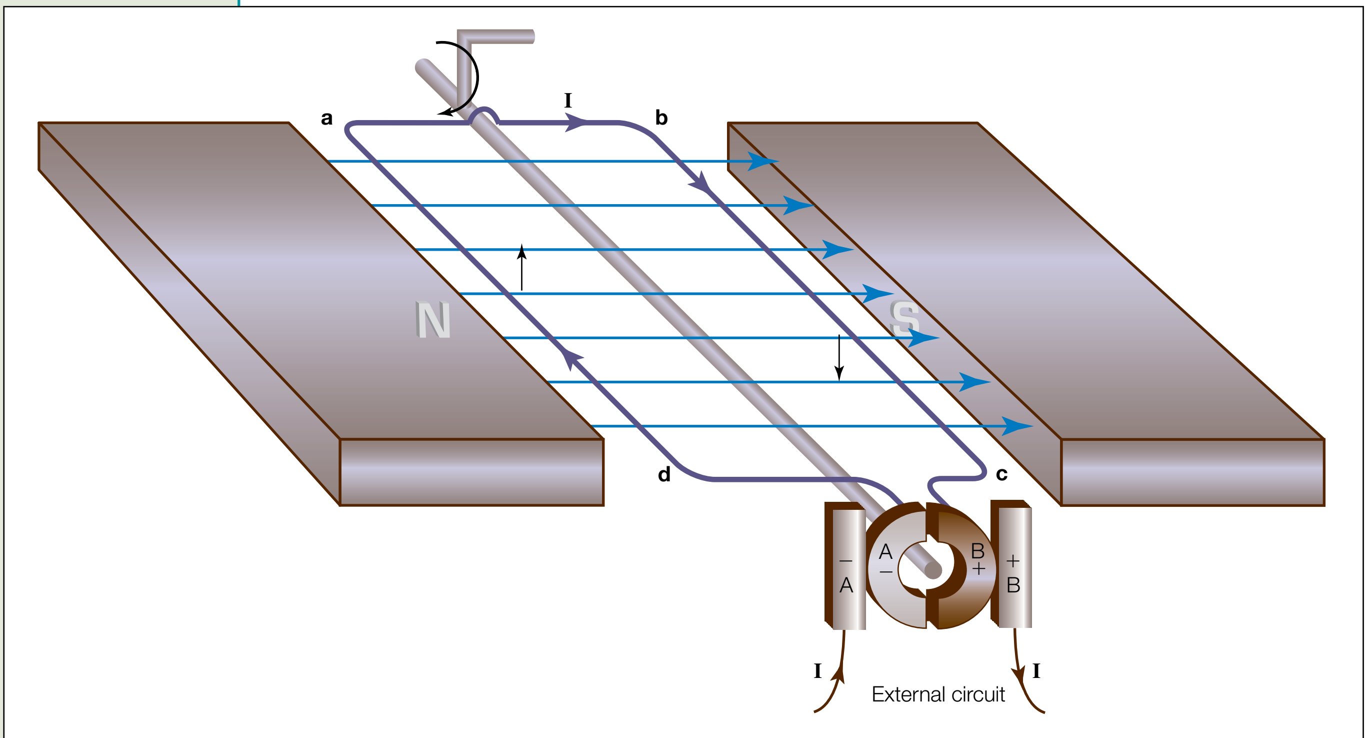


Figure 7.4
A DC generator with a split ring commutator

side 'ad', which is moving up, the palm of the right hand pushes down (Lenz's law), fingers to the right. The thumb will point from d to a, hence the current flows from d to a. Similarly, the current flows from b to c, consequently the current flows clockwise.

Hence the commutator A and the brush A will be *negative* and commutator B and brush B will be *positive*.

NOTE: Conventional current leaves at the positive terminal.

The size of the induced EMF decreases gradually and reaches zero when the coil is at the vertical position. This is shown in Figures 7.3 and 7.5. However, as soon as the coil goes pass this point, induced EMF starts to increase again as the coil now starts to cut the field lines again. As shown in Figure 7.6, by applying 'right-hand palm rule', the current is now flowing from a to d on side 'ad' and b to c on side 'bc'. More importantly the commutator A is now positive and the commutator B is negative. In other words, the polarity of the commutator is now reversed.

