Basics of Electricity

ICRC

Electricity for Construction Engineers

Basics of Electricity

A quick introduction course

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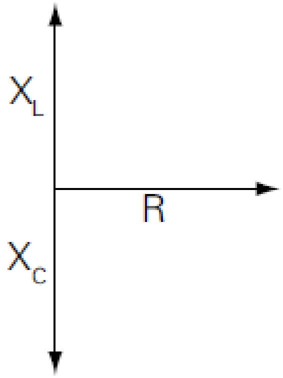
10. Series and Parallel R-L-C Circuits

Circuits often contain resistance, inductance, and capacitance. In an inductive AC circuit, current lags voltage by 90 degrees. In a capacitive AC circuit, current leads voltage by 90 degrees. Therefore, when represented in vector form, inductive and capacitive reactance are 180 degrees apart. The net reactance is determined by taking the difference between the two quantities.



An AC circuit is:

- Resistive if X_L and X_C are equal
- Inductive if X_L is greater than X_C
- Capacitive if X_C is greater than X_L

The following formula is used to calculate total impedance for a circuit containing resistance, capacitance, and inductance.

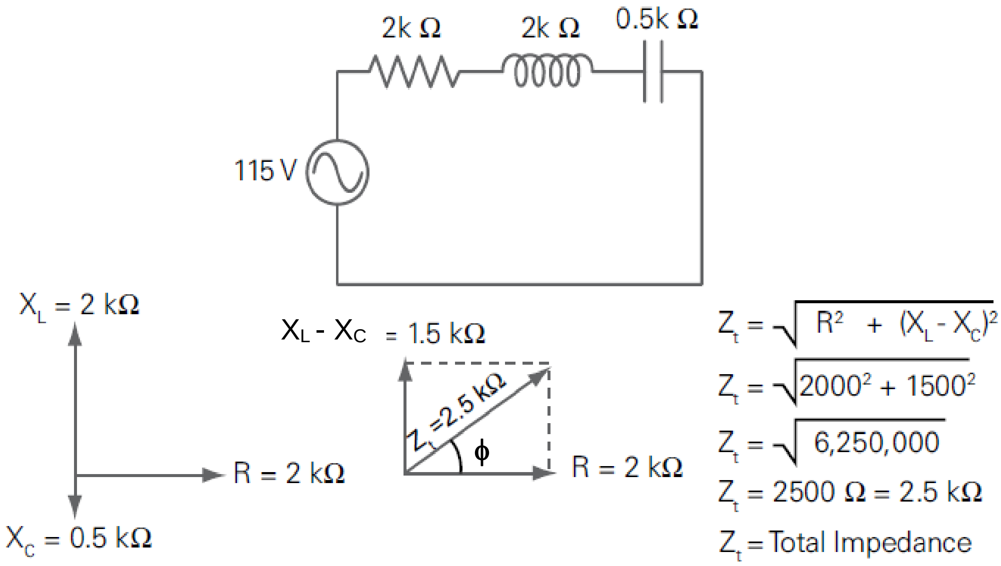
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

In the case where inductive reactance is greater than capacitive reactance, subtracting X_C from X_L results in a positive number. The positive phase angle is an indicator that the net circuit reactance is inductive and current lags voltage.

In the case where capacitive reactance is greater than inductive reactance, subtracting X_C from X_L results in a negative number. The negative phase angle is an indicator that the net circuit reactance is capacitive and current leads voltage.

Series R-L-C Circuit

The following example shows a total impedance calculation for a series R-L-C Circuit. Once total impedance has been calculated, current is calculated using Ohm's law.



$$I = \frac{E}{Z_t} = \frac{115\ \text{V}}{2500\ \Omega} = 0.046\ \text{A} = 46\ \text{mA}$$

Remember that both inductive and capacitive reactance are frequency-dependent, so if the source frequency changes, so do the reactances. For example, if the frequency increases, the inductive reactance increases, but the capacitive reactance decreases.

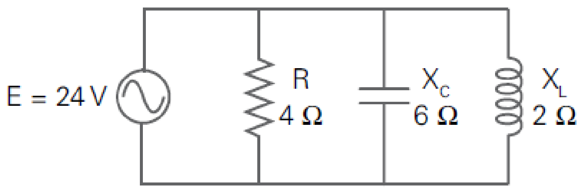
In the special case where the inductive and capacitive reactances are equal, the inductive and capacitive reactances compensate each other and the net impedance is equal the resistance only. In this case, the current is equal to the voltage divided by the resistance. This is referred to as a **series resonant circuit**.

