REET 2020

Energy Conversion

1 – Electric Power System

Electric Power Systems

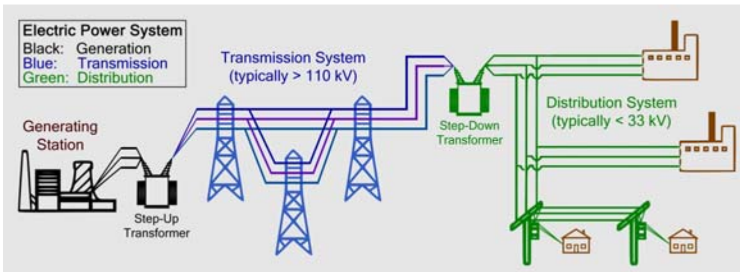
An Electric Power System is a complex network of electrical components used to reliably generate, transmit and distribute electric energy on a real-time, “as-needed” basis.

Within the United States, the primary method of distributing electric power is by means of a three-phase transmission and distribution system.

Electric Power Systems

In terms of its operation, an electric power system can be divided into three primary subsystems, each of which performs a key function:

- Generation
- Transmission
- Distribution



Electric Power Generation

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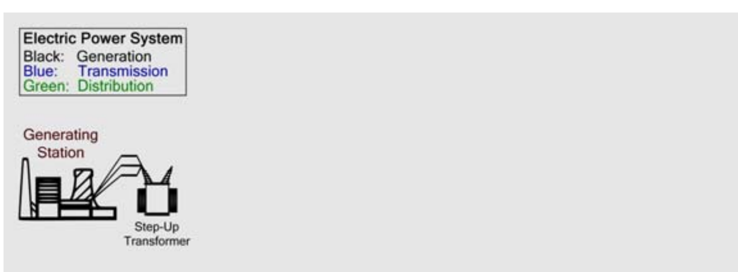


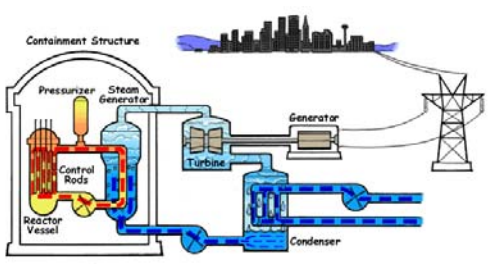
Electric Power Generation

Most of the electric energy that is transmitted/distributed by the electric power system is produced at generating stations, or "power plants" as they are commonly called.

Gas-fired Combustion Turbine Generator
Sewell Creek Energy Facility – Oglethorpe Power

Steam Turbine Generating Plants

The majority of power plants are steam turbine generating plants, in which the heat derived from fossil fuels (or other sources) is used to boil water and create high-pressure steam.



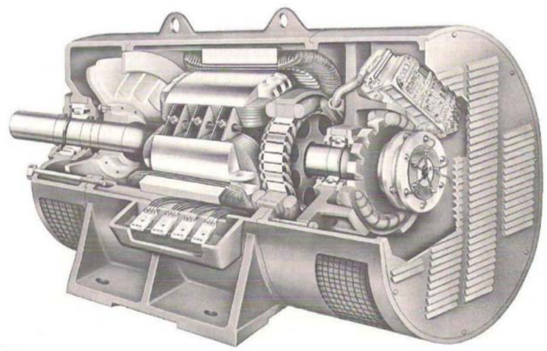
https://upload.wikimedia.org/wikipedia/commons/a/a0/PressurizedWaterReactor.gif

The steam is passed through a set of turbines that extract and convert energy from the stream into kinetic (rotational) energy.

The kinetic energy is then used to rotate an electric generator which, in-turn, converts the kinetic energy into electric energy.

Electric Generators

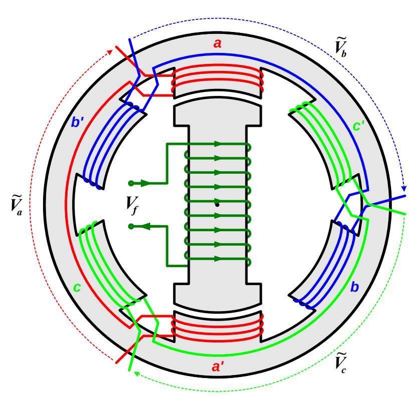
Three-Phase Synchronous Generators are almost exclusively utilized in turbine-based generating stations.



http://cdn.intechopen.com/pdfs/38933/intech-wind_turbine_generator_technologies.pdf