The importance of the split ring is that it allows the positive commutator A to contact brush B and negative commutator B to contact brush A so that brushes A and B retain the same **polarity** at all times, hence the same current flows in the external circuit even when the polarity of commutators A and B reverses. This makes the current a DC.

To summarise, the role of a split ring commutator in a DC generator is to allow each half of the commutator to contact a different brush every half rotation at the vertical positions. This is to ensure that as soon as the polarity of the half commutator reverses at the vertical positions, contact with the brush is also reversed. This is to ensure the brushes always maintain the same polarity, so that the direction of the output current can be maintained in one direction.

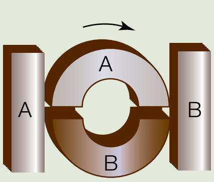


Figure 7.5 DC generator, coil at the vertical position

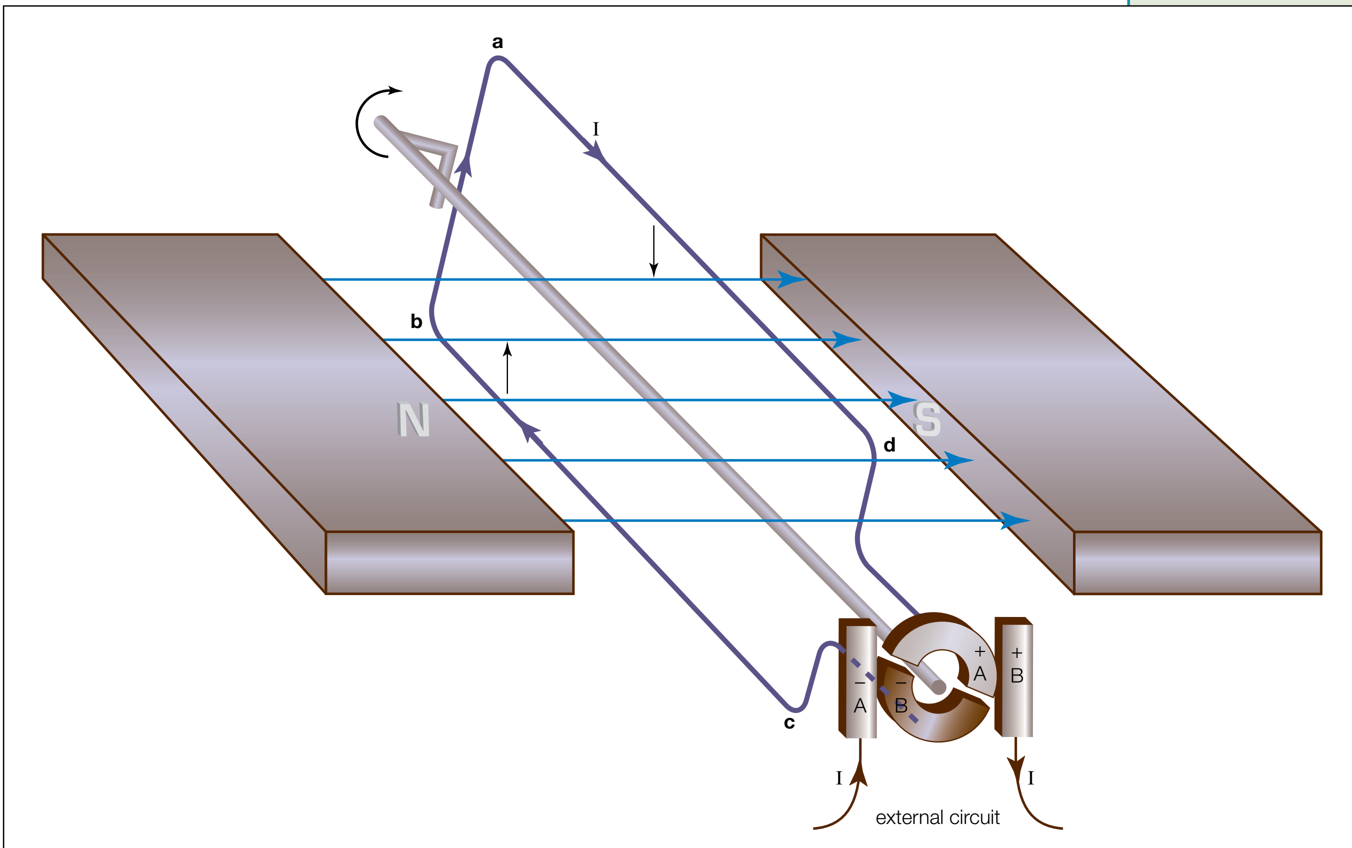


Figure 7.6 DC generator, coil at an inclined position

The EMF generated by a DC generator

To summarise all of the above, we can plot a graph of the EMF output of a DC generator against time or the position of the coil as it rotates through the magnetic field over one complete revolution:

NOTE: This DC generated is somewhat different from that generated by a galvanic cell (batteries).

