Electricity – Innovative Technologies towards Sustainable Development

'Learning-by-Notes' Package for Senior School - Physics

Lesson 6: Steam

How Do We Make Electricity from Steam?

Teaching Sustainability in High Schools: Subject Supplement

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The Natural Edge Project

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Lesson 6: Steam

How Do We Make Electricity from Steam?

According to an estimate by the Centre for International Economics, Australia has enough geothermal energy to contribute electricity for 450 years.

Sydney Morning Herald, April 2007[1]

Educational Aim

The aim of this lesson is to describe the key components of steam turbines and electric generators, and the processes used by these technologies to generate electricity from steam.

Key Words for Searching Online

Steam turbines, nozzle blade, rotor blade, nozzles, impulse turbine, reaction turbine, electric generators, electromagnetic induction, alternator

Key Learning Points

1. Making electricity from steam is generally a three step process, involving:
   1) Converting water to *high pressure steam*
   2) Using the high pressure steam in a *steam turbine* to rotate the turbine *shaft*
   3) Using the rotating turbine shaft in an *electric generator* to generate electricity

   In most cases, the used steam is converted back to water and returned to the source.
2. Water is converted to high pressure steam using either the heat from burning fuels, geothermal energy[2] or the heat from atomic fission.
3. Steam turbines convert high pressure steam to mechanical rotation in a process which involves steam at high-pressure (high pressure potential energy) and with some velocity (some linear kinetic energy) entering the turbine and being sucked through sets of different turbine blades, eventually exiting at (normal) atmospheric pressure. During this process:
   1) The steam first encounters a set of stationary blades, called nozzles, that guide the steam towards the next set of blades.
   2) The steam then encounters a set of moving blades, called rotor blades, which are connected to the turbine shaft. When the rotor blades move, the turbine shaft rotates (rotational kinetic energy).

   Thus the steam turbines convert the combined *input pressure potential energy* and *linear kinetic energy* of steam to output *rotational kinetic energy* of the turbine shaft.
4. Each pair of nozzles and rotor blades is called a stage. Some turbines use multiple stages in succession to convert as much steam energy into shaft energy as is economical.

[1] Garnaut, J. (2007) 'Scientists get hot rocks off over green nuclear power', *Sydney Morning Herald*, 12 April 2007. Available at www.smh.com.au/news/environment/hot-rock-power-the-way-ahead/2007/04/11/1175971183212.html. Accessed 12 May 2008.
[2] Geothermal energy involves finding vast blocks of 'hot rocks' with fracture systems that could generate electricity through water being injected, circulated through the fractures, and being returned to the surface as steam.

5. The energy conversion as the steam flows through the blades depends on whether the turbine is an *impulse* turbine or a *reaction* turbine. The difference between these two types of turbines lies in their blade configurations:

   1) In an *impulse turbine*, the force that moves the blades is a result of the steam striking the blades. This force is known as an *impulse*. As the steam passes through the nozzle, all of its pressure potential energy is converted to linear kinetic energy. Then as the steam passes through the rotor blades, all of its linear kinetic energy is converted to rotational kinetic energy.

   2) In a *reaction turbine*, the force that moves the blades is a result of the blades changing the direction of the steam's flow. This force is known as a *reaction force*. As the steam passes through the nozzle, some of its pressure potential energy is converted to linear kinetic energy. Then as the steam passes through the rotor blades, all of its remaining pressure potential energy and all of its linear kinetic energy is converted to rotational kinetic energy.

6. An electric generator is a device that converts the rotating turbine shaft's *kinetic energy* into *electricity*, or an electric current. The electricity then generates a voltage across an *electrical load*.

7. An electric generator works under the principle of *electromagnetic induction,* which means that if an electrical conductor, such as a wire, is moved through a magnetic field, then an electric current will be generated in the conductor.

8. The principle of electromagnetic induction is applied in an alternating current (AC) electric generator, or alternator.

Brief Background Information

Making electricity from steam is generally a three step process, where water is converted to high pressure steam, then the high pressure steam is converted to mechanical rotation of a turbine shaft, and the rotating turbine shaft then drives an electric generator.

Step 1: Water to Steam

In steam electric power plants, water is usually converted to high pressure steam using one of the following options:

- A *boiler*, which creates heat energy by burning fuels such as coal, oil, natural gas, wood or municipal waste as shown in Figure 6.1.[3]
- *Geothermal energy*, which is the heat energy in the ground near the Earth's core, as shown in Figure 6.2. Geothermal energy exploration involves finding blocks of underground radioactive 'hot rocks' which contain fractures through which water can pass. The proposition is that these support electricity generation by water being injected, circulated through the fractures, and then returned to surface as steam.

  South Australia has been described as 'Australia's hot rock haven'. According to an estimate by the Centre for International Economics, Australia has enough geothermal energy to contribute electricity for 450 years.[4] A geothermal power plant is already generating 80 kW of electricity at Birdsville, in southwest Queensland.[5]
- Atomic fission, which creates heat energy by splitting large atoms in to smaller atoms (see Figure 6.3).[6]

> ***Fundamentals***
>
> The *pressure* of a gas in an enclosure varies with *temperature* (if the *volume* remains the same):
>
> - pressure ∝ temperature
>
> The heat energy is absorbed by the gas particles, which then become more active and thus have more frequent and forceful collisions with each other and the enclosure's walls. These collisions cause pressure.

[3] Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, Office of Industrial Technologies, p 12. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007.
[4] Garnaut, J. (2007) 'Scientists get hot rocks off over green nuclear power', *Sydney Morning Herald*, 12 April 2007. Available at http://www.smh.com.au/news/environment/hot-rock-power-the-way-ahead/2007/04/11/1175971183212.html Accessed 12 May 2008.
[5] Hargroves, K. and Smith, M. (2007) 'Energy superpower or sustainable energy leader?', *CSIRO Ecos*, Oct-Nov 2007. Available at http://www.publish.csiro.au/?act=view_file&file_id=EC139p20.pdf. Accessed 12 May 2008.
[6] See Clean and Safe Energy Coalition – *How a Nuclear Power Plant Works* at http://www.cleansafeenergy.org/CASEnergyClassroom/HowaNuclearPowerPlantWorks/tabid/170/Default.aspx. Accessed 4 January 2008.

