Power System Engineering, Inc.

Power Engineering for Non-Engineers

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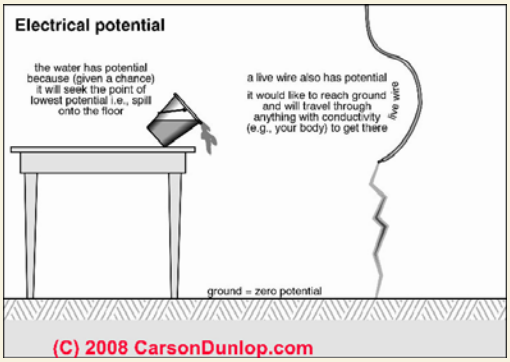
Terms

- Voltage
- Current
- Resistance
- Power
- Energy
- Load Factor
- Impedance
- Power Factor
- Losses

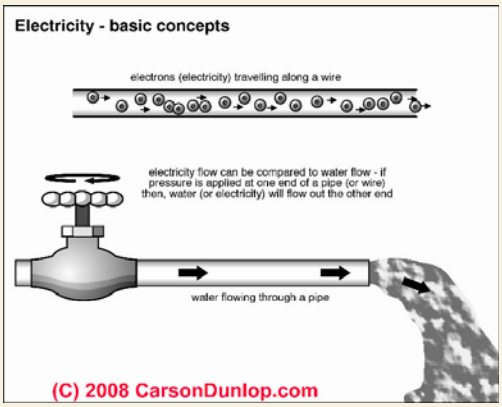
Voltage

- Measured in Volts (V)
- Electromotive force or potential between two points
- Reference = ground (0 Volts)
- Common analogy
  - Voltage is comparable to water pressure in a pipe. The pressure is available to cause the water to flow if a valve is opened.



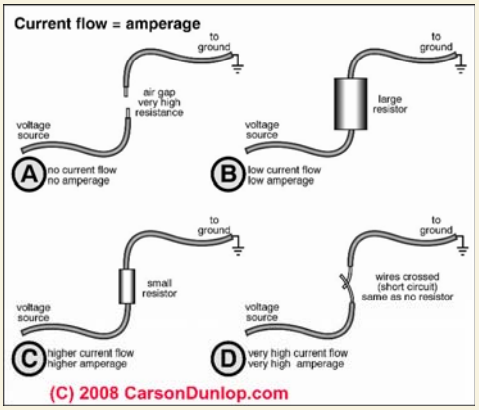
Current

- Measured in Amps (A)
- Referred to as "I" in electrical equations
- Flow of electrons through a circuit
- Water Analogy
  - Amount of water flowing through a pipe comparable to current flowing in an electrical circuit



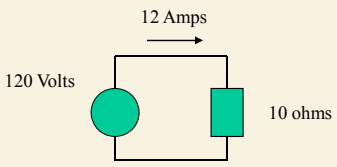
Resistance

- Measured in ohms (Ω)
- Referred to as "R" in electrical equations
- How easily electricity can flow through a circuit
- Dependent on physical properties of the circuit (i.e. size of wire)
- Water analogy
  - Smaller diameter pipes allow less water to flow than larger diameter pipes



Ohm's Law

- Voltage = Current x Resistance (V = I x R)
- Current = Voltage / Resistance (I = V / R)
- Example:
  - Voltage = 120 V
  - Resistance = 10 ohms
  - Current flowing through the circuit = 120 / 10 = 12 Amps



Power

- Measured in Watts (W)
- 1,000 W = 1 kilowatt (kW)
- 1,000,000 W = 1 Megawatt (MW)
- Power = Volts x Amps = V x I
- Amount of electricity being consumed at some moment in time
- Commonly referred to as “demand”
- Commonly “integrated” or “averaged” over some time period – 15 minutes, 30 minutes, 60 minutes