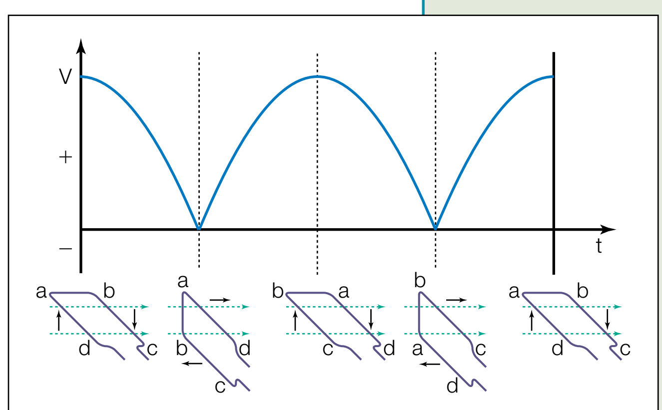


Figure 7.7 DC output

AC generator and slip ring commutator

The structure of a slip ring commutator is shown in Figure 7.8. The purpose and functional principle are simple as it is only a device to conduct electricity into and from the external circuit without tangling up the wires.

As the coil rotates inside the magnetic field, the polarity of two parts of the slip ring commutator reverses every half cycle at the vertical positions as in a DC generator (due to the reverse in the current direction in the coil). However, there is now no means by which they can change their contact with the brushes, so the polarity of the

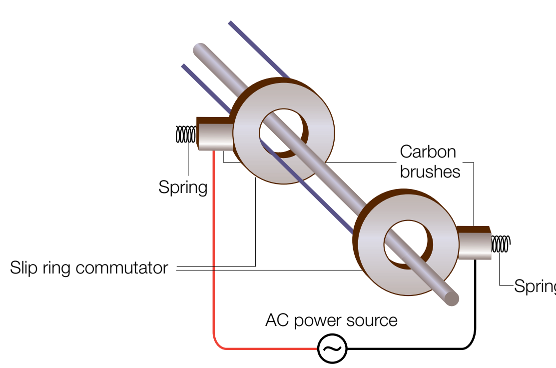


Figure 7.8 The structure of a slip ring commutator

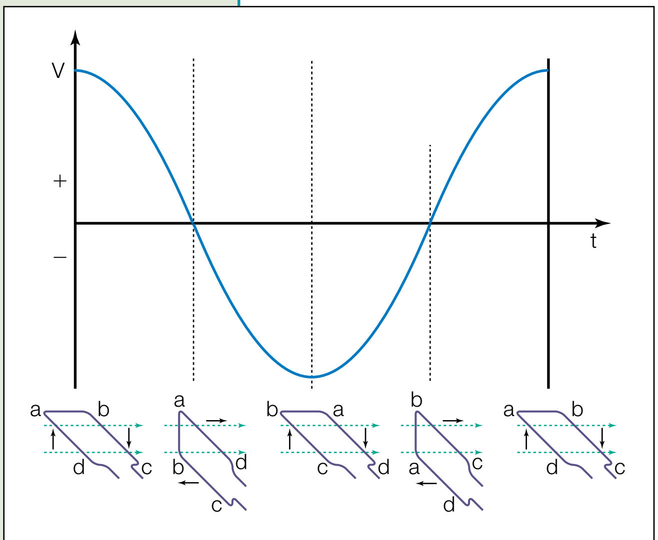


Figure 7.9
AC output

brush will also change every half cycle. This results in the current generated varying direction constantly, hence the name **alternating current** or AC.

To summarise events of the production of AC, we can also plot a graph of the EMF output of an AC generator against the position of the coil as it rotates through the magnetic field over one complete revolution, shown in Figure 7.9.