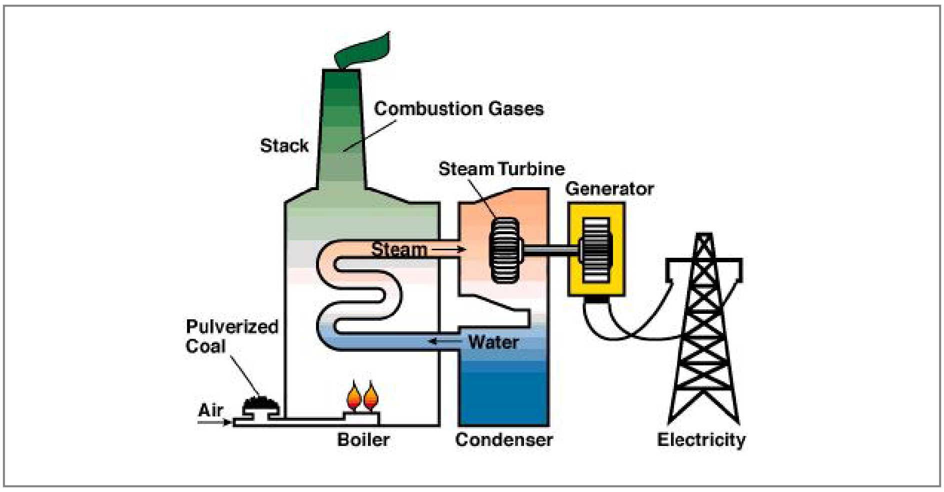

Figure 6.1. A steam electric power plant powered by a boiler

Source: TXU Energy[7]

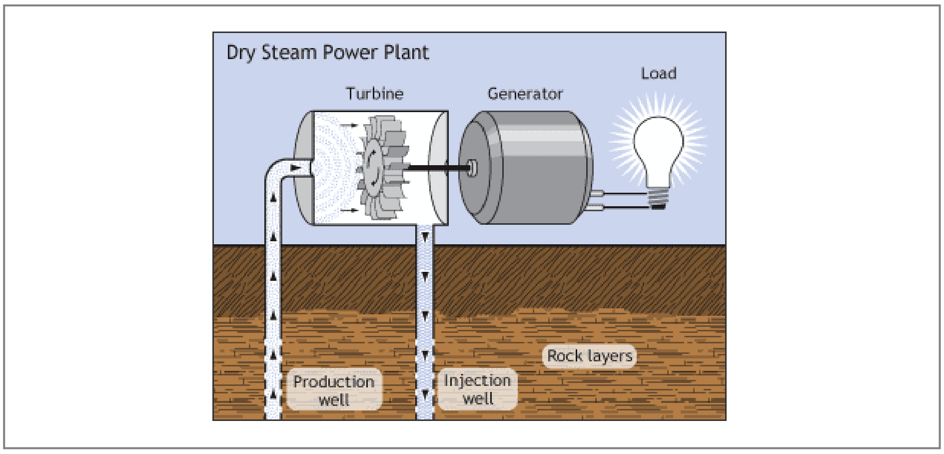

Figure 6.2. A steam electric power plant powered by geothermal energy

Source: US Department of Energy[8]

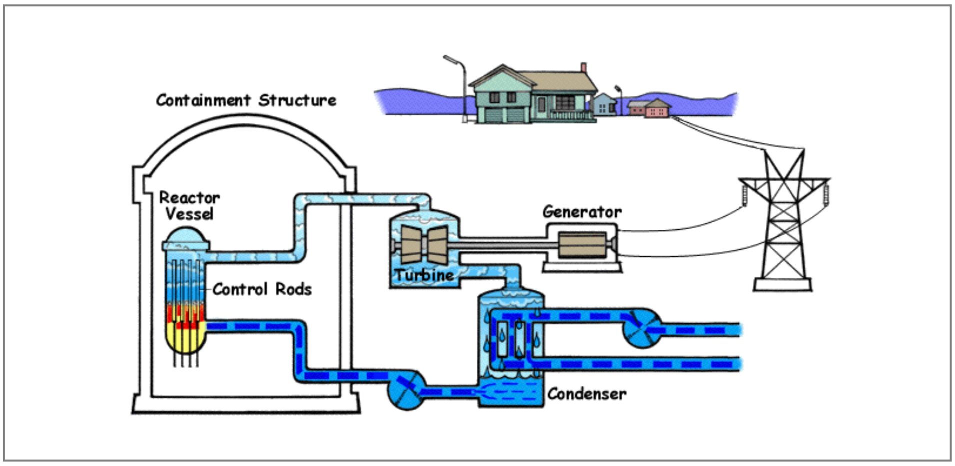

Figure 6.3. A steam electric power plant powered by nuclear fission

Source: Clean and Safe Energy Coalition[9]

[7] See TXU Energy – *Steam Turbines* at http://www.txucorp.com/responsibility/education/generation/steam.aspx. Accessed 5 December 2007.

[8] See US Department of Energy – *Geothermal Power Plants* at http://www1.eere.energy.gov/geothermal/powerplants.html. Accessed 12 November 2007.

2. Convert High Pressure Steam to Mechanical Rotation

Steam Turbines[10] convert high pressure steam to mechanical rotation. Their power output can range from 0.5 megawatts to over 1300 megawatts.[11] Steam turbines convert 10-40 percent of the combined input *pressure potential energy* and *linear kinetic energy* of steam to output *rotational kinetic energy* of the turbine shaft[12] in the following process:

> **Fundamentals**
>
> *Kinetic energy* is a form of energy in moving objects. Kinetic energy can be either *linear* or *rotational*:
>
> - linear kinetic energy ∝ linear velocity^2
> - rotational kinetic energy ∝ rotational velocity^2
>
> *Potential energy* is a form of stored energy in objects that can be converted to kinetic energy. Potential energy results in gases that are between regions of different *pressure*:
>
> - pressure potential energy ∝ pressure difference between regions

- High-pressure steam (high pressure potential energy) and with some velocity (linear kinetic energy) enters the turbine and is sucked through sets of different turbine *blades,* exiting at *atmospheric pressure*.
- The steam first encounters a set of stationary blades, which are also *converging nozzles*, that guide the steam towards the next set of blades.
- The steam then encounters a set of moving blades, called *rotor blades*, which are connected to the turbine shaft such that when the rotor blades move, the turbine shaft rotates (rotational kinetic energy).
- Each pair of nozzles and rotor blades is called a *stage*. Some turbines use multiple stages in succession to convert as much steam energy into shaft energy as is economical. The energy conversion as the steam flows through the blades depends on whether the turbine is an *impulse* turbine or a *reaction* turbine. The difference between these two types of turbines lies in their blade configurations. Each blade configuration uses a different type of primary force (impulse or reaction) to move the rotor blades, but also uses the other type of force (reaction or impulse) secondarily. The two can also be combined into an *impulse-reaction* configuration, relying heavily on both impulse and reaction

> **Fundamentals**
>
> Gases will move from small volumes at high pressure to large volumes at low pressure (if the *temperatures* of both regions are the same) in a process known as *expansion*.
>
> The pressure of the air we breathe is called *atmospheric pressure*, and is relatively low.

