

Renewable Energy Systems

Buchla, Kissell, Floyd



Generators

13

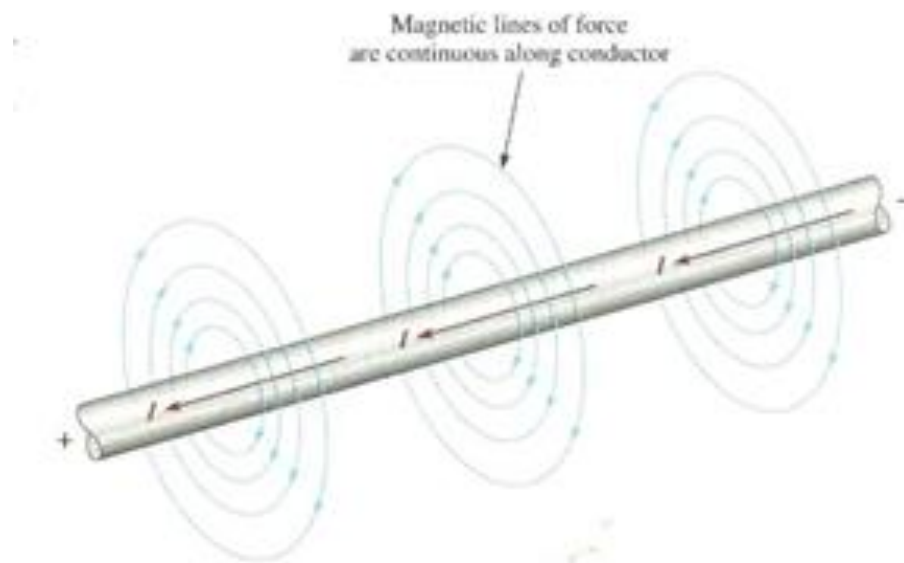
Renewable Energy Systems
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- 13-1 MAGNETISM AND ELECTROMAGNETISM
- 13-2 DC GENERATORS
- 13-3 AC SYNCHRONOUS GENERATORS
- 13-4 AC INDUCTION GENERATORS AND PERMANENT MAGNET GENERATORS

13-1 Magnetism and Electromagnetism

Generators are devices that convert mechanical energy to electrical energy and are widely used in renewable energy systems. To understand generators, it is useful to review the relationship between electricity and magnetism.

All magnetic effects have their basis in moving electric charge. Moving charge creates a magnetic field, which is the basis of electromagnets used in generators.



13-1 Magnetism and Electromagnetism

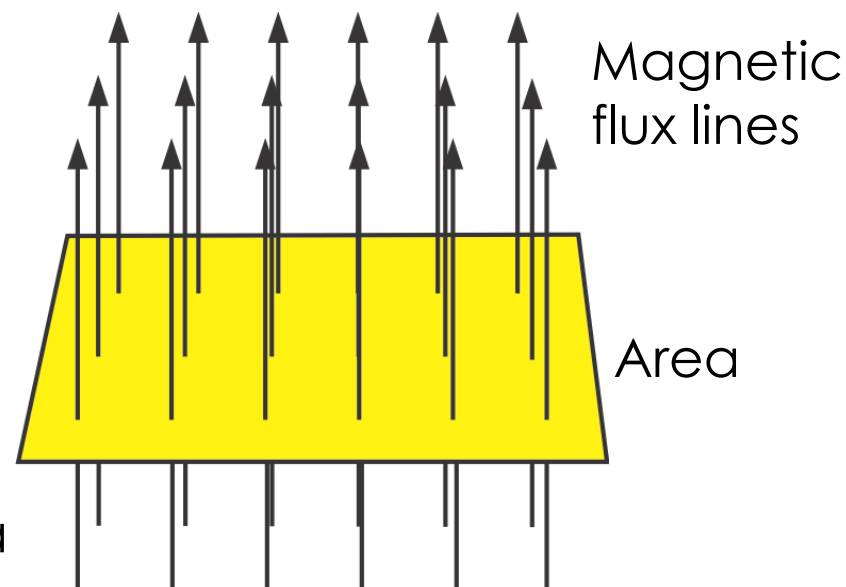
Magnetism is an invisible force that can be visualized with field lines. The group of lines going from the north pole to the south pole of a magnet is called the magnetic **flux**, symbolized by ϕ . **Flux density** is the amount of flux per unit area and is given by:

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

B = flux density in tesla (T)

ϕ = flux in Webers (Wb)

A = cross-sectional area (m^2)

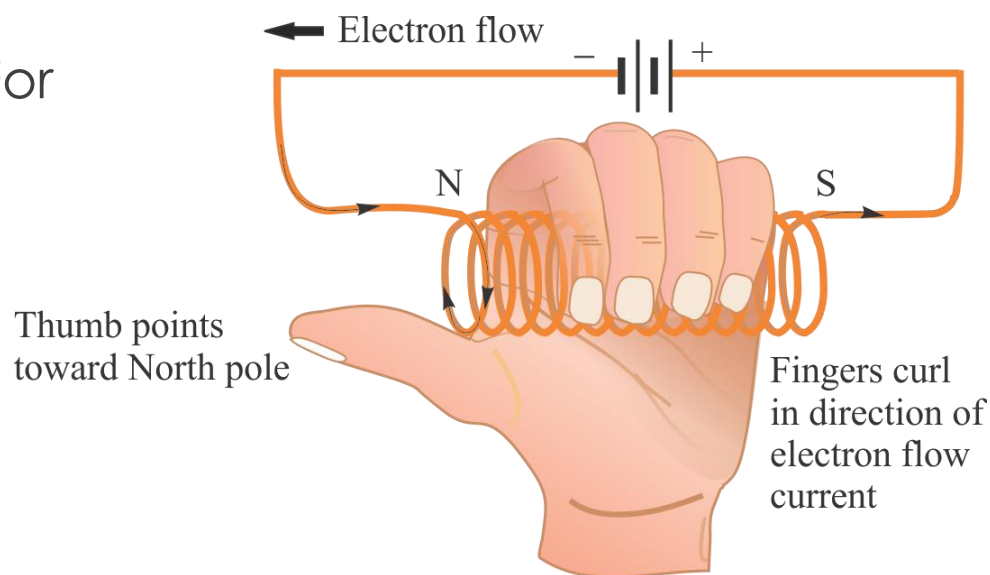


Note that $1 \text{ Wb/m}^2 = 1 \text{ T}$, which is a strong magnetic field.

13-1 Magnetism and Electromagnetism

The flux density of Earth's magnetic field at the surface of the Earth is relatively small – about $50 \mu\text{T}$ at the surface. Contrast this with the strong field of an MRI scanner, which ranges from 0.2 T to 3 T.

The flux density surrounding a current carrying wire is weak. For devices such as generators, motors, or transformers, it is necessary to increase the magnetic field strength by winding the wire into a coil.

