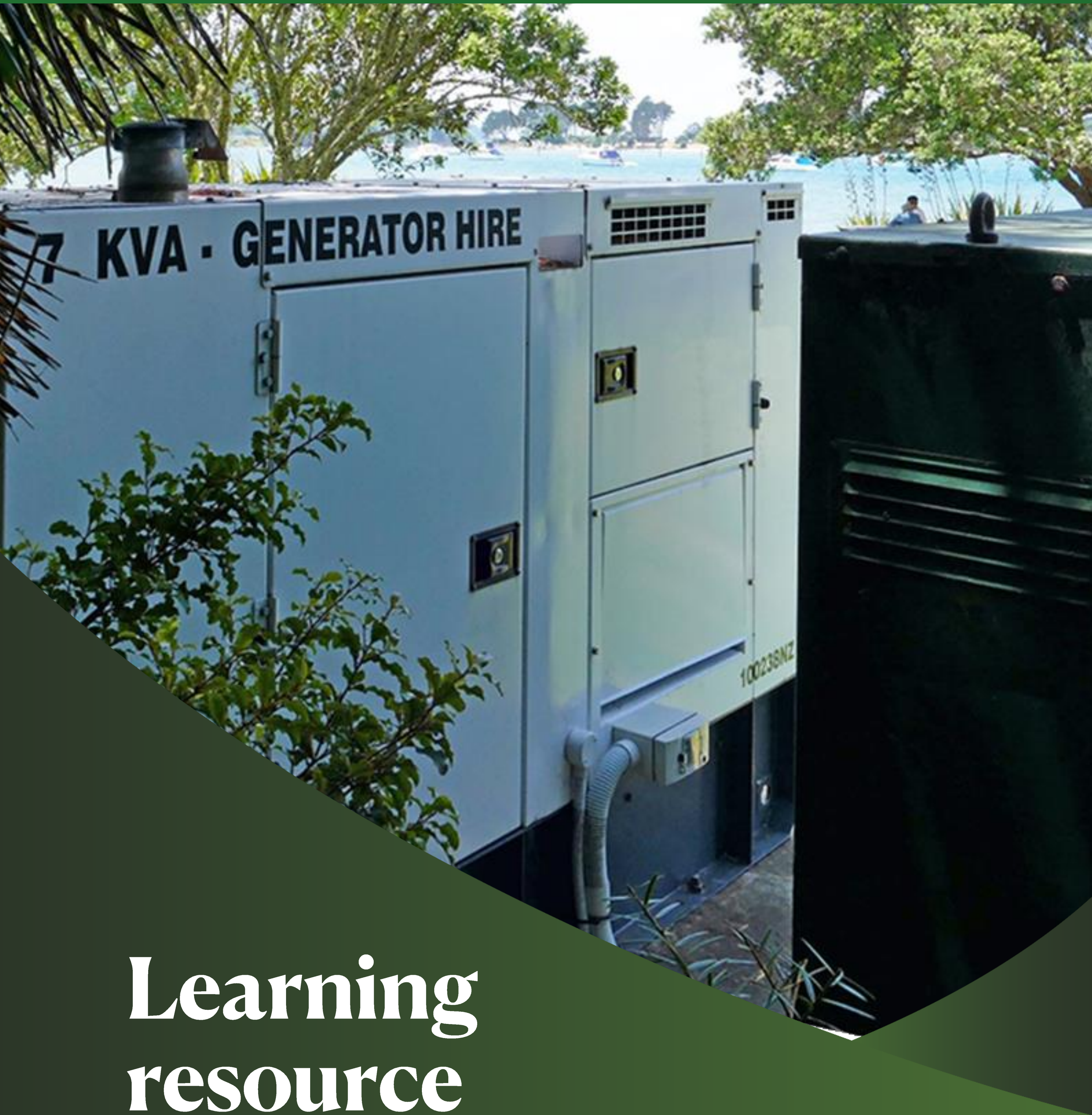

Learning resource

Demonstrate knowledge of electric motor and generator construction and operation

Level 3 | Credits 2

Te Pūkenga

Acknowledgement

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Contents

Part 1: DC Machines........1
Permanent-magnet........2
Field-wound stator........3
Separately excited machines........4
The Simple DC Generator........5
Functions of DC generator components........5
Theory of Operation........6
Simple 2 pole permanent magnet DC motor........7
Functions of DC motor components........7
Theory of Operation........8
Commutator action........9
Part 2: AC Machines........10
The Simple Alternator........10
Voltage production........10
Operation of a Simple Alternator........11
Summary of the output of an AC Generator........13
Generator construction........14
Rotating - armature machine........14
Rotating - field machine........15
Polyphase machine........16
Number of poles vs speed........17
Part 3: Prime movers........20
Choosing a suitable prime mover........21
Hydro-electric turbines........22
Wind turbines........23
Steam / thermal / geothermal power turbines........24
Part 4: AC and DC voltages and currents........25
AC terms........26
AC formulas........29
Sine wave calculations........30

Part 1: DC Machines

Motors and generators play an important role in the electrical industry and as an electrician, at some point you may well be faced with working on an AC or a DC machine in some form or other.

You will need to have some understanding of how motors and generators are constructed, operate. We will start with looking at DC machines.

There are a number of different designs for DC machines, both DC motors and generators.

Although the construction of DC motors and generators is basically the same, their operation is the opposite!

- A generator is turned - when it is turned it produces voltage and current.
- A motor is supplied with voltage and current and when it is, it turns.

	DC. motor	**DC. Generator**
Energy conversion	Converts electrical energy into mechanical energy	Converts mechanical energy into electrical energy
Rule of hand	Fleming’s left-hand rule	Fleming’s right-hand rule
Output	Rotation	Voltage

DC machine magnetic fields can be produced by permanent magnets or field windings (electromagnets).

Different DC machines are classified according to the connection of the field windings. They may be classified as:

- Separately excited.
- Shunt-excited.
- Series-excited.
- Compound excited (series and shunt fields).

Note: “Excited” is the term for generating a magnetic field by current flow. The excitation current is the current that causes the magnetic field in a generator.

Permanent-magnet

Permanent-magnet DC machines have a set of permanent magnets rather than electromagnets to produce the magnetic field.

Uses of permanent-magnet generators include wind and hydro generators and tacho-generators.

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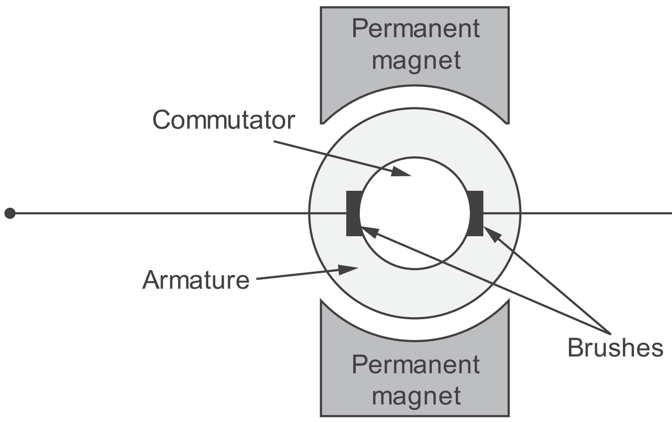
Operation of Permanent-magnet DC motor

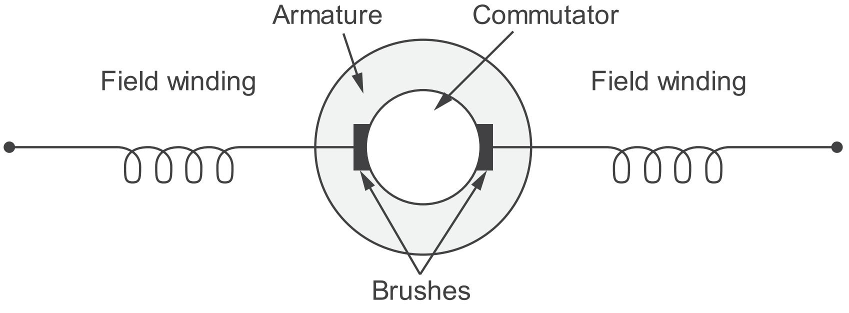


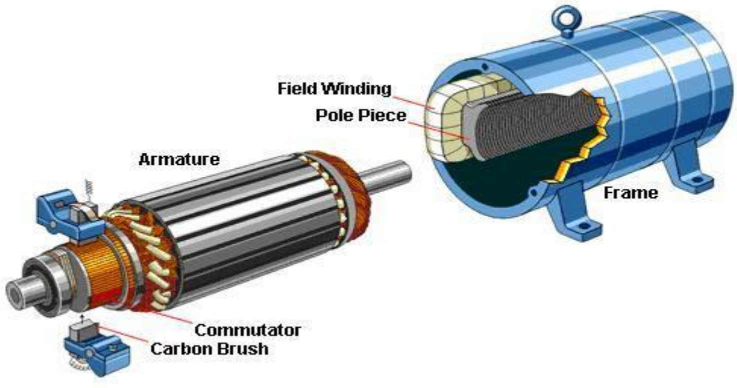
Operation

1. Current flows through the brushes then through the coils in the armature.
2. The magnetic field produced by the armature interacts with the magnetic field of the permanent magnets. This creates torque and causes the rotor to rotate on its bearings.
3. The commutator ensures the polarity of the armature current reverses every half turn, which then ensures that the torque produced remains in the same direction and the motor continues to rotate in that direction.

Field-wound stator

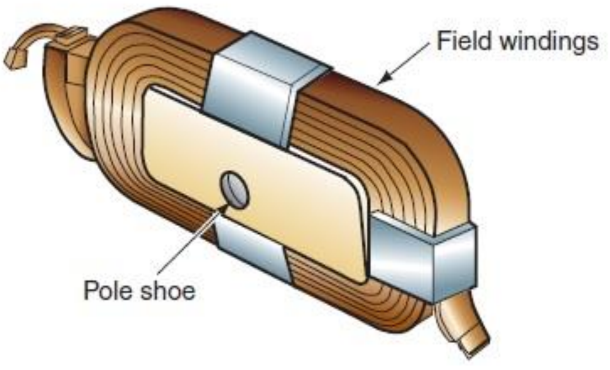
A variation to the DC motor is a Field wound stator. Field wound stator DC machines have electromagnet field windings instead of permanent magnets. A simplified series machine is shown below.