Parallel R-L-C Circuit

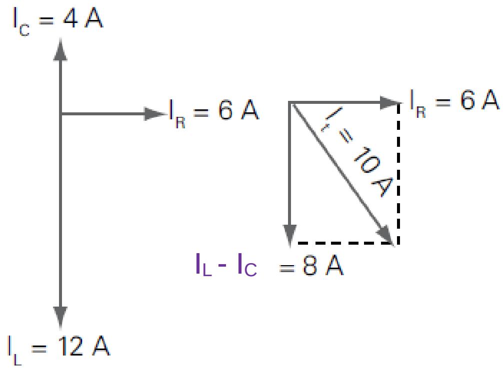
Many circuits contain values of resistance, inductance, and capacitance in parallel. One method for determining the total impedance for a parallel circuit is to begin by calculating the total current.

In a capacitive AC circuit, current leads voltage by 90 degrees. In an inductive AC circuit, current lags voltage by 90 degrees. When represented in vector form, capacitive current and inductive current are plotted 180 degrees apart. The net reactive current is determined by taking the difference between the reactive currents.

The total current for the circuit can be calculated as shown in the following example. Once the total current is known, the total impedance is calculated using Ohm’s law.



$$I_R = \frac{E}{R} = \frac{24\,V}{4\,\Omega} = 6\,A \qquad I_C = \frac{E}{X_C} = \frac{24\,V}{6\,\Omega} = 4\,A \qquad I_L = \frac{E}{X_L} = \frac{24\,V}{2\,\Omega} = 12\,A$$



I_t = Total Current

$$I_t = \sqrt{I_R^2 + (I_C - I_L)^2}$$

$$I_t = \sqrt{6^2 + 8^2}$$

$$I_t = \sqrt{100}$$

$$I_t = 10\,A$$

Z_t = Total Impedance

$$Z_t = \frac{E}{I_t} = \frac{24\,V}{10\,A}$$

$$Z_t = 2.4\,\Omega$$

Because inductive reactance and capacitive reactance are dependent upon frequency, if the frequency of the source changes, the reactances and corresponding currents also change. For example, if the frequency increases, the inductive reactance increases, and the current through the inductor decreases, but the capacitive reactance decreases and the current through the capacitor increases.

In the special case where the inductive and capacitive reactances are equal, the inductive and capacitive currents compensate each other and the net current is equal to the resistive current. In this case, the inductor and capacitor form a **parallel resonant circuit**.

11. Power and Power Factor in an AC Circuit

Power consumed by a resistor is dissipated in heat and not returned to the source. This is called **true or active power (Symbol : P)** because it is the rate at which energy is used.

Current in an AC circuit rises to peak values and decreases to zero many times a second. The energy stored in the magnetic field of an inductor, or plates of a capacitor, is returned to the source when current changes direction.

Although reactive components do not consume energy, they do increase the amount of energy that must be generated to do the same amount of work. The rate at which this non-working energy must be generated is called **reactive power (Symbol : Q)**. If voltage and current are 90 degrees out of phase, as would be the case in a purely capacitive or purely inductive circuit, the average value of active power is equal to zero. In this case, there are high positive and negative peak values of instantaneous power, but the average active power is equal to zero.

Power in an AC circuit is the vector sum of active power and reactive power. This is called **apparent power (Symbol : S)**. Active power is equal to apparent power in a purely resistive circuit because voltage and current are in phase. Voltage and current are also in phase in a circuit containing equal values of inductive reactance and capacitive reactance. In most circuits, however, apparent power is composed of both active power and reactive power.

Power Formulas

The formula for apparent power is shown below. The unit of measure for apparent power is the **volt-ampere (VA)**.

Apparent Power : S = EI

Active power is calculated from a trigonometric function, the cosine of the phase angle (cos ϕ) between current and voltage. The formula for active power is shown below. The unit of measure for active power is the **watt (W)**.

Active Power : P = EI cos ϕ

In a purely resistive circuit, current and voltage are in phase and the angle ϕ is equal to zero, so cos ϕ is equal to 1. Multiplying a value by 1 does not change the value. Therefore, in a purely resistive circuit, the cosine of the angle is ignored.

In a purely reactive circuit, either inductive or capacitive, current and voltage are 90 degrees out of phase. The cosine of 90 degrees is zero. Multiplying a value times zero results in a zero product. Therefore, no energy is consumed in a purely reactive circuit.

Although reactive components do not consume energy, they do increase the amount of energy that must be generated to do the same amount of work. The rate at which this non-working energy must be generated is called reactive power. The formula for reactive power is shown below. The unit for reactive power is the **var** (or **VAr**), which stands for volt-ampere reactive.