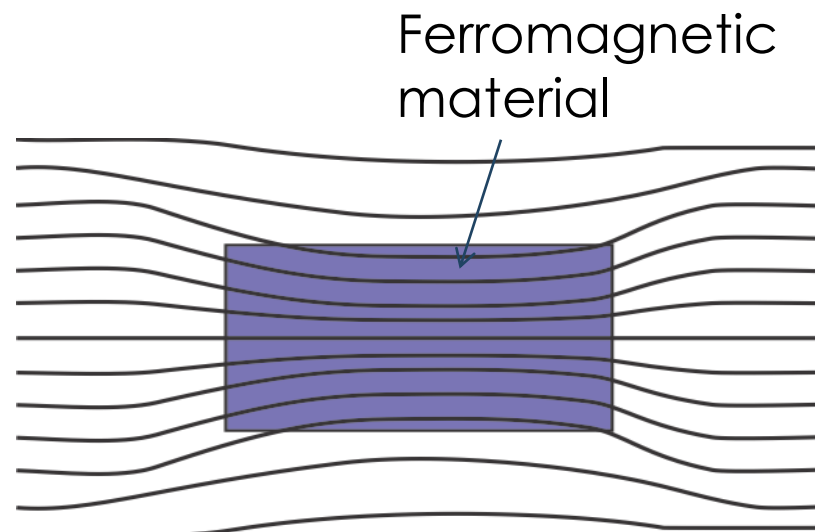


13-1 Magnetism and Electromagnetism

To increase the field for devices such as motors and generators that require a strong magnetic field, coils are wound on a magnetic core with high **permeability**, μ . Permeability is a measure of the ease a magnetic field can be established in a given material.

When a ferromagnetic material is placed in the magnetic field, flux lines concentrate in the material. By wrapping a coil around permeable materials, a stronger magnet can be created.

Magnetic
flux lines



The opposition to the establishment of a magnetic field in a material is called **reluctance** ($\mathcal{R}$).

$$\mathcal{R} = \frac{l}{\mu A}$$

$\mathcal{R}$ = reluctance (At/Wb)

l = length (m)

μ = permeability of the material (Wb/At·m)

A = area (m²)

The permeability (μ) depends on the type of material. You generally can find the relative permeability (μ_r) as a pure number and multiply the relative permeability by the permeability of a vacuum (μ_0), which is $4\pi \times 10^{-7}$ Wb/At·m to find the permeability of the material.

13-1 Magnetism and Electromagnetism

Example

Permalloy has a relative permeability (μ_r) of 8,000.

(a) What is the permeability?

(b) What is the reluctance of a 2.0 cm long circular core of permalloy that has a diameter of 0.5 cm?

Solution

(a) The permeability is 8,000 times larger than a vacuum.

$$\mu = \mu_r \mu_0 = (8000)(4\pi \times 10^{-7} \text{ Wb/At} \cdot \text{m}) = 0.010 \text{ Wb/At} \cdot \text{m}$$

(b) The area, A , is $\pi r^2 = \pi(0.0025 \text{ m})^2 = 19.6 \times 10^{-6} \text{ m}^2$

$$\mathcal{R} = \frac{l}{\mu A} = \frac{0.02 \text{ m}}{(0.01 \text{ Wb/At} \cdot \text{m})(19.6 \times 10^{-6} \text{ m}^2)} = 102 \times 10^3 \text{ At/Wb}$$

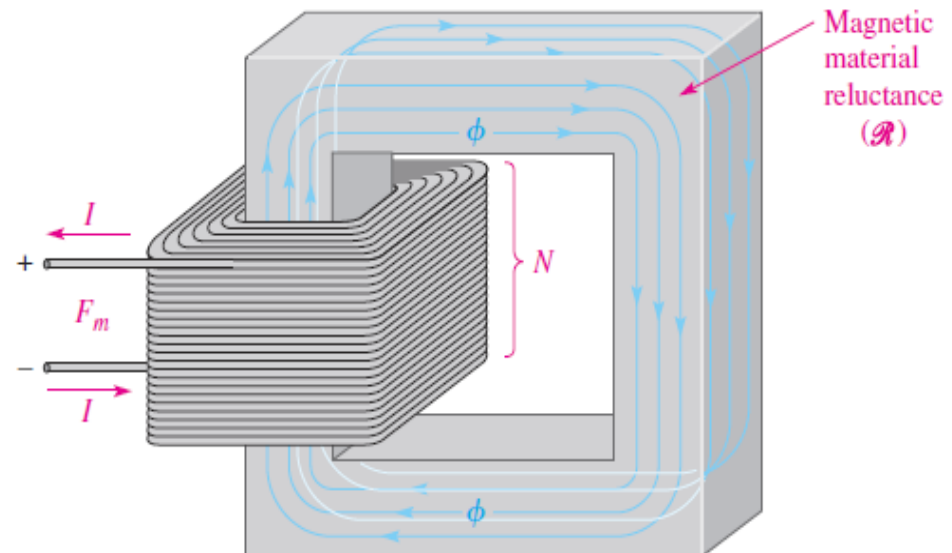
13-1 Magnetism and Electromagnetism

The cause of magnetic flux is **magnetomotive force** (mmf). The unit of mmf, the **ampere-turn** (At), is established on the basis of the current in a coil of wire. The formula for mmf is

$$F_m = NI$$

In a magnetic core, the flux, ϕ , is opposed by the reluctance of the core. This concept leads to the idea of Ohm's law for electromagnetic circuits, which is

