Introduction to Power Systems

Expensive! Influential!Intrusive!

Source: Riadh W. Y. Habash, Electromagnetic Fields and Radiation, Marcel Dekker, New York, 2001.

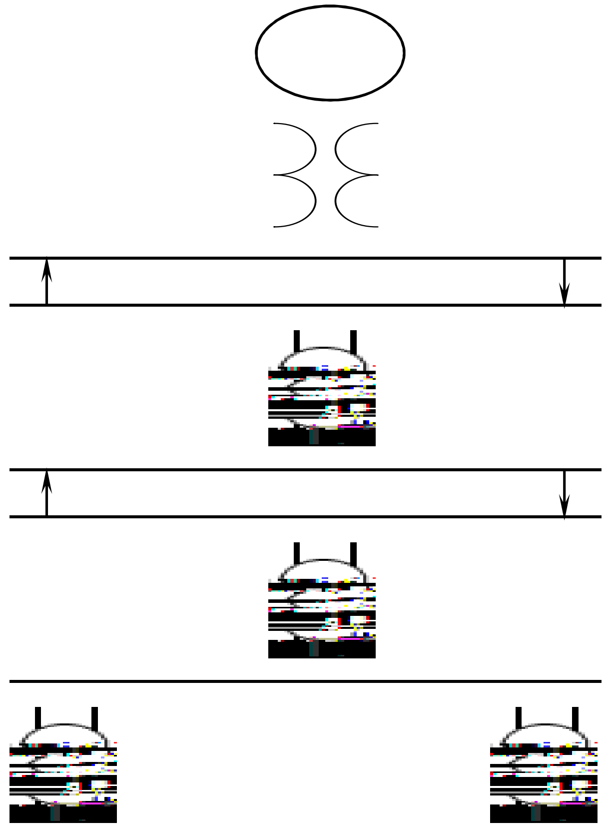
- In North America, power systems operate at a frequency of 60 Hz. However, power companies in Europe, Asia, and many other places in the world supply residential users with 50 Hz electrical powers.
- Aircraft electrical systems use 400 Hz power. Some electric trains use DC. Some high-speed electric trains use 16.67 Hz power.
- Electric commuter trains use 25 Hz electric powers and may have fields as high as 0.5 G.

Safety, First

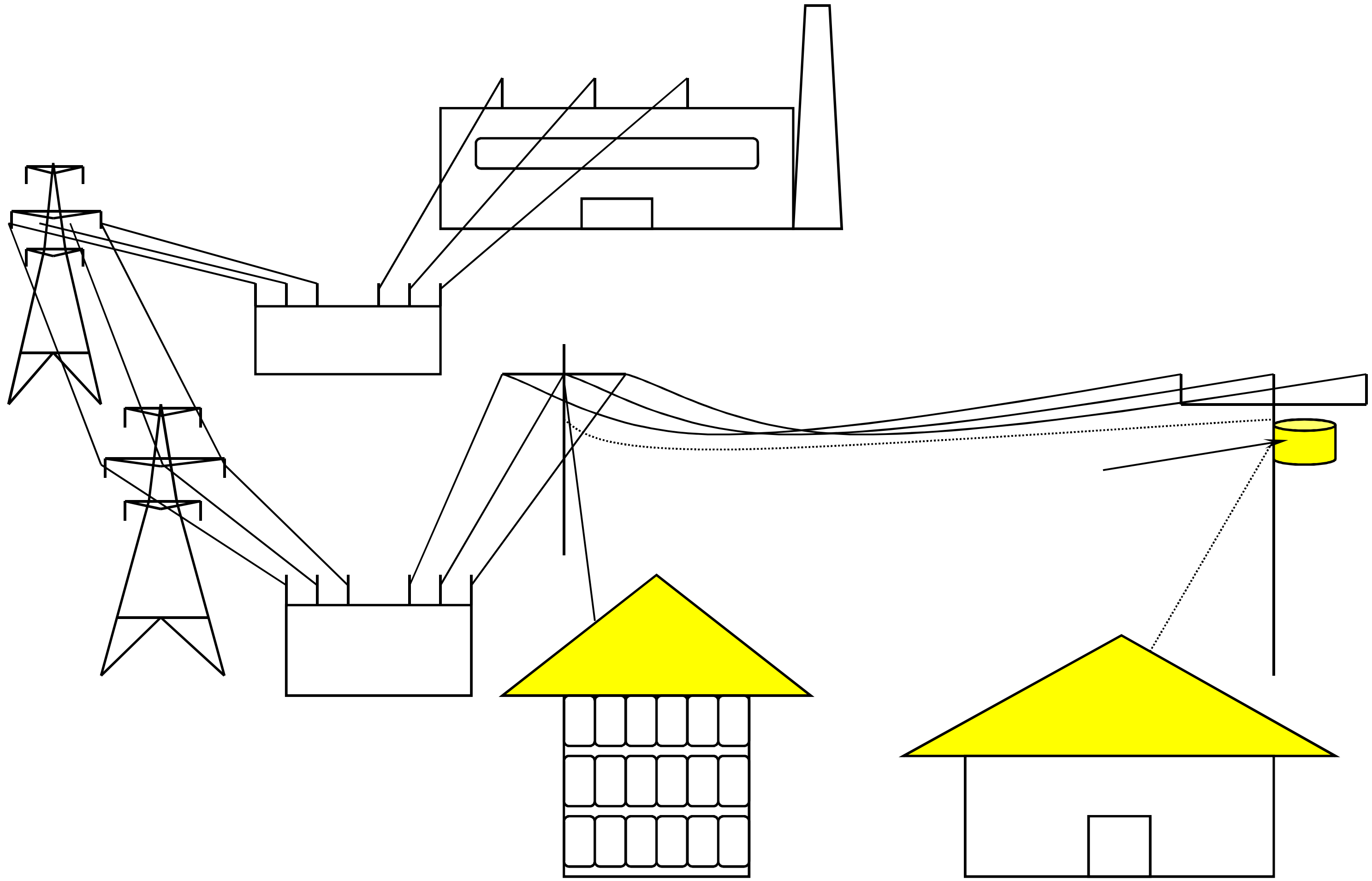
- Safety in all electric operations, for utility employees and the public at large, trumps other considerations.
- Electric utility personnel perform both live-line work and work on ‘dead’ facilities. Live-line work requires principles of “**insulate and isolate**” to keep workers from dangers; assuring facilities are ‘dead’ requires the workers to work between grounds applied to the electric facilities being handled.