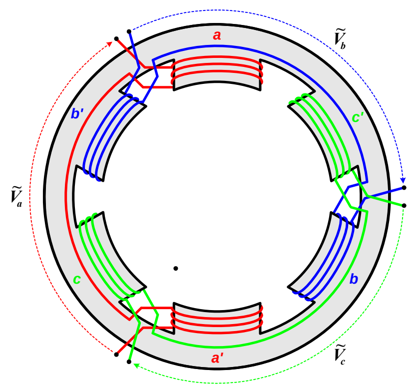
Three-Phase Synchronous Generators

The <u>3Φ Synchronous Machine</u> consists of a stator (stationary portion) and a rotor that are separated by a small air-gap.



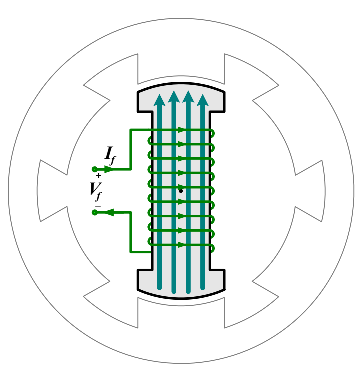
Three-Phase Synchronous Generators

The stator of the machine has is constructed such that three sets of windings are wrapped around symmetrically-placed pole faces, with each having a total of N_s turns (loops).



Three-Phase Synchronous Generators

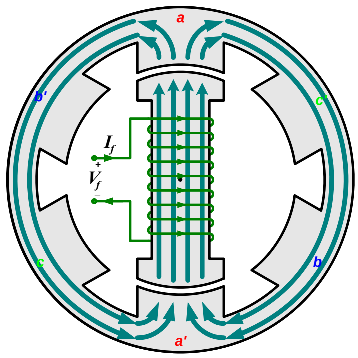
The rotor is constructed with a DC-supplied coil that creates a magnetic flux, Φ_R, the strength of which is proportional to the DC current that flows through the coil.



The DC-supplied coil acts like an electro-magnet.

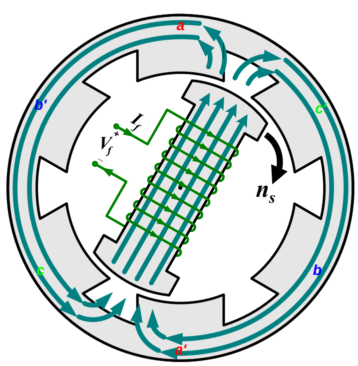
Three-Phase Synchronous Generators

The field lines of the rotor flux pass through the center of the rotor and then back around through the stator (stationary) portion of the machine to form closed loops.



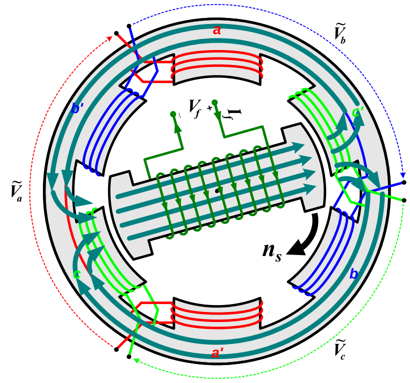
Three-Phase Synchronous Generators

The shaft of the stream turbine is coupled to the generator's rotor, providing the torque necessary to rotate the rotor, in-turn rotating the rotor flux that passes through the stator at a speed of n_s (rpm) .



Three-Phase Synchronous Generators

As the rotor flux rotates through the stator windings, it will induce a voltage across each of the windings proportional to the rate of change of the flux through the windings.



$$v(t) = N_s \cdot \frac{d\Phi_R(t)}{dt}$$

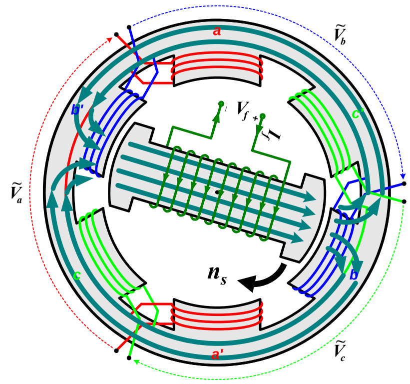
Three-Phase Synchronous Generators

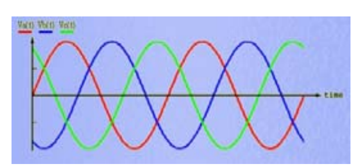
The resultant <u>stator voltages</u> will all have the <u>same magnitude</u> but will <u>differ in phase angle by 120°</u> due to the placement of the windings.