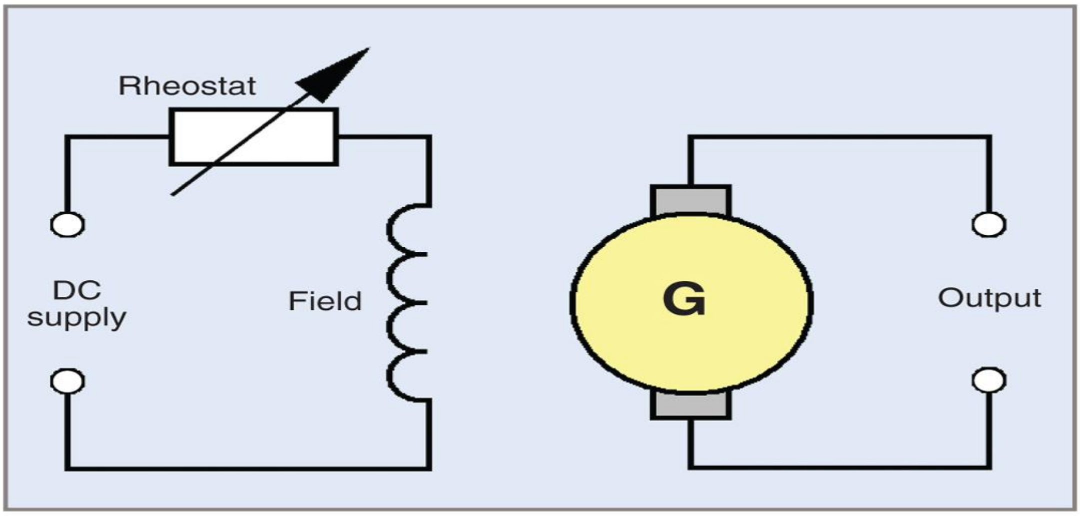
Operation

1. When current flows through the field windings they produce a magnetic field.
2. The current also flows through the brushes and through the armature. As it does, a magnetic field is produced by the armature and interacts with the magnetic field produced by the field windings.
3. This creates torque and the motor rotates.
4. The commutator on the armature reverses the polarity of the supply every half turn to ensure that the armature continues to turn in the same direction.



Separately excited machines

Separately excited machines are a version of field wound stator machines. They have field windings that are supplied from a source external to the machine.

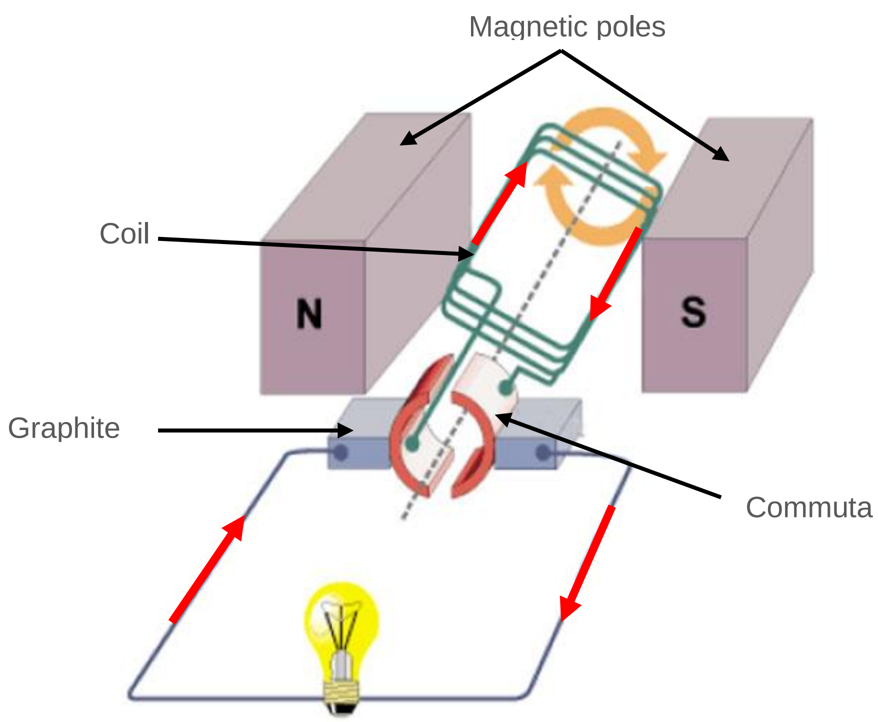


Separately excited generators are useful as they have a variable power output. The circuit above shows a rheostat connected in series with the field winding. This allows control of the field current and hence field strength and in turn the generator output.

They also have the advantage that they are not limited by the size that an effective magnet can be economically produced.

The Simple DC Generator

The figure below shows the construction of a simple DC generator. It is the same construction as for a simple DC motor, in fact, A DC “machine” can be used as either a motor or a generator.



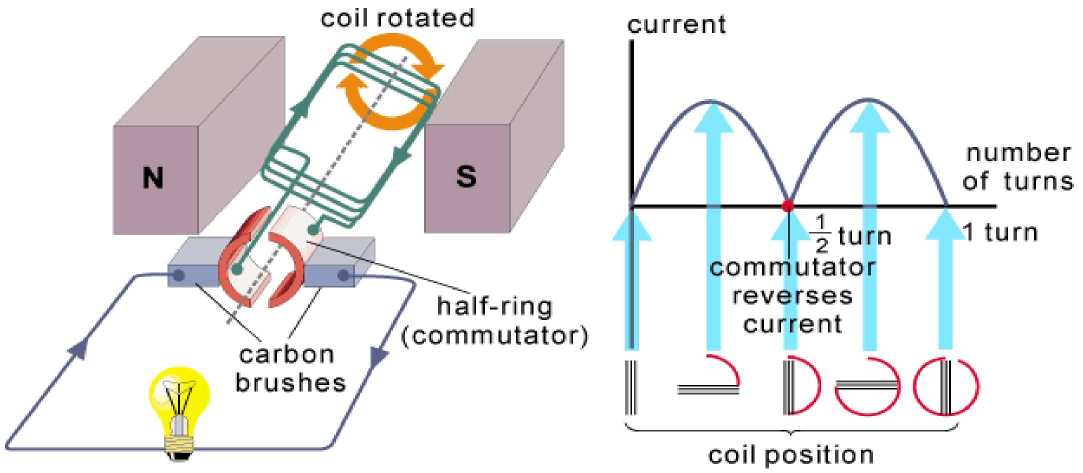
Functions of DC generator components

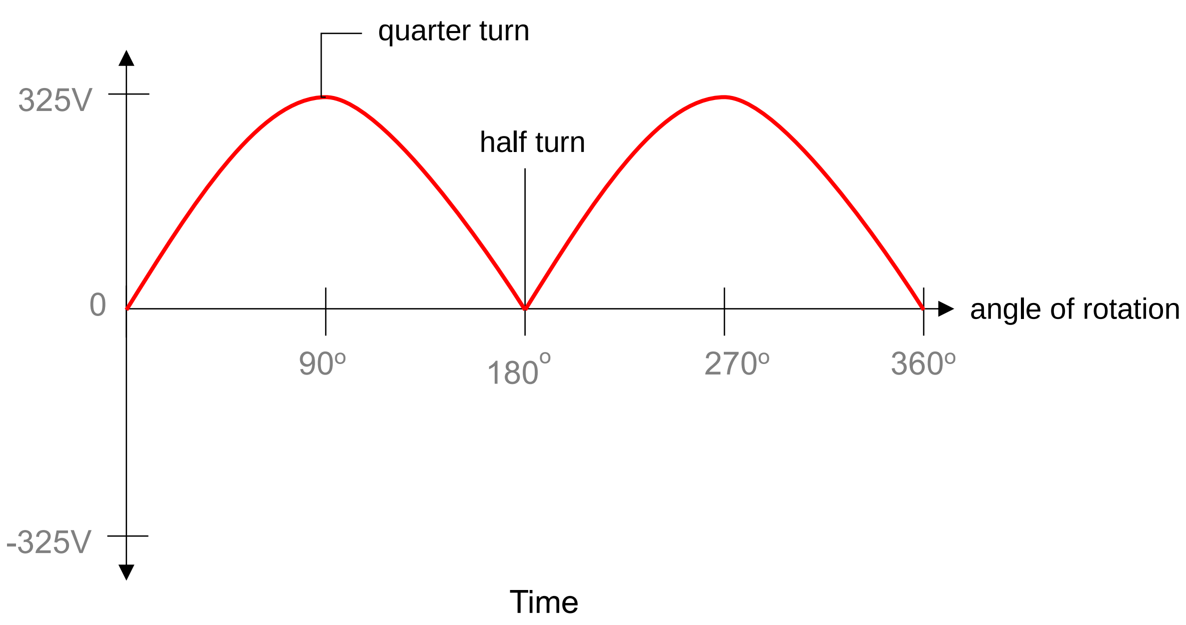
Component	Function
Magnetic poles	To supply a magnetic field
Coil	To act as a conductor and cut through the magnetic field when rotated
Commutator	To convert the AC output current to DC out
Graphite brush	To provide a low friction electrical connection to moving parts such as a commutator

Theory of Operation

- When a rotating force is applied to the coil, this physically forces the coil through the magnetic field of the permanent magnets.
- This in turn causes an EMF to be induced into the coil which connects to the commutator, brushes and supply leads.
- The commutator is used to keep the polarity of the EMF constant at the output terminals as the coil rotates.

