TRANSFORMERS

The main *purpose of a transformer* is to *change electrical voltage* from one level to another. A building may have a need for electrical power at several different voltages. A transformer is used to change the voltage to the desires level for the intended use. For example a building may be served with 3-phase power at 480/277 volts. That same building will most likely need 120 volts to supply general use receptacles. A transformer is used to change the 480/277 volts to 208/120 volts needed to supply the 120 volt receptacles and equipment. Electrical power can be moved efficiently across the country with minimal losses if the voltage is made very high. Transformers are used to increase the voltage to very high levels for transmission across the country and to reduce the voltage at each point of use.

Electrical Power Delivery System: The electrical power direct from the generator at the power plant is at about 15,000 volts. Transformers increase voltage for delivery across the country. Some transmission lines on steel towers operate with a voltage as high as 765,000 volts. A simplified electrical power generation and delivery system is shown in *Figure 218.1.*
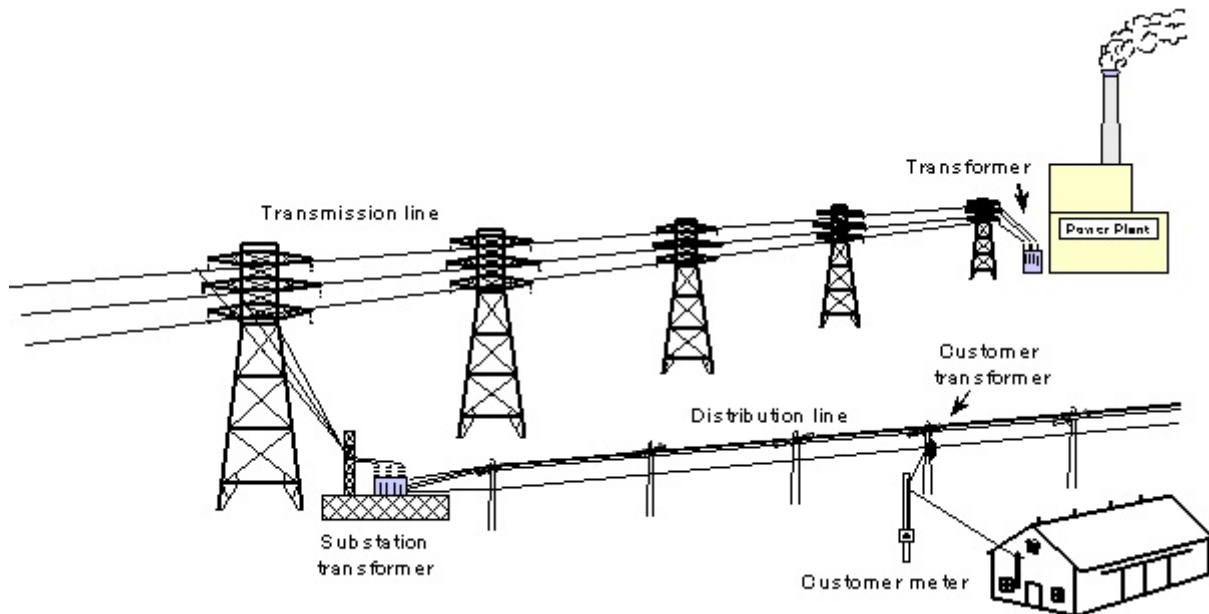

Figure 218.1   *Electrical energy from the power plant is usually delivered to an area using high voltage transmission lines and then the voltage is lowered for distribution to customers.*

Transformers are used to decrease the voltage from the transmission line to much lower levels for delivery to homes, farms, and businesses. A common single-phase distribution line operates at 7200 volts. Transformers at a fenced in location called a substation are used to lower the voltage from the transmission voltage level to the 7200 volts of the distribution line. The distribution substation is also shown in *Figure 218.1.*

   A typical home or farm using single-phase electrical power will have wires with two voltages. One voltage in a home is 120 volts, and the other is 240 volts. A transformer usually located at the top of the electrical pole in the yard lowers the 7200 volts of the distribution line to 120 volts and 240 volts needed for use in the home or on the farm.