It is important to point out that for both DC and AC output from their respective generators, the period of the wave and so the frequency, as well as the amplitude of the current, depends on the speed of rotation. The period of the EMF varies inversely with the rotational speed, whereas the frequency and amplitude are directly proportional to the speed of rotation.

Three-phase AC generator

Compared to simple AC generators, large scale AC generators are often slightly modified in terms of their structures and functional principles. At power stations and in industries, three-phase AC generators are commonly used.

The structure of a three-phase AC generator is shown by a schematic drawing in Figure 7.10. It consists of three stationary coils (stator) situated at 120° to each other and a magnet that is made to rotate at the centre as the rotor.

Each stationary coil has its own power output. Consequently, the net output of this generator is three-phase AC current, where the AC waves are out of phase by 120° as shown in Figure 7.11.

The electricity produced by a three-phase AC generator is carried to consumers by three separate active wires. The electricity is returned to the generator by a single wire to complete the circuit. At a domestic level, usually only one active wire is used; however, in many industries, all three active wires may be used.

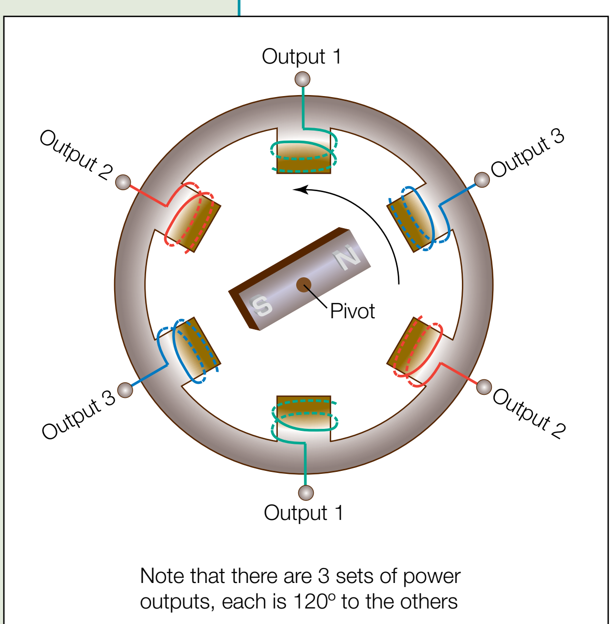


Figure 7.10
A schematic drawing of a three-phase AC generator

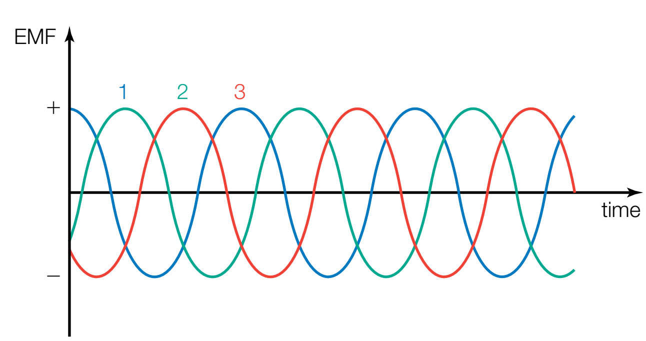


Figure 7.11 Three-phase AC current. All current waves areidentical but are out of phase by 120°

7.4

The transmission wires

Huge generators that provide electricity for a very large region are usually situated far away from the actual sites where electricity is used. Hence, electricity has to be distributed via long transmission wires. These wires run overhead over a very long distance and are supported intermittently by metal towers. Besides the cost of setting up such a distribution system, there are other issues affecting the electrical distribution system.

Insulating and protecting

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

H13.1A, B, C
H14.1B, G, H

- ***Gather and analyse information to identify how transmission lines are:***
  - ***insulated from supporting structures***
  - ***protected from lightning strikes***

Protection from lightning

When transmission wires are struck by lightning there is the risk of the system being damaged, or overloaded and shutting down, as well as damage to infrastructure like transformers, power poles and wires.

To protect these wires from lightning, there is usually another wire that runs over and parallel to the transmission wires, connected to earth. This wire does not carry current but in the case of lighting strikes, lightning will hit the overhead wire first and through it the huge current of the lightning will be diverted to earth, leaving the transmission wires untouched.