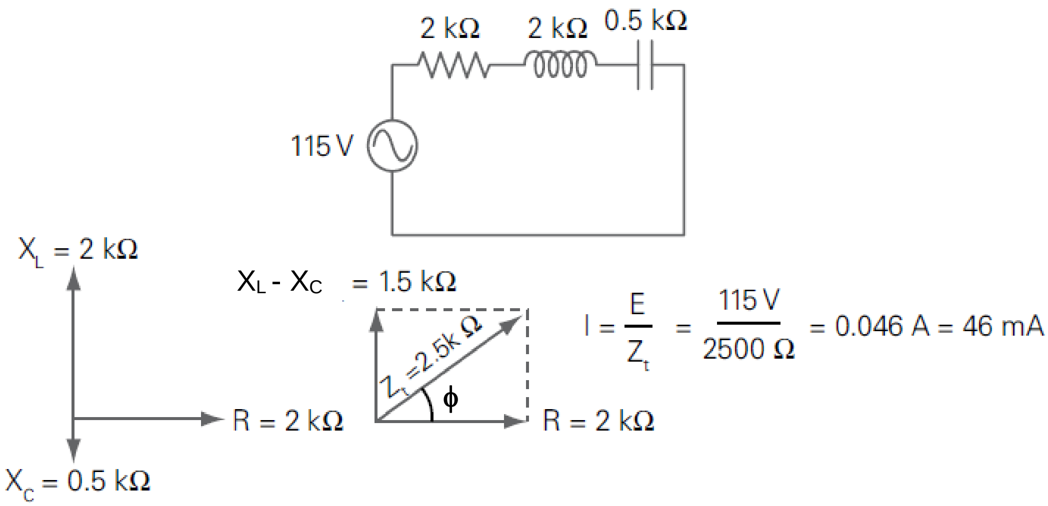
Reactive Power : $Q = EI \sin \phi$

You can also calculate the different powers using the following formula :

$$\mathbf{S^2 = P^2 + Q^2}$$

Power Calculation Example

The following example shows active power and apparent power calculations for the circuit shown.



Apparent Power = S = EI = 115 V x 0.046 A = 5.3 VA
Active Power = P = RI^2 = 2 kΩ x $(0.046 \text{ A})^2$ = 4.2 W
Reactive Power = $Q = \sqrt{S^2 - P^2} = \sqrt{5.3^2 - 4.2^2}$ = 3.2 VAr

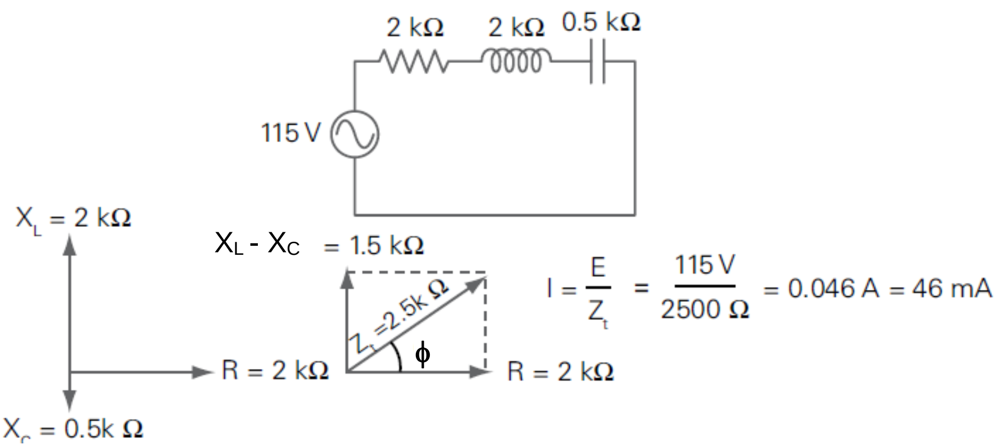
Power Factor

Power factor is the ratio of active power to apparent power in an AC circuit. As previously indicated, this ratio is also the cosine of the phase angle.

In a purely resistive circuit, current and voltage are in phase. This means that there is no angle of displacement between current and voltage. The cosine of a zero degree angle is one. Therefore, the power factor is one. This means that all energy delivered by the source is consumed by the circuit and dissipated in the form of heat.

In a purely reactive circuit, voltage and current are 90 degrees apart. The cosine of a 90 degree angle is zero.