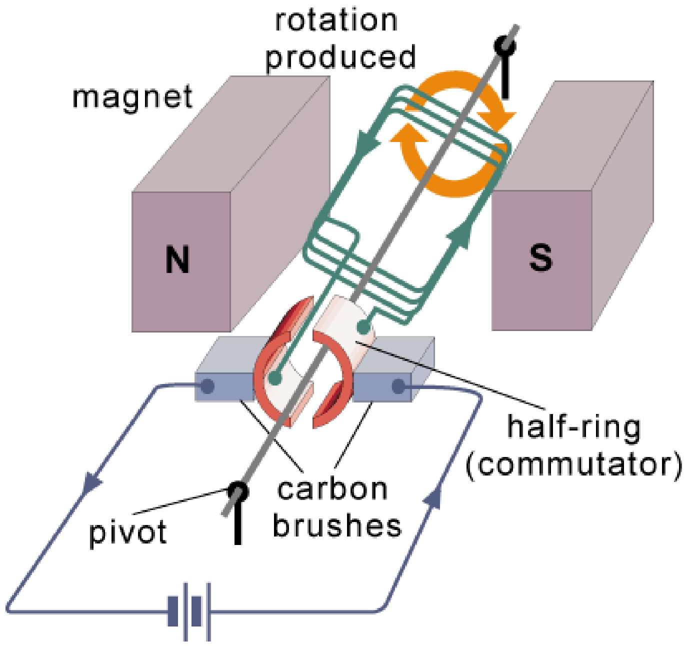
This generator gives us a (ripple) DC voltage and current output.





Simple 2 pole permanent magnet DC motor

The permanent-magnet DC motor is the most common type of DC motor.



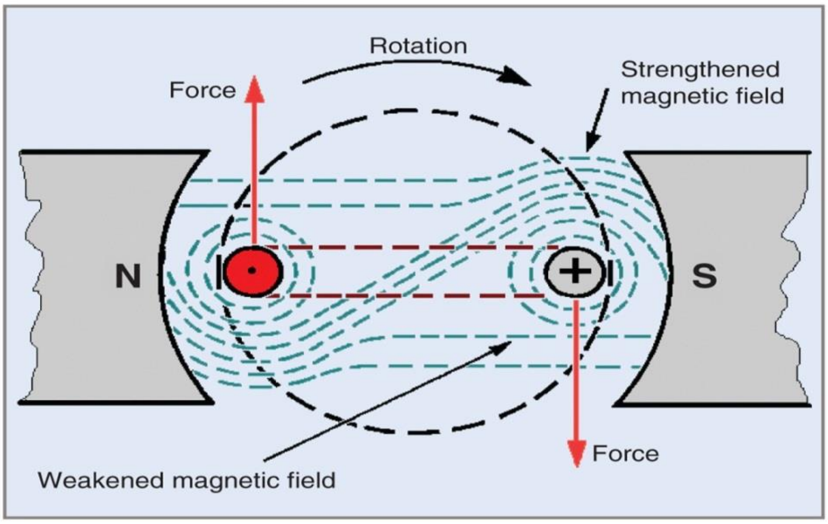
Functions of DC motor components

Component	Function
Magnetic poles	To supply a magnetic field.
Coil	To use electromagnetism to produce torque, (rotating force).
Commutator	To keep the coil current flowing the correct way to cause on-going rotation in one direction.
Graphite brush	To provide a low friction electrical connection onto the commutator.

Theory of Operation

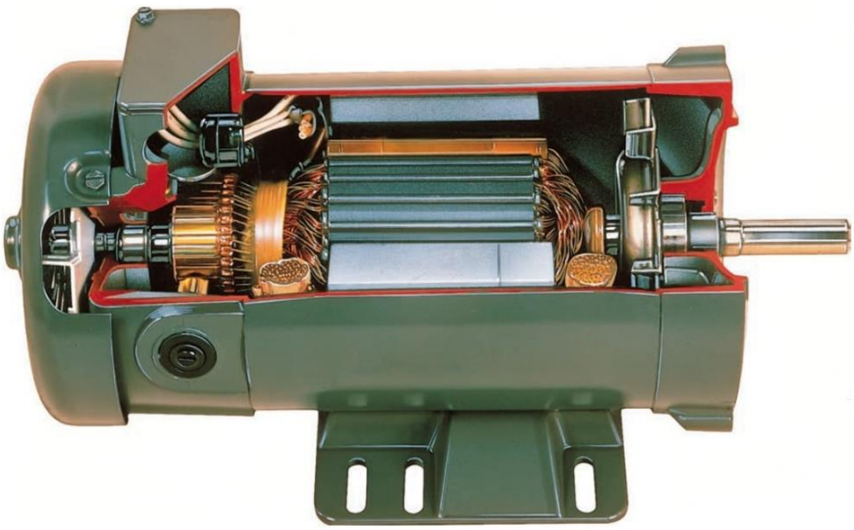
When voltage is applied to the supply leads of a simple DC motor, current flows through the brushes, commutator and into the coil.

As current flows through the coil it creates its own magnetic field which interacts with the field from the permanent magnets. This creates a turning force (or torque) which causes the coil to rotate on its bearings.



The commutator ensures that the current flow reverses every half cycle so that the coil continues to rotate in the same direction.

The direction in which the force acts on a current-carrying conductor can be determined using “Fleming’s left hand rule”

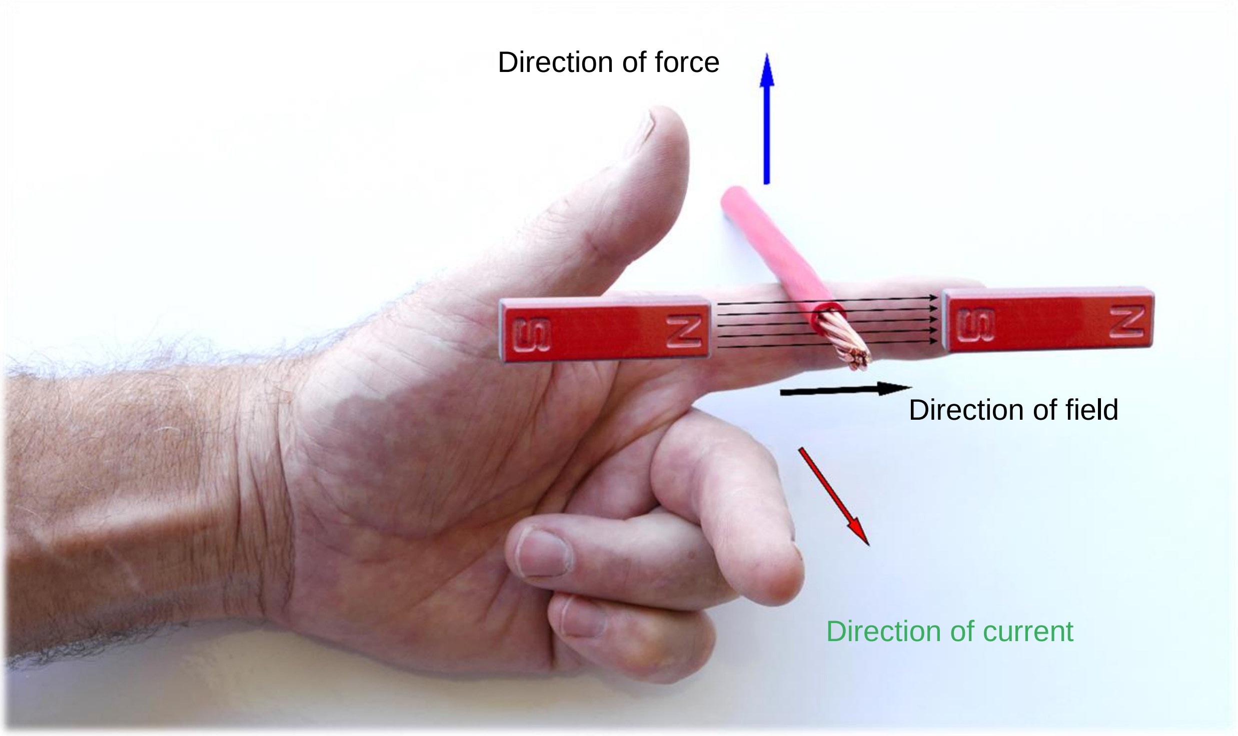


DC motor, field structure, and armature assembly. (Courtesy Reliance Electric Co.)

Fleming's Left Hand Rule (for motors).

If the first finger, second finger, and thumb of the left hand are held at right angles to each other, with the ***F***irst finger pointing in the direction of the magnetic ***F***ield, and the se***C***ond finger pointing in the direction of the ***C***urrent in the conductor, then the thu***M***b will show the direction in which the conductor will be forced to ***M***ove.

*Note how the highlighted letters **F**, **C** & **M** will help you to remember this rule.*



Commutator action

The commutator in this simple DC motor works the same way as in the DC generator, except it is for current in the opposite direction and for the opposite reason.

The commutator always feeds current into the armature coil the correct way around to keep the coil turning the right way. That is the job of the commutator in a DC motor.

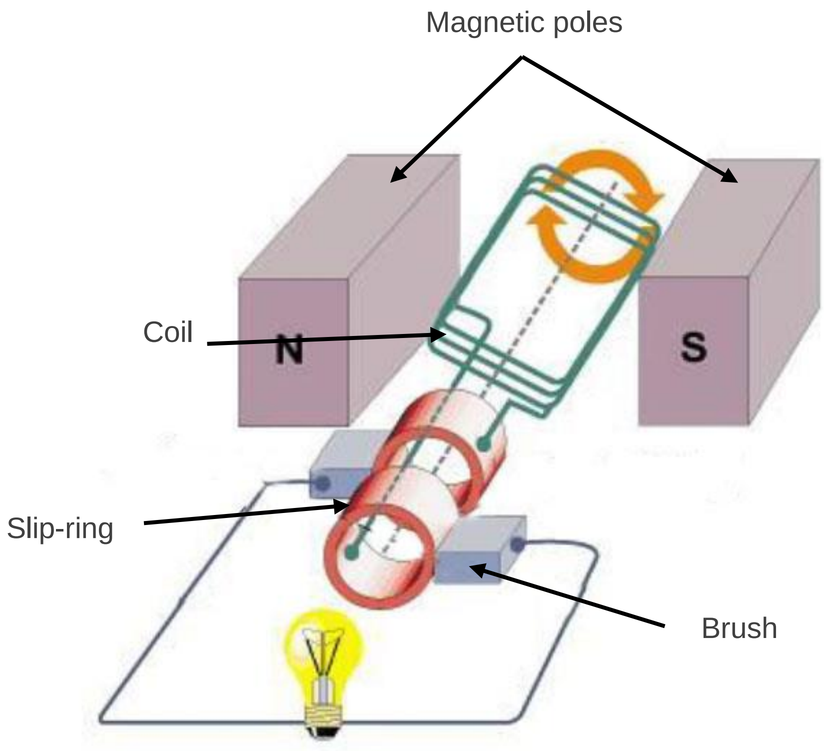
If you look at the coil and the commutator in the diagram, using Flemings left hand rule you can see that the current needs to be flowing from near you to away from you on the right-hand side of the armature coil. This will cause the motor to rotate clockwise.