Transmission wires

Insulation of transmission wires from supporting towers

Overhead transmission wires are usually bare. Therefore, if they make contact with the supporting metal towers, two things will happen:

1. The metal towers will become live so anything that makes contact with the towers will experience an electric shock.
2. The wires will short circuit and disrupt the electricity distribution.

Neither of these is desirable, so the wires must be insulated well from the metal towers. To do so, the wires are suspended from the towers by insulators that consist of stacks of disks made from ceramic or porcelain. Porcelain is chosen because it is strong and retains its insulation properties even under a very high voltage. The disk-shaped insulators also increase the effectiveness of the insulation by minimising the chance of a spark jumping across the gap.

The porcelain disks

Energy lost during transmission

■ *Discuss the energy losses that occur as energy is fed through transmission lines from the generator to the consumer*

Transmission of electricity is not 100% energy efficient; rather, energy is lost during transmission from the power station to consumers. The energy lost is mainly in the form of heat. This is because as a current flows through a conductor that has resistance, heat will be dissipated. Since the resistance of a conductor is proportional to its length, wires that run over a very long distance will have a significant amount of resistance, so the heat dissipated (energy lost) is also quite substantial.

The heat lost during transmission can be quantitatively described by using the equation:

$$P = I^2R$$

Where:

P = heat lost during transmission, measured in J

I = the current flow through the wire, measured in A

R = the total resistance of the wire, measured in Ω

This equation can be derived by combining the **power equation $P = IV$** and **Ohm's law $V = IR$**.

In addition to the heat lost in the transmission wires, transformers used to change the voltage in the transmission process are less than 100% efficient. Approximately 6%, or 600 MW, of the power generated in New South Wales is lost as heat due to the resistance in the wires and transformers. With more than 500 km of wires between the Snowy Mountains hydro electric power stations and the end users in Sydney, such losses are unavoidable.

Energy or heat lost for AC transmission is much less than DC transmission. The reasons for this are discussed in Chapter 8.

Advantages and disadvantages of AC and DC generators

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

H13, 1A, B, C
H14, 1E

■ *Gather secondary information to discuss advantages/disadvantages of AC and DC generators and relate these to their use*

So far, we have considered the way electricity is produced by generators and distributed to consumers. An obvious question is, 'Why do we have two different types of generators?' This is because AC and DC generators have their own advantages and disadvantages.

In the following section, the advantages and disadvantages of AC and DC generators are compared. Note that the advantages of one type of generators are generally the disadvantages of the other, and vice versa. Discuss whether the advantages and disadvantages of AC and DC generators influence their uses.

Disadvantages of DC generators

- A DC generator requires a split ring commutator for its function. This inevitably complicates the design of the generator. This results in more expensive construction as well as more cost and effort for maintenance.
- The gap present in the split ring commutator results in sparks being produced during the generation of electricity.
- As described in the previous section (see also Chapter 8), the output of DC generators (DC electricity) loses more energy than that of AC generators during transmission.

A DC powered drill

Advantages of DC generators

- Some devices, such as battery rechargers and cathode ray tubes, rely solely on DC currents for their function. Although AC current can be converted to DC current using electronic devices, it will be more convenient and cost effective to produce DC directly using a DC generator.
- For a given voltage, DC current is generally more powerful than AC, so that DC is preferred in heavy-duty tools. Under this circumstance, DC generators are superior.

Disadvantages of AC generators

- Refer to the advantages of DC generators.
- For correct integration of electricity throughout the nation, the frequencies of AC generators in different regions must be synchronised, that is, the AC outputs must have the same frequency and be in-phase. This requires extra coordination.
- The output of AC generators (AC) is 10 times more dangerous than the equivalent DC generator output. This is because AC, with its conventional 50 Hz frequency, can most readily cause heart fibrillation.

Advantages of AC generators

- Refer to the disadvantages of DC generator.
- Three-phase AC currents are made possible, as described earlier. Three-phase AC has a variety of applications, such as powering **induction motors** (see Chapter 9).
- AC voltage is easily increased or decreased using transformers (see Chapter 8).

It is important to note that, although most power stations use AC generators, this does not mean that AC generators are absolutely more superior to DC generators.