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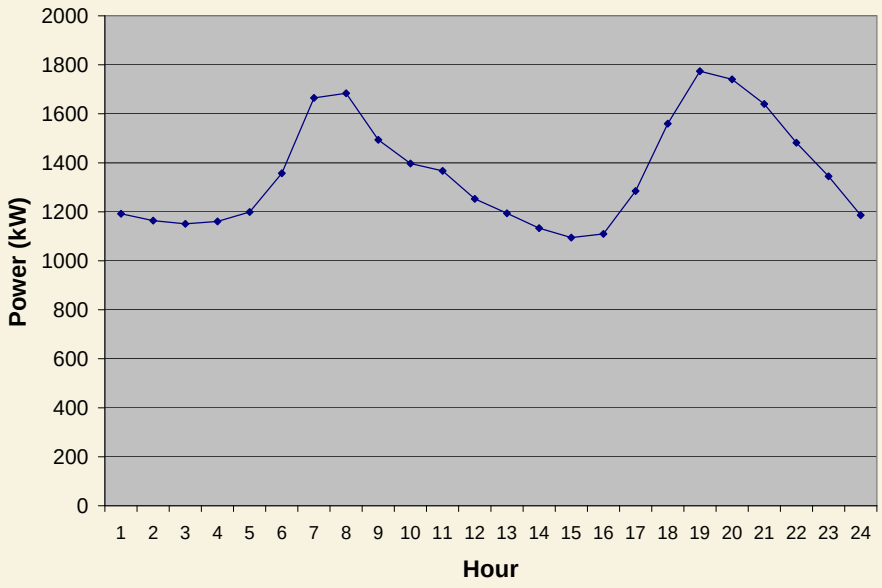

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Energy

- Measured in Watt-hours (Wh)
- 1,000 Wh = 1 kilowatt-hour (1 kWh)
- 1,000,000 Wh = 1 Megawatt-hour (1 MWh)
- 1,000,000,000 Wh = 1 Gigawatt-hour (1 GWh)
- Power consumed over time
- Example: A 100 Watt bulb left on for 10 hours = 100W x 10h = 1,000 Wh = 1 kWh consumed
- Area under the demand curve

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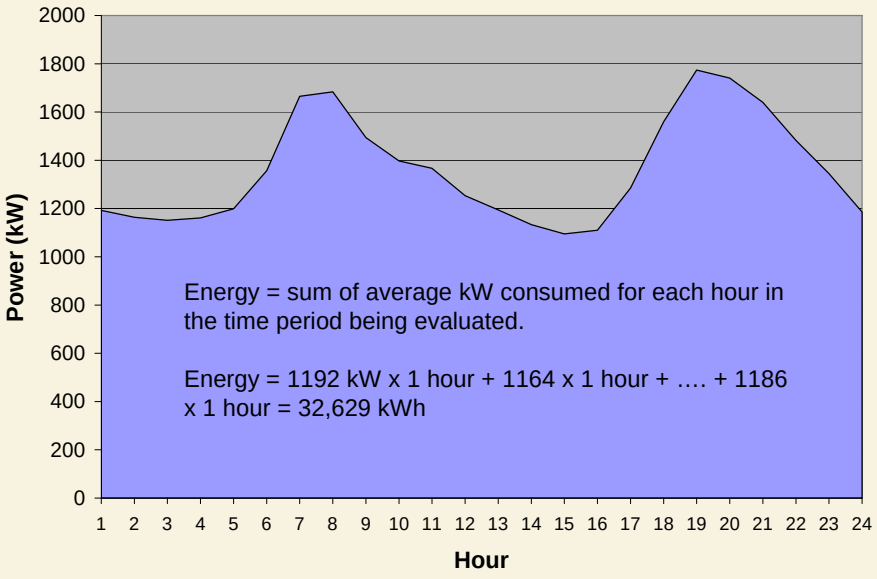

Load Factor

- Measure of energy utilization (use of resources)
- Ratio of average demand to peak demand
  - LF = average demand / peak demand
- Also expressed as the ratio of energy delivered over a given time period to the amount of energy that could be delivered
  - LF = energy delivered / (peak demand x hours)