How A Transformer Works: A typical transformer has two separate sets of insulated electrical wire wrapped around the steel core. This is shown in a simplified form in *Figure 218.2.* One principle of electricity is that when electrical current flows through a wire, a magnetic field builds up around the wire. The other important principal is that when a wire is placed in a magnetic field which is moving, electrical current will start to flow in the wire. In a transformer, electrical current is passed through one coil of wire called a winding. This winding is called the input winding or the primary winding. This electrical current produces a strong magnetic field in the steel core of the transformer. Because this is alternating current which travels back and forth through the wire 60 times every second, the magnetic field is constantly building up and collapsing 60 times every second. The moving magnetic field passes through the other coil or winding of the transformer and causes current to flow in that winding. So, electricity from the primary winding is turned into a magnetic field and then turned back into electricity at the secondary winding. This process makes it possible to change the level of voltage. The input winding (generally the higher voltage) is called the primary winding, and the output winding (generally the lower voltage) is called the secondary winding. The primary winding lead wires or terminals are labeled with the letter "H" such as H_1 and H_2 and the secondary windings are labeled with the letter "X" such as X_1 and X_2.
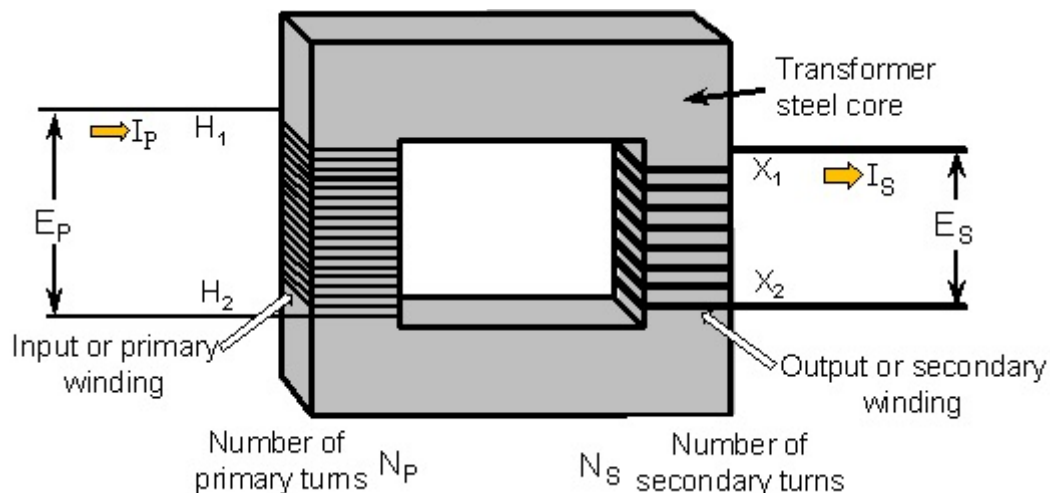

Figure 218.2   A transformer has a coil of wire called the primary winding and a separate coil of wire called the secondary winding wrapped around a steel core.

   The secret to changing the voltage in a transformer is the number of times a coil is wrapped around the steel core. If the output or secondary winding has half as many turns on the core as the input or primary winding, then the output voltage will only be half as much as the input voltage. Assume that there are 1200 turns of wire on the primary winding and only 40 turns of wire on the secondary winding. This means that the output voltage of the transformer will be 40 divided by 1200 times the input voltage. If the input voltage was 7200 volts, the output would be 240 volts. The following equation shows how to get output or input voltage when the other voltage and the number of turns on the transformer primary and secondary windings are known.

Finding secondary voltage with the primary voltage is known:

$$E_S = \frac{E_P}{TurnsRatio} \qquad\qquad E_S = E_P \times \frac{N_S}{N_P} \qquad\qquad \text{Eq. 218.1}$$

> **Example:** A transformer energized at 7200 volts on the primary has 1200 turns on the primary winding and 40 turns on the secondary winding. The output of the transformer is 240 volts.

$$E_S = 7200V \times \frac{40T}{1200T} = 240V$$

Finding primary voltage when the secondary voltage is known:

$$E_P = E_S \times TurnsRatio \qquad\qquad E_P = E_S \times \frac{N_P}{N_S} \qquad\qquad \text{Eq. 218.2}$$

Turns Ratio: Generally the actual number of turns on the primary and secondary windings are not known. Instead the ratio of the turns on the primary winding to the number of turns on the secondary winding are known. This is called the turns ratio. The turns ration can be determined if the actual number of turns on the windings are known. The turns ratio can also be determined from the rated primary and secondary voltages. Turns ratio can be determined for a transformer using the following formula.

$$TurnsRatio = \frac{N_P}{N_S} \qquad\qquad TurnsRatio = \frac{E_P}{E_S} \qquad\qquad \text{Eq. 218.3}$$

> **Example:** A single-phase transformer has an input (primary) rated at 480 volts and an output (secondary) rated at 120 volts. The turns ratio for this transformer will be 4 to 1.