$$\phi = \frac{F_m}{\mathcal{R}}$$



13-1 Magnetism and Electromagnetism

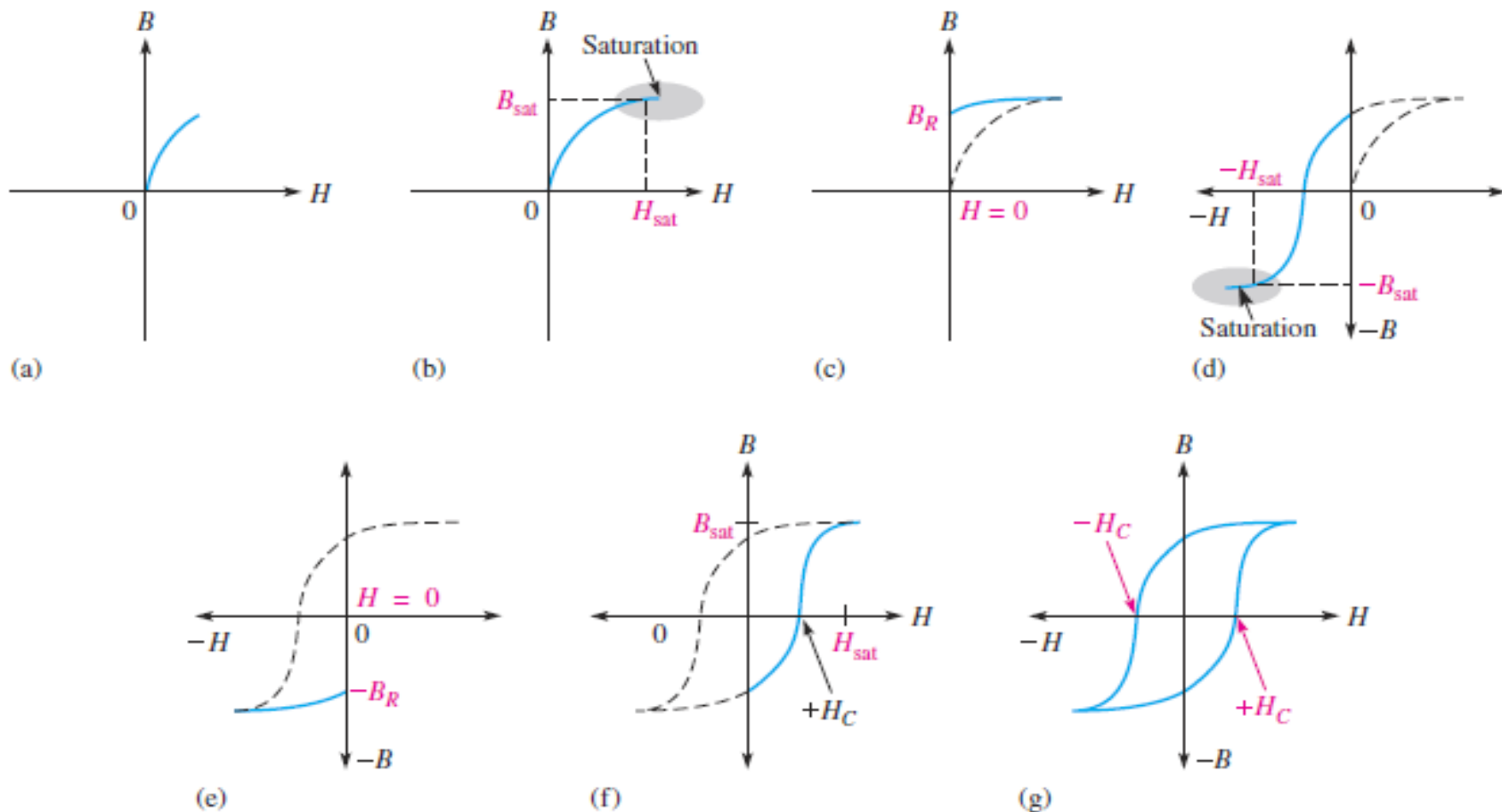
Electromagnets are magnets that can be varied in strength simply by changing the current, a concept that is applied to controlling motors and generators.

An important idea in magnetism is the **magnetic field intensity** (also called *magnetizing force*). The unit of magnetic field intensity (H) is ampere-turns per meter (At/m). The equation for magnetic field intensity is:

$$H = \frac{F_m}{l}$$

The following slide illustrates how increasing the current in a coil (and hence increasing the magnetic field intensity) affects the flux density in a magnetic material:

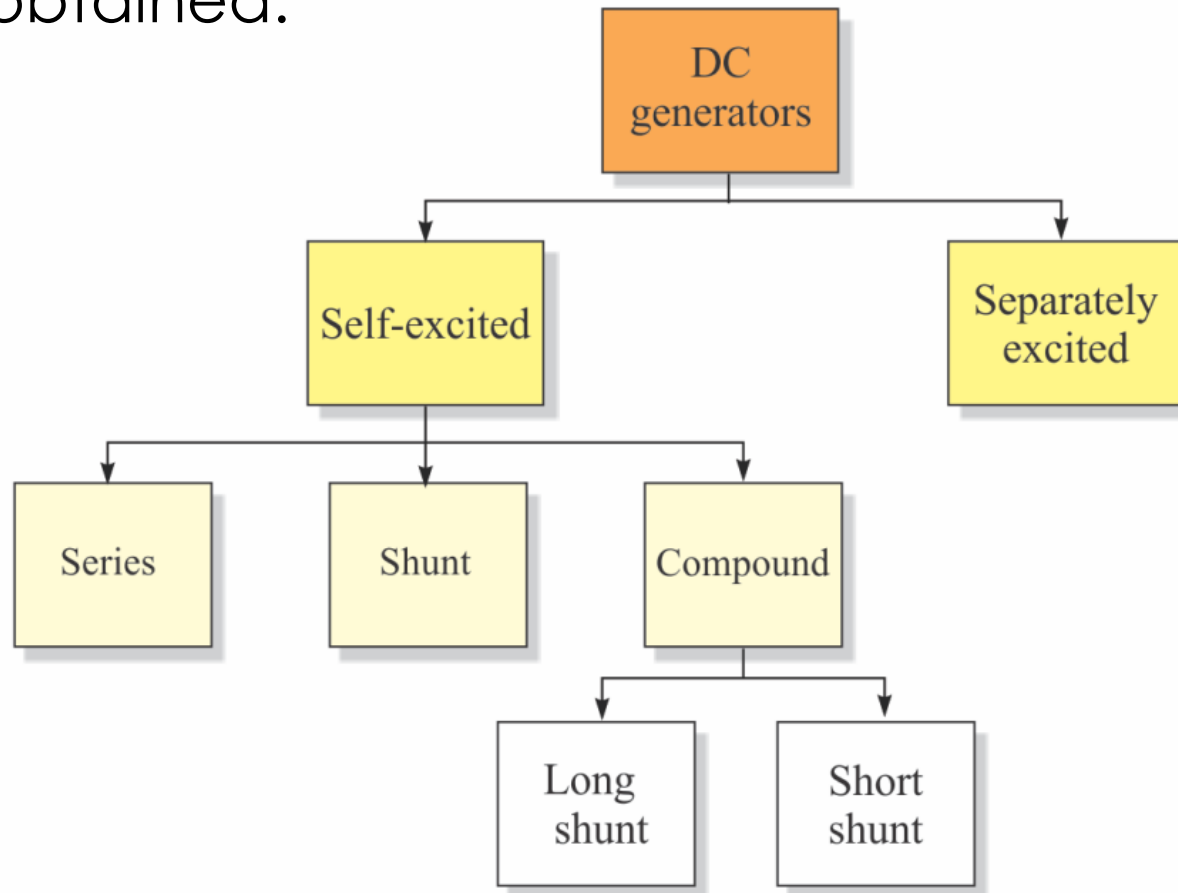
13-1 Magnetism and Electromagnetism



Development of a magnetic hysteresis ($B-H$) curve.

