

TRANSFORMERS

INTRODUCTION

A transformer is a device that transfers electrical energy from one circuit to another by electromagnetic induction (also called transformer action). It is most often used to step up or step down voltage. Occasionally, it is used as an isolating device to eliminate a direct mechanical electrical connection between the power source and the loads. The electrical energy is always transferred without a change in frequency but may involve changes in the effective value of voltage and current. Because a transformer works on the principle of electromagnetic induction, it must be used with an input source that varies in amplitude.

Examining a very unusual transformer will show power is transferred through the use of electromagnetic induction. This direct current transformer will demonstrate the actions of a step-up transformer and provide stop-action analysis of the moving magnetic field. [Figure 8-1](#) shows a one-line diagram of the primary and secondary automobile ignition system. The primary circuit, or power source side, includes the battery positive terminal, the ignition switch, the primary winding to the ignition points, and the battery negative terminal. The secondary circuit starts with the secondary winding wire and connects the distributor rotor and the spark plug.

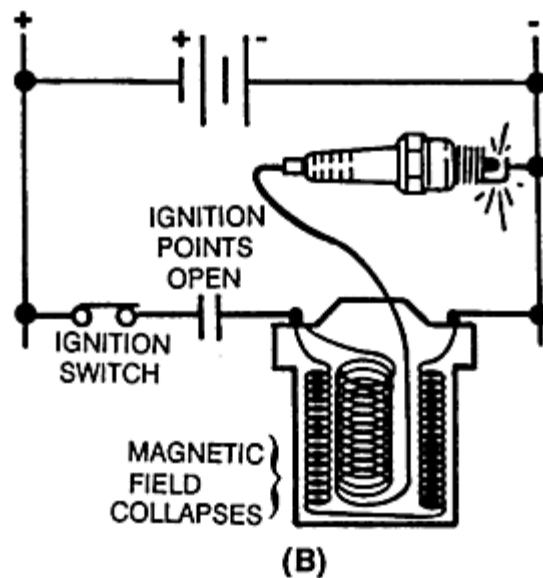
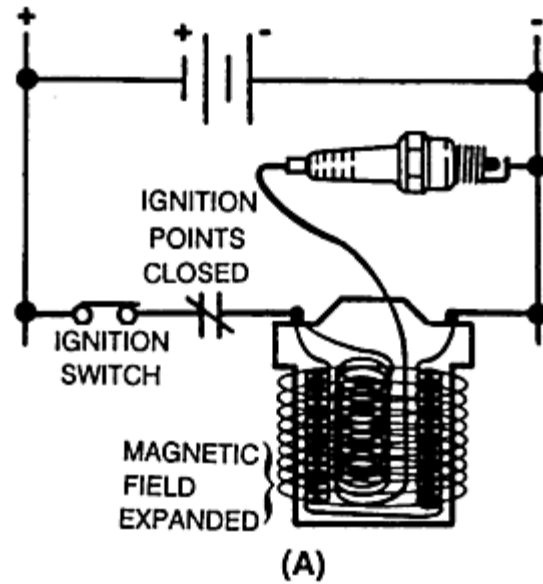


FIGURE 8-1. Automobile Step-Up Transformer.

When both the ignition switch and the points are closed, there is a complete circuit through the 12-volt battery terminals and the primary windings. As a current initially moves through the conductor, an expanding magnetic field is created. As the magnetic field from the primary winding expands across the secondary windings, a type of generator is created which produces an EMF in the secondary windings. Through electromagnetic induction, the secondary winding has all the necessities for generating an EMF a conductor (the secondary winding), the magnetic field (from the current flow

through the primary winding), and the relative motion between the expanding magnetic field and the secondary winding.

As the contact points open, the primary field collapses. With this collapse, there is again relative motion between the magnetic field and the secondary windings. This motion and the increased number of conductors in the secondary windings allow the coil to step up voltage from the original 12 volts to the 20,000 volts necessary to fire this type of ignition system.

The distributor, ignition points, and condenser that comprise this DC switching device are very costly. It is not very practical to use DC to step up voltage. AC has certain advantages over DC because it changes direction readily and has a constantly moving magnetic field. One important advantage is that when AC is used, the voltage and current levels can be increased or decreased by means of a transformer.