The simple DC motor shown above would not be very practical as its rotation would be very jerky. In a more practical DC motor the loop is formed of many coils connected to a commutator with many segments. This will result in a much smoother and more powerful DC motor.

Part 2: AC Machines

The Simple Alternator

The figure below shows the construction of a simple alternator.



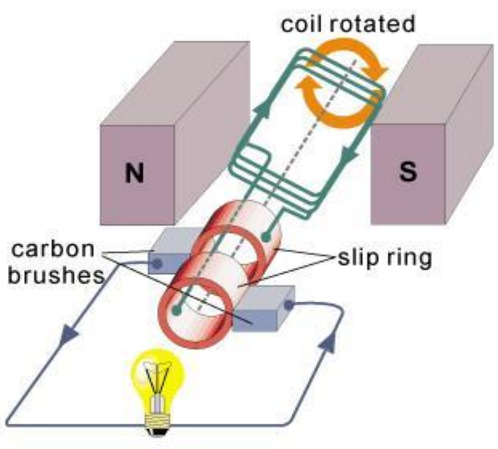
Voltage production

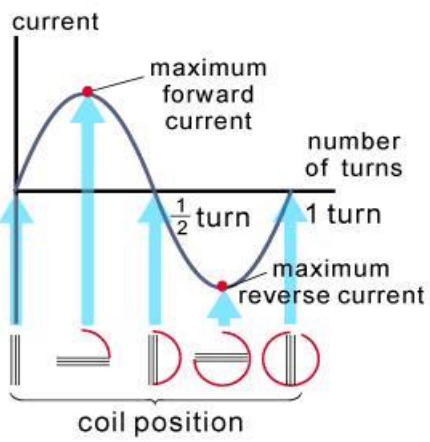
There are three conditions necessary to induce a voltage into a conductor.

1. A magnetic field.
2. A conductor.
3. Relative motion between the two.

Operation of a Simple Alternator

- As long as the loop is stationary, the magnetic field has no effect (because there is no relative motion between the magnetic field and the coil).
- When a rotating force is applied to the coil of an AC generator, it forces the coil through the magnetic field created by the permanent magnets.
- As this is a conductor moving through a magnetic field, this causes an EMF to be mutually induced into the coil.
- The coil connects to the slip rings and carbon brushes make sliding contact with the slip-rings to provide an electrical connection to the supply leads. This allows the induced EMF to be exported to an external circuit.
- An alternating EMF output is produced in the coil as it rotates in the magnetic field. If you follow just the left-hand side of the coil as it rotates, first it moves upwards through the magnetic field and then it moves downward. The direction the coil travels through the field determines the polarity of the EMF produced. The polarity will reverse every half revolution.
- The direction of the emf produced when a conductor cuts across magnetic lines of force can be found by using Fleming's Right Hand Rule.
- The slip rings allow the polarity of the output to the external circuit to alternate during rotation.
- The greatest emf (measured in volts), is induced in the coil as it moves at right angles to the magnetic flux as the conductor is cutting the most magnetic lines of force.
- No emf is induced when it moves parallel to the magnetic flux because the coil is not cutting any magnetic lines of force.
- A single-loop coil rotating in the uniform magnetic field will produce an emf that when graphed, has the shape of a sine wave.

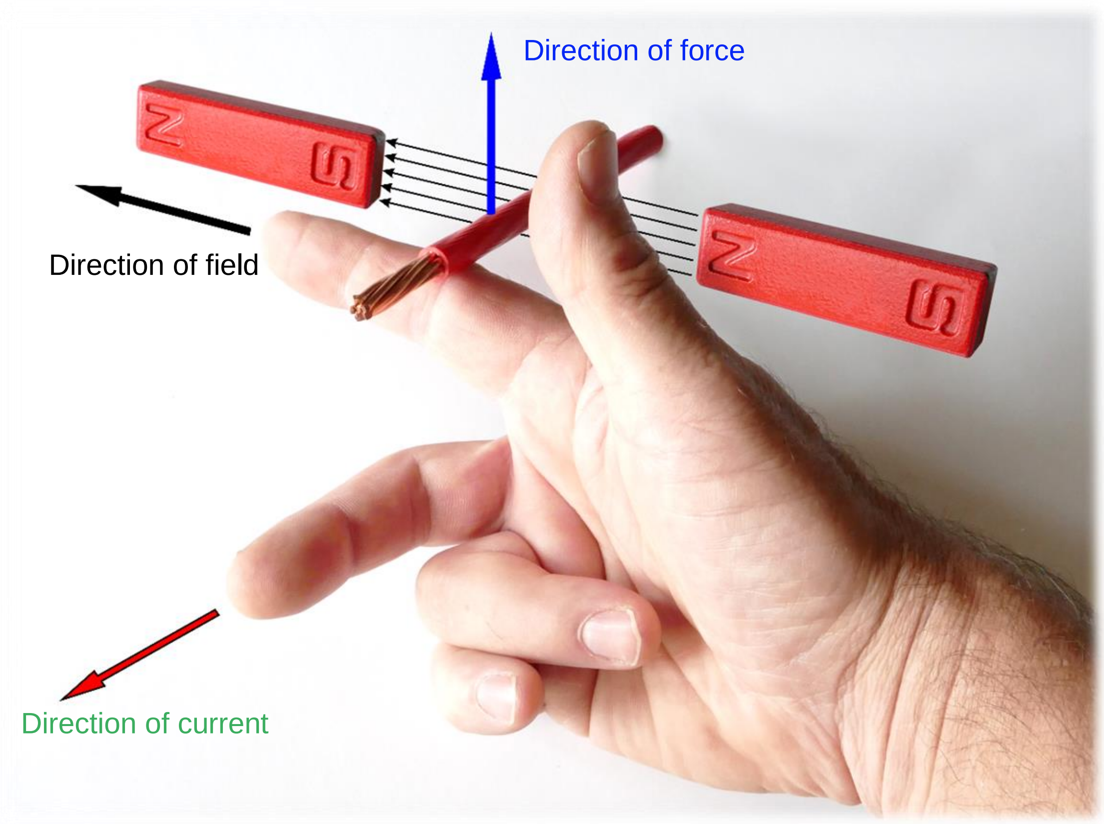




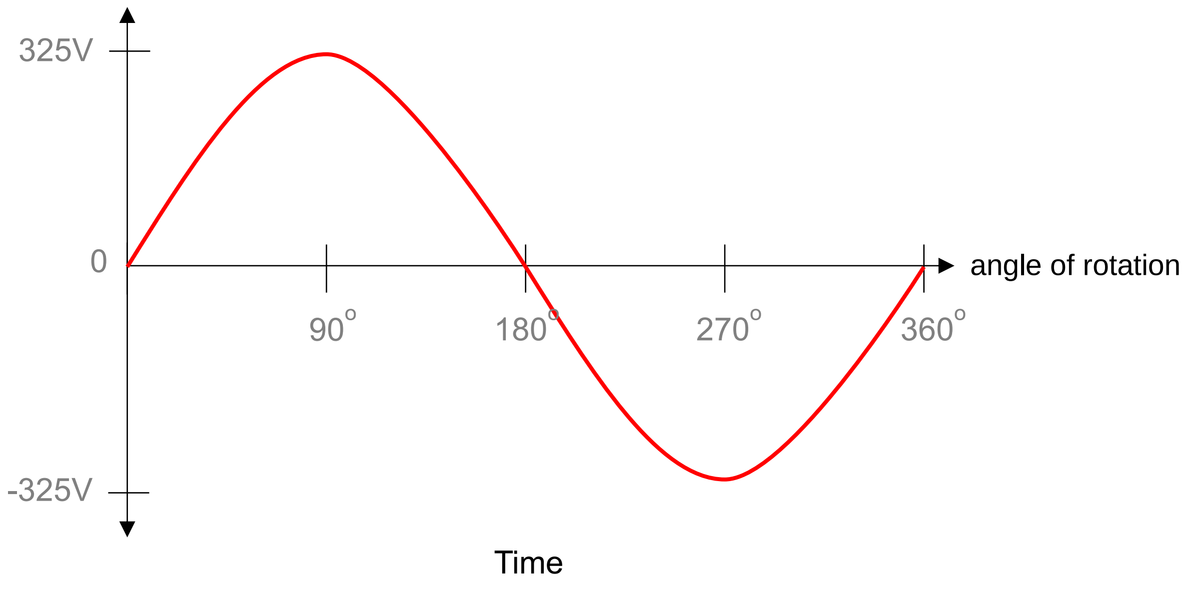
Fleming's Right Hand Rule (for generators) states:

If the first finger, second finger, and thumb of the right hand are held at right angles (90 degrees) to each other, with the **F**irst finger pointing in the direction of the magnetic **F**ield, and the thu**M**b pointing in the direction which the conductor is **M**oving across the magnetic field, then the se**C**ond finger will show the direction of the **C**urrent induced into the conductor.