$$TurnsRatio = \frac{480V}{120V} = \frac{4}{1}$$

Transformer Diagram: A diagram is used to indicate a transformer in an electrical circuit. *Figure 218.3* shows a typical diagram for a transformer which may supply single-phase electrical power to a home or farm. The primary input wires are shown on the left, and the secondary output wires are shown on the right. It is usually difficult to show the actual number of turns of wire on the windings, so the number of turns may be stated next to the diagram. The transformer shown in *Figure 218.3* is typical of the type used to supply single-phase power to homes and farms. It has three wires coming from the secondary winding. The *National Electrical Code* requires the middle wire of the secondary winding be grounded to the earth often with a ground rod. *The middle wire is called the neutral.* The voltage from the bottom wire to the top wire is 240 volts. This is how two voltages are produced for use in a home or a farm building. From the bottom wire to the middle wire is 120 volts and from the middle wire to the top wire is 120 volts. The top and bottom wires are called the ungrounded (hot) wires, and the middle wire is called the grounded (neutral) wire. There is other grounding of a typical utility transformer pole that is not shown in *Figure 218.3.*
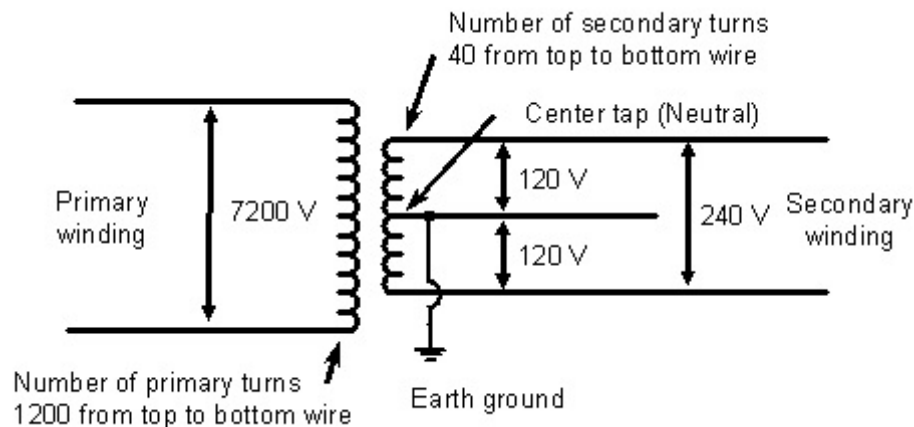
Figure 218.3 *This diagram of a transformer shows how the 7,200 volts of the primary distribution line is changed to 120 volts and 240 volts for use in a home or farm building.*

Utility Transformer: The power supplier transformer on a pole contains the two windings inside of a steel tank. The high voltage terminal is usually on top of the transformer and the low voltage terminals are usually on the side of the tank. There are actually three secondary terminals which deliver single-phase power to homes and farms. A diagram of a power supplier transformer is shown in *Figure 218.4.* Sometimes the transformer has two insulators on top and sometimes only one. It may seem that only one primary wire connects to the transformer, but there are actually two wires. It may be difficult to tell how the primary grounded wire is connected to the transformer primary or the input winding. The connections are usually made inside of the transformer and the grounded wire of the primary line is often connected to the grounded wire of the home or farm, and also to a terminal on the side of the transformer tank.
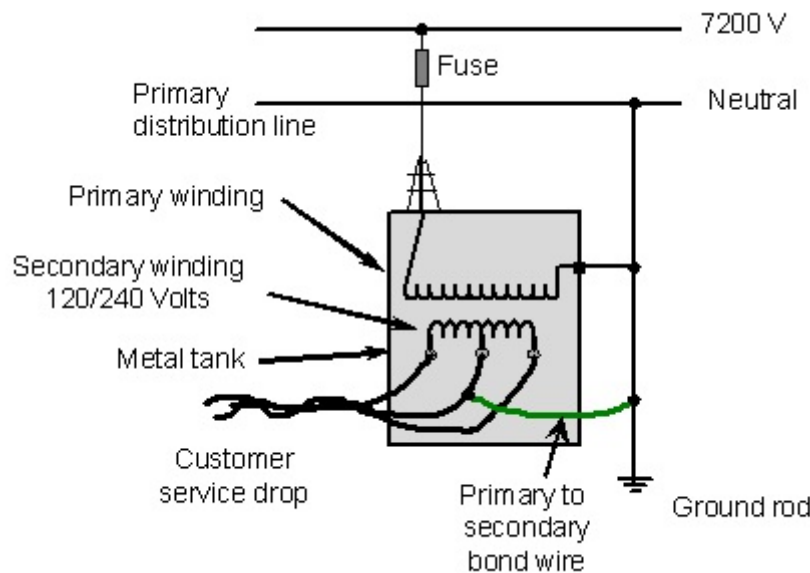

Figure 218.4 *A power supplier transformer on a pole has the windings and steel core contained on the inside of the transformer tank.*