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[9] See Clean and Safe Energy Coalition – *How a Nuclear Power Plant Works* at http://www.cleansafeenergy.org/CASEnergyClassroom/HowaNuclearPowerPlantWorks/tabid/170/Default.aspx. Accessed 4 January 2008.

[10] Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, Office of Industrial Technologies, pp 12-13. Available from http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007.

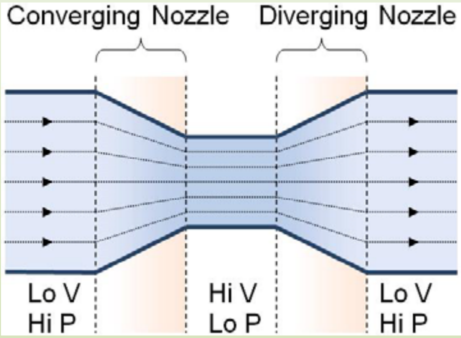
[11] Educogen (2001a) *The European Education Tool on Cogeneration*, 2nd ed., The European Association for the Promotion of Cogeneration, Belgium, p 47. Available at http://www.cogen.org/Downloadables/Projects/EDUCOGEN_Tool.pdf. Accessed 17 April 2007; Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, Office of Industrial Technologies, pp 5, 12. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007; United Nations Environment Programme (n.d.) *Energy Technology Fact Sheet: Cogeneration*, UNEP Division of Technology, Industry and Economics - Energy and OzonAction Unit, France. Available at http://www.cogen.org/Downloadables/Publications/Fact_Sheet_CHP.pdf. Accessed 17 April 2007.

[12] Educogen (2001a) *The European Education Tool on Cogeneration*, 2nd ed., The European Association for the Promotion of Cogeneration, Belgium, p 47. Available at http://www.cogen.org/Downloadables/Projects/EDUCOGEN_Tool.pdf. Accessed 17 April 2007; Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, Office of Industrial Technologies, p 5. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007; United Nations Environment Programme (n.d.) *Energy Technology Fact Sheet: Cogeneration*, UNEP Division of Technology, Industry and Economics - Energy and OzonAction Unit, France. Available at http://www.cogen.org/Downloadables/Publications/Fact_Sheet_CHP.pdf. Accessed 17 April 2007.

forces to move the rotor blades.

Impulse Turbines

The energy conversion for an impulse turbine is shown in Figure 6.4. In the impulse blade configuration (see Figure 6.5(a) and Figure 6.5(b)), there is high pressure at the nozzle's inlet, atmospheric pressure between the nozzle and rotor blade, and atmospheric pressure at the rotor blade's outlet. A nozzle is usually at the outlet of a guiding tube and rotor blades are connected to the rotor, which is also connected to the turbine's shaft. Since the nozzle's inlet pressure is higher than its outlet pressure, the steam expands through the nozzle – most of the steam's pressure potential energy is converted to linear kinetic energy. After flowing through the nozzle, steam then strikes the rotor blades and applies a force. This force results in an *impulse* on the rotor blades, transferring most of the steam's linear kinetic energy to the rotor blades' linear kinetic energy and hence the turbine shaft's rotational kinetic energy.

> ***Fundamentals***
>
> A *nozzle* is a tube-like device that either *converges* or *diverges*. As a fluid flows through a nozzle, its *linear velocity* increases as the nozzle converges and decreases as the nozzle diverges. The increase/ decrease in the fluid's linear velocity, and hence its linear kinetic energy, is converted from/to its *pressure* potential energy:
>
> - linear velocity $\propto$ 1/pressure
>
> 
>

> ***Fundamentals***
>
> Applying a *force* on an object for some *time* results in an *impulse*. An impulse increases the object's *velocity* in the direction of the force.

Since a rotor blade's inlet and outlet are both at atmospheric pressure, the steam does not expand and thus rotor blades are not designed to converge nor diverge (see Figure 6.5(c)). After flowing through the rotor blades, the steam is finally exhausted at low pressure and low velocity. A commonly recognised application of the impulse configuration is the Pelton wheel (see Figure 6.5(d)).

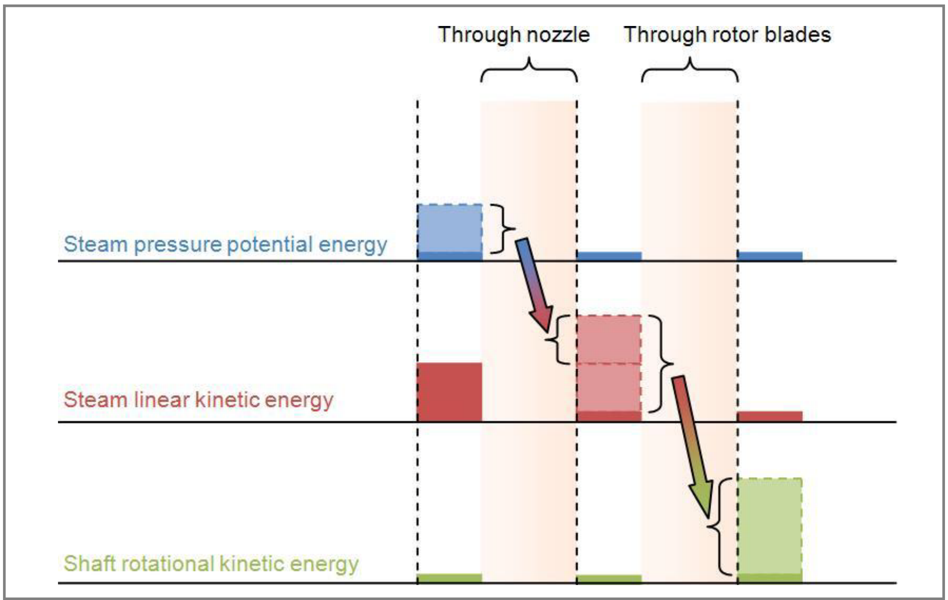


Figure 6.4. Energy conversion in an impulse turbine.