$$\tilde{V}_a = V\angle\phi$$

$$\tilde{V}_b = V\angle\phi - 120°$$

$$\tilde{V}_c = V\angle\phi - 240°$$



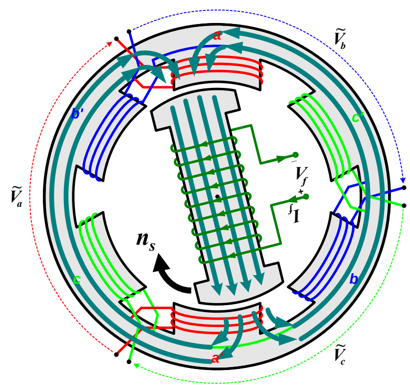


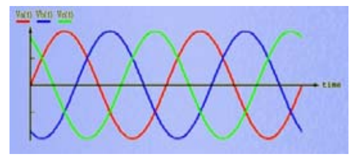
Three-Phase Synchronous Generators

It is important to note that the frequency of the voltages will be proportional to the rotational speed of the rotor, n_s.

$$n_s = \frac{120 \cdot f_{elec}}{\#\text{ of poles}}$$

The "# of poles" is a constructional feature relating to the design of both the stator and the rotor. The machine shown in the figure has a two (2) pole design.





Three-Phase Synchronous Generators

In the case of a grid-connected generator, it is imperative that the frequency of the generated voltages remain at 60Hz because this is a highly-regulated value.

$$n_s = \frac{120 \cdot f_{elec}}{\#\text{ of poles}}$$

$$\tilde{V}_a = V\angle\phi$$

$$\tilde{V}_b = V\angle\phi - 120°$$

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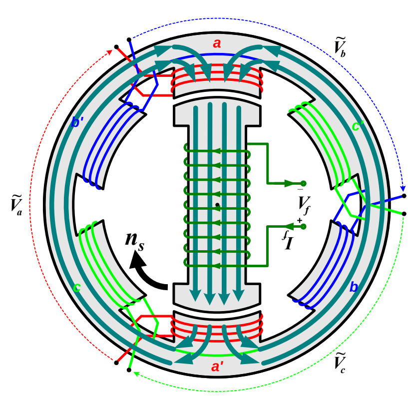

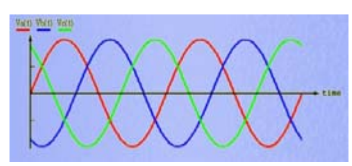

Review of Basic Electric Quantities

In electric circuits, current is defined as a measure of the rate at which charge flows through a device, and is assigned the base unit of amperes (amps), where:

1 ampere ≡ 1 Coulomb of charge flow per second

Voltage, or electromotive force (emf), can be thought of as a measure of a overall potential force that a device develops to either create or prevent the flow of charge (current).

Voltage is defined in terms of the amount of energy per unit of charge, and is assigned the base unit of volts, where:

1 volt ≡ 1 joule per coulomb of charge

Electric Energy

Electric energy is defined in terms of volt·amp·seconds where:

1 V·A·s ≡ 1 Joule

Thus, when an electric generator converts kinetic energy into electric energy, it does so by creating a current at some voltage magnitude over a duration of time.

Examples: A generator produces 50,000 J of electric energy each second:

- by creating 100A of current at a voltage of 500V*, or
- by creating 1A of current at a voltage of 50,000V*, or
- by creating 2.5A of current at a voltage of 20,000V*…

* – this assumes RMS magnitudes of a single-phase AC generator that is supplying a purely resistive load

Electric Generator Ratings

Large modern generators typically produce electric energy at voltage levels ranging from 13.8kV to 24kV.

Nameplate from 165MVA, 13.8kV, 3Φ Generator

Note that, although the generating stations are actually producing electric energy, they are rated in terms of electric power, which defines the rate at which they can produce electric energy.

Additionally, despite the fact that power is the rate at which they are producing electric energy, generating stations are often casually stated to be "producing electric power".

Although this may seem large, higher voltages are required in order to efficiently transport the energy over large distances.

Electric Power Generation

A step-up transformer is located at each power plant in order to increase the magnitude of the generator's output voltage up to a much higher level in order to connect the plant to the electric power system's transmission network.