The electric power network is operated at several voltage levels. This figure shows a simple power system with typical voltage levels from generation to consumption.

- Generation (11-33 kV)
- Transmission (138-765 kV)
- Sub-transmission (23-138 kV)
- Distribution (4.16-34.5 kV)
- Utilization (240-480 V)

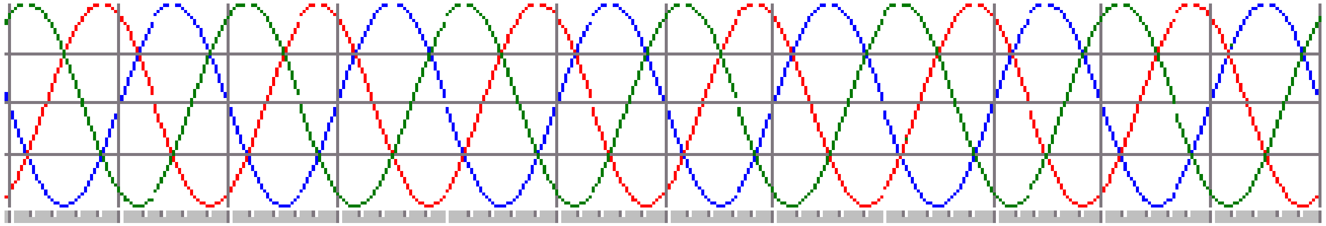


Actual Electric Utility System



Generation and Transmission

- Electricity is typically generated at voltage levels ranging from 11 to 33 kV for three-phase synchronous generators.
- The output voltage of the generator is stepped up to transmission levels in the generating plant substation.
- Usually, power is transferred on transmission lines at a very high voltage in order to reduce energy losses along the way (the higher the voltage, the lower the losses).
- Transmission voltages typically range from 138 to 765 kV. Currently available are higher voltage overhead transmission lines for up to 1100 kV.



- The three-phase four-wire standard system is common for AC supply. The supply is standard at 50/60 Hz. There are three live conductors, each called the *phase* or *line*.
- The phase means the relationship of two waveforms with respect to time.
- The voltage between any of these three phases is usually 415 V. If a neutral conductor is grounded, then the voltage between any phase conductor and the neutral will be 240 V. Supplies to premises are always connected to different phases to balance the load.

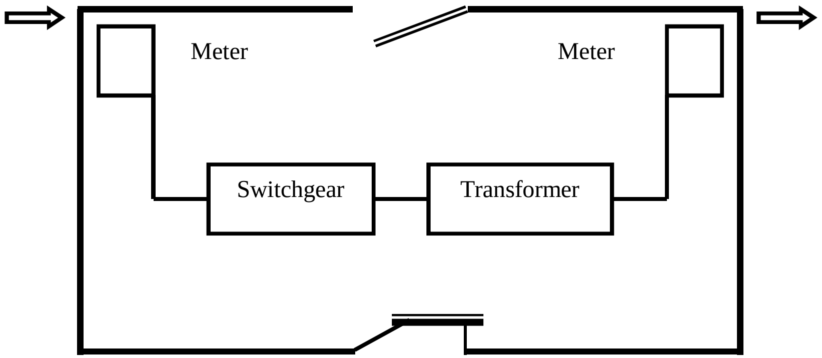
Single Phase and Three Phase Systems

- If the user is a small one, a house for example, the supply cable will have two conductors, live and neutral. The supply voltage is usually 240/120 V, and such configuration is known as single-phase two-wire system.
- The single-phase supply is the most common supply for domestic premises and other single-occupier premises where the demand for energy is relatively small.
- Larger consumers receive three-phase four-wire supplies. The higher voltage is generally used for motors and heavy loads. Other small loads are connected across the outers and the neutral in such a way that when the whole installation is operating, the load across the three phases is reasonably balanced.

Substations!

They serve many functions in controlling and transferring power on electric systems. Several substation layouts are used by electric utilities to achieve reliable system operation. Some of these layouts are used in large commercial and industrial power systems.