13-2 DC Generators

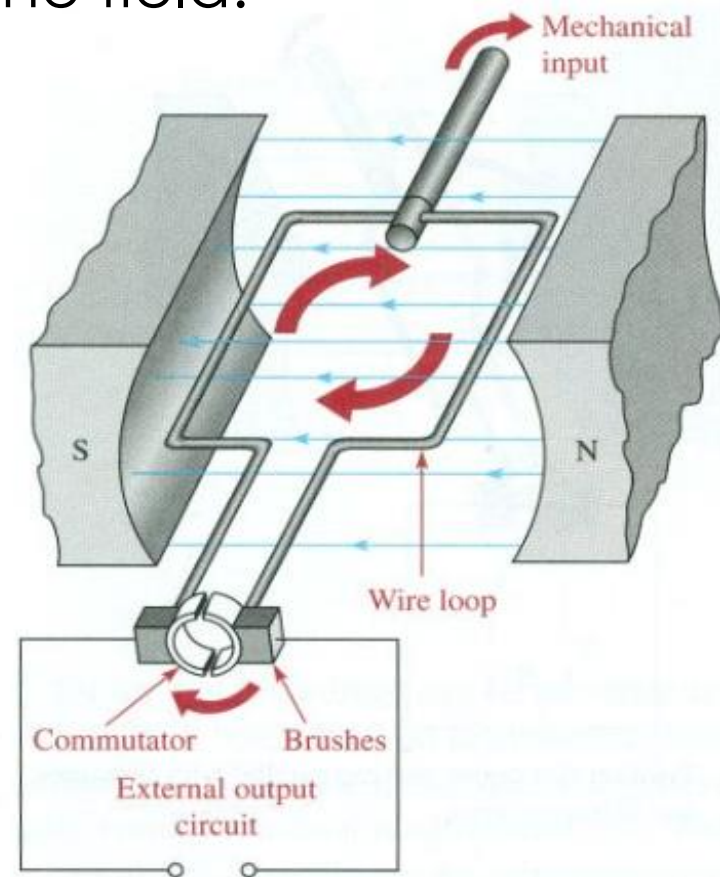
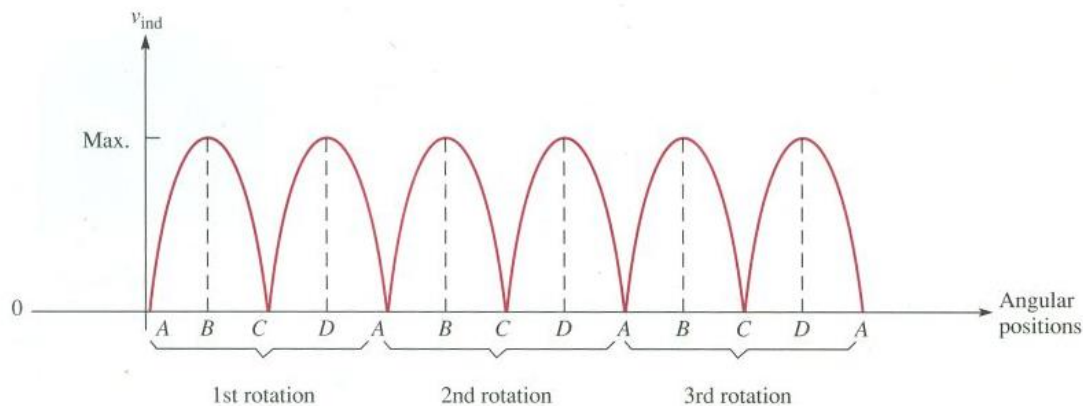
DC generators are classified by how the magnetic field is obtained.



13-2 DC Generators

The simplest dc generator to understand uses a permanent magnet to create the field.

An external force spins the rotor loop through the magnetic field, creating current. The current is determined by the position of the rotor loop. During one full rotation, the output maintains the same polarity because of the commutator arrangement.



13-2 DC Generators

In practical generators the **rotor** is wound with many turns and many coils on a ferromagnetic core. Each coil has its own pair of **commutator** segments, which acts as a mechanical rectifier. **Brushes** (not shown) contact the segments to carry current to the output.

The induced voltage can be calculated from the equation:

$$v_{ind} = B_{\perp} l v$$

v_{ind} = induced voltage, (V)

$B_{\perp}$ = perpendicular flux density (Wb/m²).

l = length of conductor (m)

v = velocity of the conductor (m/s)



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13-2 DC Generators

The **stator** is the entire fixed portion of the generator. It has coils or a permanent magnet for creating the field and includes the case and end bells that support the bearings.

There are two ways to provide current for the field:

- 1) Provide a separate source for field current.
- 2) Connect a portion of the generator's own output to supply current for the field.

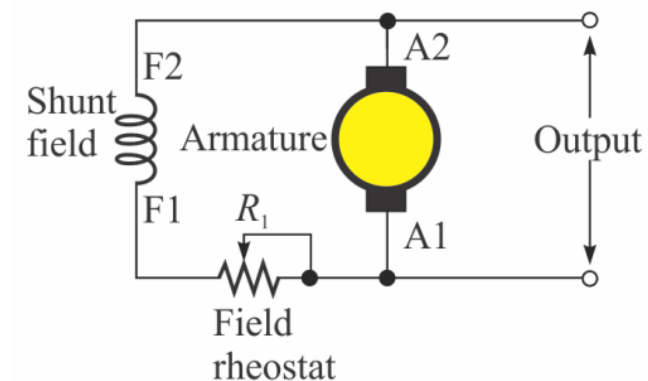
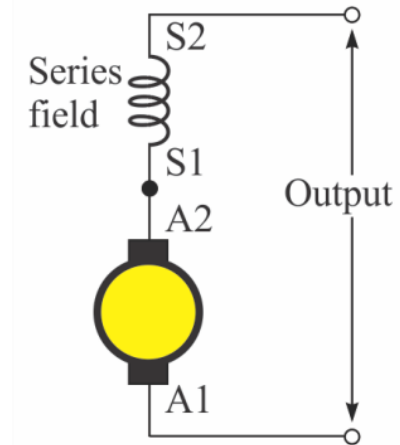


Source: Tom Kissell

13-2 DC Generators

There are three wiring methods for dc generators.

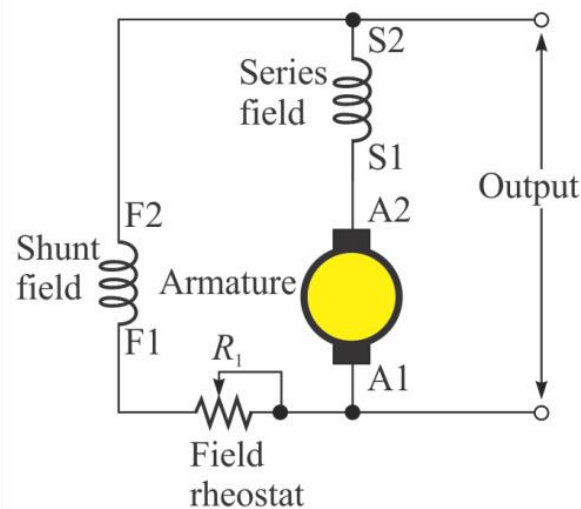
1. In a series wound self-excited dc generator, the field winding is in series with the armature. Starting is accomplished from residual magnetism.
2. In a shunt wound self-excited dc generator, the field winding is in parallel with the armature. A fraction of the generated current is used to supply field current.