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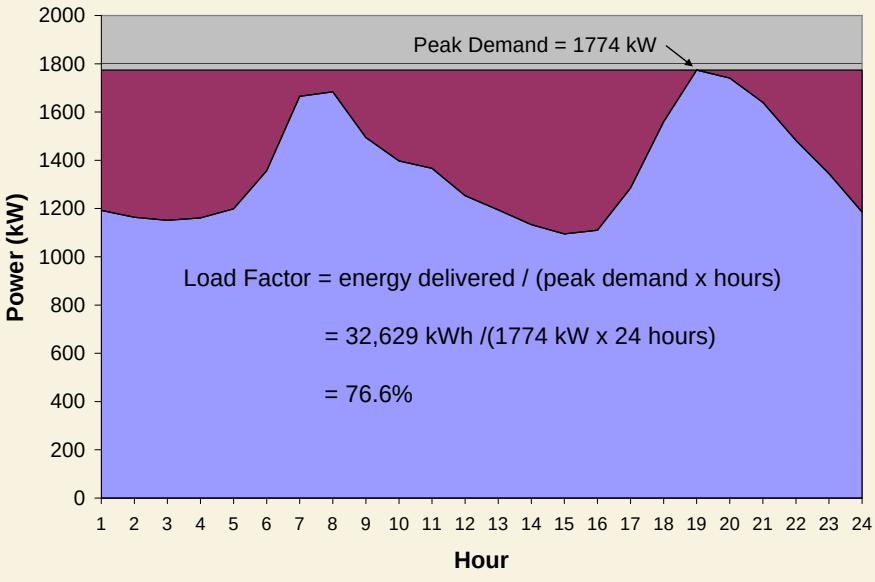

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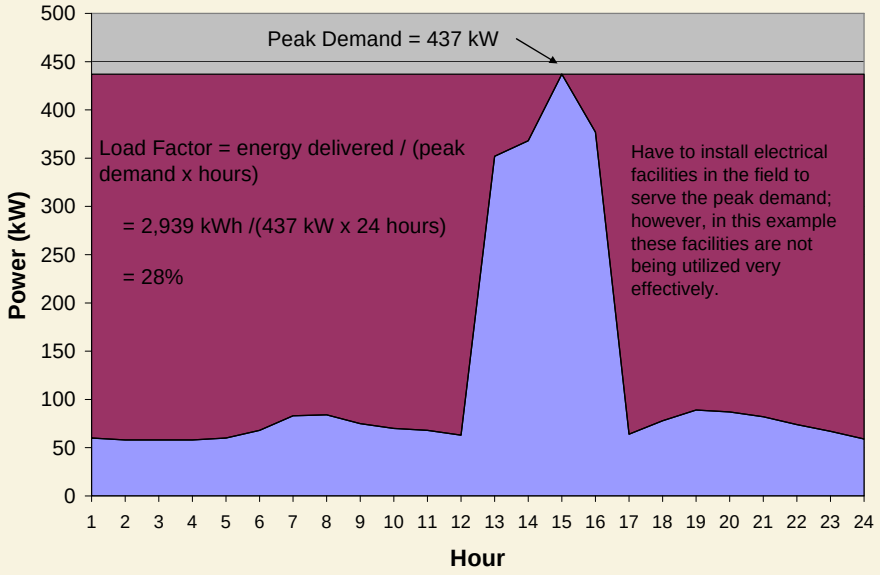
Poor Load Factor Example



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Typical Load Factors

- System = 50% - 70%
- Residential = 50% - 70%
- Small Commercial = 30% - 40%
- Large Commercial = dependent on type of operations

- For consumers with low load factors, a retail rate with a demand charge may be justified.
  - Demand charge recovers the cost of the facilities installed in the field to meet the peak demand