BASIC OPERATION OF A TRANSFORMER

The transformer circuit in [Figure 8-2](#) shows basic transformer action. The primary winding is connected to a 60 hertz AC source. The magnetic field (flux) expands and collapses about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an EMF into the winding. When a circuit is completed between the secondary winding and a load, this voltage causes current to flow. The voltage may be stepped up or down depending on the number of turns of conductor in the primary and secondary windings.

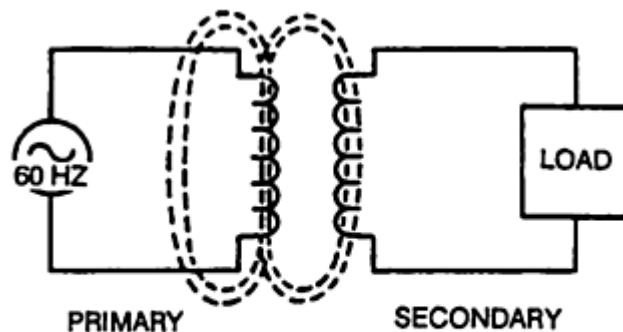


FIGURE 8-2. Basic Transformer Action.

The ability of a transformer to transfer power from one circuit to another is excellent. For marine engineering applications, the power loss is negligible. Power into the transformer is considered equal to power out. It is possible to increase, or step up, the voltage to loads with a subsequent reduction in current. The power formula ($P = I \times E$) demonstrates this phenomenon. The transformer is rated by power or VA for volts times amps. Transformers are rated more often in kVA for thousands of volt amps. The terms "step up" or "step down" refer to the actions of the voltage. A step-down transformer means that the voltage of the source has been reduced to a lesser value for the loads.

Examples of step-down transformers can be found on most Army watercraft. The ship service generator provides 450 VAC to the distribution system. The lighting panels and smaller motors require 115 VAC for a power supply. The ship's transformers step down the 450 volts to 115 volts. Although there is a lesser voltage in the load side than in the power supply side, the current in the load side will be greater than the current provided from the source side.

For example, if the ship service generator provides 450 VAC at 20 amperes to the primary winding of the transformer, the secondary winding of the transformer will provide 115 VAC at 78 amperes to the loads.

Primary (generator) side:

$$P = I \times E$$

$$P = 20 \text{ amps} \times 450 \text{ volts}$$

$$P = 9,000 \text{ VA (or 9kVA)}$$

Secondary (load) side:

$$P = I \times E \text{ or } I = \frac{P}{E}$$

$$I = \frac{9,000 \text{ VA}}{115 \text{ volts}}$$

$$I = 78 \text{ amps}$$

The conventional constant-potential transformer is designed to operate with the primary connected across a constant-potential source, such as the AC generator. It provides a secondary voltage that is substantially constant from no load to full load.

Transformers require little care and maintenance because of their simple, rugged, and durable construction.

APPLICATIONS

Various types of small single-phase transformers are used in electrical equipment. In many installations, transformers are used in switchboards to step down the voltage for indicating lights. Low-voltage transformers are included in some motor control panels to supply control circuits or to operate contractors and relays.

Instrument transformers include potential, or voltage, transformers and current transformers. Instrument transformers are commonly used with AC instruments when high voltages or large currents are to be measured.

TRANSFORMER COMPONENTS

The principle parts of a transformer and their functions are --

- The core, which provides a path for the magnetic lines of flux.
- The primary winding, which receives power from the AC power source.
- The secondary winding, which receives power from the primary winding and delivers it to the load.
- The enclosure, which protects the above components from dirt, moisture, and mechanical damage.

CORE CHARACTERISTICS

The composition of a transformer core depends on such factors as voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others. Generally, air-core transformers are used when the voltage source has a high frequency (above 20 kHz). Iron-core transformers are usually used when the source frequency is low (below 20 kHz). A soft-iron-core transformer is useful when the transformer must be physically small, yet efficient. The iron-core transformer provides better power transfer than does the air-core transformer. A transformer whose core is constructed of laminated sheets of steel dissipates heat readily, providing efficient transfer of power. Most transformers in the Army marine field contain laminated steel cores. These steel laminations ([Figure 8-3](#)) are insulated with a nonconducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick.