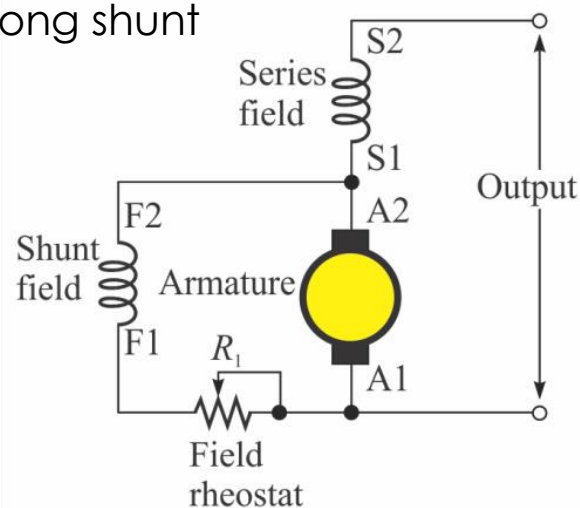
13-2 DC Generators

3. In a compound wound self-excited dc generator, there are two field windings: one in series; the other in parallel. The two windings can be wired so that the shunt field is in parallel with the output (long shunt) or in parallel with the armature (short shunt).

The main advantage to the compound generator is that it can maintain a relatively constant voltage over varying load conditions. For more stringent regulation, a voltage regulator is used.



(a) long shunt



(b) short shunt

13-3 AC Synchronous Generators

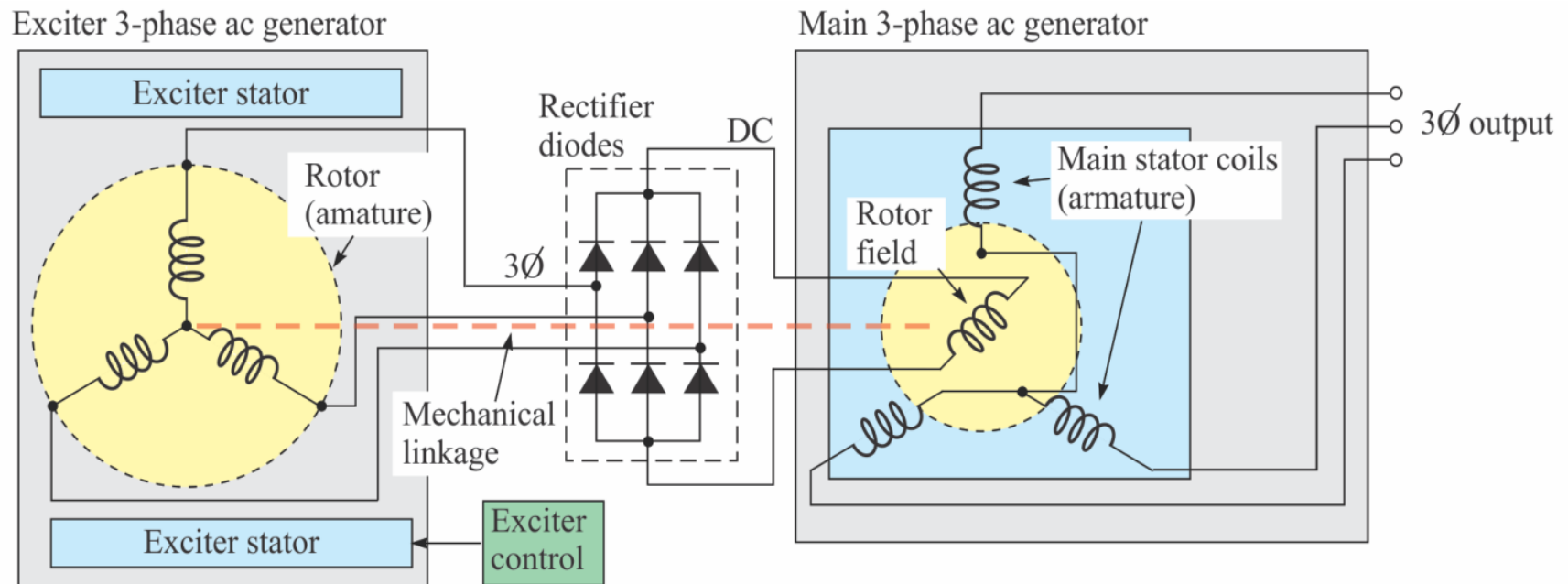
A **synchronous generator** is a machine that produces an ac voltage that is synchronized with the rotation of the generator. It is widely used by utilities to maintain a constant frequency for the grid. There are two configurations of synchronous ac generators:

1. In a **rotating armature ac generator**, slip rings and brushes pass current from the rotor to the electrical terminals on the frame.
2. In a **rotating field ac generator**, the field is on the rotor and the armature is on the stator. Slip rings and brushes are not necessary if rotor current can be supplied from a separate rotating exciter.

Source: NREL

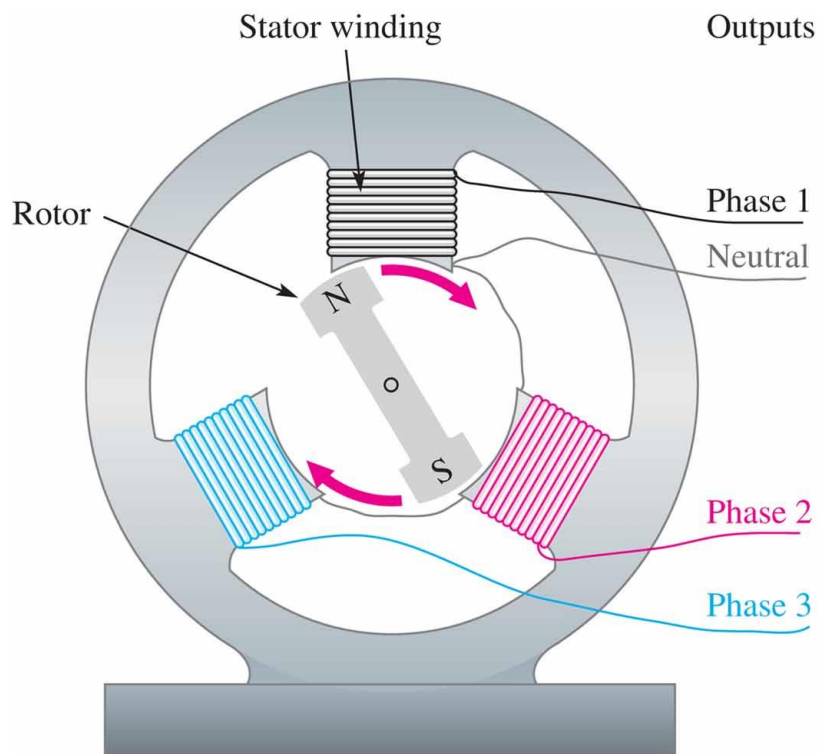
13-3 AC Synchronous Generators

Large synchronous generators are rotating field generators using a wound rotor. Rotor current is generally supplied by an **exciter**. This is a small generator that takes current from the rotating armature to supply the field of the main generator.