Impedance

- For Alternating Current (AC) systems, the resistance (R) is actually comprised of a resistive component and a reactive component and referred to as the impedance (Z)
- $Z = R + jX$
  - R = resistive component
  - X = reactive component
- Reactive component can be an inductance or a capacitance

Reactance

- Typical loads served include resistive and inductive loads
  - Incandescent light = resistive load
  - Electric resistance heat = resistive load
  - Motors = inductive load
  - Compact Florescent Lights = partially an inductive load
- The reactive component of an impedance is undesirable because it causes current to flow through the system that does not do any useful work.
  - Non-useful work measured in VARs
  - 1,000 VARs = 1 kVAR

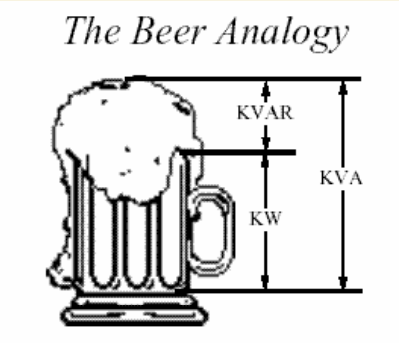
Power Factor

- Power factor helps to describe how much of the current flowing through a circuit is performing useful work.
- A power factor of 1.0 means that no current is flowing to serve reactive loads – amount of current required is minimized and the efficiency of the system is maximized
- A power factor < 1.0 means that there is some amount of undesirable reactive current flowing

Apparent Power and True Power

- Recall that Power = Volts x Amps
  - This formula actually calculates the "apparent power" in AC systems
  - Gives results in Volt-Amps (VA)
  - 1,000 VA = 1 kVA
- True Power = Volts x Amps x Power Factor
  - Gives results in Watts (W)
  - 1,000 W = 1 kW
  - For a power factor of 1.0, true power = apparent power
- kW = kVA x pf ; kVA = kW /pf

Beer Analogy



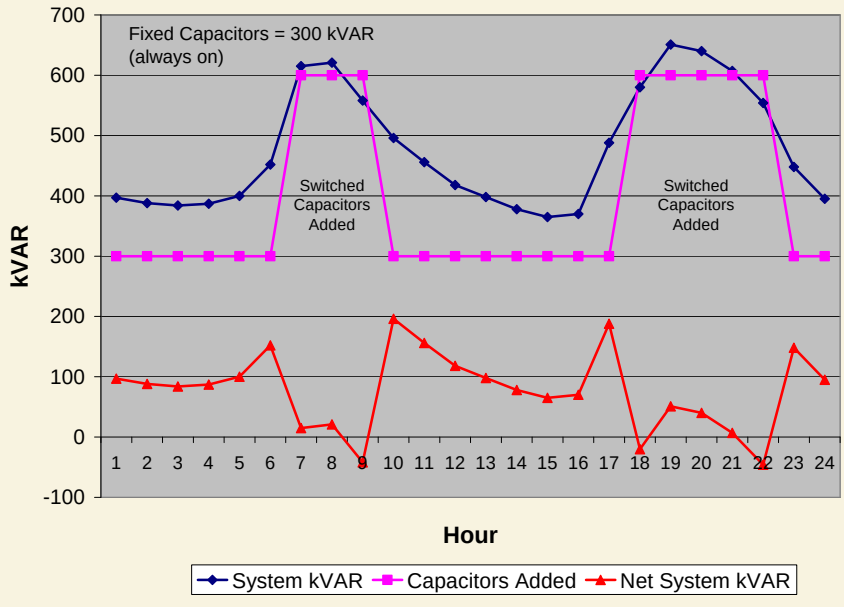
- True power (kW) that does useful work can be compared to the beer in the mug
- The non-useful power (kVAR) can be compared to the foam
- The apparent power (kVA) can be compared to the capacity of the beer mug which is required to hold both the beer and the foam

