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TECHNICAL MANUAL

POWER TRANSFORMER MAINTENANCE AND ACCEPTANCE TESTING

HEADQUARTERS, DEPARTMENT OF THE ARMY

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Power Transformer Maintenance and Acceptance Testing

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CHAPTER 1

INTRODUCTION/SAFETY

1-1. Purpose

This manual contains a generalized overview of the fundamentals of transformer theory and operation. The transformer is one of the most reliable pieces of electrical distribution equipment (see figure 1-1). It has no moving parts, requires minimal maintenance, and is capable of withstanding overloads, surges, faults, and physical abuse that may damage or destroy other items in the circuit. Often, the electrical event that burns up a motor, opens a circuit breaker, or blows a fuse has a subtle effect on the transformer. Although the transformer may continue to operate as before, repeat occurrences of such damaging electrical events, or lack of even minimal maintenance can greatly accelerate the eventual failure of the transformer. The fact that a transformer continues to operate satisfactorily in spite of neglect and abuse is a testament to its durability. However, this durability is no excuse for not providing the proper care. Most of the effects of aging, faults, or abuse can be detected and corrected by a comprehensive maintenance, inspection, and testing program.

1-2. Scope

Substation transformers can range from the size of a garbage can to the size of a small house; they can be equipped with a wide array of gauges, bushings, and other types of auxiliary equipment. The basic operating concepts, however, are common to all transformers. An understanding of these basic concepts, along with the application of common sense maintenance practices that apply to other technical fields, will provide the basis for a comprehensive program of inspections, maintenance, and testing. These activities will increase the transformers's service life and help to make the transformer's operation both safe and trouble-free.

1-3. References

Appendix A contains a list of references used in this manual.

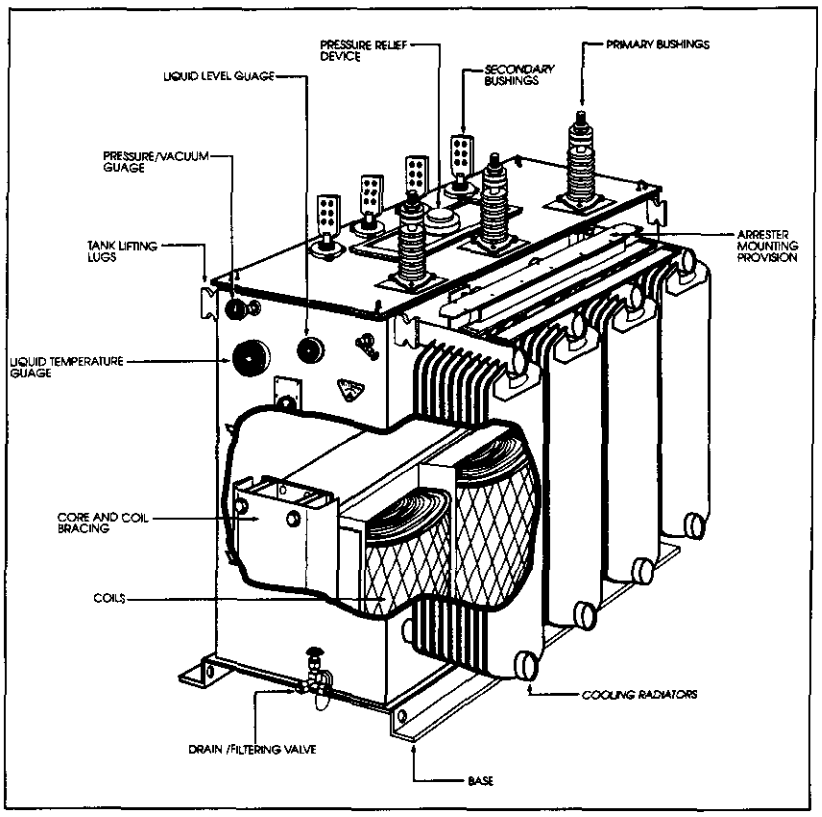

Figure 1-1. Typical power transformer.

1-4. Maintenance and testing

Heat and contamination are the two greatest enemies to the transformer's operation. Heat will break down the solid insulation and accelerate the chemical reactions that take place when the oil is contaminated. All transformers require a cooling method and it is important to ensure that the transformer has proper cooling. Proper cooling usually involves cleaning the cooling surfaces, maximizing ventilation, and monitoring loads to ensure the transformer is not producing excess heat.

a. Contamination is detrimental to the transformer, both inside and out. The importance of basic cleanliness and general housekeeping becomes evident when long-term service life is considered. Dirt build up and grease deposits severely limit the cooling abilities of radiators and tank surfaces. Terminal and insulation surfaces are especially susceptible to dirt and grease build up. Such buildup will usually affect test results. The transformer's general condition should be noted during any activity, and every effort should be made to maintain its integrity during all operations.

b. The oil in the transformer should be kept as pure as possible. Dirt and moisture will start chemical reactions in the oil that lower both its electrical strength and its cooling capability. Contamination should be the primary concern any time the transformer must be opened. Most transformer oil is contaminated to some degree before it leaves the refinery. It is important to determine how contaminated the oil is and how fast it is degenerating. Determining the degree of contamination is accomplished by sampling and analyzing the oil on a regular basis.

c. Although maintenance and work practices are designed to extend the transformer's life, it is inevitable that the transformer will eventually deteriorate to the point that it fails or must be replaced. Transformer testing allows this aging process to be quantified and tracked, to help predict replacement intervals and avoid failures. Historical test data is valuable for determining damage to the transformer after a fault or failure has occurred elsewhere in the circuit. By comparing test data taken after the fault to previous test data, damage to the transformer can be determined.