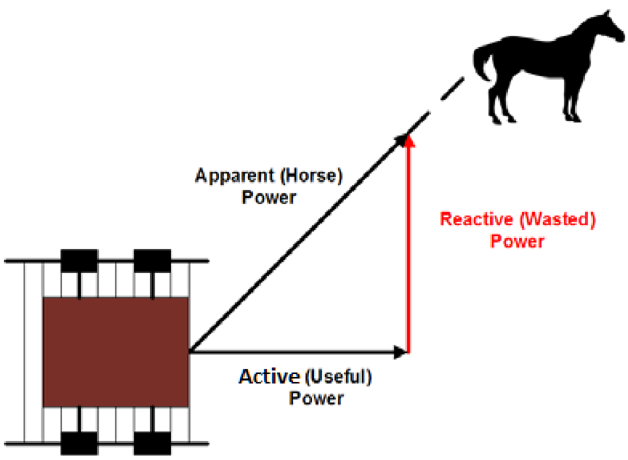
Therefore, the power factor is zero. This means that the whole energy received by the circuit from the source is returned to the source.
For the circuit in the following example, the power factor is 0.8. This means the circuit uses 80 percent of the energy supplied by the source and returns 20 percent to the source.



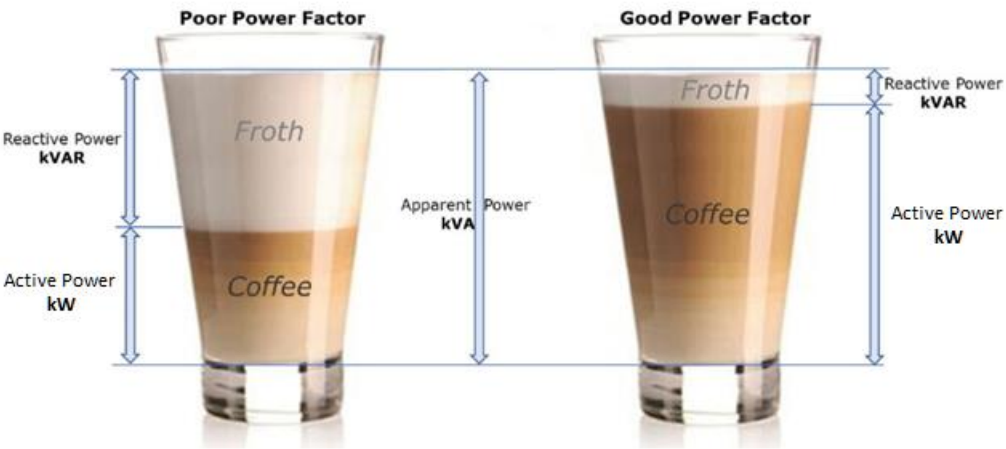
Apparent Power = S = EI = 115 V x 0.046 A = 5.3 VA
Active Power = P = RI^2 = 2 kΩ x (0.046 A)^2 = 4.2 W
Power Factor (PF) = $(\text{Active Power})/(\text{Apparent Power}) =$
$\cos\Phi$ (cosine of angle ϕ)
Power Factor (PF) = $4.2/5.3 = 0.8$

Active Power = Apparent Power x Power Factor = Apparent Power x $\cos\phi$

Another way of expressing active power is to multiply apparent power by the power factor. This is also equal to I times E times the cosine of the phase angle.



The dimensional concept of power can be understood using the analogy in the above diagram. The apparent power S is that which the horse must provide in order to pull the cart, but only part of the power is really necessary to make it move forwards.



Or with the above analogy, an efficient latte poor results in more consumable coffee (real power) and less froth (reactive power). The coffee portion represents power that can be used for useful work while froth is the non-working power required to operate a device.

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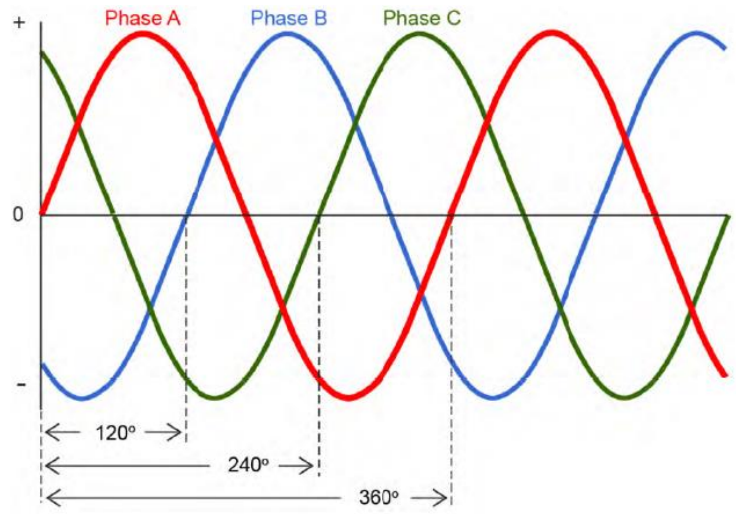
1. An AC circuit is __________ if inductive reactance and capacitive reactance are equal.
2. A series AC circuit is __________ if there is more inductive reactance than capacitive reactance.
3. A series AC circuit is __________ if there is more capacitive reactance than inductive reactance.
4. In a 240 V, 50 Hz series circuit with resistance of 1000 W, 10 mh of inductance, and 4 mF of capacitance, impedance is __________ Ω and current is __________ A.
5. For a circuit with a 240 V AC source and a current of 10 A, the apparent power is __________ VA.
6. For a circuit with an apparent power of 3000 VA and a power factor of 0.8, the active power is __________ W.