Apparent Power and True Power - Example

- Example:
  - A 10 kW load with a power factor of 1.0 = 10 kVA (kVA = kW / pf = 10 / 1.0 = 10 kVA)
  - For a power factor of 0.8, the apparent power = 12.5 kVA (10 / 0.8)
  - A 10 kVA transformer serving this load would be 100% loaded at a power factor of 1.0 and 125% loaded at a power factor of 0.8
  - Therefore, investment in additional system capacity is required to serve loads with power factors < 1.0

Correcting Power Factor

- Inductive kVARs can be cancelled by adding an equal amount of capacitive kVARs.
  - This is why capacitors are added to power systems
  - Because inductive loads on the system vary over time, some portion of the capacitors added to the system may be required to be switched in and out as the inductive load increases and decreases.
  - Too many capacitors on the system are just as bad as not enough capacitors



System Losses

System Losses = Energy purchased – Energy sold

As % of Energy purchased:

$$\frac{\textit{System losses}}{\textit{Energy purchased}}$$

CAUTION!!!

Difference in time and load when consumer meters are read compared to when substation meters are read can lead to errors in loss calculations.

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System Losses

- Total losses from generation to member consumer can be 10% to 20% (distribution system losses are typically 5% to 10%)
- Two types of losses
  - Load losses – change with load
  - No-load losses – constant regardless of load

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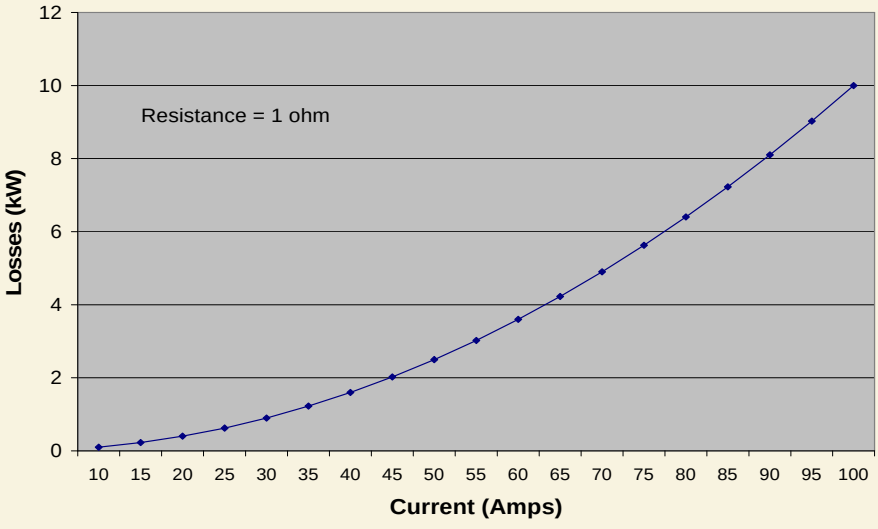
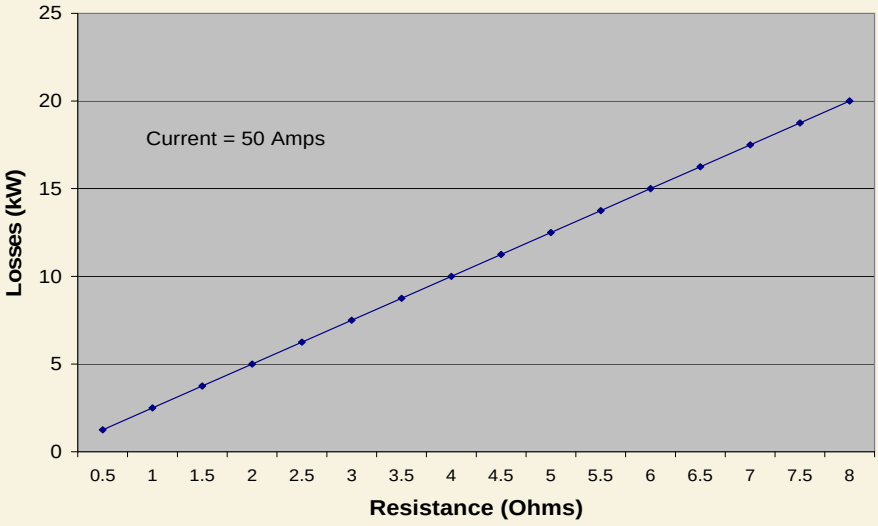
Load Losses