*Note how the highlighted letters **F**, **C** & **M** will help you to remember this rule.*



Summary of the output of an AC Generator



Stage	Description
0° to 90°	As the coil rotates, it cuts through the magnetic field at an ever-increasing angle. The voltage increases until maximum voltage is induced when the conductor is cutting directly across the field at right angles.
90° to 180°	As the coil continues to rotate past 90°, the conductor cuts the magnetic field at a decreasing angle and the voltage begins to decrease until the voltage is 0 at 180o, half way through one cycle.
180° to 270°	The coil continues to rotate and the angle it cuts through the field increases again. This time however, the induced voltage is negative. The voltage is at its maximum negative value when the conductor is moving through the field at right angles at 270°.
270° to 360°	As the coil continues to rotate past 270°, it cuts through the magnetic field at an ever-decreasing angle and the voltage starts to decrease. At 360° voltage has dropped to 0 and the cycle is ready to start again.

Generator construction

There are three types of AC generator construction we are going to briefly have a look at in this resource.

- Rotating armature.
- Rotating field.
- Polyphase.

Note: AC generators are called alternators.

An armature can be the rotor of an AC machine or it can be the stationary windings. "Armature" is the term for the part of the machine that "receives" the "results" - that the machine is made to achieve. For example:

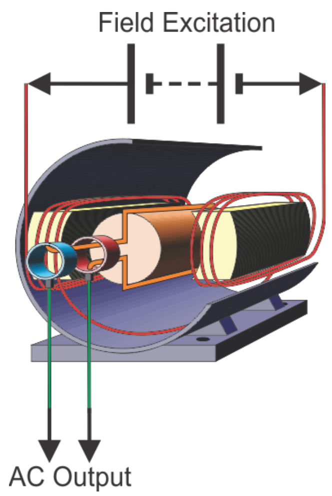
- If the generated output comes out of the rotor, then the rotor is the armature.
- If the generated output comes out from the stator windings, then the stator windings are the armature.

Rotating - armature machine

This type of alternator has:

- The field coils placed in the stator (stationary part of the machine) and so the magnetic field is stationary.
- The armature coils are placed in the rotor and so the coils that are induced with voltage are rotating.
- Slip rings and brushes to connect the generated output to an external circuit.

(Incidentally, rotating armature machines with a commutator is the standard choice for DC generators as it is difficult to get a DC output from the stator).

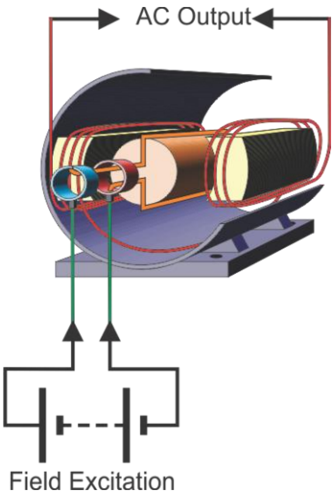


These types of machines are suited to lower power applications and are reasonably economical to manufacture for this level of machine.

Rotating - field machine

This type of AC generator has:

- A rotating field as the field winding is in the rotor.
- The armature in the stator.



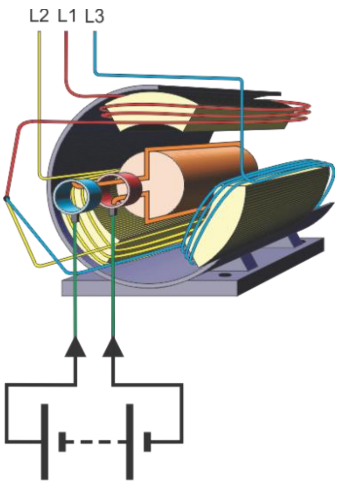
It becomes uneconomical and difficult to design high power rotating connections to a rotor and, the high number conductors needed to produce high voltage would be hard to fit on a rotor and would make it bulky and heavy.

Alternator rotor

It is far easier to have small excitation current slip ring connections and a stationary armature with the heavy-duty connections to it. There is also more room in the stator for higher numbers of windings.

This type of AC generator is ideal for high power machines especially in generators that produce 11kV and up.

Polyphase machine



Most electricity produced and transmitted around the national grid is polyphase, i.e. more than one phase.

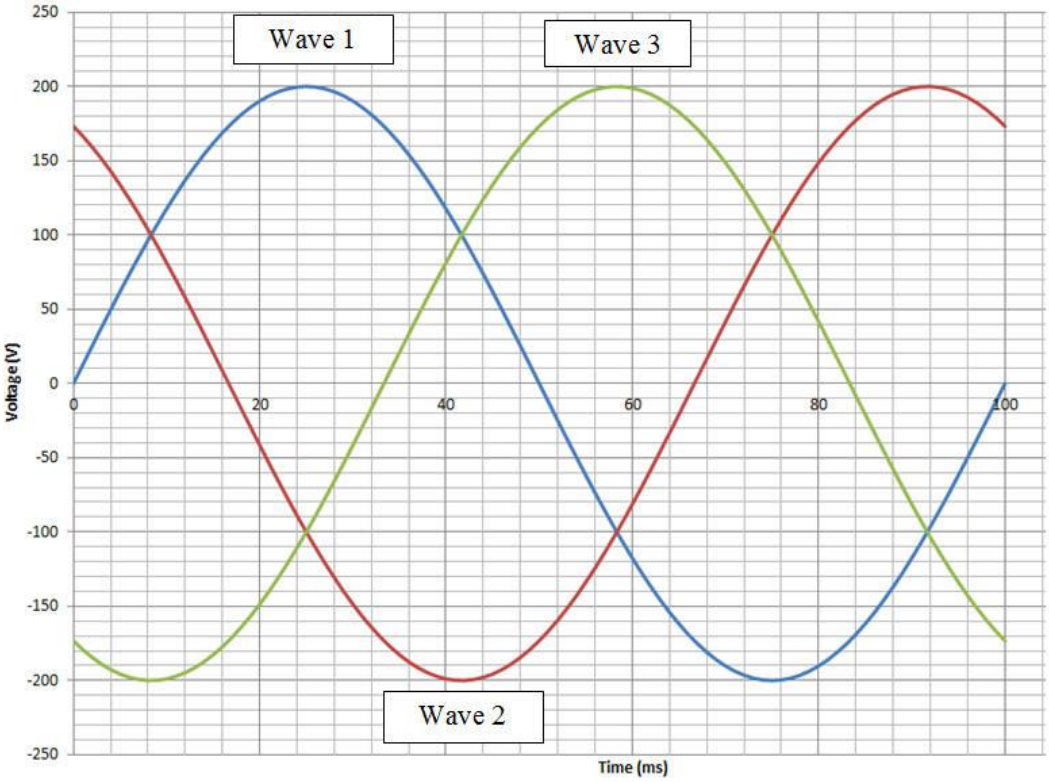
The most common poly phase number in use is three phase.

If you want a generator to produce three phase, you will need three sets of windings in the generator.

A poly phase generator has:

- A rotating magnetic field.
- (Usually three) sets of phase electromagnetic coils.
- Phases evenly distributed around the stator.

Poly phase alternators use the space in the stator efficiently, they produce consistent power eliminating pulsations and are widely used to produce domestic, commercial and industrial power.



An alternator is rated according to:

Frequency

Voltage

Current

The output is given in VA since the power factor of the load is beyond the control of the manufacturer.

Number of poles vs speed

The speed at which the rotor of an alternator has to spin depends on two things. The frequency the AC output needs to be, and the number of pole pairs.

The relationship between speed, frequency and number of poles is:

$$f(x) \qquad f = \frac{n \times p}{60}$$

Where:

n = speed of the rotating magnetic field in rpm

f = supply frequency in Hz

p = number of pairs of poles

Note: this formula uses pairs of poles, be careful when reading questions that you are using the correct number in your equation.

- The faster you run the alternator, the higher the frequency output.
- The more pairs of poles you have, the higher the frequency output.

If an alternator has a pair of magnetic poles (a north and a south pole, one either side of the armature) and the alternator is required to produce 50 Hz (50 cycles per second) then it stands to reason that the armature will have to move past the poles 50 times a second.

To get this to happen, the generator will have to rotate at:

$$n = \frac{f \times 60}{p}$$

$$n = \frac{50 \times 60}{1}$$

$$n = \frac{3000}{1}$$

$$n = 3000\ rpm$$

What if you don't want to run an alternator that fast? What could you change to be able to run it slower? That's easy, add more pairs of poles.

If you have two pairs of poles, then you will run the armature past two sets of poles per turn and produce two output cycles per rotation.

If you want an output of 50 Hz from your alternator with 2 pairs of poles, instead of having to rotate the armature at 3000 rpm, you will be able to produce 50 Hz from 1500 rpm, half the speed.

$$n = \frac{f \times 60}{p}$$

$$n = \frac{50 \times 60}{2}$$

$$n = \frac{3000}{1}$$

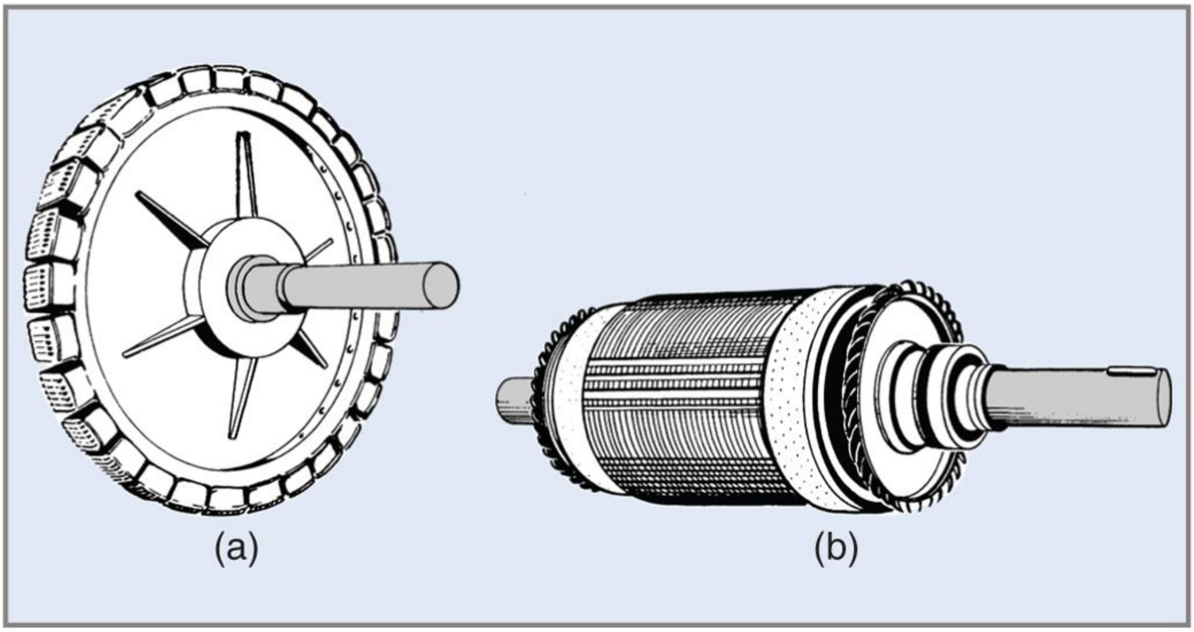
$$n = 1500\, rpm$$

If you ran your 4-pole alternator at the same speed as your 2-pole alternator, it would produce double the frequency output, i.e. 100Hz.