The competition between Westinghouse and Thomas Edison

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

12.3A, B, D
12.4A, C, E, F

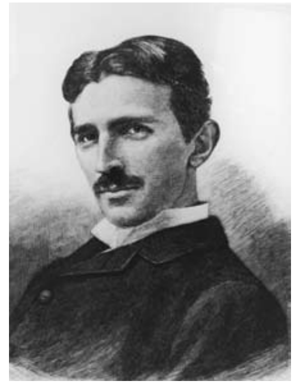
- ***Analyse secondary information on the competition between Westinghouse and Edison to supply electricity to cities***

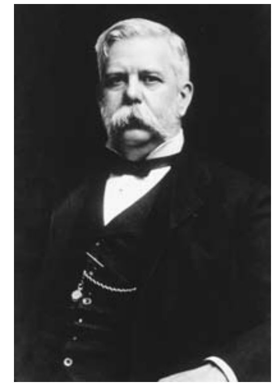
What were the contributions made by Thomas Edison and his system of supplying electricity?

Thomas Edison was a famous inventor. He collected many patents throughout his life. He was famous for the invention of electric light bulbs.

Edison was the first person to set up business to supply electricity (in 1878), and his system at the time was DC based. He initially installed light bulbs for homes, then street lights, which were all running on DC. His electricity and lighting system lit up New York City, and was shown to be very successful. He also developed DC motors and other appliances that ran on DC.


Thomas Edison


Nikola Tesla


George Westinghouse

Who was Nikola Tesla?

Nikola Tesla was the first person to demonstrate the production of AC and its transmission system in 1883. He worked for Edison for a few years. During this time, Edison did not approve his proposal to develop AC systems.

Nikola Tesla also invented AC motors, which made AC even more efficient to use.

Who was George Westinghouse and what was his system of supplying electricity?

Westinghouse was a wealthy businessman who bought the patent of the AC system from Tesla and opened up his own electric company (in 1885) in order to compete with Edison. His electricity supplying system was based on AC generators and transmission systems.

Who won and why?

Westinghouse was the overall winner, as the AC system was more efficient for two reasons. The split ring commutator in DC generators posed a problem with high speed rotation. Most importantly, AC transmissions through the action of **transformers** were much more energy efficient. This allowed electricity to be transmitted over longer distances with only a small amount of energy loss.

In 1886, there was a competition for inventors to propose plans to build a power plant using the power of Niagara Falls to supply electricity to distant cities. Both Edison and Westinghouse participated. Westinghouse proved the high energy efficiency of his AC system through many demonstrations, and eventually won the competition. He built his AC system at Niagara Falls a few years later, which confirmed the superiority of his system over Edison's DC system.

7.5 Assess the impacts of the development of AC generators on society and the environment

SR

'Assess'

■ *Assess the effects of the development of AC generators on society and the environment*

This is an 'assess' dot point, in which students need to give their own opinions and support them by examples and evidence. It is important to note that there is no perfect answer; however, the arguments must be logical and succinct.

The following sections discuss some impacts of AC generators. You may come up with your own opinions or ideas and may also research your own examples and evidence.

Wood-fired stove

Positive effects and impacts

Improvements in the standard of living

AC generators enable people to have electricity at home. Electricity makes people's lives more comfortable and luxurious. It allows people to have lights, heaters, air conditioners, electric tools, and so on. It provides people with entertainment, for instance, TV, movies, computers, all of which make life more exciting.

Electric oven

Efficient and clean energy

Electricity is very efficient energy. It is a matter of switching on an electrical device. Compare switching on a light bulb or an electric stove to lighting up a diesel lamp or a wood-fire stove—electricity is instantaneous and far more efficient.

Domestically, electricity appears to be the cleanest form of energy: compare an electric heater to a coal-fire heater that generates dirt and smoke. However, electricity is not an absolutely clean energy, because at the global level, pollution released by power plants still poses a major threat to the environment.

Concentration in production of electricity

If AC generators had not been developed, electricity production would be, at best, at very small regional levels. The invention of AC generators allows electricity to be generated at one centre. Such a concentration of energy production makes pollution much easier to manage. Also, because these big power plants are often situated far away from urban areas, the pollution effects on cities and people are reduced.

Regulation of energy production

Concentration of energy production also means energy production and consumption can be recorded and monitored. This is important for managing energy production as well as research.