- Current flowing through a resistance yields losses in the form of heat
- Losses (power) = V x I
- Recall from Ohm's law that V = I x R
- Therefore Losses = (I x R) x I = I^2 x R
- From this formula we can see that losses increase exponentially with current. Anything we can do to lower current will have a dramatic effect on lowering losses.
  - Reducing current by ½ will reduce losses to ¼

Load Losses as a Function of Current



Load Losses as a Function of Resistance



No-Load Losses

- Core losses of transformers
- Come from magnetizing transformer cores
- Essentially constant; however, core losses do vary with the voltage applied to the transformer

System Losses: Contributors

- Substation Transformers
- Line Voltage Regulators
- Pri. & Sec. Conductor
- Capacitors
- Distribution Transformers

Which is the biggest contributor?

Area of System	Losses as a % of Total System Energy Requirements
Substation Transformers and Regulators	1.0
Distribution Lines and Regulators	3.5
Distribution Transformers	2.5
Secondary and Services	1.5
Metering Equipment	0.5
Total System	9.0

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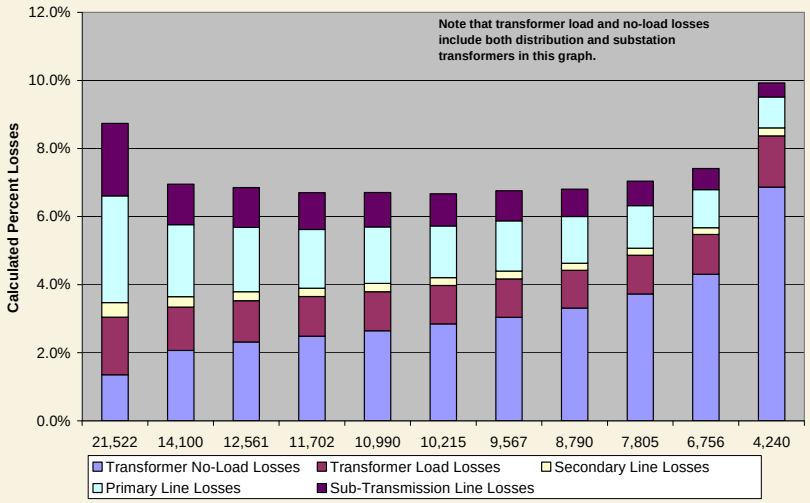
Percent Losses



PF and Losses - Example

1-phase, 7.2 kV Primary line carrying 50 A. kW = 300. Losses = 7,500 W.

What is the kVA and PF?

*(7.2 kV) * (50A) = 360 kVA*

PF = 300 / 360 = 0.833 or 83.3%

What Losses will occur if PF is 100% instead of 83.3%?