- Substations are main components in the power transmission system, which adjust levels of electricity and thereby provide a link with the electricity supply.
- A substation is an assemblage of circuit breakers, disconnecting switches, and transformers designed to change and regulate the voltage of electricity. Power lines carrying high voltages bring the current from the power plant to the substation, where transformers reduce it to lower voltages.

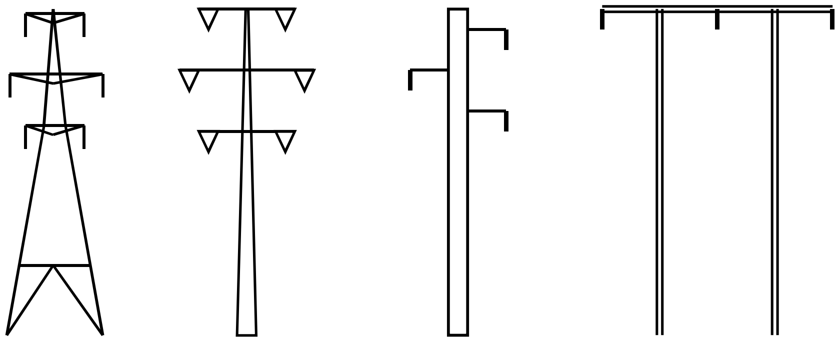


Substation

Power Lines!

Overhead power lines are the cheapest method of carrying electrical power. They are usually constructed as parallel wires, which conduct lots of power very efficiently, but radiate very little.

- Power lines include transmission lines (mounted on large metal towers) and distribution lines (mounted on concrete or wood poles placed on the road reserve).
- Transmission lines carry electricity over long distances and operate at different amounts of voltages and currents, usually above 100 kV.
- Distribution lines operate at lower voltages and bring power from substations to businesses and homes.

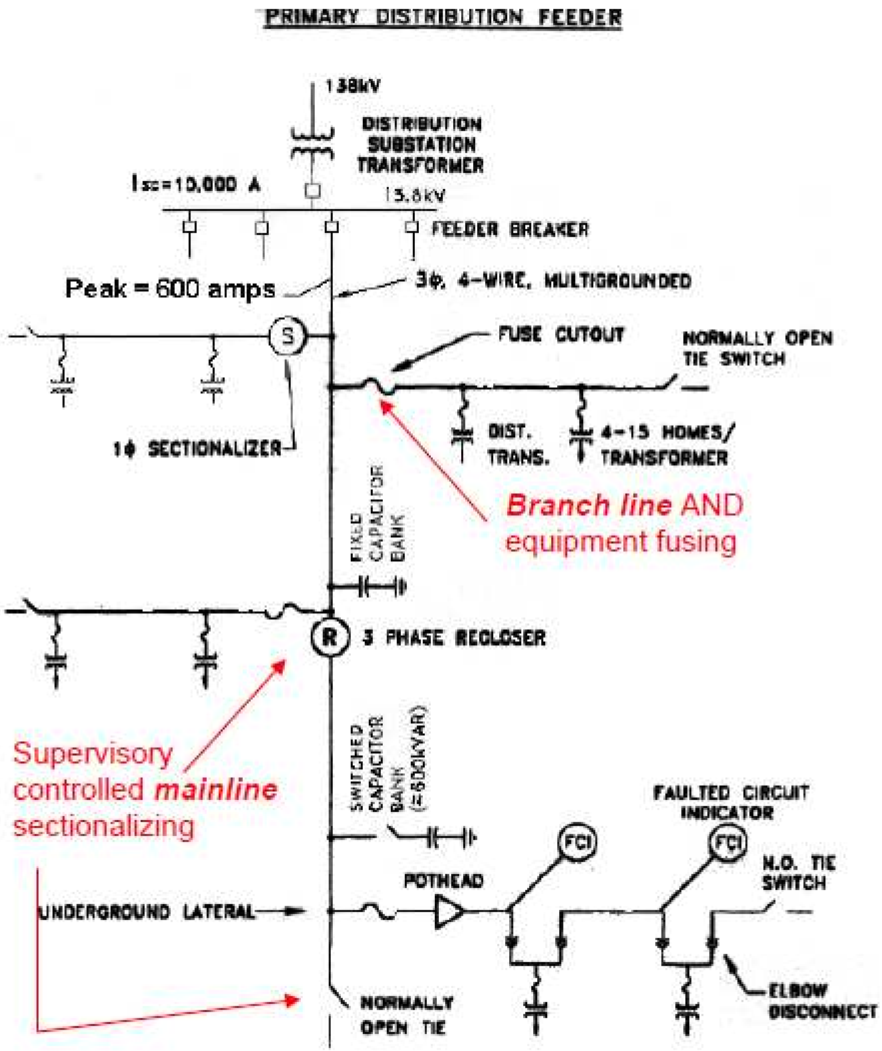


See the three lines hanging from a power line!

Electric Utility Distribution Systems

- North America:
  - 80% of distribution is "13 kv"
  - Standards are: 12.47, 13.2, 13.8, and 14.4 kv
  - Some use higher: 23, 27, and 33 kv distribution
  - Older standards are lower voltages (e.g., 4.16 kv)
  - Vast majority are wye-grounded.