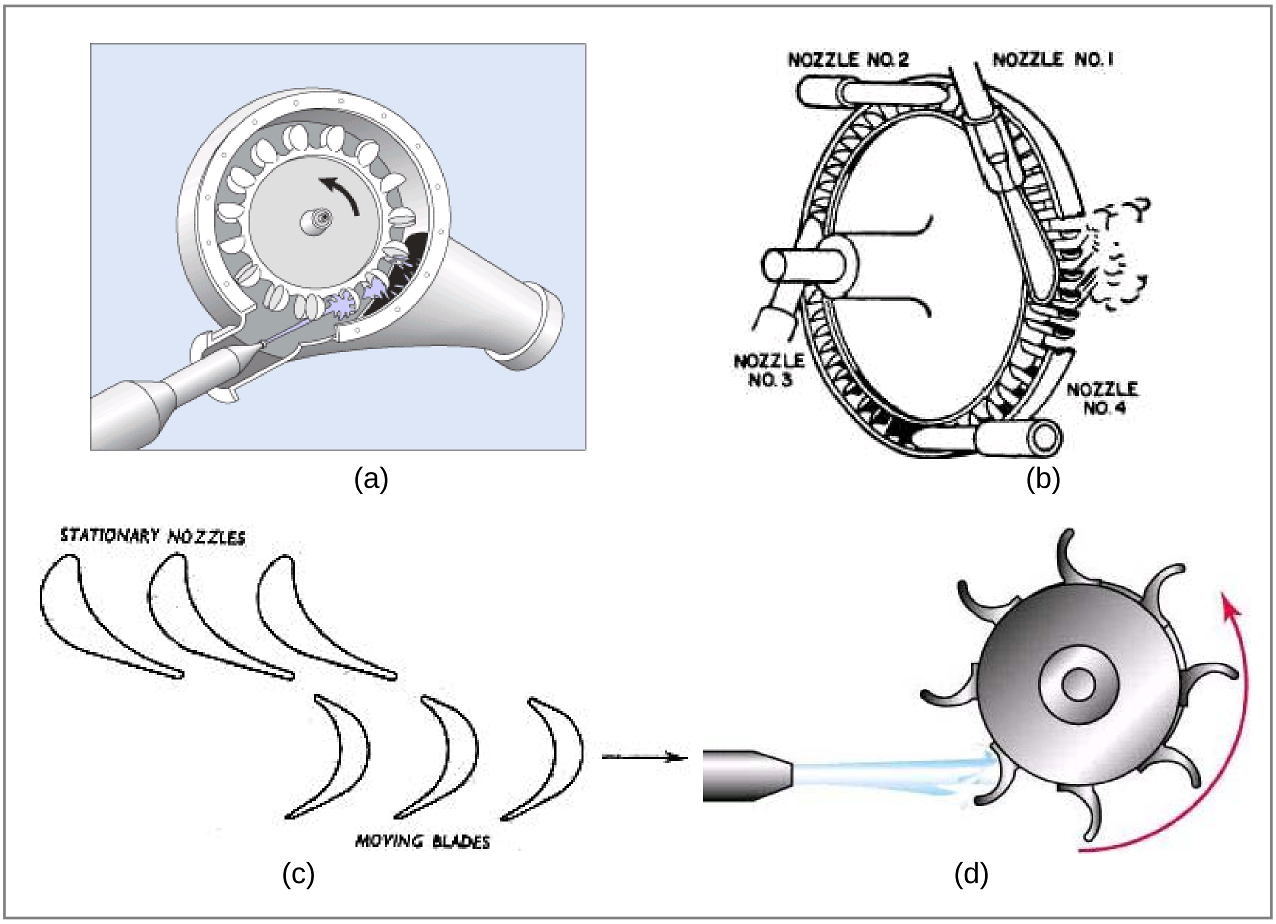


Figure 6.5. (a) Single-nozzle impulse turbine; (b) four-nozzle impulse turbine; (c) impulse nozzle blade configuration; (d) Pelton wheel

Source: (a) US Department of Energy;[13] (b) Integrated Publishing (n.d.);[14] (c) Adapted from Beardmore, R (2006)[15] by TNEP; (d) Adapted from The Free Dictionary[16] by TNEP

Reaction Turbines

The energy conversion for a reaction turbine is shown in Figure 6.6. In the reaction blade configuration (see Figure 6.7(a) and Figure 6.7(b)), there is high pressure at the nozzle's inlet, moderate pressure between the nozzle and rotor blade, and atmospheric pressure at the rotor blade's outlet. Nozzles are usually connected to the turbine's casing and rotor blades are connected to the rotor, which is also connected to the turbine's shaft. Since the nozzle's inlet pressure is higher than its outlet pressure, the steam expands through the nozzle – some of the steam's pressure potential energy is converted to linear kinetic energy. After flowing through the nozzle, steam then flows through the rotor blades, where it is forced to change direction. This force on the steam results in a *reaction force* on the rotor blades, transferring most of the steam's pressure potential energy and linear kinetic energy to the rotor blades' linear kinetic energy and hence the turbine shaft's rotational kinetic energy.

[13] See US Department of Energy – *Microhydropower System Turbines, Pumps, and Waterwheels* at http://www.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=11120. Accessed 20 December 2007.
[14] Integrated Publishing (n.d.) 'Chapter 10: Actuators' in *Fluid Power*, Integrated Publishing, pp 10.11-10.12. Available at http://www.tpub.com/content/engine/14105/css/14105_164.htm. Accessed 20 December 2007.
[15] Beardmore, R. (2006) *Thermodynamics – Steam Turbine*. Available at http://www.roymech.co.uk/Related/Thermos/Thermos_Steam_Turbine.html. Accessed 20 December 2007.
[16] See The Free Dictionary – *Turbine* at http://www.thefreedictionary.com/Turbines. Accessed 20 December 2007.