$P = I^2R = 7{,}500 = 50^2 * R$

$R = 3$ ohms

@ PF = 100%, kW = kVA = 300

A = kVA/kV = 300/7.2 = 41.67A

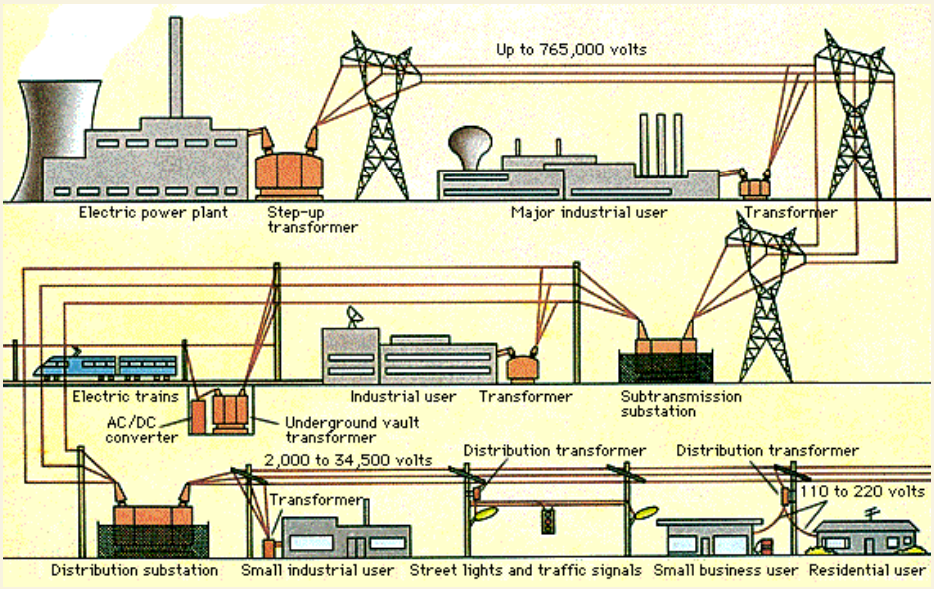
New Losses = I^2R =

$(41.67A)^2 * 3$ ohms = **5,209 W**

Losses go down when power factor approaches unity

Power System Components

- The electrical grid is comprised of many different components to reliably deliver electricity from generation stations to the member consumers.
- Along the way, voltage may change multiple times.
- Common voltages:
  - Transmission: 69,000 Volts (69 kV) and up
  - Sub-Transmission: 23 kV, 34.5 kV, 46 kV
  - Distribution: 12.47 kV, 24.9 kV
  - Utilization: 120V, 240V, 480V



Source: http://brain101.info/EMF.php

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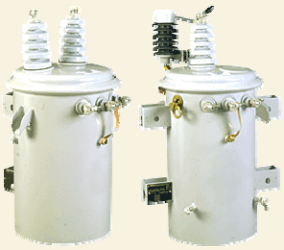
Transmission and Sub-Transmission

- Higher voltages mean that more power can be sent across the system
  - P = V x I (higher voltage yields more power at lower currents)
  - Load losses = I^2 x R (lower currents yield lower losses)
- Equipment with higher voltage ratings, however, is much more expensive and higher voltages are obviously more dangerous. Therefore, voltages are lowered on distribution systems.

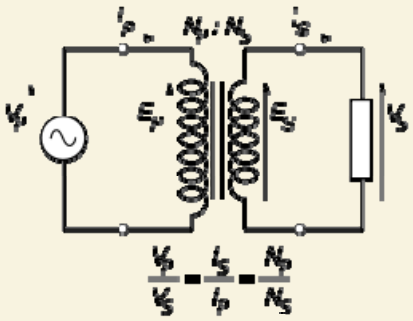
Transformers

- Voltage is changed using transformers



Transformers

- Transformers are comprised of one or more windings to step-up or step-down the voltage



Example

Vp = 7200 Volts

Vs = 120 Volts

Np / Ns = 60

Is = 60 x Ip

Transformer Losses

- No-load (core losses)
  - essentially constant
  - will vary with voltage dependent on transformer design
  - greatest impact on energy losses
- Load (winding or copper losses)
  - varies with transformer loading
  - winding losses = (kVA load / rated transformer kVA)^2 x rated load loss
  - greatest impact on demand losses

Transformer Losses - Example

- 10 kVA transformer
  - Rated no-load losses = 40 Watts
  - Rated load losses = 180 Watts
- No-load losses for one year = 40 Watts x 8,760 hours = 350 kWh
- Load losses at any given time
  - 25% loaded = 6.25% of 180 Watts = 11.25 Watts
  - 50% loaded = 25% of 180 Watts = 45 Watts
  - 100% loaded = 100% of 180 Watts = 180 Watts
  - 150% loaded = 225% of 180 Watts = 405 Watts