1-5. Safety

Safety is of primary concern when working around a transformer. The substation transformer is usually the highest voltage item in a facility's electrical distribution system. The higher voltages found at the transformer deserve the respect and complete attention of anyone working in the area. A 13.8 kV system will arc to ground over 2 to 3 in. However, to extinguish that same arc will require a separation of 18 in. Therefore, working around energized conductors is not recommended for anyone but the qualified professional. The best way to ensure safety when working around high voltage apparatus is to make absolutely certain that it is de-energized.

a. Although inspections and sampling can usually be performed while the transformer is in service, all other service and testing functions will require that the transformer is de-energized and locked out. This means that a thorough understanding of the transformer's circuit and the disconnecting methods should be reviewed before any work is performed.

b. A properly installed transformer will usually have a means for disconnecting both the primary and the secondary sides; ensure that they are opened before any work is performed. Both disconnects should be opened because it is possible for generator or induced power to backfeed into the secondary and step up into the primary. After verifying that the circuit is de-energized at the source, the area where the work is to be performed should be checked for voltage with a "hot stick" or some other voltage indicating device.

c. It is also important to ensure that the circuit stays de-energized until the work is completed. This is especially important when the work area is not in plain view of the disconnect. Red or orange lock-out tags should be applied to all breakers and disconnects that will be opened for a service procedure. The tags should be highly visible, and as many people as possible should be made aware of their presence before the work begins.

d. Some switches are equipped with physical locking devices (a hasp or latch). This is the best method for locking out a switch. The person performing the work should keep the key at all times, and tags should still be applied in case other keys exist.

e. After verifying that all circuits are de-energized, grounds should be connected between all items that could have a different potential. This means that all conductors, hoses, ladders and other equipment should be grounded to the tank, and that the tank's connection to ground should be verified before beginning any work on the transformer. Static charges can be created by many maintenance activities, including cleaning and filtering. The transformer's inherent ability to step up voltages and currents can create lethal quantities of electricity.

f. The inductive capabilities of the transformer should also be considered when working on a de-energized unit that is close to other conductors or devices that are energized. A de-energized transformer can be affected by these energized items, and dangerous currents or voltages can be induced in the adjacent windings.

g. Most electrical measurements require the application of a potential, and these potentials can be stored, multiplied, and discharged at the wrong time if the proper precautions are not taken. Care should be taken during the tests to ensure that no one comes in contact with the transformer while it is being tested. Set up safety barriers, or appoint safety personnel to secure remote test areas. After a test is completed, grounds should be left on the tested item for twice the duration of the test, preferably longer.

h. Once the operation of the transformer is understood, especially its inherent ability to multiply voltages and currents, then safety practices can be applied and modified for the type of operation or test that is being performed. It is also recommended that anyone working on transformers receive regular training in basic first aid, CPR, and resuscitation.

1-6. Nameplate data

The transformer nameplate contains most of the important information that will be needed in the field. The nameplate should never be removed from the transformer and should always be kept clean and legible. Although other information can be provided, industry standards require that the following information be displayed on the nameplate of all power transformers:

a. Serial number. The serial number is required any time the manufacturer must be contacted for information or parts. It should be recorded on all transformer inspections and tests.

b. Class. The class, as discussed in paragraph 4-1, will indicate the transformer's cooling requirements and increased load capability.

c. The kVA rating. The kVA rating, as opposed to the power output, is a true indication of the current carrying capacity of the transformer. kVA ratings for the various cooling classes should be displayed. For three-phase transformers, the kVA rating is the sum of the power in all three legs.

d. Voltage rating. The voltage rating should be given for the primary and secondary, and for all tap positions.

e. Temperature rise. The temperature rise is the allowable temperature change from ambient that the transformer can undergo without incurring damage.

f. Polarity (single phase). The polarity is important when the transformer is to be paralleled or used in conjunction with other transformers.

g. Phasor diagrams. Phasor diagrams will be provided for both the primary and the secondary coils. Phasor diagrams indicate the order in which the three phases will reach their peak voltages, and also the angular displacement (rotation) between the primary and secondary.

h. Connection diagram. The connection diagram will indicate the connections of the various windings, and the winding connections necessary for the various tap voltages.

i. Percent impedance. The impedance percent is the vector sum of the transformer's resistance and reactance expressed in percent. It is the ratio of the voltage required to circulate rated current in the corresponding winding, to the rated voltage of that winding. With the secondary terminals shorted, a very small voltage is required on the primary to circulate rated current on the secondary. The impedance is defined by the ratio of the applied voltage to the rated voltage of the winding. If, with the secondary terminals shorted, 138 volts are required on the primary to produce rated current flow in the secondary, and if the primary is rated at 13,800 volts, then the impedance is 1 percent. The impedance affects the amount of current flowing through the transformer during short circuit or fault conditions.

j. Impulse level (BIL). The impulse level is the crest value of the impulse voltage the transformer is required to withstand without failure. The impulse level is designed to simulate a lightning strike or voltage surge condition. The impulse level is a withstand rating for extremely short duration surge voltages. Liquid-filled transformers have an inherently higher BIL rating than dry-type transformers of the same kVA rating.

k. Weight. The weight should be expressed for the various parts and the total. Knowledge of the weight is important when moving or untanking the transformer.

l. Insulating fluid. The type of insulating fluid is important when additional fluid must be added or when unserviceable fluid must be disposed of. Different insulating fluids should never be mixed. The number of gallons, both for the main tank, and for the various compartments should also be noted.

m. Instruction reference. This reference will indicate the manufacturer's publication number for the transformer instruction manual.

CHAPTER 2

CONSTRUCTION/THEORY

2-1. Transformer applications

A power transformer is a device that changes (transforms) an alternating voltage and current from one level to another. Power transformers are used to "step up" (transform) the voltages that are produced at generators to levels that are suitable for transmission (higher voltage, lower current). Conversely, a transformer is used to "step down" (transform) the higher *transmission voltages to levels that are suitable for use* at various facilities (lower voltage, higher current). Electric power can undergo numerous transformations between the source and the final end use point (see figure 2-1).