12. Three-Phase AC

Up till now, we have been talking only about **single-phase AC power**. Single-phase power is used in homes, offices, and many other types of facilities.

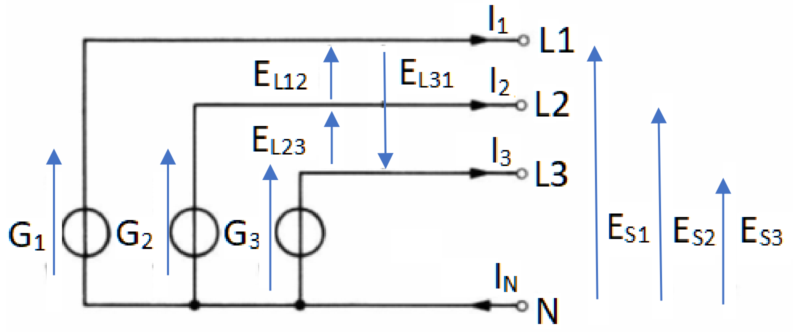
However, power companies generate and distribute **three-phase power**. Three-phase power is used in commercial and industrial applications that have higher power requirements than a typical residence.

Three-phase power, as shown in the following illustration, is a continuous series of three overlapping AC cycles. Each wave represents a phase and is offset by 120 electrical degrees from each of the two other phases.



Three-phase generation

The power can be coming whether directly from the grid, from transformers or from generators. As it can be seen in the above figure the voltage between two phases will be bigger than between the phase and the neutral.

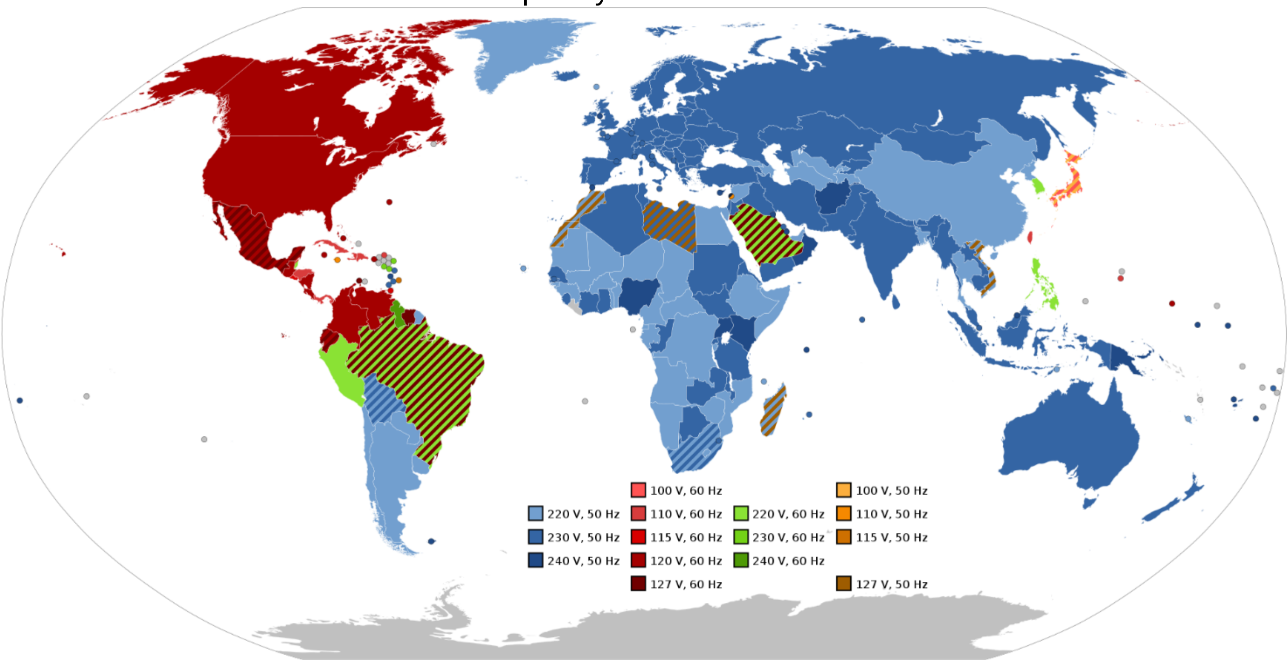


So we distinguish two different voltages:

The **Line** (line to line) or network voltage: **E_L** (400 V in EU)
The **Simple** (line to neutral) voltage: **E_S** (230 V in EU)

They are related by the square root of three:
$E_L = \sqrt{3}E_S \approx 1{,}732 \times E_S$

The following map represents the simple voltage and the frequency worldwide.