There are two types of alternator rotors:

1. Low speed (salient pole).
2. High speed (cylindrical, non-salient).

Note: Salient basically means sticking out and obvious.



Salient rotor

A salient pole rotor is a low speed rotor which is made so that lots of pairs of poles can fit around the outside. The problem that causes is that it is only suitable for slow speed otherwise it will fly apart.

Salient pole rotors are suited to a slow loping prime mover like a wind turbine or a water turbine in a power station running at 300rpm.

Cylindrical / non-salient rotor

A cylindrical / non-salient pole rotor is built for high speeds. It is constructed to be low profile and strong.

The disadvantage is that there is not much room for pairs of poles and so higher alternator speeds are required to produce the required frequency output, but hey, that is what they are made for.

You would choose a cylindrical / non-salient pole rotor when your prime mover is a fast one.

Part 3: Prime movers

A generator needs something to turn it. The thing that turns a generator is called a prime mover.

> Note: The thing that turns a generator is called a prime mover

Some examples of low speed prime movers include:

- Diesel engines
- Hydro-electric turbines.
- Wind turbines

High speed prime movers include:

- Steam turbines
- Gas turbines.

Depending on the situation, there are a number of factors that might lead you to choose one prime mover over another.

Choosing a suitable prime mover

The type of prime mover chosen will depend on things like:

- Purchase price.
- Starting methods.
- Load sizes and alternator capacities.
- Efficiency.
- Type of service.
- Initial cost.
- The cost and availability of fuel.
- The availability of other useable energy sources such as wind or water.
- Ease of access.

Let's look at three common prime movers used for driving generators.

- Hydro-electric turbines
- Wind turbines
- Steam turbines / thermal power / geothermal

Hydro-electric turbines

Hydro-electric turbines come in a variety of sizes, from a micro hydro scheme in the creek at home to the large hydro power plants that generate electricity by storing water in vast reservoirs behind massive dams.

Water flows down penstocks from the reservoir spinning turbines to power generators. The water then goes on to flow back into the water way below the dam or scheme.

Hydro-electric turbines produce power at any time, day or night, as long as there is a supply of water.

The reasons why hydro-electric prime movers may be chosen can include:

- There is a plentiful supply of water.
- Water is a renewable source of energy.
- Hydro-electric turbines operate on simple principles.
- Hydro-electric turbines are capable of generating a large amount of electricity.
- Hydro-electric turbines are a clean source of energy.

Wind turbines

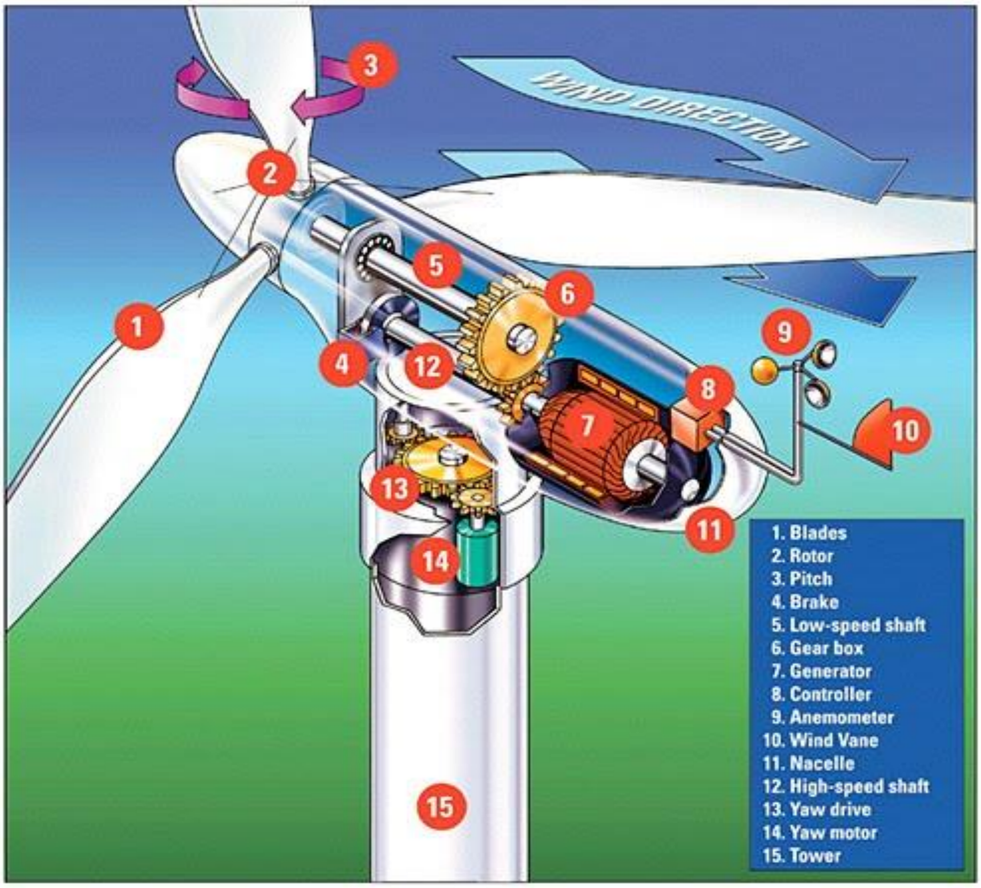
Windmills have been used for centuries to produce mechanical power.

With continuous technological advancement, wind turbines have become economically viable and are being used to produce electricity

Wind power is a renewable source of energy. It does not produce greenhouse gases and many other pollutants that degrade the environment.

The reasons why wind turbine prime movers may be chosen can include:

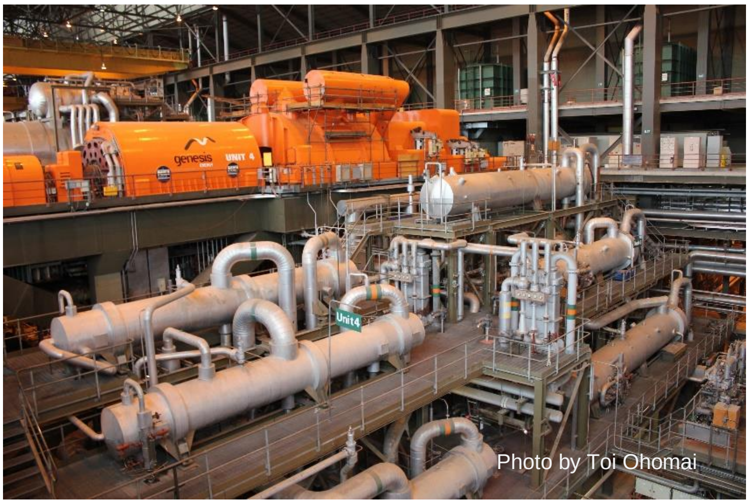
- There is a good supply of constant wind.
- Wind turbines use wind which is a great renewable source of energy.
- Wind turbines operate on simple principles.
- Wind turbines are a clean source of energy.



Steam / thermal / geothermal power turbines

Steam/gas turbines are used in a variety of ways to produce electricity.