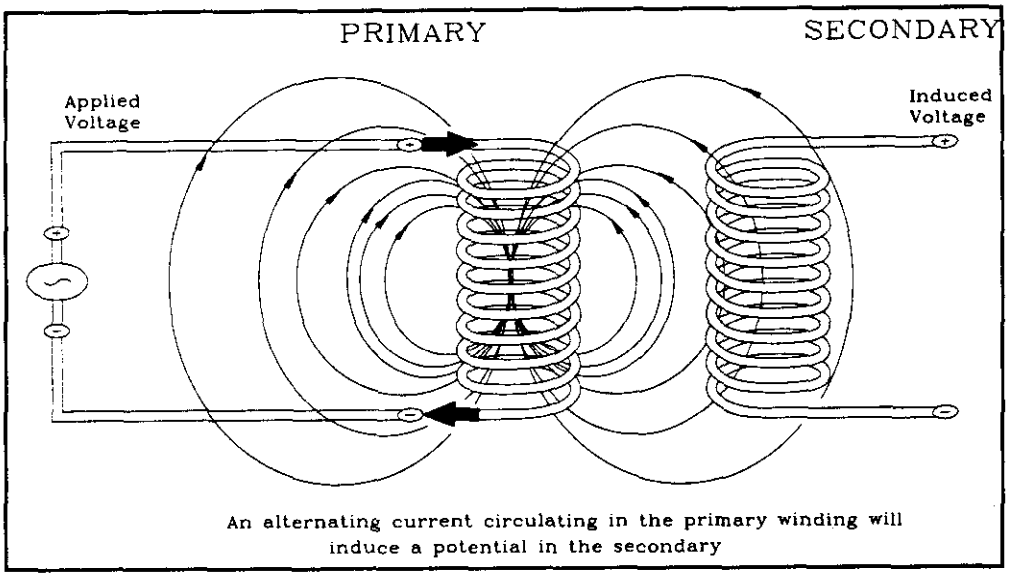

Figure 2-1. Distribution system schematic.

a. Voltages must be stepped-up for transmission. Every conductor, no matter how large, will lose an appreciable amount of power (watts) to its resistance (R) when a current (I) passes through it. This loss is expressed as a function of the applied current ($P=I^2xR$). Because this loss is dependent on the current, and since the power to be transmitted is a function of the applied volts (E) times the amps (P=IxE), significant savings can be obtained by stepping the voltage up to a higher voltage level, with the corresponding reduction of the current value. Whether 100 amps is to be transmitted at 100 volts (P=IxE; 100 amps × 100 volts = 10,000 watts) or 10 amps is to be transmitted at 1,000 volts (P=IxE; 10 amps × 1,000 volts = 10,000 watts) the same 10,000 watts will be applied to the beginning of the transmission line.

b. If the transmission distance is long enough to produce 0.1 ohm of resistance across the transmission cable, $P=I^2R$; $(100 \text{ amp})^2 \times 0.1$ ohm = 1,000 watts will be lost across the transmission line at the 100 volt transmission level. The 1,000 volt transmission level will create a loss of $P=I^2R$; $(10 \text{ amp})^2 \times 0.1$ ohm = 10 watts. This is where transformers play an important role.

c. Although power can be transmitted more efficiently at higher voltage levels, sometimes as high as 500 or 750 thousand volts (kV), the devices and networks at the point of utilization are rarely capable of handling voltages above 32,000 volts. Voltage must be "stepped down" to be utilized by the various devices available. By adjusting the voltages to the levels necessary for the various end use and distribution levels, electric power can be used both efficiently and safely.

d. All power transformers have three basic parts, a primary winding, secondary winding, and a core. Even though little more than an air space is necessary to insulate an "ideal" transformer, when higher voltages and larger amounts of power are involved, the insulating material becomes an integral part of the transformer's operation. Because of this, the insulation system is often considered the fourth basic part of the transformer. It is important to note that, although the windings and core deteriorate very little with age, the insulation can be subjected to severe stresses and chemical deterioration. The insulation deteriorates at a relatively rapid rate, and its condition ultimately determines the service life of the transformer.

2-2. Magnetic flux

The transformer operates by applying an alternating voltage to the primary winding. As the voltage increases, it creates a strong magnetic field with varying magnetic lines of force (flux lines) that cut across the secondary windings. When these flux lines cut across a conductor, a current is induced in that conductor. As the magnitude of the current in the primary increases, the growing flux lines cut across the secondary winding, and a potential is induced in that winding. This inductive linking and accompanying energy transfer between the two windings is the basis of the transformer's operation (see figure 2-2). The magnetic lines of flux "grow" and expand into the area around the winding as the current increases in the primary. To direct these lines of flux towards the secondary, various core materials are used. Magnetic lines of force, much like electrical currents, tend to take the path of least resistance. The opposition to the passage of flux lines through a material is called reluctance, a characteristic that is similar to resistance in an electrical circuit. When a piece of iron is placed in a magnetic field, the lines of force tend to take the path of least resistance (reluctance), and flow through the iron instead of through the surrounding air. It can be said that the air has a greater reluctance than the iron. By using iron as a core material, more of the flux lines can be directed from the primary winding to the secondary winding; this increases the transformer's efficiency.

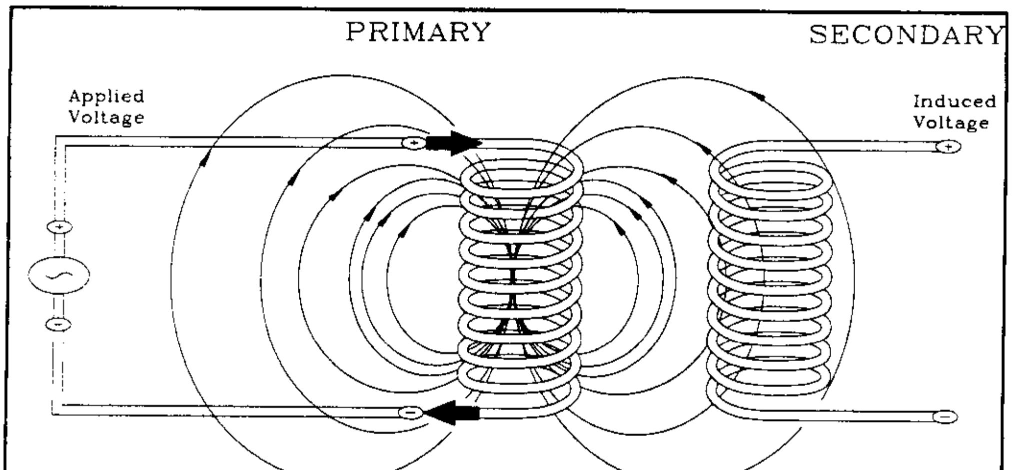

Figure 2-2. Transformer flux lines.

2-3. Winding, current and voltage ratios

If the primary and secondary have the same number of turns, the voltage induced into the secondary will be the same as the voltage impressed on the primary (see figure 2-3).

a. If the primary has more turns than the secondary, then the voltage induced in the secondary windings will be stepped down in the same ratio as the number of turns in the two windings. If the primary voltage is 120 volts, and there are 100 turns in the primary and 10 turns in the secondary, then the secondary voltage will be 12 volts. This would be termed a "step down" transformer as shown in figure 2-4.