When current is the same in all three lines, it is said to be **balanced**. In each phase, current has two paths to follow. For example, current flowing from L1 to the connection point at the top of the delta can flow down through one coil to L2, and down through another coil to L3.

Three-phase power

Assuming that the current is balanced, the power can be calculated using the following formulas. If the power is not balanced, the average of the current should be used.

Active power: $\mathrm{P} = \sqrt{3}E_L I \cos\phi$

Reactive power: $\mathrm{Q} = \sqrt{3}E_L I \sin\phi$

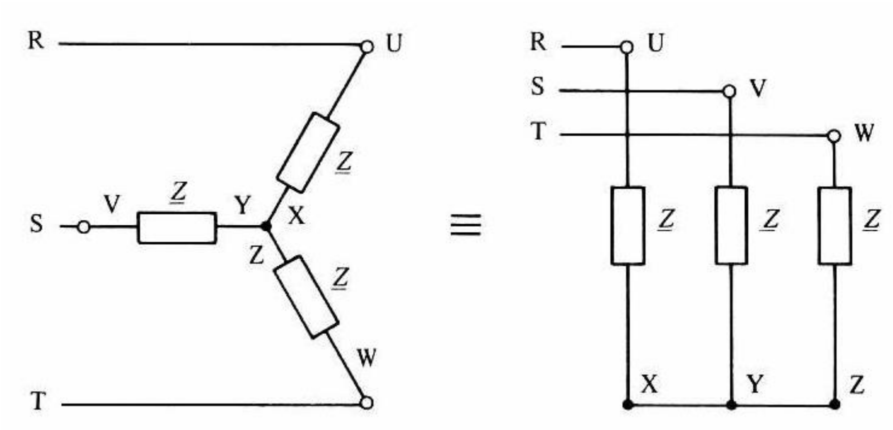
Apparent power: $\mathrm{S} = \sqrt{3}E_L I$

Three-phase impedance

the impedance in general is $\mathrm{Z} = \mathrm{E}/I$

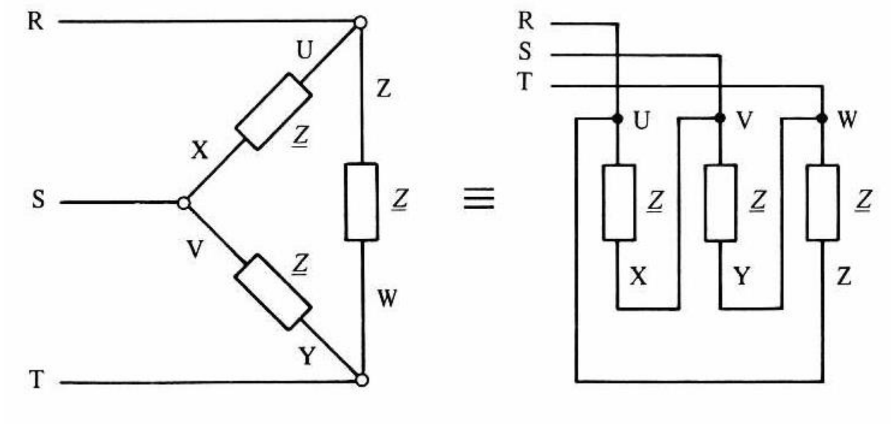
For the **star connection**, the line current is passing in each impedance and the volage applied is the line to neutral voltage, so that :

$$\mathrm{Z} = \frac{E_S}{I} = \frac{E_L}{\sqrt{3}I}$$



For the **delta connection**, the current is divided between the impedances and the volage applied is the line to line voltage, so that :

$$\mathrm{Z} = \frac{E_L}{\left(\frac{I}{\sqrt{3}}\right)} = \frac{\sqrt{3}E_L}{I}$$