Distribution Design



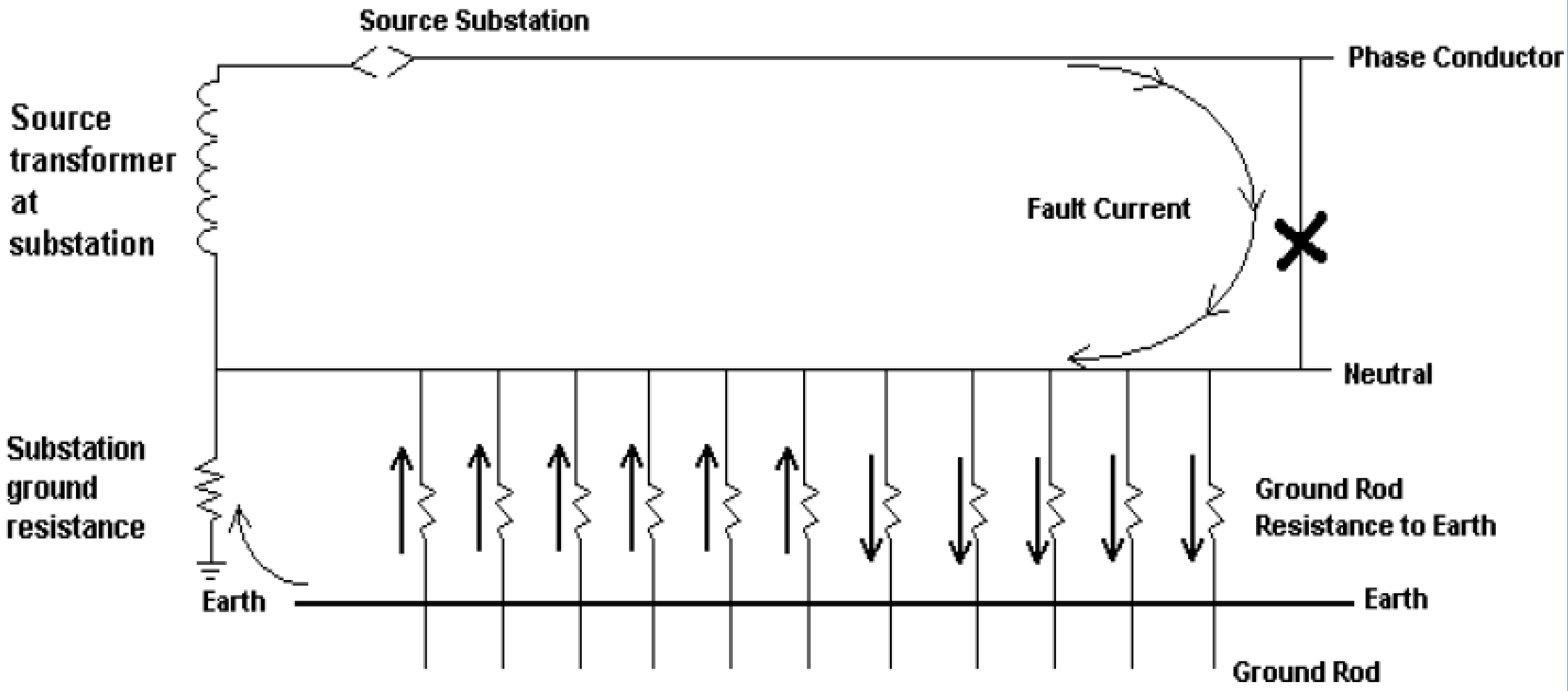
Threads to the Distribution System

- Environmental conditions
  - Moisture intrusion damage (connectors)
  - Mechanical damage (dig in, car hit, people stunts)
  - Tree intrusion
  - Wildlife intrusion
- Weather (violent)
  - Wind (more trees into wires, wire stress)
  - Lightning
  - Ambient heat ("summer heat waves")
- Electrical
  - Equipment failures (switches, transformers, communications)
  - Overload; carrying fault current at times
- Simple Age and Deterioration
  - Splice failures ("nothing lasts forever")
  - Equipment failures (transformers, switches, lightning arresters, poles, cable)
- System Operations Consequences
  - Switching transients
  - Out of phase conditions
  - Emergency switching (point emergencies, pre-emergencies, load relief, construction
- Anything else you can imagine

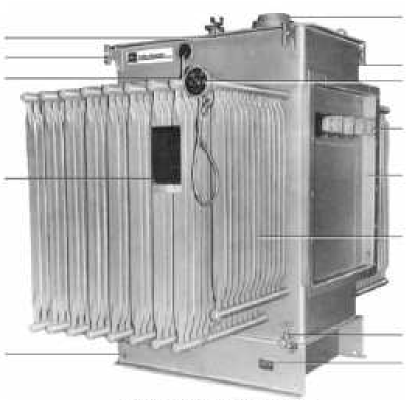
Distribution System Grounding

- Low ground rod resistance to earth is a the right technique.
- Low ground rod resistance is usually very difficult to achieve.
- Neutral and ground systems are isolated.
- Ground Rod Resistance is Affected by:
  - **Soil resistivity**
  - **Ground rod diameter (not too much)**
  - **Ground rod length (depth)**
  - **Parallel rods**