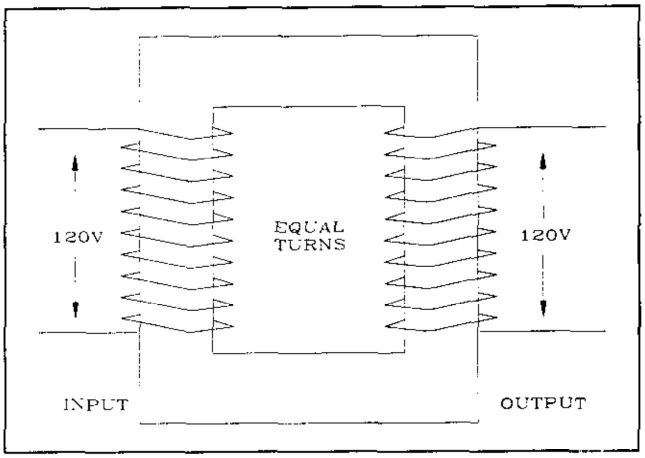

Figure 2-3. Transformer equal turns ratio.

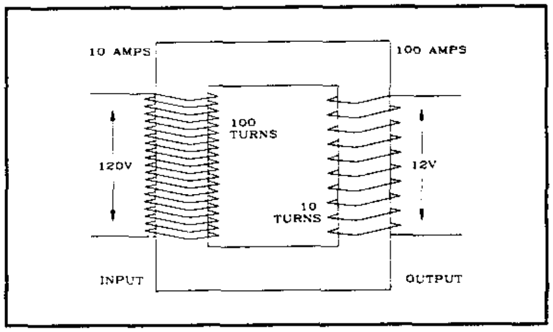

Figure 2-4. Transformer 10:1 turns ratio.

b. A "step up" transformer would have more turns on the secondary than on the primary, and the reverse voltage relationship would hold true. If the voltage on the primary is 120 volts, and there are 10 turns in the primary and 100 turns in the secondary, then the secondary voltage would be 1200 volts. The relationship between the number of turns on the primary and secondary and the input and output voltages on a step up transformer is shown in figure 5-2.

c. Transformers are used to adjust voltages and currents to the level required for specific applications. A transformer does not create power, and therefore ignoring losses, the power into the transformer must equal the power out of the transformer. This means that, according to the previous voltage equations, if the voltage is stepped up, the current must be stepped down. Current is transformed in inverse proportion to the ratio of turns, as shown in the following equations:

$$\frac{N_p \text{ (turns on primary)}}{N_s \text{ (turns on secondary)}} = \frac{I_s \text{ (amperes in secondary)}}{I_p \text{ (amperes in primary)}}$$

$$\frac{E_p \text{ (volts primary)}}{E_s \text{ (volts secondary)}} = \frac{I_s \text{ (amperes secondary)}}{I_p \text{ (amperes primary)}}$$

d. The amount of power that a transformer can handle is limited by the size of the winding conductors, and by the corresponding amount of heat they will product

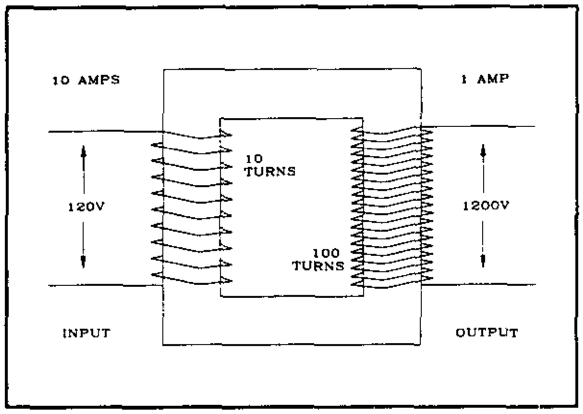

Figure 2-5. Transformer 1:10 turns ratio.

when current is applied. This heat is caused by losses, which results in a difference between the input and output power. Because of these losses, and because they are a function of the impedance rather than pure resistance, transformers are rated not in terms of power (Watts), but in terms of kVA. The output voltage is multiplied by the output current to obtain volt-amps; the k designation represents thousands.

2-4. Core construction

To reduce losses, most transformer cores are made up of thin sheets of specially annealed and rolled silicone steel laminations that are insulated from each other. The molecules of the steel have a crystal structure that tends to direct the flux. By rolling the steel into sheets, it is possible to "orient" this structure to increase its ability to carry the flux.

a. As the magnetic flux "cuts" through the core materials, small currents called "eddy currents" are induced. As in any other electrical circuit, introducing a resistance (for example, insulation between the laminations), will reduce this current and the accompanying losses. If a solid piece of material were used for the core, the currents would be too high. The actual thickness of the laminations is determined by the cost to produce thinner laminations versus the losses obtained. Most transformers operating at 60 Hertz (cycles per second) have a lamination thickness between 0.01 and 0.02 in. Higher frequencies require thinner laminations.

b. The laminations must be carefully cut and assembled to provide a smooth surface around which the windings are wrapped. Any burrs or pointed edges would allow the flux lines to concentrate, discharge and escape from the core. The laminations are usually clamped and blocked into place because bolting would interrupt the flow of flux. Bolts also have a tendency to loosen when subjected to the vibrations that are found in a 60 cycle transformer's core. It is important that this