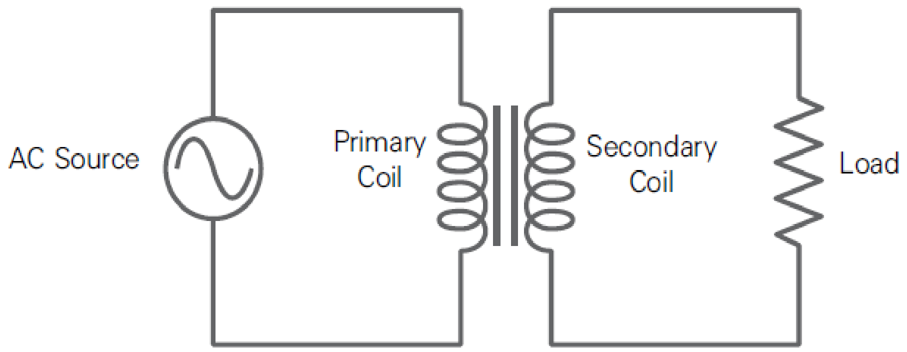
Review 9

1. In Colombia, the Line voltage is __________ V.
2. The active power of a 3-phase motor, 400V, 10A and power factor of 0,8 is __________ kW.
3. The reactive power of a 3-phase motor, 400V, 10A and power factor of 0,8 is __________ kVAr.
4. The apparent power of a 3-phase motor, 400V, 10A and power factor of 0,8 is __________ kVA.
5. The impedance of the above motor with star connection is ___________ kΩ.
6. The impedance of the above motor with delta connection is ___________ kΩ.

13.Transformers

Transformers are electromagnetic devices that transfer electrical energy from one circuit to another by **mutual induction**. A single-phase transformer has two coils, a **primary** and a **secondary**. Mutual induction is the transfer of electrical energy from the primary to the secondary through magnetic fields . A single-phase transformer circuit is schown below. The AC generator provides electrical power to the primary coil. The magnetic field produced by the primary induces a voltage into the secondary coil, which supplies power to a load.

Single-phase, Iron Core Transformer



Transformers are used to step a voltage up to a higher level, or down to a lower level. To understand the need to stepping up or down voltages, consider how electrical power is generated and distributed.

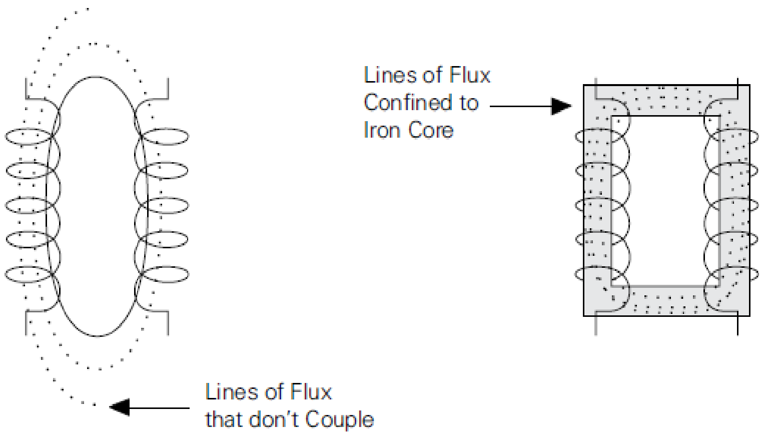
Generators used by power companies typically generate voltages of 30 kV or less. While this is a relatively high voltage compared to the voltages used by power customers, it is more efficient for utilities to transmit this power at still higher voltages, up to as high at 765 kV.

The electrical power is received at substation transformers many kilometers away where it is stepped down and distributed locally. When it arrives at the customer's location, it is further stepped down to the level needed for the type of customer.

Even within a customer's facility, voltage may need to be stepped down further to meet requirements of some equipment.

This process of stepping up or down the voltage throughout a power distribution system is accomplished using transformers. The sizes and ratings of the transformers vary, but the basic operation of these devices is the same.

Mutual inductance between two coils depends on their flux linkage. Maximum coupling occurs when all the lines of flux from the primary coil cut through the secondary winding. The amount of coupling which takes place is referred to as **coefficient of coupling**. To maximize coefficient of coupling, both coils are often wound on an iron core which is used to provide a path for the lines of flux. The following discussion of step-up and step-down transformers applies to transformers with an iron core.



There is a direct relationship between voltage, impedance, current, and the number of primary and secondary coil turns in a transformer. This relationship can be used to find either primary or secondary voltage, current, and the number of turns in each coil. The following "rules-of-thumb" apply to transformers:
If the primary coil has fewer turns than the secondary coil, the transformer is a **step-up transformer**.
If the primary coil has more turns than the secondary coil, the transformer is a **step-down transformer**.
When the number of turns on the primary and secondary coils of a transformer are equal, input voltage, impedance, and current are equal to output voltage, impedance, and current.