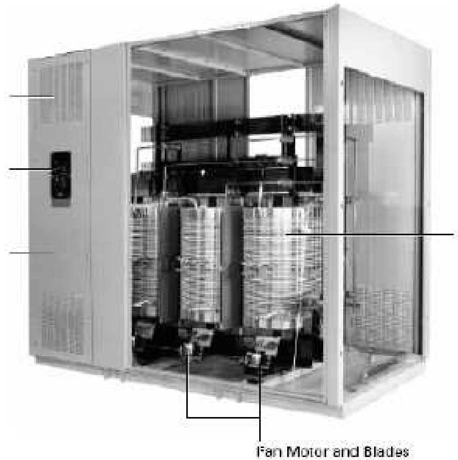
Grounding!


Source Substation
Phase Conductor
Source transformer at substation
Fault Current
Neutral
Substation ground resistance
Ground Rod Resistance to Earth
Earth
Earth
Ground Rod

Transformers



Liquid-Filled Substation Transformer



Dry-Type Substation Transformer

Typical Pad-Mounted Transformer

Cast Coil Substation Transformer

Unit Substation Transformers

- 112.5 through 20,000 kVA
- Maximum 69 kV Primary
- Maximum 34.5 kV Secondary
- Bushings wall mounted
- Part of a substation lineup
- Can be custom designed to meet custom dimensions

Padmount Transformers

- Up to 5,000 kVA
- Maximum 34.5 kV Primary
- Maximum 600 V Secondary
- Weather resistant high and low voltage compartments
- Tamper-resistant Design
- No Fan Cooling Available

Network Transformers

- 300-2500 kVA
- Maximum 34.5 kV Primary
- Maximum 600 V Secondary
- Used in areas of high load density
- Designed for use in a secondary network system in either subway or vault applications.

Liquid Filled Technology Benefits

- Lowest Purchase Cost
- Lowest Loss Per Purchase Dollar
- Ability to operate in adverse conditions
- Excellent Dielectric Properties
  - Smaller Footprint
  - Better losses
- Options available for “Safety-Related” and “Environmentally Sensitive Applications”

Dry Type Technology Benefits

- Environmentally Safe
- Non-flammable
- Minimal Maintenance
- Coordination Flexibility
- Higher Fan Cooled Rating

Comparison of Transformer Costs

Liquid Filled Transformers

- Mineral Oil (Outdoor) 1.00
- Vegetable Oil (Indoor/Outdoor) 1.20
- Silicone (Indoor/Outdoor) 1.35
- Pad Mounted – 5% Less than Substation Design

Dry Type Transformers

- Vacuum Pressure Impregnated 1.25
- Vacuum Pressure Imp. - Epoxy 1.35
- Cast Coil 1.55 to 2.0
- Lower Temperature Rise – 15% to 35%
- Outdoor – Add 20%

Loss Evaluation

I^2R Losses = Total Losses (TL) - No Load Losses (NL)

I^2R Losses are proportional to the Load Factor Squared

Load Factor = Actual Load kVA/Rated Base kVA

Operating Losses = No Load Losses + I^2R Losses at the appropriate Load Factor

Loss Evaluation Example

Losses in watts for a 1000 kVA oil-filled transformer:

1,800 watts no load losses

15,100 watts full load losses

Load losses are approximately 13,300 watts (15,100 – 1,800)

At 0% load: 1,800 watts

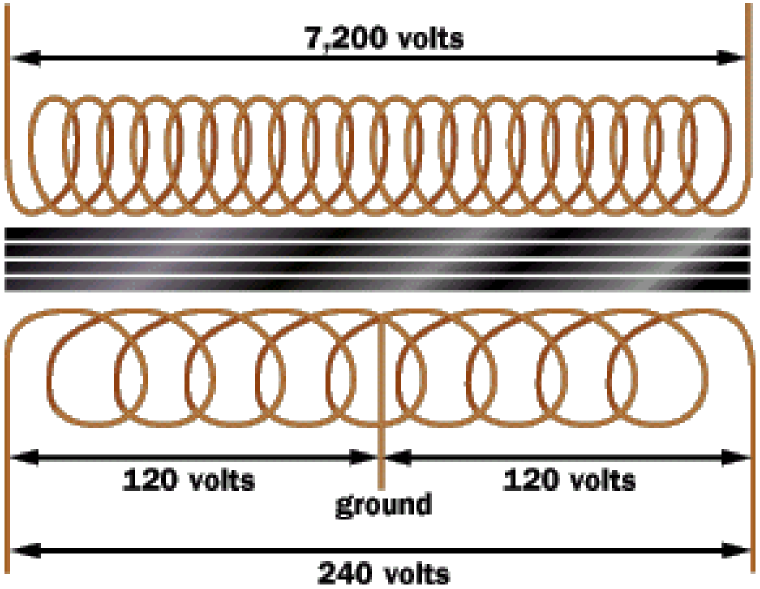
At 50% load: 1,800 watts + $(13{,}300)(.5)^2$ = 1,800 watts + 3,325 watts = 5,125 watts