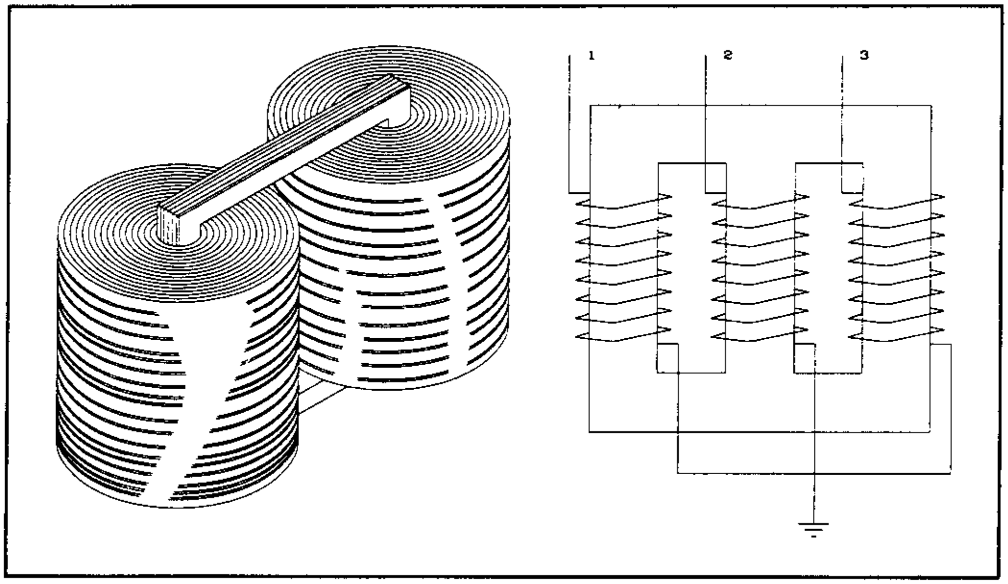

Figure 2–6. Transformer shell construction.

clamping arrangement remains tight; any sudden increase in noise or vibration of the transformer can indicate a loosening of the core structure.

2–5. Core form construction

There are two basic types of core assembly, core form and shell form. In the core form, the windings are wrapped around the core, and the only return path for the flux is through the center of the core. Since the core is located entirely inside the windings, it adds a little to the structural integrity of the transformer's frame. Core construction is desirable when compactness is a major requirement. Figure 2–6 illustrates a number of core type configurations for both single and multi-phase transformers.

2–6. Shell form construction

Shell form transformers completely enclose the windings inside the core assembly. Shell construction is used for larger transformers, although some core-type units are built for medium and high capacity use. The core of a shell type transformer completely surrounds the windings, providing a return path for the flux lines both through the center and around the outside of the windings (see figure 2–7). Shell construction is also more flexible, because it allows a wide choice of winding arrangements and coil groupings. The core can also act as a structural member, reducing the amount of external clamping and bracing required. This is especially important in larger application where large forces are created by the flux.

a. Certain wiring configurations of shell form transformers, because of the multiple paths available for the flux flow, are susceptible to higher core losses due to harmonic generations. As the voltage rises and falls at the operating frequency, the inductance and capacitance of various items in or near the circuit operate at a frequency similar to a multiple of the operating frequency. The "Third Harmonic" flows primarily in the core, and can triple the core losses. These losses occur primarily in Wye-Wye configured transformers (see chapter 3).

b. The flux that links the two windings of the transformer together also creates a force that tends to push the conductors apart. One component of this force, the axial component, tends to push the coils up and down on the core legs, and the tendency is for the coils to slide up and over each other. The other component is the longitudinal force, where the adjacent coils push each other outward, from side to side. Under normal conditions, these forces are small, but under short circuit conditions, the forces can multiply to hundreds of times the normal value. For this reason, the entire coil and winding assembly must be firmly braced, both on the top and bottom and all around the sides. Bracing also helps to hold the coils in place during shipping.

c. The bracing also maintains the separation that is a necessary part of the winding insulation, both from the tank walls, and from the adjacent windings. Nonconductive materials, such as plastic, hardwood or plywood blocks are used to separate the windings from each other and from the tank walls. These separations in the construction allow paths for fluid or air to circulate, both adding to the insulation strength, and helping to dissipate the heat thereby cooling the windings. This is especially important in large, high voltage transformers, where the heat buildup and turn-to-turn separations must be controlled.

d. The windings of the transformer must be separated (insulated) from each other and from the core, tank, or other grounded material. The actual insulation

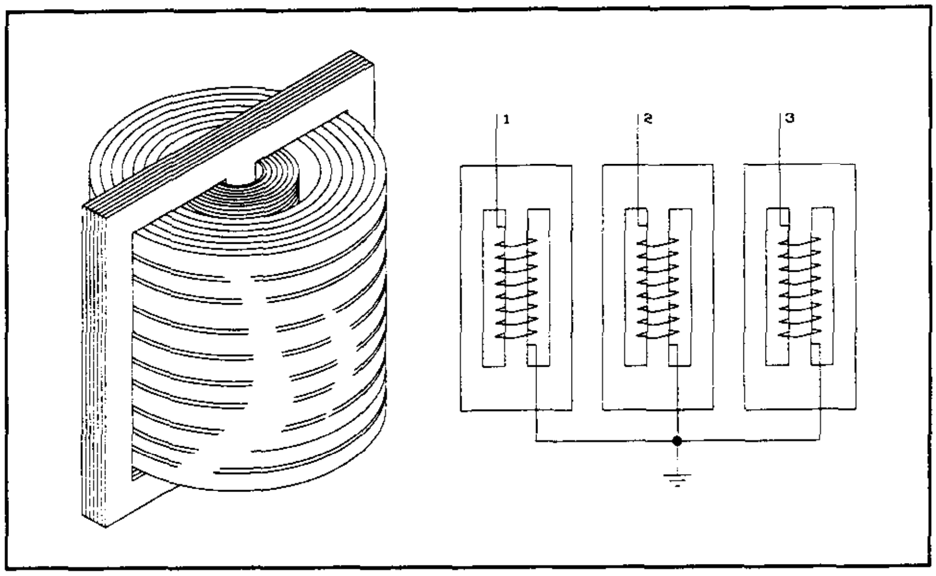

Figure 2-7. Transformer shell construction.

between the turns of each winding can usually be provided by a thin enamel coating or a few layers of paper. This is because the entire voltage drop across the windings is distributed proportionately across each turn. In other words, if the total voltage drop across a winding is 120 volts, and there are 100 turns in that winding, the potential difference between each turn is 1.2 volts (120/100).

e. Transformers are designed to withstand impulse levels several times, and in some cases, hundreds of times higher than one operating voltage. This is to provide adequate protection in the case of a lightning strike, a switching surge or a short circuit. By allowing oil to circulate between the windings, the turn-to-turn insulating level can be appreciably increased and the amount of heat built up in the windings can be efficiently dissipated.