In its ideal form, a transformer receives electric energy at one set of voltage and current magnitudes, and "transforms" that energy to a different set of voltage and currents magnitudes such that:

$$V \cdot A_{in} = V \cdot A_{out}$$

Thus, if a specific transformer increases the voltage magnitude by a factor of "a", then the transformer must decrease the associated current magnitude by a factor of "1/a".

13.8kV – 230kV Step-Up Transformer

Electric Power Generation

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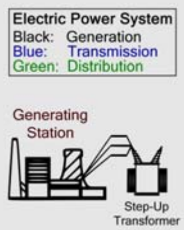
- Transmission
- Distribution



Generating Station

Step-Up Transformer

Electric Power Transmission

In terms of its operation, an electric power system can be divided into three primary subsystems, each of which performs a key function:

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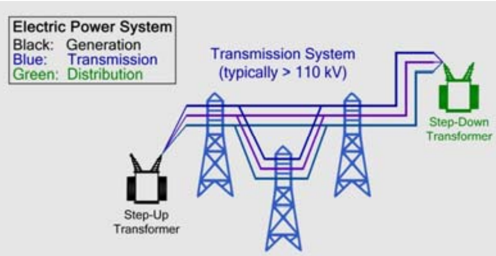


Electric Power Transmission

<u>Electric Power Transmission</u> is the bulk transfer of electric energy within an electric power system from the various generating stations to the "substations" that connect the transmission system to the distribution networks.

An <u>electric power substation</u> is an assembly of equipment through which electric energy is passed for transmission, transformation, distribution, or switching purposes.

Electric Power Generation

The generating stations are often located at great distances both from each other and from the end users of the electric energy that they produce.

All of the power plants and the electric loads are connected together by a complex, wired, transmission & distribution network, across which the electric energy is transported from the various sources to the individual loads.

Electric Power Generation

The losses associated with the transportation of electric energy across a practical (lossy) transmission line are proportional to the square of the current magnitude, making it more efficient to transport the energy at a higher-voltage/lower-current levels.

Furthermore, there is a limit to the amount of current that can be allowed to continuously flow in a transmission line of given size. This also makes it more practical to transfer large amounts of electric energy at a higher voltage levels (and lower current levels).

Electric Power Transmission

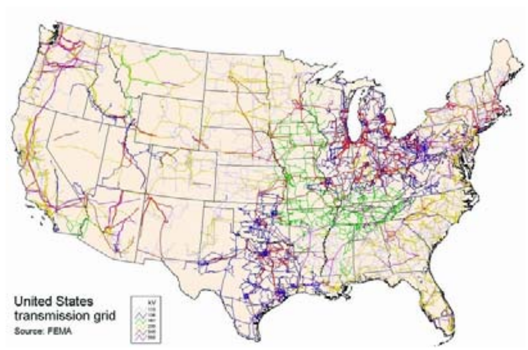
The Transmission Network or "Power Grid" consists of an interconnection of high-voltage transmission lines that allow large amounts of electric energy to flow from point to point across long distances.

Since the transmission network forms the backbone of the electric power system, interconnecting the generating stations to the various regional load centers, it must be able to deliver very large amounts of electric energy to the load centers and it must be able to accommodate any operational changes in the system.

Electric Power Transmission

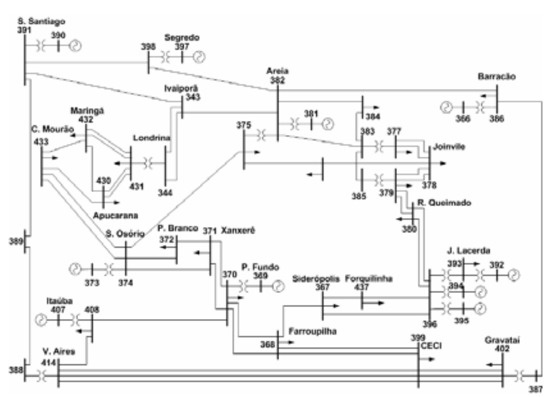
The <u>standard operating voltages</u> for a transmission network are:

High Voltage (HV): 115, 138 & 230kV
Extra High Voltage (EHV): 345, 500 & 765kV



Electric Power Transmission

The help ensure that the electric energy is able to reach the end-users, even during times of equipment failure or other disruption, the transmission system is setup such that it provides multiple (redundant) paths for the energy to flow.



Electric Power Transmission

In terms of system design, it is uneconomical to connect all of the required distribution substations to the high-voltage transmission lines that are used to transport large amounts of energy across long distances due the size and cost of the high-voltage equipment.