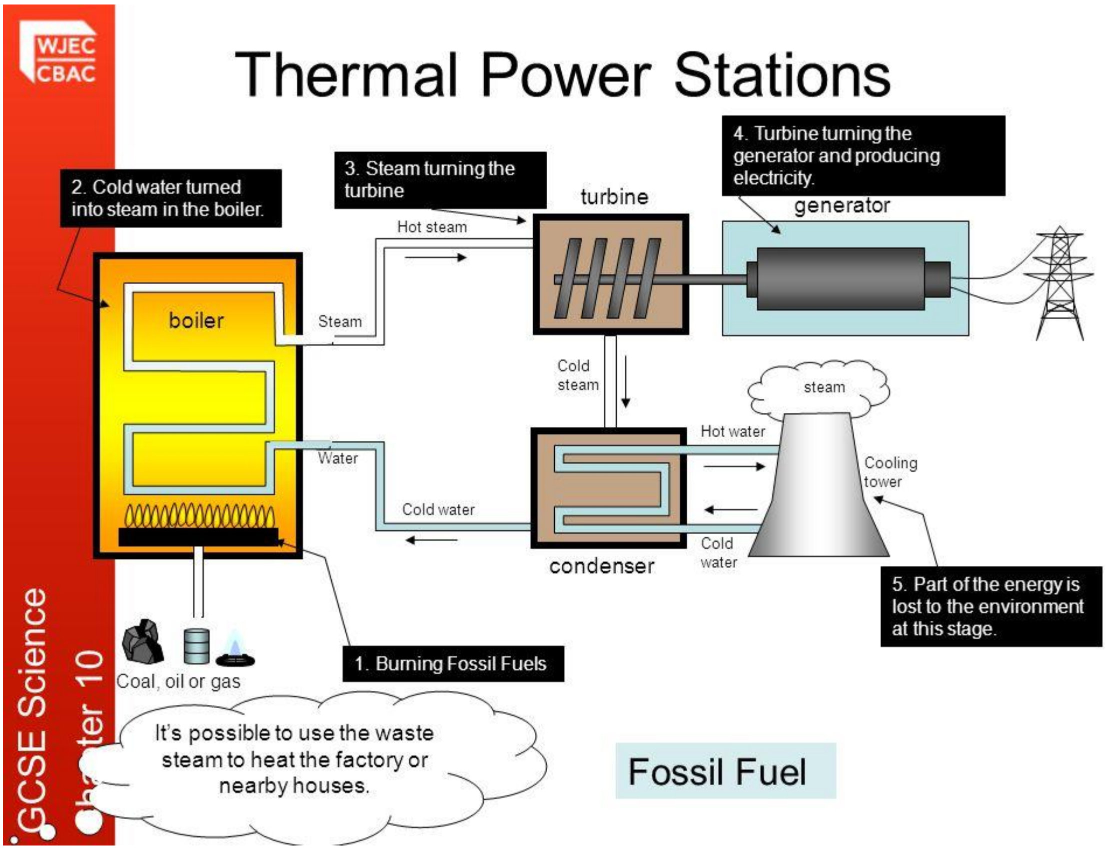
Thermal powered turbines use water or other mediums such as pentane. The medium is heated by burning fossil fuels like coal or natural gas to produce pressurised steam / gas to drive the turbine.



Geothermal powered turbines use either the hot water or the steam from the ground to produce a pressurised steam or gas to drive the turbine.

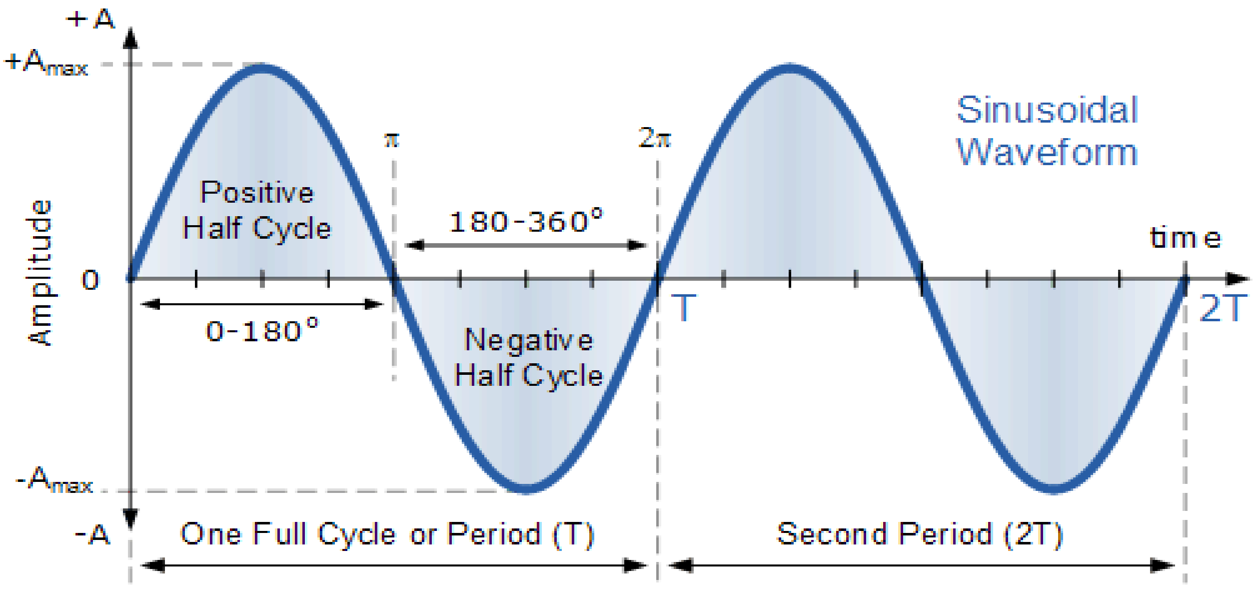
The reasons why thermal / geothermal turbine prime movers may be chosen can include:

- There is a large supply of geothermal hot water or natural gas resources.
- Geothermal hot water is a renewable source of energy.
- Thermal / geothermal powered turbines are capable of generating a large amount of electricity.



Part 4: AC and DC voltages and currents

A sine wave is a mathematical curve that describes a smooth repetitive oscillation. A sine wave is a continuous wave. It is named after the mathematical function sine, of which it is the graph.



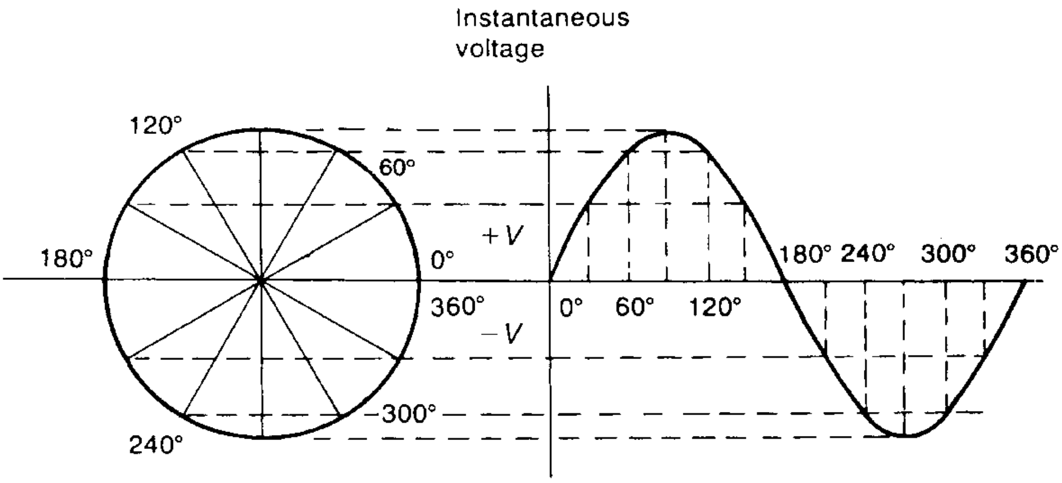
The graph of AC voltage against time is in the form of a sine wave, or, the graph is the shape of the sine of the instantaneous angles the between 0° and 360° as shown below.

Angle	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
Sine	0	0.5	0.866	1.0	0.866	0.5	0	-0.5	-0.866	-1.0	-0.866	-0.5	0

AC terms

There are some terms and jargon that accompany AC voltage and current sine waves that you will need to understand.

AC Terms	Definition/Description
Average Value	The average of all the instantaneous values of an alternating voltage or current over one-half cycle. It is calculated by 0.637 x peak value. It is important when AC is converted to DC in rectifier circuits.
Cycle	One complete sinewave to the point it is about to repeat.
Frequency	The number of cycles per second. The unit of frequency is Hertz (Hz) and one Hz is one cycle per second. The NZ electricity supply system has a frequency of 50 Hz.
Form factor	The ratio between the RMS value and the average value of a sine wave. It is found by dividing the RMS by the average value. $\frac{rms\ voltage}{average\ value}$ It is useful for various things including the process of how some measuring instruments work.
Instantaneous Value	The value produced at any given point of a sine wave, it is calculated by Sin Ø x peak.
Peak Value	The maximum value attained by an alternating waveform during one cycle. There is one “positive” peak and one “negative” peak per cycle.
Peak to peak	The difference between the maximum positive and the maximum negative peaks of a waveform.
Period	The time taken to complete one cycle. In the NZ electricity supply system, the period is 1/50 second (= 20 milliseconds).
RMS Value	The value of AC voltage or current which will produce the same heating effect as DC in the same resistor. It can be calculated by 0.707 x peak value.

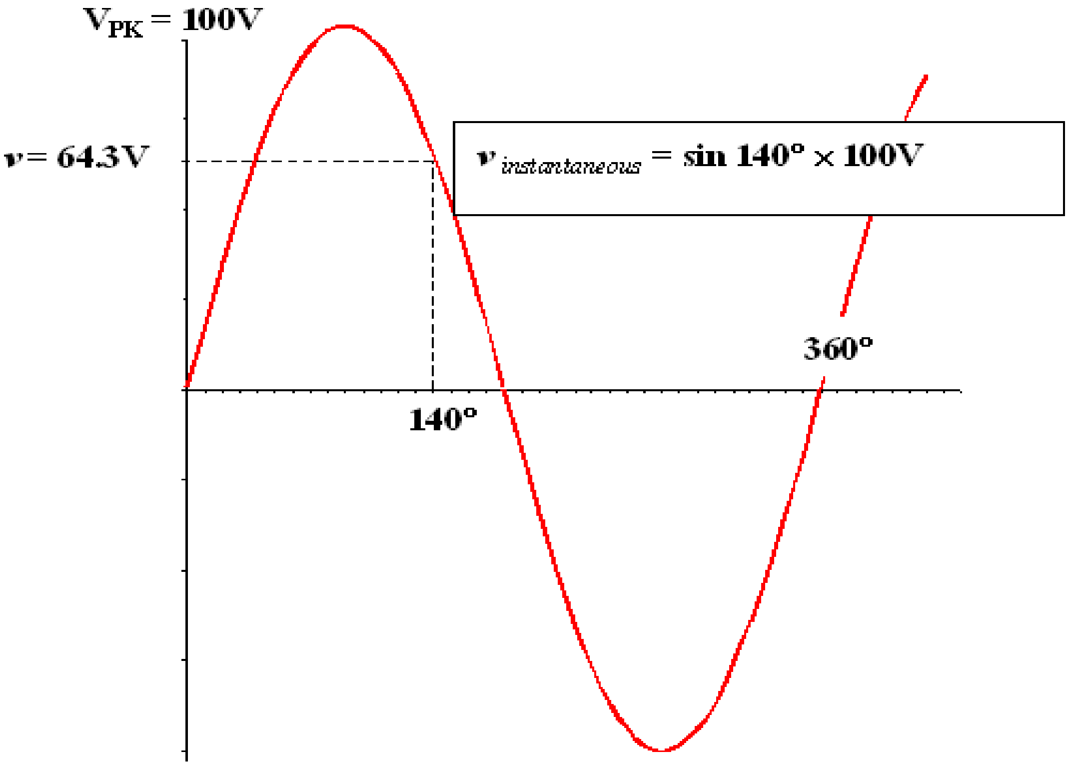


The Instantaneous Value

The value of a sinewave at any given instance in time can be found by multiplying the peak value and the sine of the angle at the instant you would like to know the value.