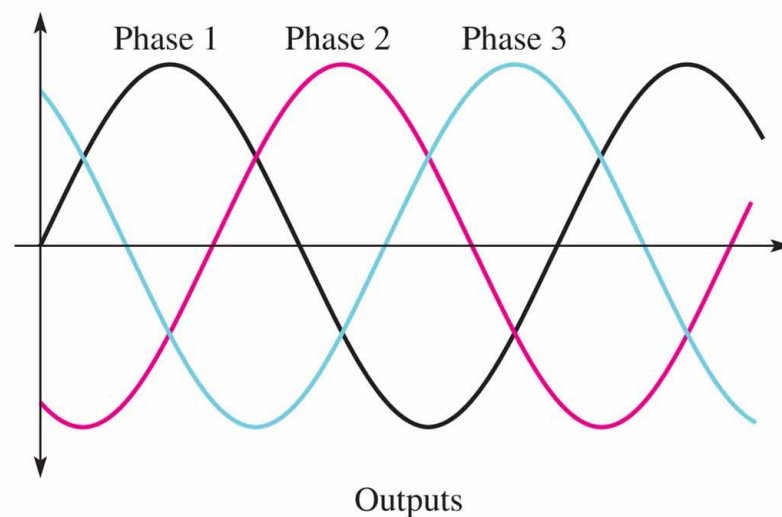


13-3 AC Synchronous Generators

The output from utility ac generators is three-phase. In three-phase systems, three equal outputs are separated by 120° each.



(a) Three-phase rotating-field generator



(b) Three-phase sine wave

13-3 AC Synchronous Generators

Large synchronous generators are used in some wind turbines. This can eliminate the need for an inverter, however the shaft must rotate at nearly constant speed to keep the frequency constant.

In order to generate the correct frequency with lower rotor speeds, the wind turbine generator will be designed with many poles.

The equation for frequency from a synchronous generator is

$$f = N_p \times rpm / 120$$

f = frequency in Hz

N_p = number of poles

rpm = rotational speed in revolutions per minute



Source: NREL

13-3 AC Synchronous Generators

Example

What speed (in rpm) does a 12 pole generator need to turn to generate a frequency of 60 Hz?

Solution

$$rpm = \frac{120 f}{N_p} = \frac{120(60)}{12} = 600 \text{ rpm}$$

Question

Is it possible to build a generator with 15 poles? Why or why not?

Answer

It is not possible. Magnetic poles always come in pairs (a North Pole and a South Pole), so only an even number of poles is possible.

13-4 Induction Generators and PM Generators

An **induction generator** always starts out as an induction *motor* and becomes a generator when it is spun by an external prime mover past the synchronous speed.



Source: Tom Kissell

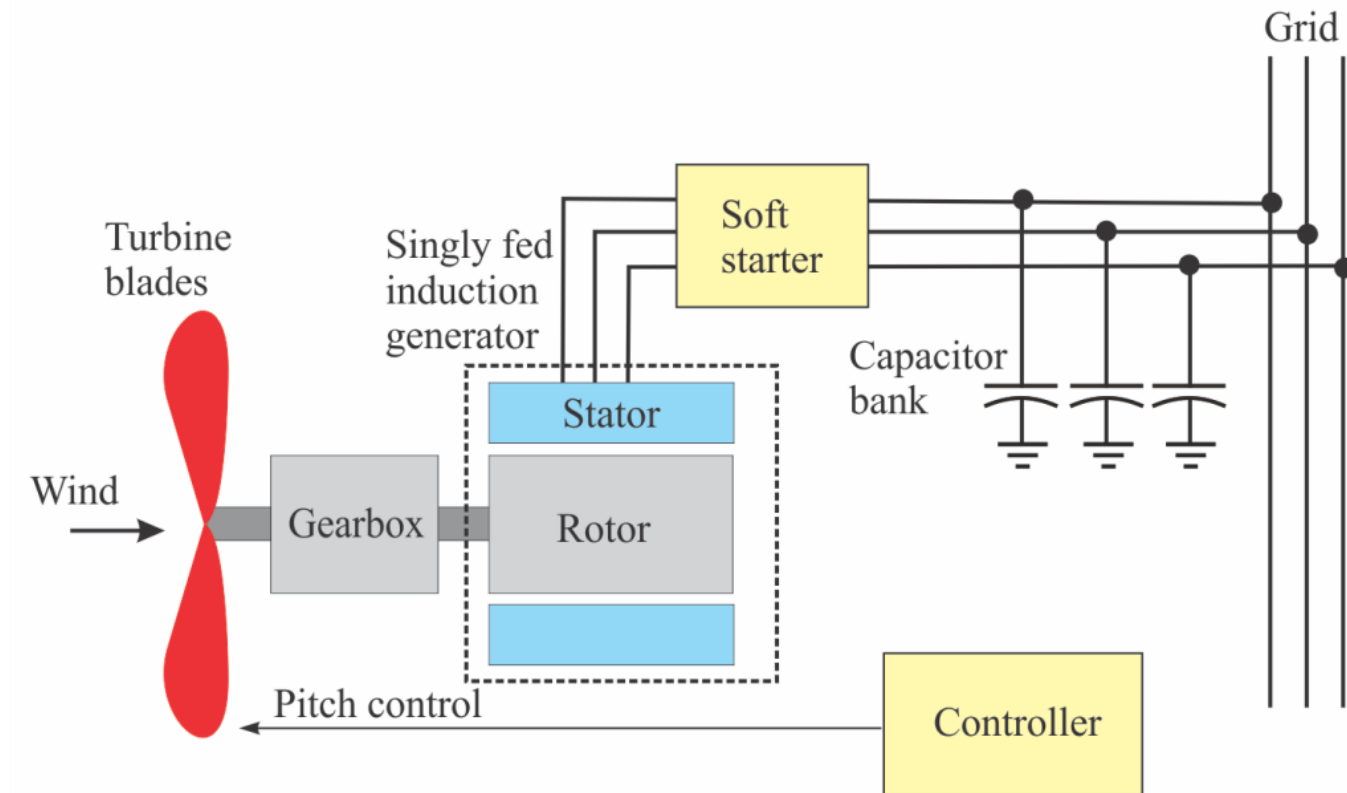
1. Squirrel cage rotor: Rotor current is *induced* by transformer action to create the field.