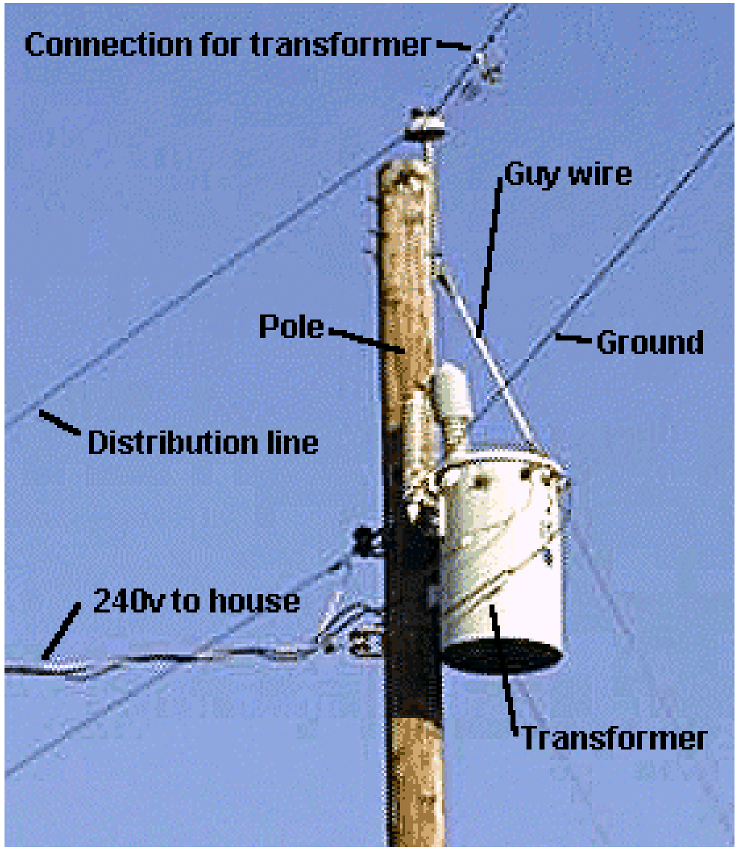
At 100% load: 1,800 watts + 13,300 watts = 15,100 watts

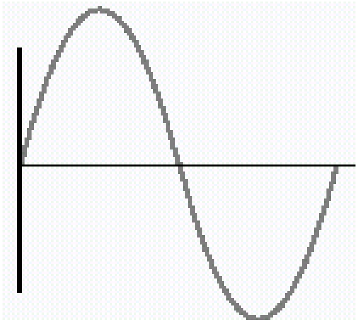
At 110% load: 1,800 watts + $(13{,}300)(1.1)^2$ = 1,800 watts + 16,093 watts = 17,893 watts

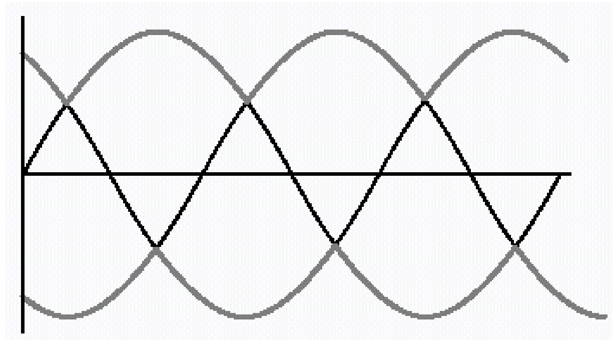
From Distribution Lines to Houses via Transformers