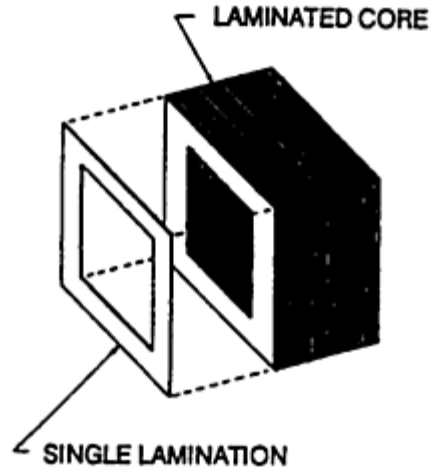


FIGURE 8-3. Hollow-Core Construction.

The laminations reduce certain losses which will be discussed later. The most effective transformer core is one that offers the best path for the most lines of flux with the least magnetic and electrical energy loss.

Two main shapes of cores are used in laminated steel-core transformers: the hollow core and the shell core.

The hollow core is shaped with a square through the center ([Figure 8-3](#)). The core is made up of many laminations of steel. [Figure 8-4](#) shows how the transformer windings are wrapped around both sides of the core.

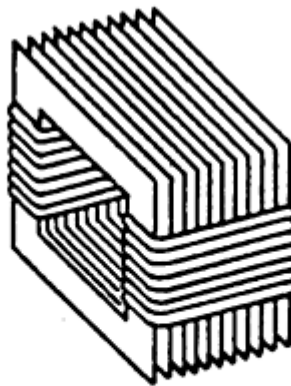


FIGURE 8-4. Windings Wrapped Around Laminations.

The shell core is the most popular and efficient transformer ([Figures 8-5 through 8-7](#)).

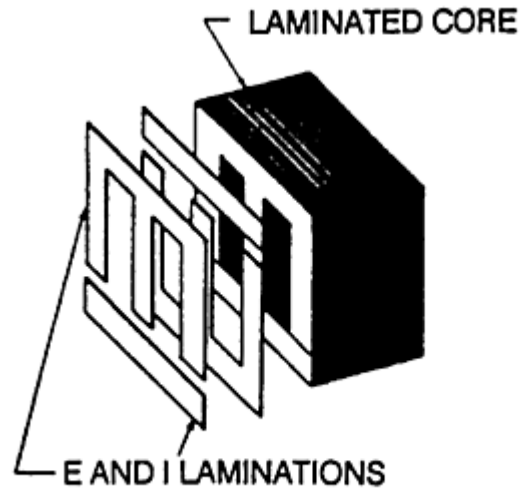


FIGURE 8-5. Shell-Type Core Construction.

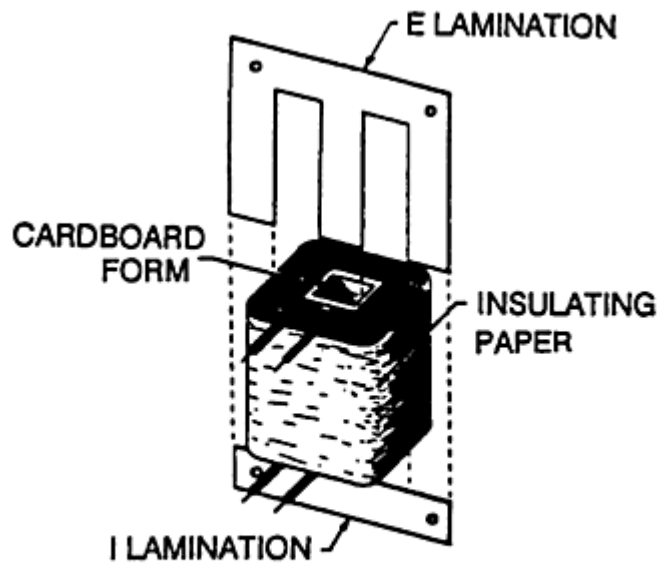


FIGURE 8-6. Exploded View of Shell-Type Transformer Construction.