f. Most large power transformers have their windings immersed in some type of fluid. Although larger dry-type transformers ar constantly being produced, and many new forms of construction, such as resin cast and gas filled, are being used for power applications, the most common method of insulating the windings and dissipating the heat is by submerging the windings and core in an insulating fluid. Silicone, trichloroethane, and a wide variety of low fire point hydrocarbon based fluids are just a few of the fluids currently in use. This manual primarily applies to mineral oil-filled transformers. Although there are similarities between mineral oil and many other fluids being used, the manufacturer's specifications and instructions for each fluid should always be considered. Any reference in this manual to insulating, unless otherwise stated, will be implied to mean mineral oil.

g. Heat must be dissipated by fluid because no transformer is 100 percent efficient. There are many forms of losses in a transformer, and although they have different sources, the resultant product of these losses is heat build up within the tank. Transformer losses can be divided into two general categories, load losses and no-load losses. No-load losses are independent of the applied load, and include core losses, excitation losses, and dielectric losses in the insulation. Load loses consist of the copper losses across the windings that are produced by the applied current (I^2R), and of the stray currents in the windings that appear when the load is applied. These loses are usually listed by the manufacturer for each type of transformer. They are especially important when considering the cooling requirements of the transformer.

h. Some of the important transformer equations are as follows:

Basic transformer ratio:

$$\frac{N_p \text{ (\# turns primary)}}{N_s \text{ (\# turns secondary)}} = \frac{E_p \text{ (volts primary)}}{E_s \text{ (volts secondary)}}$$

Current equation:

$$I_p \times N_p = I_s \times N_s$$

Percent efficiency:

$$\frac{\text{output} \times 100\%}{\text{input}} = \frac{\text{output} \times 100\%}{\text{output} + \text{losses}}$$

CHAPTER 3

TRANSFORMER CONNECTIONS AND TAPS

3-1. Tapped primaries and secondaries

To composite for changing input voltages, multiple connections or "taps" are provided to allow different portions of the winding to be used. When the taps are connected on the primary winding, the turn-to-turn ratio is changed, and the required secondary voltage can be obtained in spite of a change in source voltage. Manufacturers usually provide taps at 2-1/2 percent intervals above and below the rated voltage (see figure 3-1) Taps at 2.5 percent allow the number of turns on the primary to change.

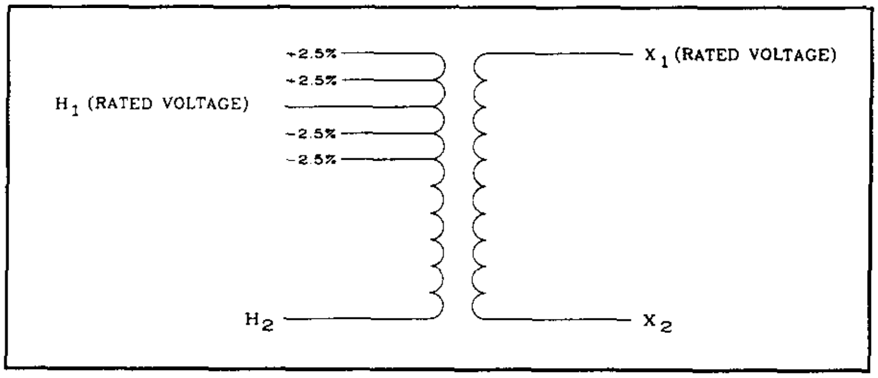

Figure 3-1. Transformer taps.

a. Taps are usually changed by turning a crank or hand-wheel, although some transformers require that a cover be removed and the actual winding leads be connected on a terminal board where all of the taps can be accessed. Tap changers can be either "Load Tap Changing" or "No-Load Tap (N.L.T.) Changing" units, although most of them must be changed with the transformer de-energized.

b. Smaller single-phase transformers are usually provided with center-tapped secondaries, with the leads brought out from both halves of the tapped winding. When the center tap leads are connected together, that winding becomes one continuous coil, and it is said to be connected in series (see figure 3-2). Because the maximum number of turns are used, the maximum voltage is obtained, at the corresponding current level.

c. When the center taps are connected to the opposite output leads, the winding becomes two separate windings working in parallel (see figure 3-2). A lower voltage at a corresponding higher current level is obtained.

3-2. Polarity

Note that, when the center tap is connected in parallel, both windings are oriented in the same direction with respect to the primary. The clockwise or counterclockwise direction that the windings are wound on the core determine the direction of the current flow (the right-hand rule). This relationship of winding orientation to current flow in the transformer is known as polarity.

a. The polarity of a transformer is a result of the relative winding directions of the transformer primary conductor with respect to the transformer secondary (see figure 3-3). Polarity is a function of the transformer's construction. Polarity becomes important when more than one transformer is involved in a circuit. Therefore, the polarities and markings of transformers are standardized. Distribution Transformers above 200 KVA or above 860 volts are "subtractive."

b. Transformer polarity is an indication of the direction of current flow through the high-voltage terminals,

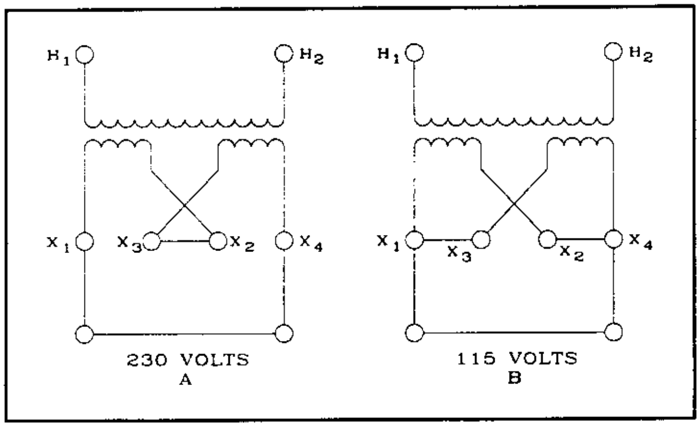

Figure 3-2. Single phase transformer secondary winding arrangements.

with respect to the direction of current flow through the low-voltage terminals at any given instant in the alternating cycle. Transformers are constructed with additive or subtractive polarity (see figures 3-4). The terminal markings on transformers are standardized among the various manufacturers, and are indicative of the polarity. However, since there is always the possibility that the wiring of a transformer could have been changed, it is important to check the transformer's polarity before making any wiring changes.

c. The polarity is subtractive when the high-side lead (H1) is brought out on the same side as the low-side lead (X1). If a voltage is placed on the high-side, and a jumper is connected between the H1 and X1 terminals (see figure 3-5), the voltage read across the H2 and X2 terminals will be less than the applied voltage. Most large power transformers are constructed with subtractive polarity.

d. When the high-side lead (H1) is brought out on the opposite side of the low-side lead (X1) and is on the same side as the low side lead (X2), the polarity is additive. If a voltage is placed across the high-side, and a jumper is connected between the H1 and X2 terminals, the voltage read across the H2 and X1 terminals will be greater than the applied voltage (see figure 23-6).