A motor used in industry

Minimisation of energy lost through transmission

Because of the high energy efficiency in transmission of the AC system compared to the DC system, AC power plants can generally be situated far away from the site of energy consumption without losing significant amounts of energy during transmission. This results in less waste and less demand on energy resources. It also makes electricity cheaper to use.

Development of industry

Development of AC generators, especially with the invention of AC induction motors, stimulated the development of industry. AC generators also have an overall effect on stimulating the progress of technology.

Environmental pollution

Negative effects

Environmental pollution

Currently, the main source of energy used for AC generators is fossil fuels. Burning fossil fuels releases a variety of pollutants that can contaminate the atmosphere. The major one is CO_2, which contributes to the enhanced greenhouse effect. Hot water discharges from power plants into local waterways leads to thermal pollution of rivers and streams.

Nuclear energy also has a position in electricity production. Wastes from nuclear energy can pose a major threat to the environment.

Disturbance of natural habitats

Constructing large AC power plants requires modification to the landscape. This will inevitably disturb or even destroy local habitats or natural heritages. For instance, building a hydro-electric power plant might raise surrounding water levels by many metres, severely disturbing natural habitats. Nuclear power stations may also disturb natural habitats. Mining of energy sources (coal) has a similar effect.

Accidents

Injuries and deaths from electric shocks have become more common with the widespread use of AC power. Fire hazards and other accidents associated with AC powers are also very common.

Accidents at nuclear power stations can be disastrous, such as the accidents in Chernobyl and Three Mile Island.

Replacement of labour

Many tasks that used to be done by humans have now been replaced by electric tools and machines. This causes unemployment, adding a burden to society.

Overwhelming industrialisation

Development of AC power enhances industrialisation. However, excessive industrial development brings a lot of adverse effects to both society and the environment.

NOTE: In your answer, you can also assess the positive and negative impacts of the development of AC generators, but at the end, your own opinion and value should be expressed very clearly.

The production of an alternating current

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H11.1A
H11.2E
H11.3A, B, C
H12.1A, D
H12.2A, B

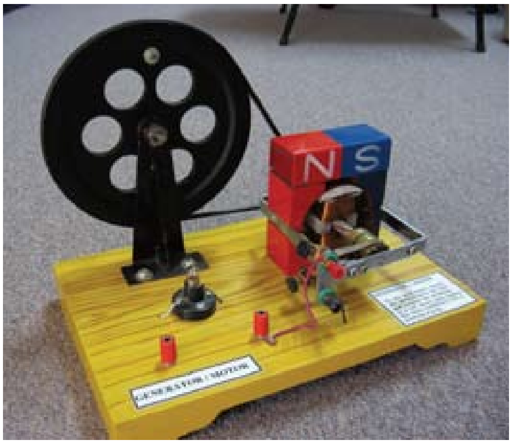
- ***Plan, choose equipment or resources for, and perform a first-hand investigation to demonstrate the production of an alternating current***

Demonstrate the production of an alternating current

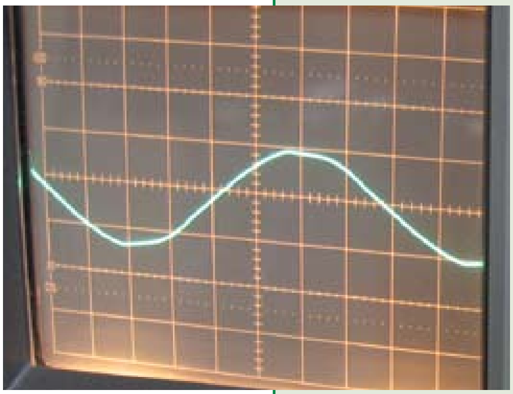
In this experiment, you need to produce AC using a simple AC generator. It is important to note that AC output *cannot* be measured using a galvanometer. In order to assess the frequency and size of the AC produced, a cathode ray oscilloscope (CRO) needs to be used. When conducting the experiment, note:

- What effect does the speed of rotation have on the amplitude or size of the AC output?

- What effect does the speed of rotation have on the frequency of the AC output? How can the frequency of AC be determined from the information displayed on the CRO?
- Optional: How would the variation in size and frequency of the AC output be demonstrated in a load, such as a light bulb?