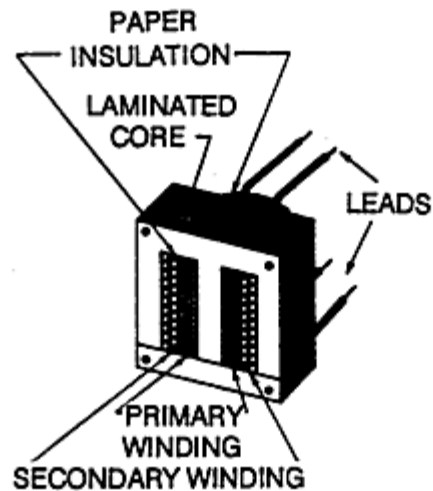


FIGURE 8-7. Cutaway View of Shell-Type Core With Windings.

As [shown](#), each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form laminations. The laminations are insulated from each other and then pressed together to form a core.

TRANSFORMER WINDINGS

Two wires called windings are wound around the core. Each winding is electrically insulated from the other. The terminals are marked according to the voltage: H indicates the higher voltage, and X indicates the lesser voltage. [Figure 8-8](#) shows examples of this.

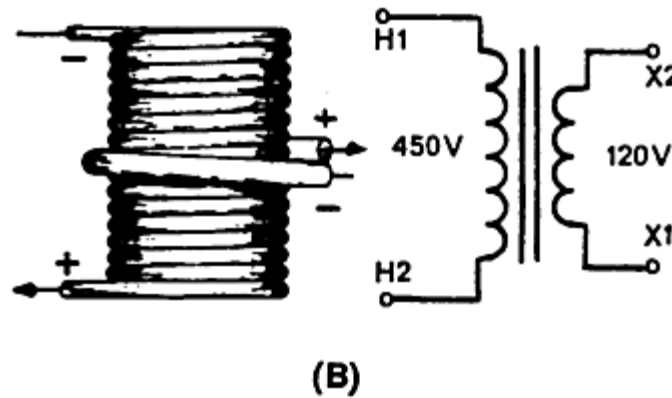
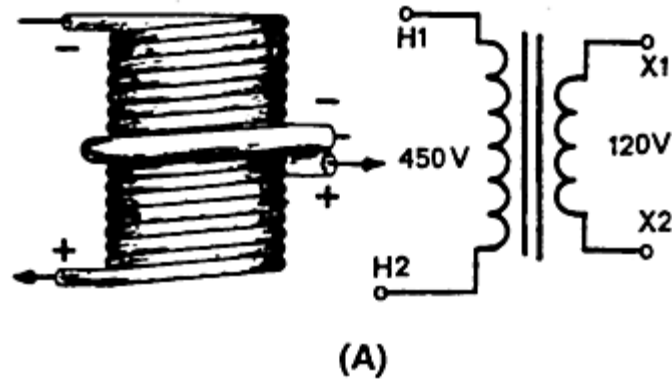


FIGURE 8-8. 450/120 Volt Step-Down Transformer.

Additionally, H1 and X1 indicate polarity. Since AC is constantly changing polarity, the H1 and X1 indicate that the polarities at both these terminals are identical during the same instant in time. At the same moment H1 has current moving through it in a given direction, the induced current through terminal X1 is moving in the same direction. When H1 and X1 are directly opposite each other, a condition known as subtractive polarity is formed ([Figure 8-9 view B](#)). When the H1 and the X1 are diagonally positioned, a condition known as additive polarity is formed ([view A](#)).