3-3. Autotransformers

Although the examples illustrated up to this point have used two separate windings to transform the voltage and current, this transformation can be accomplished by dividing one winding into sections. The desired ratio can be obtained by "tapping" the winding at a prescribed point to yield the proper ratio between the two sections. This arrangement is called an "Autotransformer."

a. Even though the winding is continuous, the desired voltages and currents can be obtained. Although an autotransformer is made up of one continuous winding, the relationship of the two sections can be more readily understood if they are thought of as two separate windings connected in series. Figure 3-7 shows the current and voltage relationships in the various sections of an autotransformer.

b. Autotransformers are inherently smaller than nor-

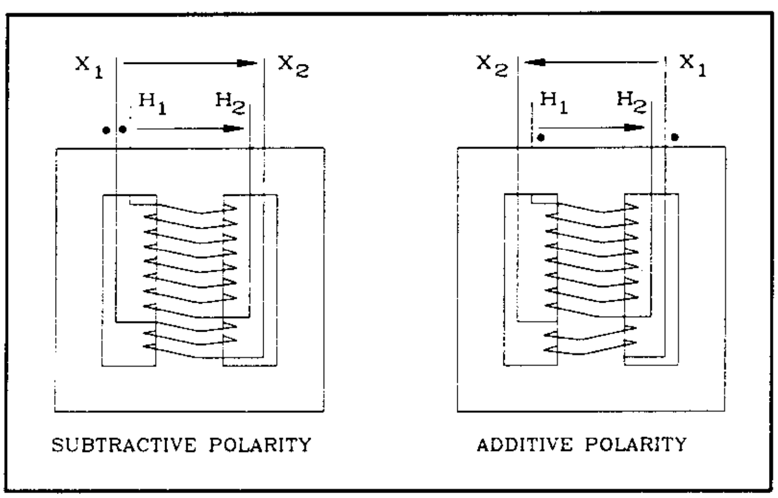

Figure 3-3. Physical transformer polarity.

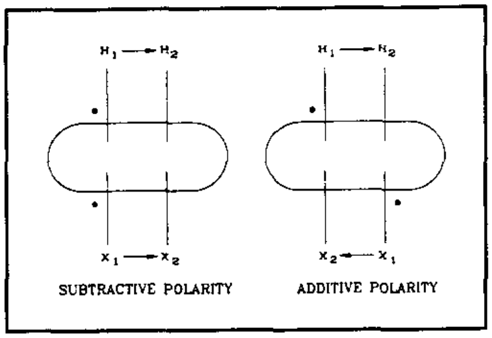

Figure 3-4. Diagrammatic transformer polarity.

mal two-winding transformers. They are especially suited for applications where there is not too much difference between the primary and secondary voltages (transformer ratios usually less than 5:1). An autotransformer will have lower losses, impedance, and excitation current values than a two-winding transformer of th same KVA rating because less material is used in its construction.

c. The major drawback of autotransformers is that they do not provide separation between the primary and secondary. This non-insulating feature of the autotransformer should always be remembered; even though a low voltage may be tapped from an autotransformer, the low voltage circuit must be insulated to the same degree as the high voltage side of the transformer. Another drawback is that the autotransformer's impedance is extremely low, and it provides almost no opposition to fault current. Autotransformers are usually primarily for motor staring circuits, where lower voltages are required at the start to reduce the amount of inrush current, and higher voltages are used once the motor is running. Autotransformers are used in power applications where the difference between the primary and secondary voltages is not too great.

3-4. Single and multi-phase relationships

All transformations occur on a single-phase basis; three-phase transformers are constructed by combining three single-phase transformers in the same tank. As indicated by its name, a single-phase transformer is a transformer that transforms one single-phase voltage and current to another voltage and current level.

a. Alternating current single-phase power can be represented by a graph of constantly changing voltage versus time (a sine wave). The potential changes continuously from positive to negative values over a given time period. When the voltage has gone through one complete series of positive and negative changes, it is said to have completed one cycle. This cycle is expressed in degrees of rotation, with 360 degrees representing one full cycle. As shown in figure 3-8 a start point is designated for any sine wave. The sine wave position and corresponding voltage can be expressed in degrees of rotation, or degrees of displacement from the starting point.

b. This alternating voltage can be readily produced by rotating generators, and in turn can be easily utilized by motors and other forms of rotating machinery. Single-phase power is used primarily in residential or limited commercial applications.

c. Most industrial or institutional systems utilize a three-phase power configuration. Three single-phase lines are used (A, B and C), and it is only when they are connected to an end use device, such as a motor or transformer that their relationships to each other become important. By convention, the individual phas-