Instantaneous value:

$f(x)$	$Instantaneous\ value = \sin\emptyset \times peak$



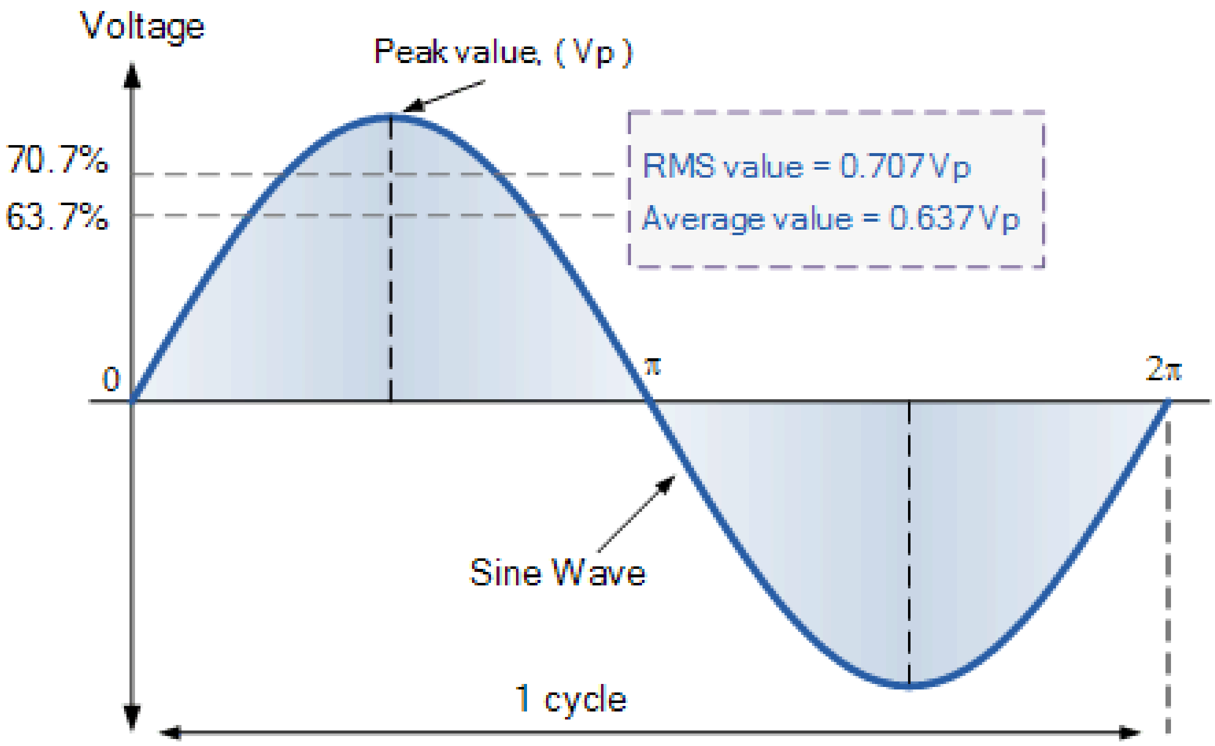
The RMS Value

The RMS value (also called the "effective value") of an AC voltage or current is defined as:

- The RMS value of a given AC waveform, is the equivalent DC value that would produce the same quantity of heat if both were connected to the same value of resistance for the same period of time.

- RMS value

$f(x)$	$RMS = peak \times 0.707$



AC formulas

The formulas for working with AC sine waves are as follows.

$f(x)$

RMS value

$$RMS = peak \times 0.707$$

Average value

$$Average = peak \times 0.637$$

Frequency *(Hz) (cycles per second)*

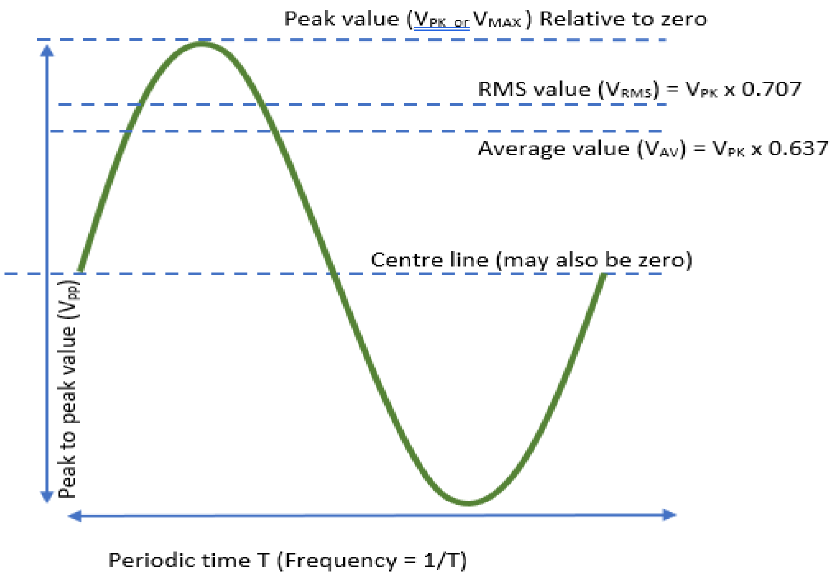
$$Frequency = \frac{1}{period}$$

Period *(T) (seconds)*

$$Period = \frac{1}{frequency}$$

Instantaneous value

$$Instantaneous\ value = \sin \emptyset \times peak$$



Sine wave calculations

Example 1.1

A circuit is supplied with an AC voltage which has a peak value of 325 volts at a frequency of 50 Hz**.**

1. *What is the RMS value of this voltage?*

V_{RMS} = 0.707 x V_{peak}

= 0.707 x 325

= 229.78 volts ⇒ 230 volts

2. *What is the time period for one cycle of this voltage?*

50Hz = 50 cycles per second

So, period = 1/50 second

= 20 milliseconds (time for one cycle)

3. *What is the frequency of an AC voltage which completes one cycle in 40 milliseconds (40 x 10^{-3} seconds)?*

Period (time) = $\frac{1}{frequency}$

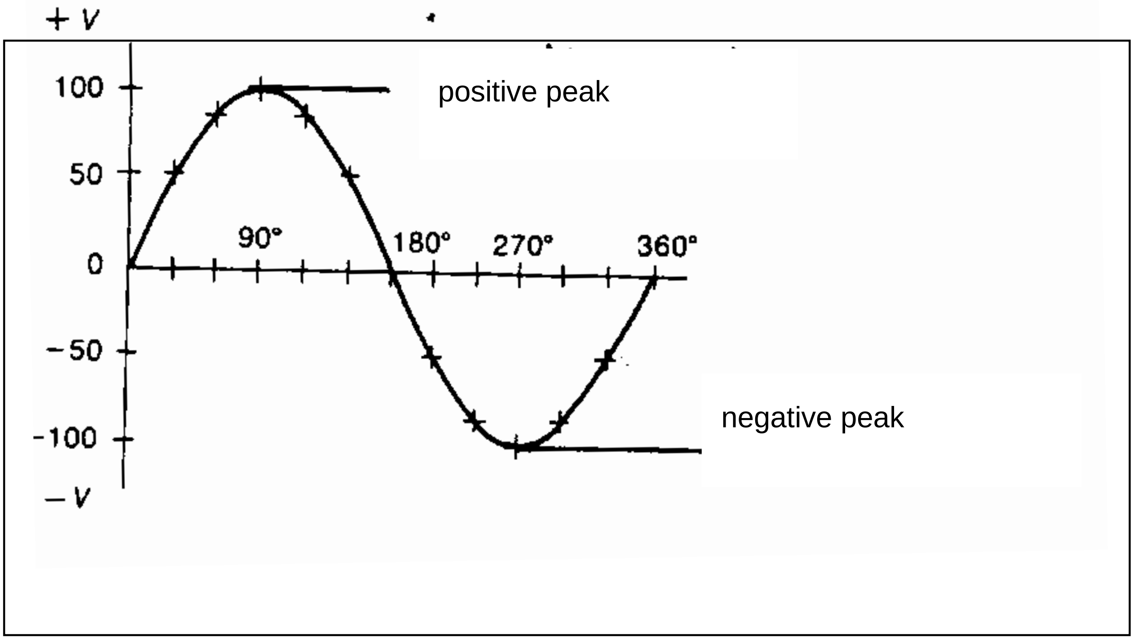
F = $\frac{1}{time}$

= $\frac{1}{40\ x\ 10^{-3}}$

= 25 Hz

Example 1.2

If an AC voltage waveform has its zero values at 0°**,** 180°**,** and 360°, at what angles does it produce its positive and negative peak values?



Values of a sine wave voltage or current

Positive peak value at 90°

Negative peak value at 270°

Example 1.3

A circuit is supplied with AC voltage which has a peak value of 400V.

What is the instantaneous voltage at 37°?

V_{INST} = sinØ x Peak

= sin37 x 400

= **240.73V**

Example 1.4

What is the frequency of an AC voltage that completes one cycle in 0.02 seconds?

Period = $\frac{1}{frequency}$

Frequency = $\frac{1}{period}$

= $\frac{1}{0.02}$

= 50Hz

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