2. Wound rotor: windings on the rotor are connected through slip rings and brushes to create the field.

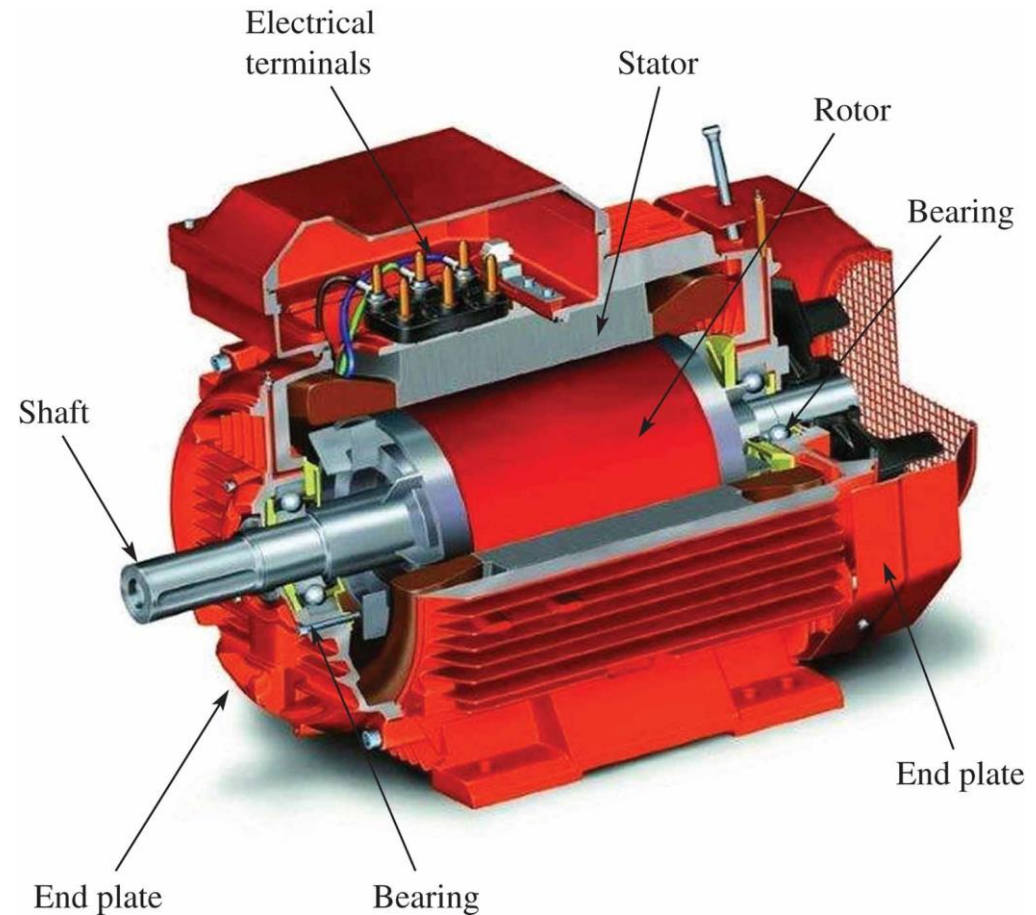
13-4 Induction Generators and PM Generators

The simplest induction generator is referred to as a singly-fed induction generator (SFIG) that uses a squirrel cage rotor. The drawing shows one with a wind turbine as the prime mover.



13-4 Induction Generators and PM Generators

The cutaway view shows a squirrel cage rotor, which is in close proximity to the stator to minimize magnetic losses.

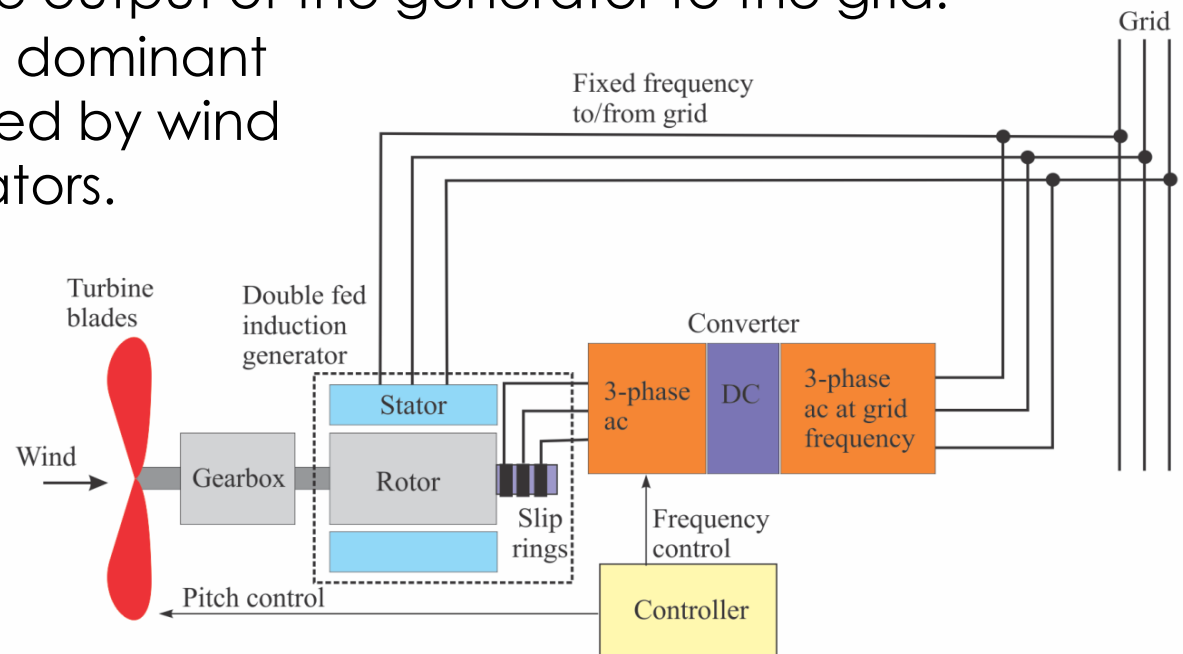


Courtesy of Aerostar, Inc.