Source: http://howstuffworks.lycoszone.com/power5.htm







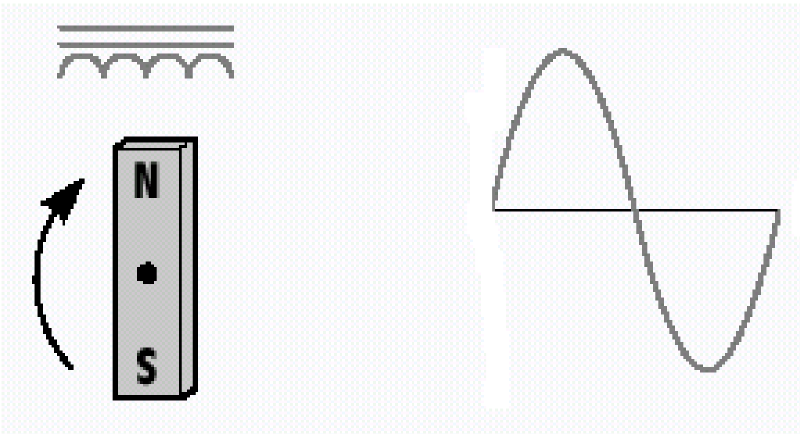


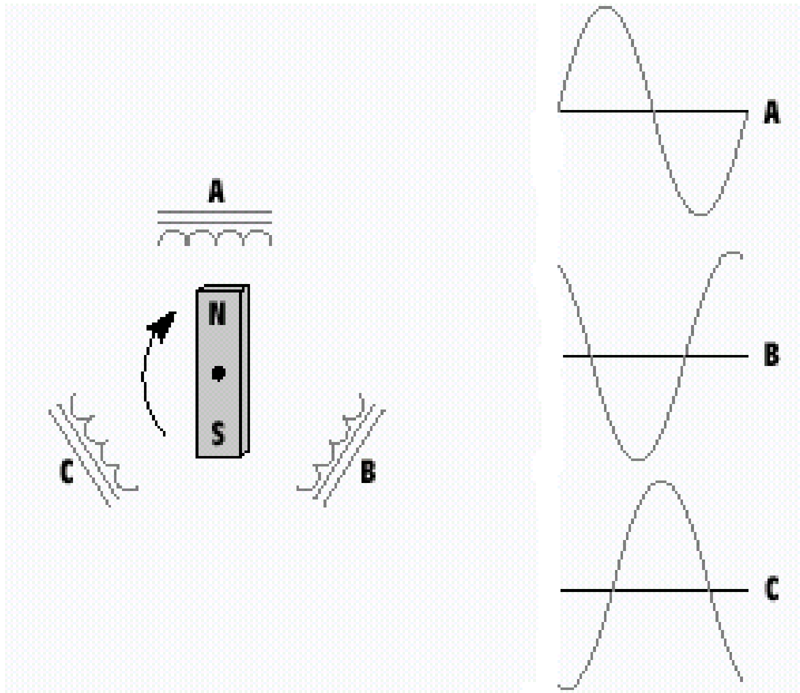
Why Three Phase Circuits!

- Higher Ratings (horsepower and KVA).
- The power delivered by a single-phase system falls to zero three times during each cycle. However, the power delivered by a three-phase circuit never falls to zero.
- In a balanced three-phase system, the conductors need be only about 75% the size of conductors for single-phase two-wire system.

Single- and Three-Phase Voltage

Source: Stephen Herman, Electric Circuits for Trades, Thomas Learning.