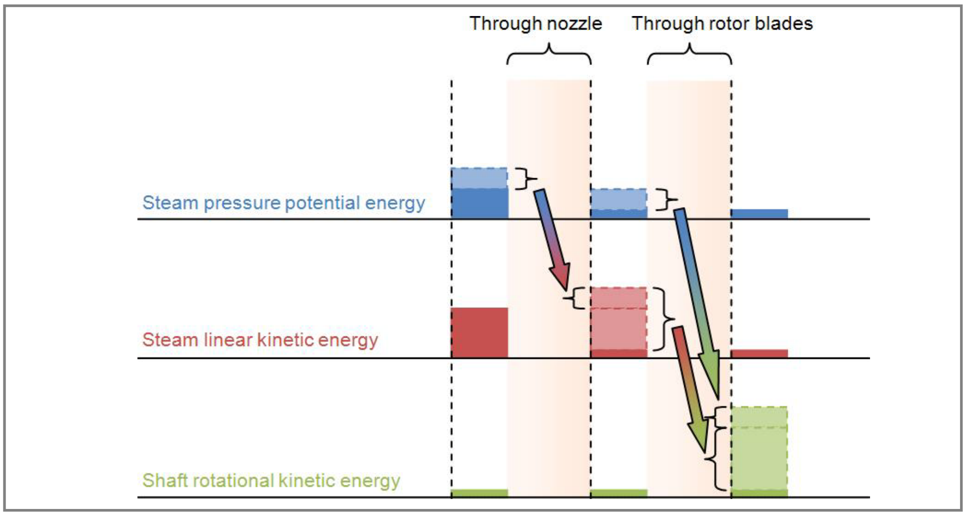


Figure 6.6. Energy conversion in a reaction turbine

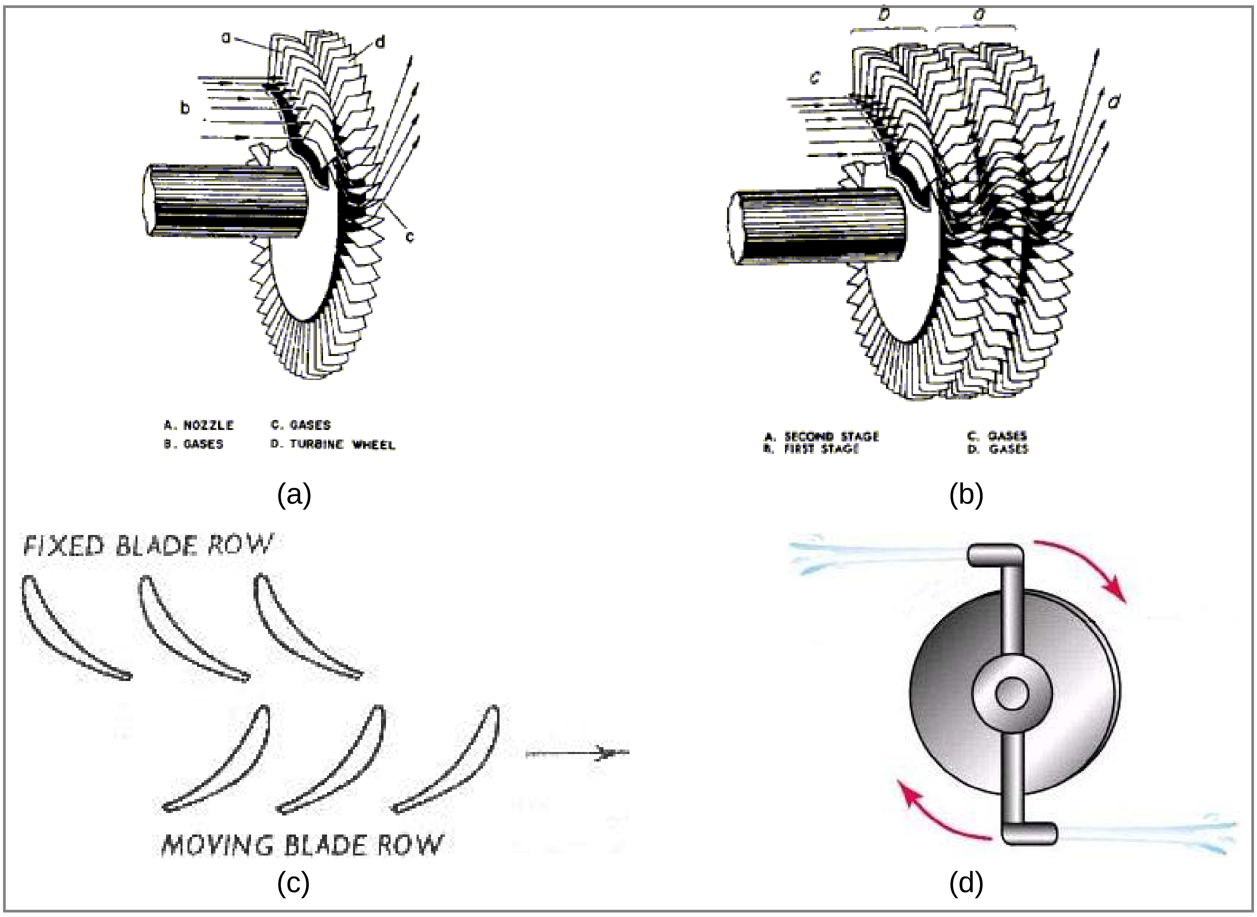


Figure 6.7. (a) Blades of a single-stage reaction turbine; (b) Blades of a two-stage reaction turbine; (c) reaction nozzle blade configuration; (d) Catherine wheel

Source: (a) & (b) Global Security (n.d.);[17] (c) Adapted from Beardmore, R. (2006);[18] (d) Adapted from The Free Dictionary[19]

[17] Global Security (n.d.) *Aircraft Gas Turbine Engines, Subcourse No. AL0993*, 5th edition, Lesson 2: Major Engine Sections. Available at http://www.globalsecurity.org/military/library/policy/army/accp/al0993/le2.htm. Accessed 21 December 2007.
[18] Adapted from Beardmore, R. (2006) *Thermodynamics – Steam Turbine,* Roymech, UK. Available at http://www.roymech.co.uk/Related/Thermos/Thermos_Steam_Turbine.html. Accessed 20 December 2007.
[19] See The Free Dictionary – *Turbine* at http://www.thefreedictionary.com/Turbines. Accessed 20 December 2007.

Since a rotor blade's inlet pressure is higher than its outlet pressure, the steam expands and thus rotor blades are designed as converging nozzles in the same shape as the nozzle blade (see Figure 6.7(c)). After flowing through the rotor blades, the steam is finally exhausted at low pressure and low velocity. A commonly recognised application of the impulse configuration is the Catherine wheel (see Figure 6.7(d)).