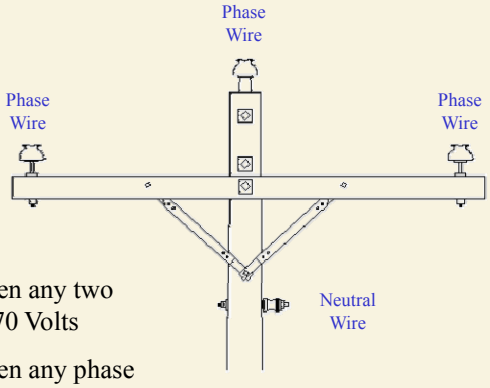
Transformer Efficiency

- Transformer efficiency is a function of both no-load and load losses
- It can be shown that maximum transformer efficiency occurs at the load level where winding losses and core losses are equal
- Transformer size is key
  - Too large of a transformer usually yields larger core losses than necessary
  - Too small of a transformer usually yields larger winding losses than necessary

Distribution System

- Used to deliver electricity to member consumers
- Typically a 4-wire multi-grounded system
  - 3 phase wires (commonly referred to as A, B, C)
  - 1 neutral wire for return current
- Single-phase taps
  - 1 phase wire
  - 1 neutral wire

Three-Phase Distribution System



Voltage between any two phases = 12,470 Volts

Voltage between any phase and the neutral (ground) = 7,200 Volts

Balancing Loads

- Services and single-phase taps are connected to each of the phases of a three-phase system
- To improve system efficiency, mitigate losses and limit voltage drop, loads should be balanced between all three phases as much as practical – particularly during peak time periods
- Simple Example
  - A phase = 24 Amps
  - B phase = 42 Amps
  - C phase = 15 Amps
  - When balanced, each phase would ideally carry 27 Amps

Distribution System – Voltage Drop

- ANSI Std C84.1 sets requirements for voltage levels

Location	Maximum (V)	Minimum (V)
Substation regulated bus	126	--
Transformer	126	118
Meter or entrance switch	126	114
Point of utilization	126	110

Voltages on a 120 V base (referenced to the secondary side of an unloaded distribution transformer)

7200 V / 120 V = 60 (transformer turns ratio)

126 V correlates to 126 x 60 = 7,560 V (105% of nominal voltage)

118 V correlates to 118 x 60 = 7,080 V (98.3% of nominal voltage)

Voltage Drop Criteria

- Voltage drop across distribution system limited to maximum of 8 Volts (126 – 118). This amount will be lower if the substation bus and/or line voltage regulators are set at lower levels.
  - Planning engineer's responsibility
- Voltage drop across distribution transformers and secondary/service conductors limited to maximum of 4 Volts (118 – 114).
  - Line staking engineer's responsibility
- Voltage drop between meter and point of utilization limited to maximum of 4 Volts (114 – 110).
  - Electrician's responsibility.

Voltage Drop - Example

Information Available:

- 1-phase line
- 3 miles long
- Nominal voltage = 7.2 kV
- Current flowing across line = 50 Amps
- Resistance of line = 1 ohm / mile
- Power Factor = 100%

Solution:

Total R = 1 ohm / mile x 3 miles = 3 ohms

Voltage drop = I x R = 50 Amps * 3 ohms = 150 V

Voltage drop (on a 120V base) = 150 V / 60 = 2.5 V

System Planning

- System Planning identifies projects to correct deficiencies based on established planning criteria
- Projects are generally recommended for the following reasons
  - To correct low voltage
  - To increase conductor and equipment capacity
  - To improve contingency capability
  - To improve reliability
  - To reduce losses
  - Age & condition

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Remediation Methods to Correct Deficiencies

- Balance load on three-phase lines
- Install capacitors
- Load transfers
- Install voltage regulators
- Line conductor replacement
- Conversion of single-phase lines to three-phase
- Construction of tie lines
- Upgrades of existing substation equipment
- Addition of new substations and/or feeders

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Questions?

Thank You!

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