Transformer (xfmr) Primary & Secondary Current Ratings: For the purpose of calculations it is assumed that the produce of primary voltage and primary current (E_P x I_P) is equal to the product of secondary voltage and secondary current (E_S x I_S). This is represented by *Equation 218.4.* Actually there are small losses which will make the product of primary voltage and current slightly larger than secondary voltage and current, but this small difference is generally not considered in calculations.

$$E_P \times I_P = E_S \times I_S$$ **Eq. 218.4**

If Equation 218.4 is true than when E_P and E_S are not the same value, I_P and I_S will not be the same value. If E_S is smaller than E_P, I_S will have a larger value than I_P. If primary and secondary voltage are known as well as either I_S or I_P, then the other current can be calculated using either Equation 218.5 or Equation 218.6.

$$I_P = I_S \times \frac{E_S}{E_P} \qquad I_P = \frac{I_S}{TurnsRatio}$$ **Eq. 218.5**

$$I_S = I_P \times \frac{E_P}{E_S} \qquad I_S = I_P \times TurnsRatio$$ **Eq. 218.6**

Example: A 25 kVA single-phase transformer has a primary energized at 240 volts with a secondary output of 240 volts and a full load secondary current of 104 amperes. Determine the primary full-load current. (Use Equation 218.5)

$$I_P = 104A \times \frac{240V}{480V} = 52A$$

As is evident by this calculation, the size of primary wire supplying this transformer is permitted to be much smaller than the secondary wire supplying the load.

Transformer Ratings: Transformers are rated in the amount of current each winding can handle at a given voltage which is expressed in voltage times current in amperes or volt-amperes. Generally the rating is in thousands of volt-amperes or kVA. The letter **k** is the metric symbol for 1000 and VA represents volt-amperes. The primary and secondary windings are designed to both have the same kVA rating. Assume the transformer used in the earlier example has a rating of 25 kVA and a primary winding operating at 7200 volts and a secondary winding operating at 240 volts. The amount of current each winding can handle is determined by multiplying the kVA rating by 1000 and then dividing by the winding voltage as shown in the following formula.

Transformers kVA, single-phase:

$$kVA_{1-phase} = \frac{E_P \times I_P}{1000} \qquad kVA_{1-phase} = \frac{E_S \times I_S}{1000}$$ **Eq. 218.7**

For the previous example of the 25 kVA transformer, the primary winding full-load current was 52 amperes when the secondary winding is delivering 104 amperes to the load. These are continuous current ratings. The windings can handle this much current indefinitely. Utility transformers are designed to deliver overload current at higher levels for short periods of time without damaging the windings.

A task frequently experienced by an electrician or an engineer is to determine the minimum size of wire required for the primary feeding the transformer and the secondary delivering current to the load. Specific rules can be found in *Article 450 of the National Electrical Code.* The process determination of the full-load rating of both the primary and secondary of the transformer. For a single-phase transformer simply multiply the kVA rating by 1000 and then divide by either the primary voltage or the secondary voltage. The following equations are used for that purpose.

$$I_S = \frac{kVA \times 1000}{E_S} \qquad I_P = \frac{kVA \times 1000}{E_P} \qquad \text{Eq. 218.8}$$

Transformer kVA, 3-phase: A 3-phase load may be supplied with a 3-phase transformer or the load can be supplied using individual single-phase transformers. For more on this subject see *Tech Note 220.* The 3-phase transformer will be supplied with three conductors where the current sine wave is $120°$ out of phase with the current sine wave of the other two conductors. The equations are similar to single-phase, but for 3-phase calculations an additional factor must be used in the equations. This additional factor is the square root of 3 which is the number 1.73. When determining the full-load current of a 3-phase transformer with the system phase-to-phase primary or secondary voltage known the 3-phase transformer kVA rating includes the value 1.73. Here are several equations useful when working with 3-phase transformers.

$$kVA = \frac{1.73 \times E_P \times I_P}{1000} \qquad kVA = \frac{1.73 \times E_S \times I_S}{1000} \qquad \text{Eq. 218.9}$$

$$I_S = \frac{kVA \times 1000}{1.73 \times E_S} \qquad I_P = \frac{kVA \times 1000}{1.73 \times E_P} \qquad \text{Eq. 218.10}$$

Example: The maximum secondary current rating of 3-phase transformer required for a 208 volts secondary of a 37,5 kVA transformer is ?

$$I_S = \frac{37.5 kVA \times 1000}{1.73 \times 208V} = 104 A \qquad I_P = \frac{37.5 \times 1000}{1.73 \times 480} = 45 A$$

The calculation is the same as single-phase except for the factor 1.73.