Laboratory shot of a small AC generator

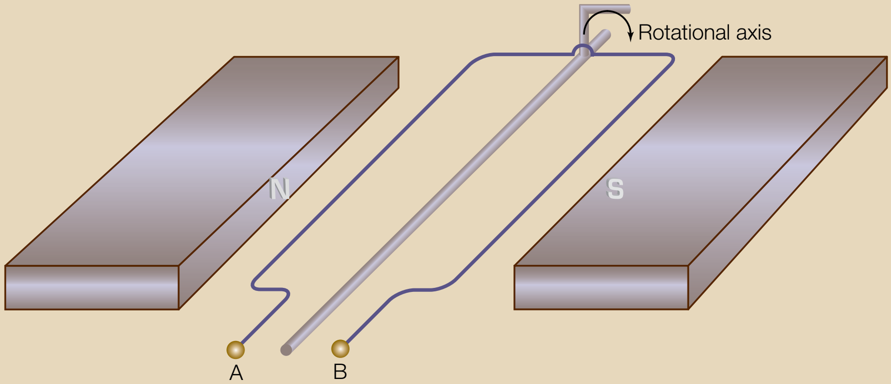

Display of the electricity output using a CRO

TR

Risk assessment matrix

CHAPTER REVISION QUESTIONS

1. (a) List the essential components of a DC generator.
   (b) How does the armature of a DC generator differ from a DC motor?
2. Describe the role of a split ring commutator in a DC generator. How does that compare to that in a DC motor?
3. A simple AC generator is shown in the diagram below:

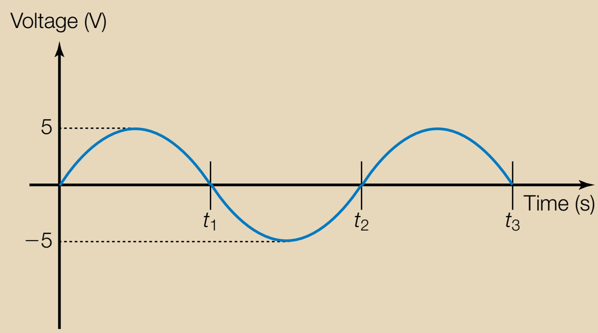


   (a) Sketch a graph that describes the changes in magnetic flux as the coil completes one revolution within the magnetic field.
   (b) Sketch a graph that describes the rate of change in magnetic flux as the coil completes one revolution within the magnetic field.
   (c) What can you say about the similarity and difference between these graphs?

(d) Based on the graph you drew for (b), sketch another graph that describes the size of the induced EMF as the coil rotates once inside the magnetic field (with respect to A). On the same axis, sketch another graph when the number of turns of the coil is increased by 20 times.

(e) What changes would you make to this design in order to generate a DC current?

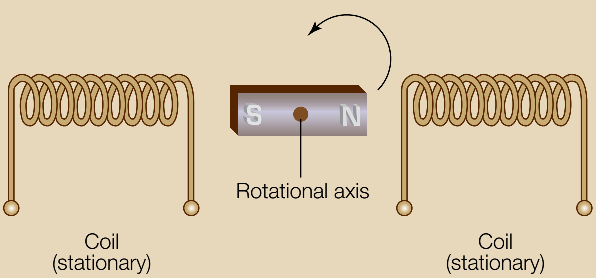
4. The following graph shows the voltage profile of a AC generator over time.



(a) Draw a graph to describe the voltage profile when the magnets of the generator are changed to ones that are twice as strong.

(b) Draw a graph to describe the voltage profile when the armature of the generator is turned twice as fast.

5. A generator can also be made when the magnet is made to spin in between sets of coils. See the drawing below.



(a) What is the advantage of this design?

(b) What is the nature of the output voltage? Is it AC or DC?

(c) Use this idea to illustrate how a three-phase AC generator can be constructed?

6. (a) Describe the infrastructures used to deliver electricity from a power station to consumers.

(b) Describe how these infrastructures are protected from lightning strikes.

7. (a) Justify why AC generators are more commonly used than DC generators in today's society.

(b) Identify one drawback of using AC generators.

8. Assess the development of AC generators on society and the environment.

9. A student was turning the handle of an AC generator in a school laboratory to power a small light bulb. The student realised that the handle was much harder to turn when the switch for the light bulb was on. If the student came to you for advice, how would you explain this phenomenon?

TR

Verb scaffolds

SR

Answers to chapter revision questions