Impulse-Reaction Turbines

In the impulse-reaction blade configuration, the rotor blades are usually designed like an impulse blade at the root and like a reaction blade at the tip (see Figure 6.8).[20]

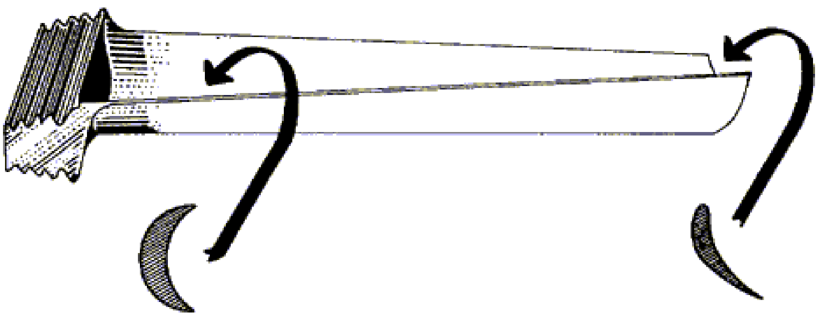


Figure 2.8. Impulse-reaction turbine blade

Source: Global Security[21]

Electric Generator

An electric generator is a device that converts kinetic energy into electricity, or an *electric current*. The electricity then generates a voltage across an electrical load. An electric generator works under the *principle of electromagnetic induction*, which means that if an electrical conductor, such as a wire, is moved through a magnetic field, then an electric current will be generated in the conductor.

> ***Fundamentals***
>
> *Vectors* have both *magnitude* and *direction* and are usually denoted in **bold** or with an arrow. The *cross product* (x) of two vectors, **A** x **B**, results in a another vector that has:
>
> - magnitude = (magnitude of **A**) x (magnitude of **B**) x sin(angle between **A** and **B**); and
> - direction perpendicular to both **A** and **B** as given by the *right hand rule*.

> ***Fundamentals***
>
> A positive electrical current (which is assumed in the right hand rule) flows from positive voltage to negative voltage. A negative electrical current flows from negative voltage to positive voltage.

The magnitude of the current in the wire is given by Equation 6.1 and Table 6.1; the direction of the current is given by the right hand rule (see Figure 6.9); and the magnitude of the voltage across the load is given by Equation 6.2 and Table 6.2.

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[20] The blade in the image is for an aircraft's gas turbine rather than for a steam turbine, but the image serves to demonstrate the impulse-reaction blade configuration.

[21] Global Security (n.d.) *Aircraft Gas Turbine Engines, Subcourse No. AL0993*, 5th edition, Lesson 2: Major Engine Sections. Available at http://www.globalsecurity.org/military/library/policy/army/accp/al0993/le2.htm. Accessed 21 December 2007.

Table 6.1: Symbol Nomenclature for Equation 6.1

Symbol	Quantity	Unit
I	Electrical current generated in wire	Ampere (A)
F	Force acting on current-carrying wire	Newton (N)
B	Magnetic field strength acting on wire	Tesla (T)
l	Length of wire	metres (m)
θ	Angle between the force and magnetic field strength	Degree (^{o}) or Radian (rad)

$$I = \frac{F}{Bl \sin \theta}$$

Equation 6.1. Electric current generated in a conducting wire that is moved through a magnetic field

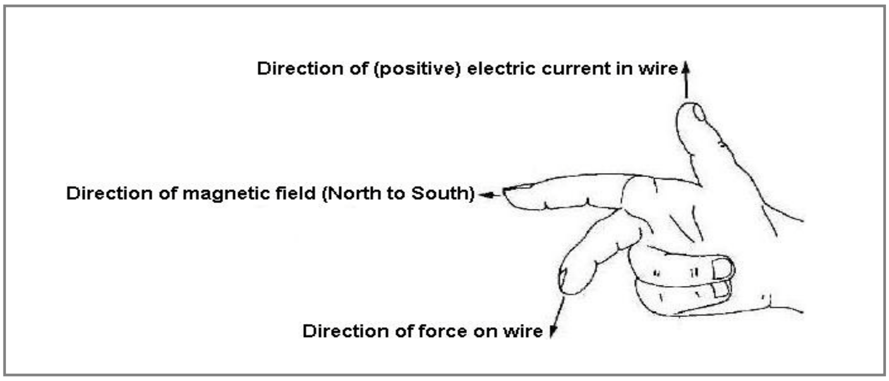


Figure 2.9. Right hand rule

Source: Adapted from Integrated Publishing[22]

Table 6.2: Symbol Nomenclature for Equation 6.2

Symbol	Quantity	Unit
V	Voltage generated across load	Volts (V)
I	Electrical current generated in wire	Ampere (A)
Z	Electrical impedance of load	Ohm (Ω)

$$V = IZ$$

Equation 6.2. Voltage generated across an electrical load due to an electric current

AC Generator

The way the principle of electromagnetic induction is applied in a simple AC electric generator, or *alternator*, is shown in Table 6.3. The magnetic field, which acts from North to South, is provided by two magnets. The force to move the wire is provided by the rotating output shaft of

[22] Integrated Publishing (n.d.) *Neets, Module 01 – Introduction to Matter, Energy, and Direct Current*, Integrated Publishing, Chapter 2: Radio Wave Propagation, p 2.11. Available at http://www.tpub.com/content/neets/14182/css/14182_71.htm. Accessed 5 December 2007.

the steam turbine or some other device. The general shape of the current graph and voltage graph are almost the same – the only difference is that one graph is usually stretched vertically compared to the other graph. One of the easiest ways to understand Table 6.3 is to step through each entry while:

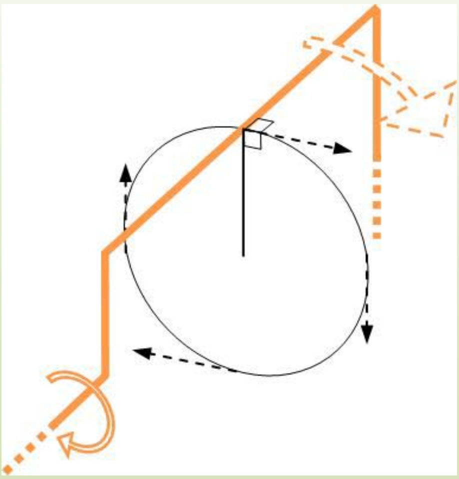
1. using the right hand rule to match the directions of the magnetic field, force and electric current; and
2. considering how much of the force is acting perpendicular to the magnetic field.

Alternatively, see the online animations by Wolfe, J. (n.d.)[23] and Wisconsin Valley Improvement Company.[24] These resources also have animations for DC generators.

Most practical electric generators use several loops of wire in a *coil*, rather than just one loop of wire. Some electric generators rotate the magnets while holding the wire stationary.