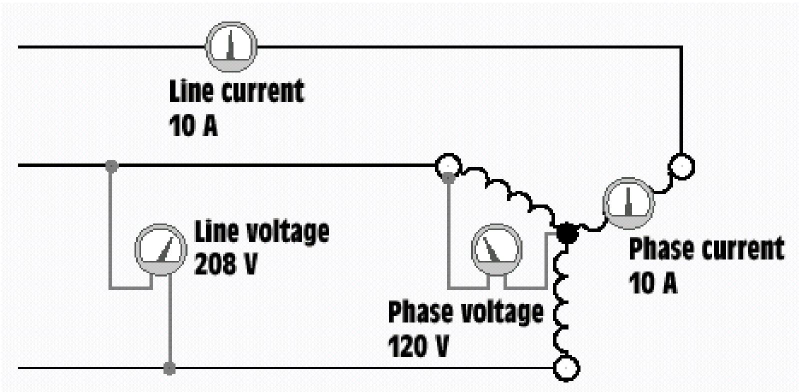


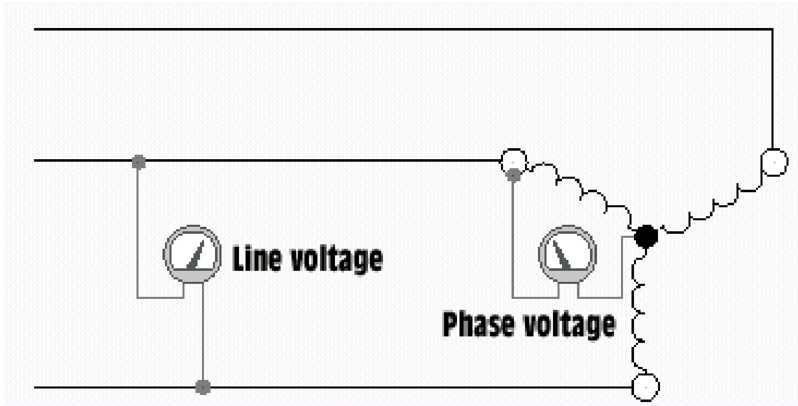


WYE (Star) Connection

$$V_{line} = \sqrt{3}\, V_{phase}$$

$$I_{line} = I_{phase}$$

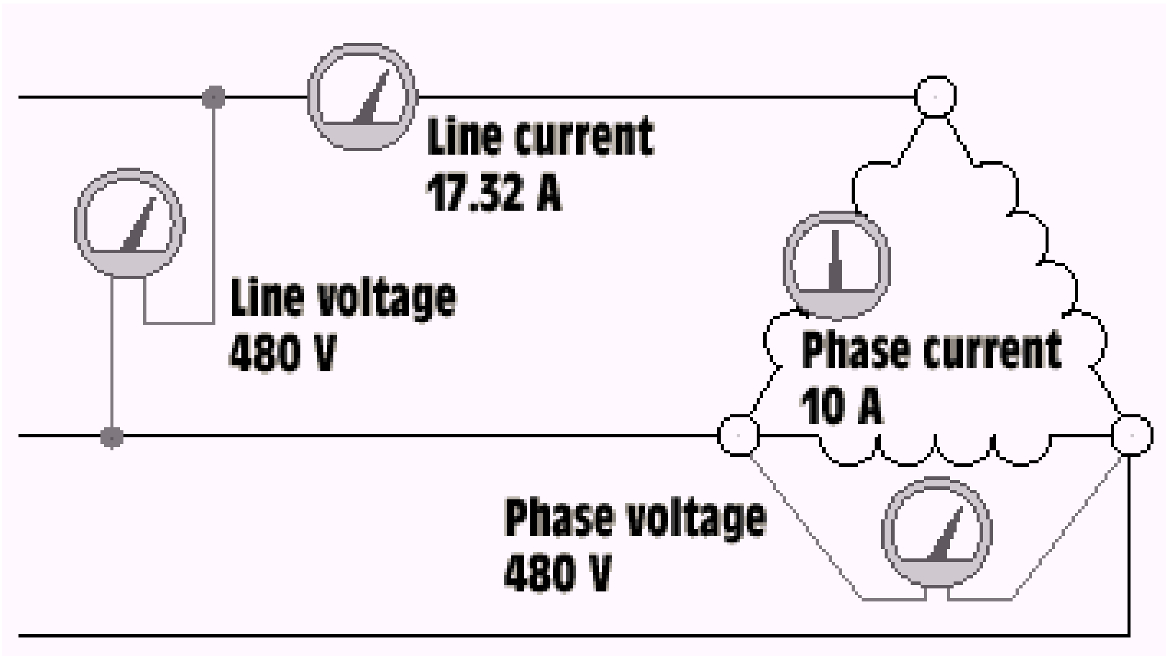




Delta Connection

$$V_{Line} = V_{Phase}$$

$$I_{Line} = \sqrt{3} I_{Phase}$$



Example 1: A Y-connected three phase generator (line voltage of 480 V) supplies power to a delta-connected resistive load (8 Ω each). Find $E_{L(load)}$, $E_{P(load)}$, and $I_{P(load)}$, $I_{L(load)}$, $I_{L(gen)}$, $I_{P(gen)}$, $E_{P(gen)}$, and the true power..

$E_{L(load)} = 480\text{ V}$

In delta load, the phase voltage is same as the line voltage.

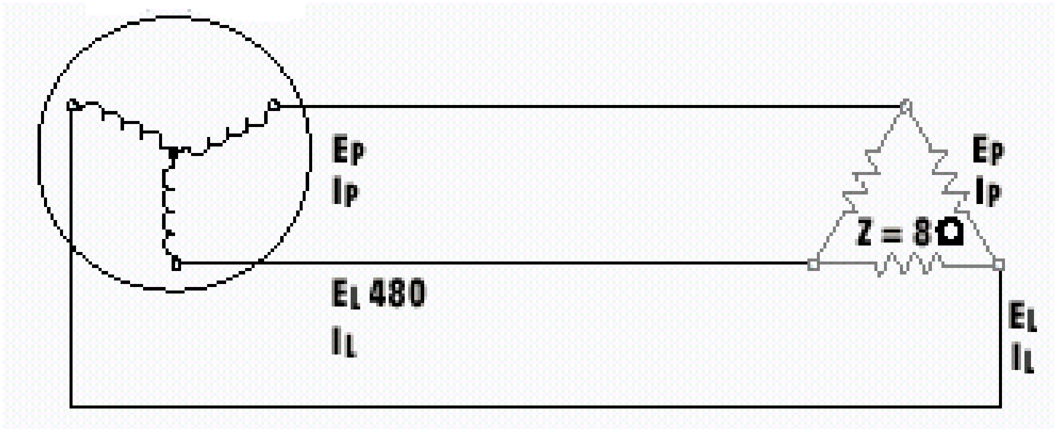
$E_{P(load)} = E_{L(load)} = 480\text{ V}$

$$I_{p(load)} = \frac{E_{P(load)}}{Z} = \frac{480}{8} = 60A$$

$I_{L(load)} = 60 \times \sqrt{3} = 103.92A$

$I_{L(generator)} = 60 \times \sqrt{3} = 103.92A$

$I_{P(generator)} = 103.92A$



$$E_{P(generator)} = \frac{E_{L(generator)}}{\sqrt{3}} = \frac{480}{\sqrt{3}} = 277.13V$$

$P = \sqrt{3} \times E_{L(generator)} \times I_{L(generator)}$

$= \sqrt{3} \times 480 \times 103.92 = 86395W$

Example 2: A delta-connected generator is connected to a Y-connected resistive load. The generator produces a line voltage of 240 V and the resistors have a value of 6 Ω each. Find, $E_{L(load)}$, $EP_{(load)}$, $I_{P(load)}$, $I_{L(load)}$, $I_{L(gen)}$, $I_{P(gen)}$, $E_{P(gen)}$, and the true power.

$$E_{L(load)} = 240\text{ V}$$

$$E_{P(load)} = \frac{240}{\sqrt{3}} = 138.57\text{ V}$$

$$I_{P(load)} = \frac{E_{P(load)}}{Z} = \frac{138.57}{6} = 23.1\text{ A}$$

$$I_{L(load)} = 23.1\text{ A}$$

$$I_{L(generator)} = 23.1\text{ A}$$

$$I_{P(generator)} = \frac{I_{L(generator)}}{\sqrt{3}} = \frac{23.1}{\sqrt{3}} = 13.34\text{ A}$$

$$E_{P(generator)} = 240\text{ V}$$

$$P = \sqrt{3} \times E_L \times I_L = \sqrt{3} \times 240 \times 23.1 = 9602\text{ W}$$