Transformer Formulas

There are a number of useful formulas for calculating, voltage, current, and the number of turns between the primary and secondary of a transformer. These formulas can be used with either step-up or step-down transformers. The following legend applies to the transformer formulas:

$\mathbf{E_S}$ = secondary voltage
$\mathbf{E_P}$ = primary voltage
$\mathbf{I_S}$ = secondary current
$\mathbf{I_P}$ = primary current
$\mathbf{N_S}$ = turns in the secondary coil
$\mathbf{N_P}$ = turns in the primary coil

To find voltage: $E_S = \frac{E_P \times I_p}{I_S}$

To find the number of coil turns: $N_S = \frac{E_S \times N_p}{E_P}$

Transformer Ratings

Transformers are rated for the amount of apparent power they can provide. Because values of apparent power are often large, the transformer apparent power rating is frequently given in **kVA (kilovolt-amperes)**. The kVA rating determines the current and voltage a transformer can deliver to its load without overheating.

For a single-phase transformer, the apparent power rating is calculated by multiplying secondary voltage by the maximum load current. This means that if a transformer needs to provide a secondary voltage of 240 V at a maximum load current of 75 A, the kVA rating of the transformer must be at least 18 kVA.

240 V x 75 A = 18,000 VA = 18 kVA

Transformer Losses

Most of the electrical energy provided to the primary of a transformer is transferred to the secondary. Some energy, however, is lost in heat in the wiring or the core. Some losses in the core can be reduced by building the core of a number of flat sections called laminations.

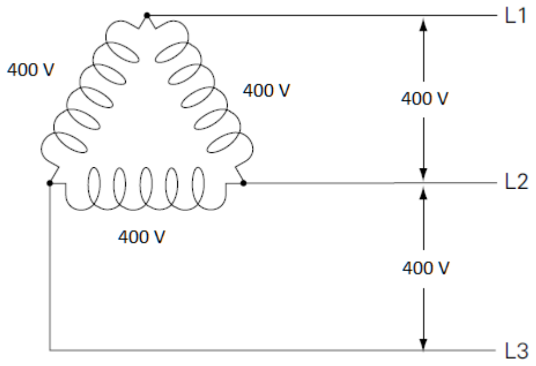
Three-Phase Transformers

Three-phase transformers are used when three-phase power is required for larger loads such as industrial motors. There are two basic three-phase transformer connections, **delta** and **wye (=star)**.

Delta Connections

Delta transformers are schematically drawn in a triangle. The voltages across each winding of the delta triangle represents one phase of a three-phase system. The voltage is always the same between any two wires. A single phase (such as L1 to L2) can be used to supply single phase loads. All three phases are used to supply three phase loads.

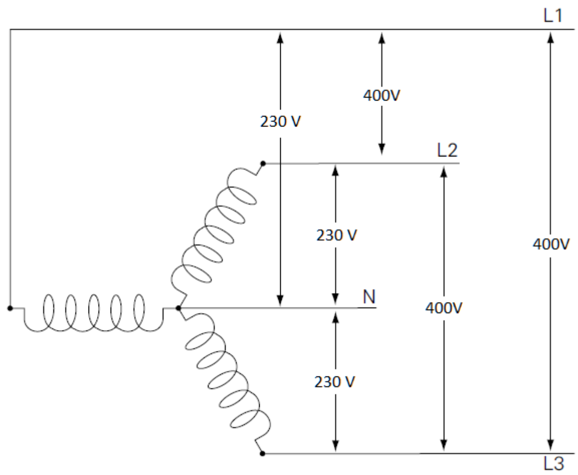
The secondary of a delta transformer is illustrated below. For simplicity, the primary is not shown in this example. The voltages shown on the illustration are examples. Just as with a single-phase transformer, the secondary voltage depends on both the primary voltage and the turns ratio.



Star Connections

The star connection is also known as a wye connection. Three coils are connected to form a "Y" shape. The wye transformer secondary has four leads, three phase leads and one neutral lead. The voltage across any phase (line-to-neutral) will always be less than the line-to-line voltage. The line-to-line voltage is the square root of 3 times the line-to-neutral voltage. The following example shows a wye transformer secondary with a line-to-neutral voltage of 230 volts and a line-to-line voltage of 400 volts.

$$V_{Line\text{-}to\text{-}Line} = \sqrt{3} \times 230\ V \approx 400\ V$$



Distribution transformers

Distribution transformers are used to connect the medium voltage lines (range between 1kV to 36kV) to the low voltage system (anything below 1kV). It is done with a delta connection on the medium voltage side and star connection on the low voltage side, where the ground is connected to the Neutral

Review 10

1. If the primary of a transformer has more turns than the secondary, it is a __________ transformer.

2. If the primary of a transformer has fewer turns than the secondary, it is a __________ transformer.

3. The secondary voltage of an iron-core transformer with 240 V on the primary, 40 A on the primary, and 20 A on the secondary is __________ V.

4. A single-phase transformer with a 480 V and a maximum load current of 20 A must have an apparent power rating of at least __________ kVA.

5. A star-connected, three-phase transformer secondary, with 380 V line-to-line will have __________ V line-to-neutral.