Fundamentals

The direction of the *force* on the wire at any point during its rotation is perpendicular to both the wire and the radius. The wire is held in rotation by the rest of the loop – if the wire is released at any point, it would fly off in the direction of the force.



[23] Wolfe, J. (n.d.) *Electric Motors and Generators*, School of Physics, University of New South Wales. Available at http://www.physclips.unsw.edu.au/jw/electricmotors.html. Accessed 5 December 2007. See 'An Alternator' for AC electric generator and 'Motors and Generators' for DC electric generator.

[24] See Wisconsin Valley Improvement Company – *How an Electric Generator Works* at http://www.wvic.com/how-gen-works.htm. Accessed 5 December 2007. Select 'Without commutator' for AC electric generator and 'With commutator' for DC electric generator.

Table 6.3: Operation of a simple AC electric generator

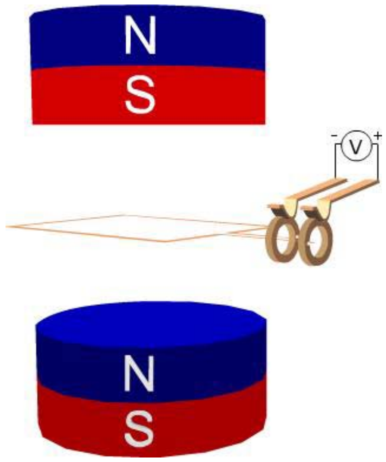
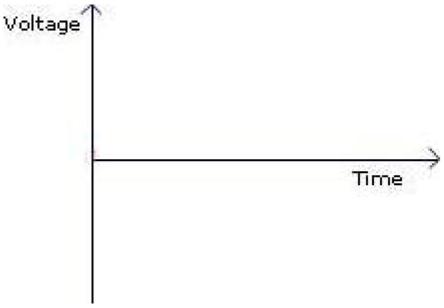
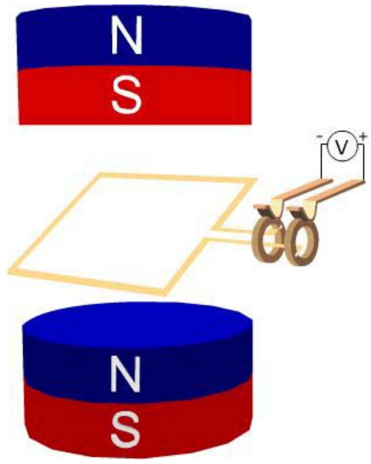
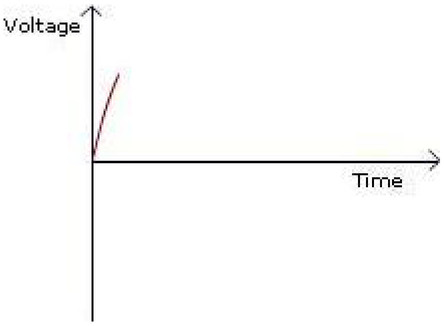
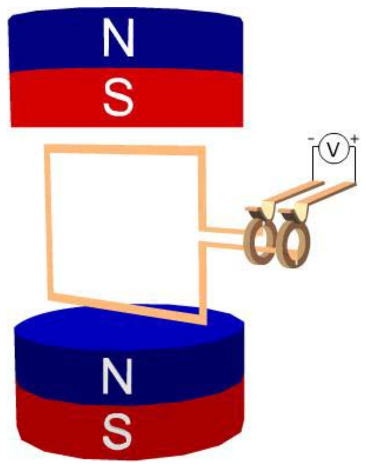
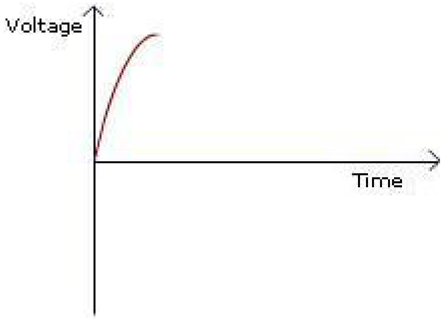
Confguration	Electric Current and Voltage	Comments
	***Magnitude:*** Zero ***Sign:*** – ***Trend:*** Increasing 	None of the force is acting perpendicular to the magnetic field, so zero electric current is generated.
	***Magnitude:*** Moderate ***Sign:***Positive ***Trend:*** Increasing 	In the first half of the cycle, electric current flows from positive voltage to negative voltage, which is the positive direction, thus the voltage is positive. Some of the force is acting perpendicular to the magnetic field, so moderate electric current is generated.
	***Magnitude:*** Maximum ***Sign:*** Positive ***Trend:*** Turning point 	All of the force is acting perpendicular to the magnetic field, so maximum electric current is generated.