For this reason, the networks utilized for electric power transmission are divided into two categories based on their operating voltages:

Transmission: typically 115kV – 765kV
Sub-transmission: typically 34.5kV – 115kV

Electric Power Transmission

Unlike the transmission network that moves large amounts of power between regions, the <u>Sub-Transmission Network</u> provides power to a specific region.

For this reason, sub-transmission circuits are usually arranged in loops so that a single line failure does not cut-off power to a large amount of customers for more than a short time.

Sub-transmission networks operate at lower voltages than transmission networks, allowing for more economical connection to all of the distribution system substations.

Electric Power Transmission

Note that there is no fixed cutoff between transmission and sub-transmission networks.

As systems have evolved, the operating voltages of the sub-transmission networks have increased such that they overlap with those of the transmission networks, sometimes reaching up to 138kV.

Electric Power Distribution

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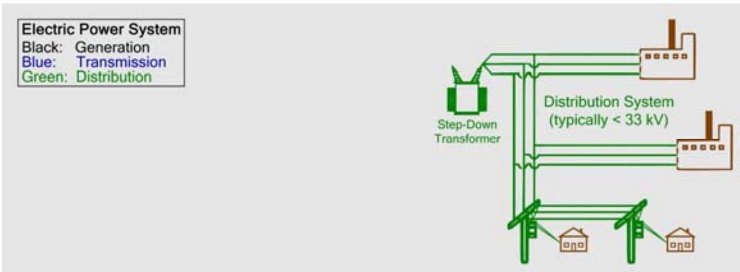


Electric Power Distribution

<u>Electric Power Distribution</u> is the final stage in the transfer of electric energy within an electric power system, during which the energy that was transferred from the transmission system to the distribution system is delivered to the customers.

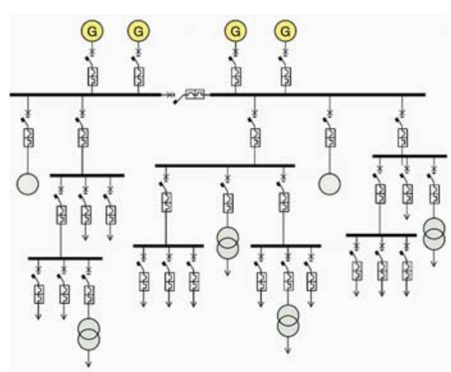
The distribution system operates at medium-level voltages ranging from 4kV to 34.5kV, most commonly in the 11kV to 15kV range.

Electric Power Distribution

Distribution networks are typically configured as one of either two types:

- **Radial**
- **Interconnected**

<u>Radial networks</u> serve their network area from a single substation, with no connection to any other supply.



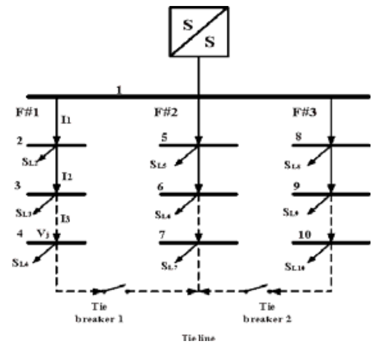
Electric Power Distribution

Distribution networks are typically configured as one of either two types:

- **Radial**
- **Interconnected**

<u>Interconnected networks</u> are radial networks that have connections to other radial networks.

The connections that are normally open, but can be closed as needed during faults or times of maintenance.



Electric Power Distribution

Although some large customers are fed directly from the distribution lines, most customers are supplied through a transformer that steps down the distribution voltage to a relatively low level for use by the equipment in the customer facility.

https://www.energy.gov/sites/prod/files/2015/09/f26/QTR2015-3F-Transmission-and-Distribution_1.pdf

Electric Power Plants

An <u>electric power plant</u> is an industrial facility that is used for the generation of electric power.

Traditional power plants contain one or more generators, rotating machines that convert mechanical power into electrical power.

The energy source harnessed to turn the generator varies widely. Most power stations burn fossil fuels such as coal, oil, and natural gas to generate electricity, while others use nuclear power or a variety of cleaner renewable energy sources such as solar, wind, wave and hydroelectric.

Three-Phase AC Power

The majority of the electric power systems utilize three-phase AC power as the standard for large-scale power generation, transmission, and distribution across the modern world.

https://www.energy.gov/downloads/chapter-3-enabling-modernization-electric-power-system