13-4 Induction Generators and PM Generators

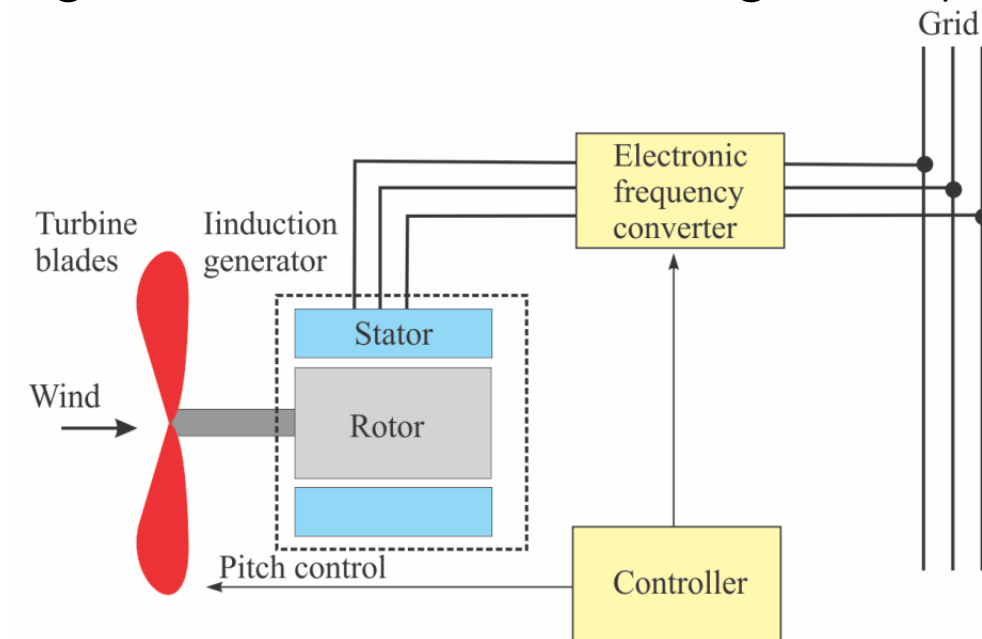
The doubly-fed induction generator (DFIG) can synchronize to the utility frequency despite variations in the rotor speed, a significant advantage for wind turbines. A converter produces a variable frequency that can add or subtract from the mechanical rotation frequency of the rotor to synchronize the output of the generator to the grid.

The DFIG is the dominant technology used by wind turbine generators.



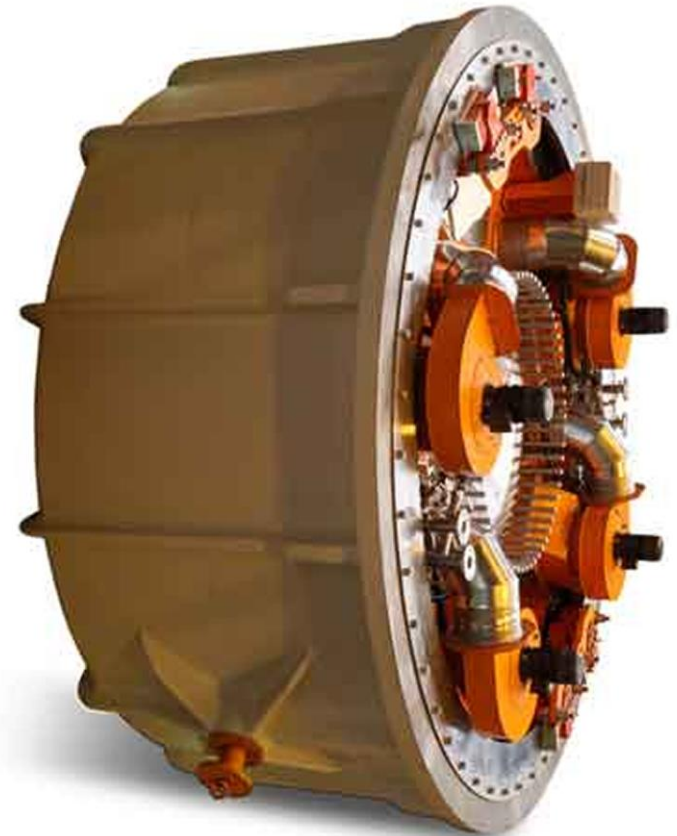
13-4 Induction Generators and PM Generators

A variable speed induction generator (VSI_G) is simpler but uses more complex electronics to synchronize to the grid. The VSI_G uses the mechanical rotation of the rotor to determine the output frequency. The output is not fed directly to the grid but rather to an electronic frequency converter that generates a match to the grid frequency.



13-4 Induction Generators and PM Generators

Another option is to use a permanent magnet rotor to create the magnetic field. They use expensive rare earth magnets, but the advantage is a completely sealed unit that needs much less maintenance. These are popular in large offshore generators because of the cost of maintenance.



Source: The Switch

Selected Key Terms

Compound generator

A generator that has two field windings – one in series and one in parallel. Typically, the output voltage tends to be independent of the load.

Doubly-fed induction generator (DFIG)

An ac induction generator that has a wound rotor that is connected to a different source of ac than the stator. AC from the grid or from an inverter is supplied to the fields in the stator. Also known as a *double-excited induction generator*.

Exciter

A smaller auxiliary generator that supplies field current for a larger generator.

Induction generator

An asynchronous electrical machine that can function as a motor or as a generator.

Selected Key Terms

Magnetic field intensity

The magnetomotive force per unit length of the magnetic material. The unit is the ampere-turns per meter; also known as *magnetizing force*.

Self-excited shunt generator

A generator that supplies its voltage from its armature to create the field current. The field and armature windings are in parallel.

Squirrel-cage rotor

A rotor for a motor or generator that is an aluminum “cage” with conducting bars that are shorted together at each end by a ring. The cage surrounds an iron core that provides a path for the magnetic field.

Synchronous generator

An ac generator in which the output frequency is synchronized to the position of the rotor.

true/false quiz

1. All magnetic fields have their basis in moving electric charge.

true/false quiz

2. The unit for magnetic flux is the tesla.

true/false quiz

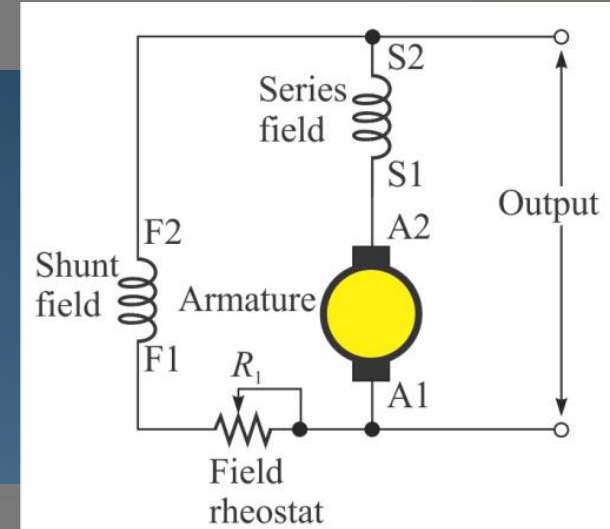
3. The magnetic flux in a core is directly proportional to the mmf.

true/false quiz

4. The brushes in a dc generator rub against the slip rings.

true/false quiz

5. This is a diagram for a compound generator.



true/false quiz

6. Three phase generators produce three equal outputs separate in phase by 90° .

true/false quiz

7. A squirrel cage rotor uses slip rings to bring rotor current to the rotating field.

true/false quiz

8. A doubly-fed induction generator has a variable frequency applied to the rotor.

true/false quiz

9. Large synchronous generators can use an exciter to supply field current to the rotor of the main generator.

true/false quiz

10. Permanent magnet generators tend to have higher maintenance costs.

true/false quiz

Answers:

1.T

6.F

2.F

7.F

3.T

8.T

4.F

9.T

5.T

10. F