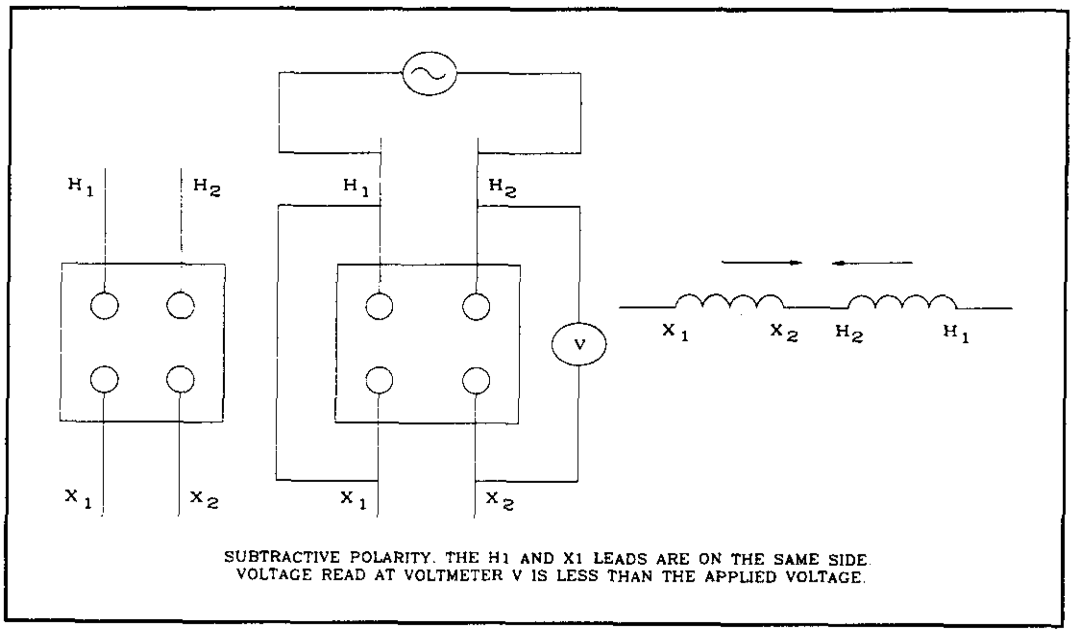

Figure 3-5. Transformer subtractive polarity test.

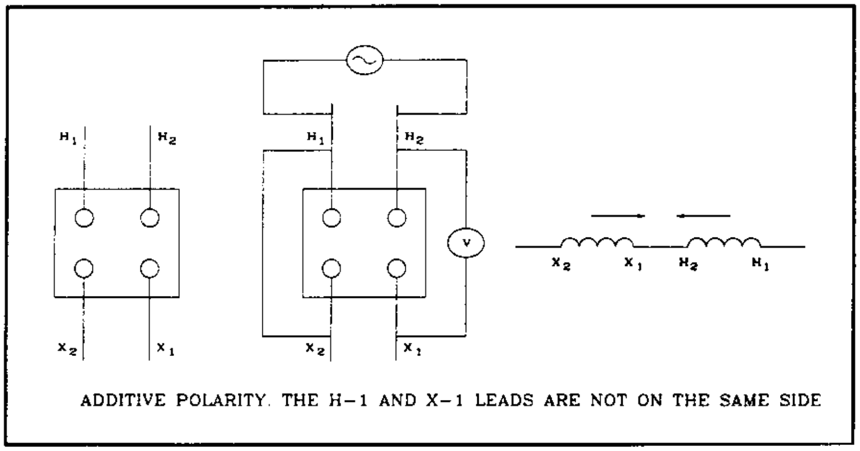

Figure 3–6. Transformer additive polarity test.

es of a three-phase distribution system are displaced 120 degrees (one third of a cycle) apart (see figure 3–9).

d. Rather than draw sine waves to show the position of the phases, the relative angular displacement (degrees ahead of or later than) is depicted by phasor diagrams. Phasor diagrams are convenient because they not only show the angular displacement, but they also show how the phases are physically connected. Transformer manufacturers use phasor diagrams on the nameplate of the transformer to indicate the connections and angular displacement of the primary and secondary phases (see figure 3–10). The polarity of three-phase transformers is determined both by where the leads are brought out of the transformer, and by the connection of the phases inside the tank. The two most common connections for three-phase transformers are delta and wye (star).

e. Delta and wye are the connections and relations of the separate phase on either the primary or the secondary windings. The basic three-phase transformer primary-to-secondary configurations are as follows:

–Delta-delta
–Delta-wye
–Wye-wye
–Wye-delta

f. These configurations can be obtained by connecting together three single-phase transformers or by combining three single-phase transformers in the same tank. There are many variations to these configurations, and the individual transformer's design and application criteria should be considered.

g. The wye connection is extremely popular for use on the secondary of substation transformers. By connecting the loads either phase-to-phase or phase-to-neutral, two secondary voltages can be obtained on the secondary. A common secondary voltage on many distribution transformers is 208/120V, with the 208V (phase-to-phase) connections being used to supply motors, and the 120V (phase-to-neutral) connections

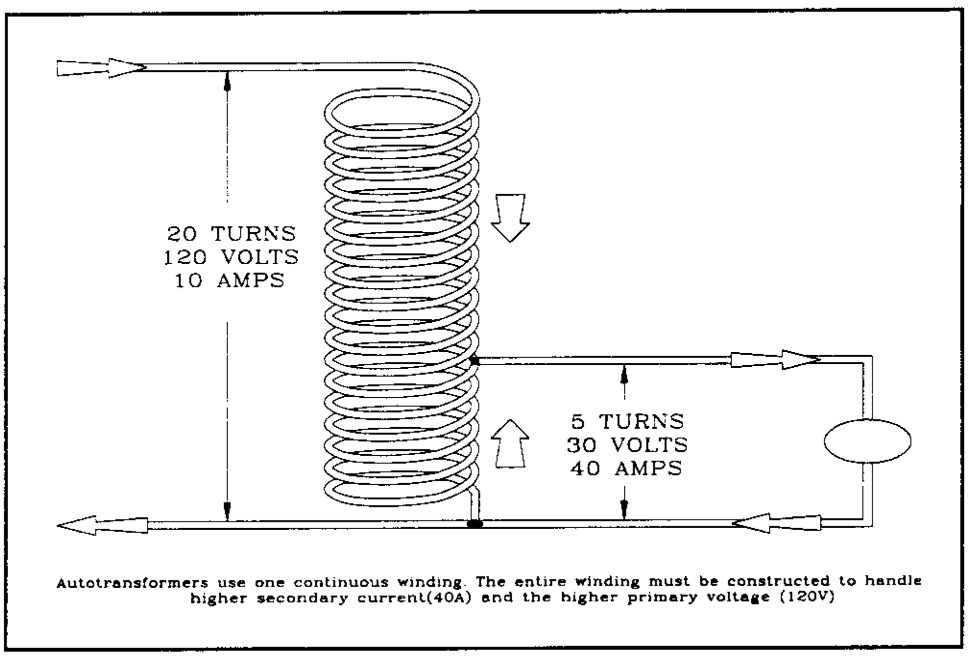

Figure 3–7. Autotransformer.