Table 6.3: Operation of a simple AC electric generator *(Continued)*

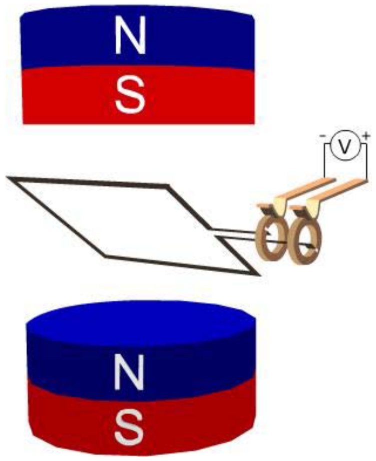
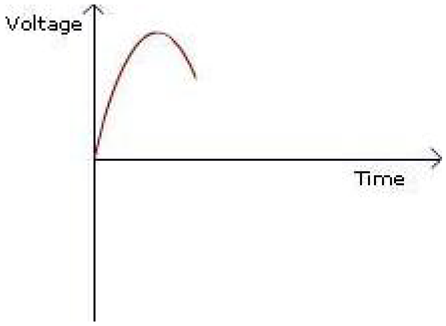
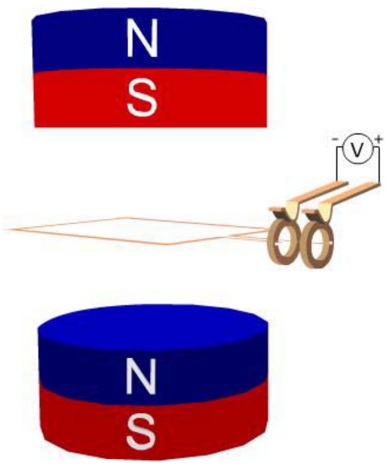
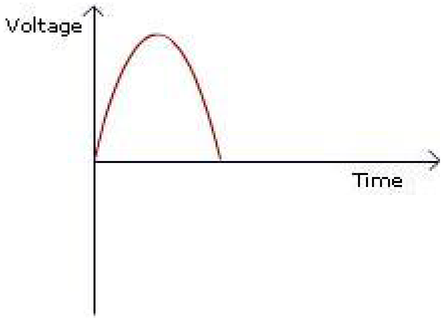
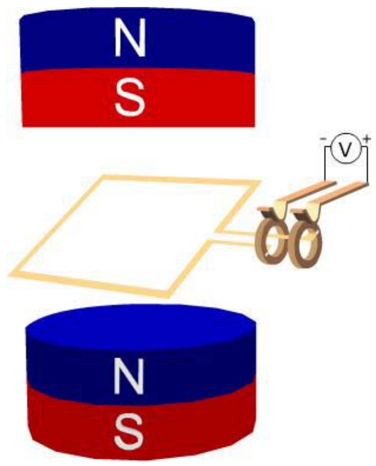
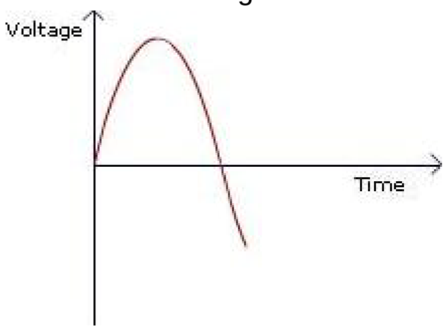
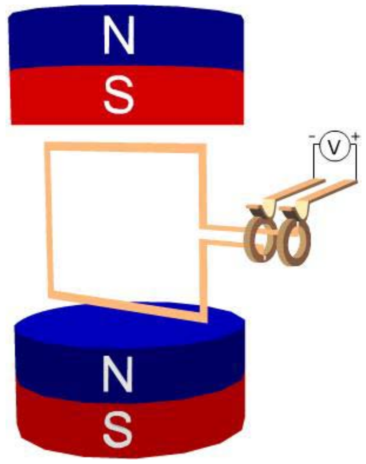
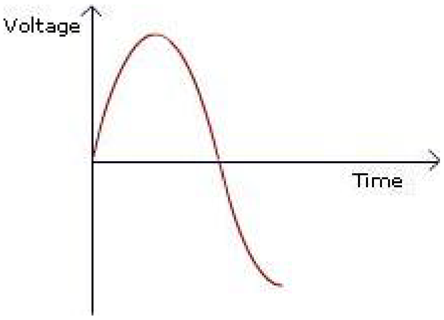
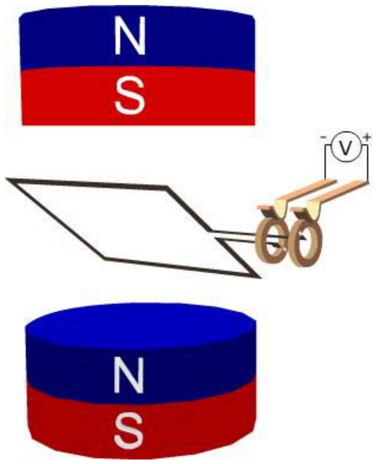
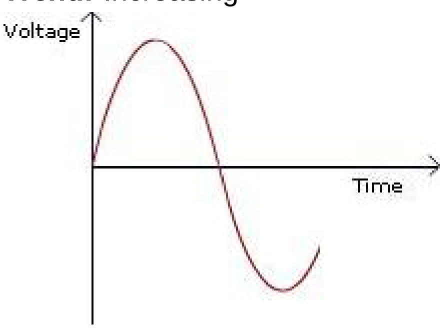
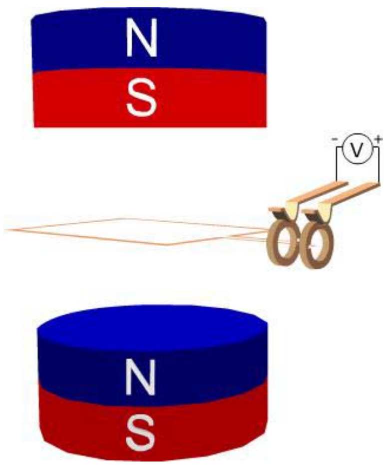
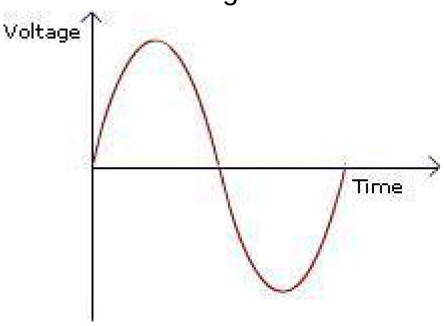
Confguration	Electric Current and Voltage	*Comments*
	***Magnitude:*** Moderate ***Sign:*** Positive ***Trend:*** Decreasing 	Some of the force is acting perpendicular to the magnetic field, so moderate electric current is generated.
	***Magnitude:*** Zero ***Sign:*** – ***Trend:*** Decreasing 	None of the force is acting perpendicular to the magnetic field, so zero electric current is generated.
	***Magnitude:*** Moderate ***Sign:*** Negative ***Trend:*** Decreasing 	In the second half of the cycle, electric current flows from negative voltage to positive voltage, which is the negative direction, thus the voltage is negative. Some of the force is acting perpendicular to the magnetic field, so moderate electric current is generated.

Table 6.3: Operation of a simple AC electric generator *(Continued)*

Confguration	Electric Current and Voltage	*Comments*
	***Magnitude:*** Maximum ***Sign:*** Negative ***Trend:*** Turning point 	All of the force is acting perpendicular to the magnetic field, so maximum electric current is generated.
	***Magnitude:*** Moderate ***Sign:*** Negative ***Trend:*** Increasing 	Some of the force is acting perpendicular to the magnetic field, so moderate electric current is generated.
	***Magnitude:*** Zero ***Sign:*** – ***Trend:*** Increasing 	None of the force is acting perpendicular to the magnetic field, so zero electric current is generated.

Source: Adapted from Wolfe, J. (n.d.)[25] by TNEP

[25] Wolfe, J. (n.d.) *Electric Motors and Generators*, School of Physics, University of New South Wales. Available at http://www.physclips.unsw.edu.au/jw/electricmotors.html. Accessed 5 December 2007.

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