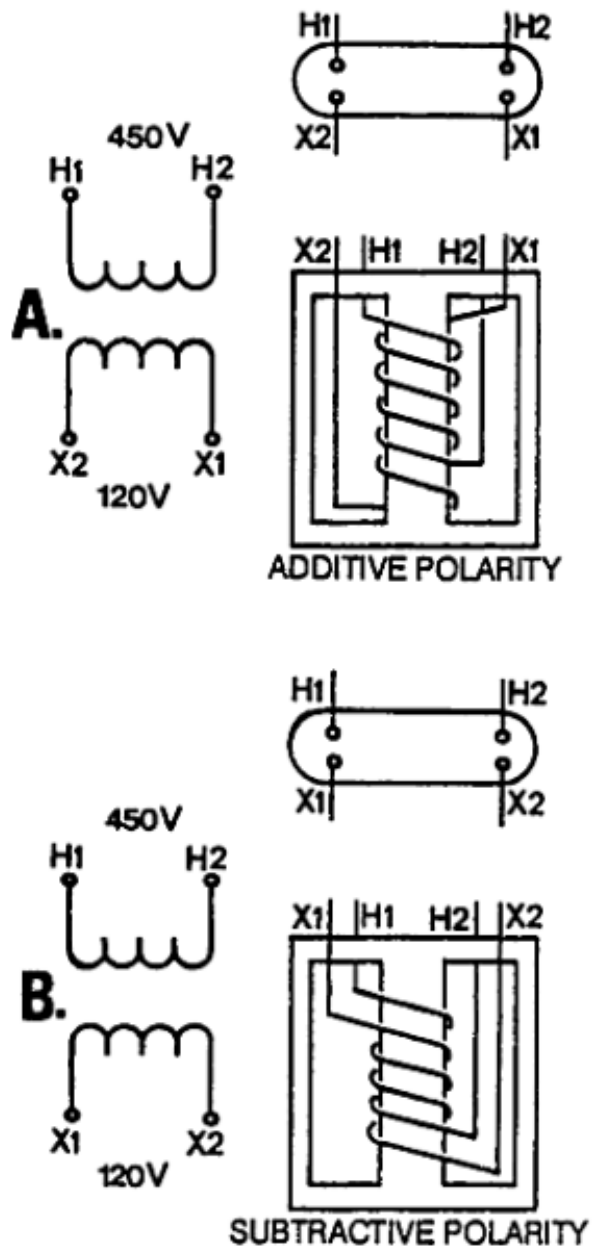


FIGURE 8-9. Polarity Markings for Large Transformers.

Another form of polarity marking is through the use of dots. Dot notation is used with diagrams to express which terminals are positive at the same instant in time ([Figure 8-10](#)).

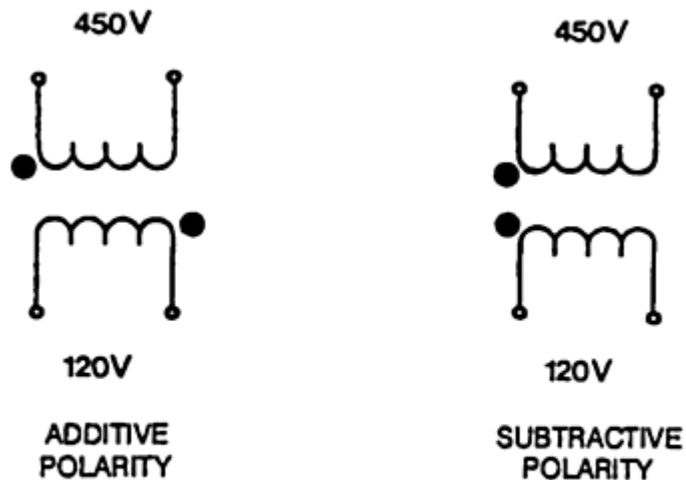


FIGURE 8-10. Instantaneous Polarity.

All transformers are not wired the same way, and improper connections can damage the entire electrical circuit. The terms "additive polarity" and "subtractive polarity" come from the means of testing unmarked transformers. Do not connect a transformer opposite to its intended purpose. Do not connect a step-down transformer for step-up application because the internal stresses set up within the transformer may damage it.

SCHEMATIC SYMBOLS FOR TRANSFORMERS

[Figure 8-11](#) shows typical schematic symbols for transformers. [View A](#) shows the symbol for an air-core transformer. [Views B](#) and [C](#) show iron-core transformers. The bars between the windings indicate an iron core. Frequently, additional connections are made to the transformer windings at points other than the ends of the windings. These additional connections are called taps. When a tap is connected to the center of the winding, it is called center tap. [View C](#) shows the schematic representation of a center-tapped iron-core transformer.

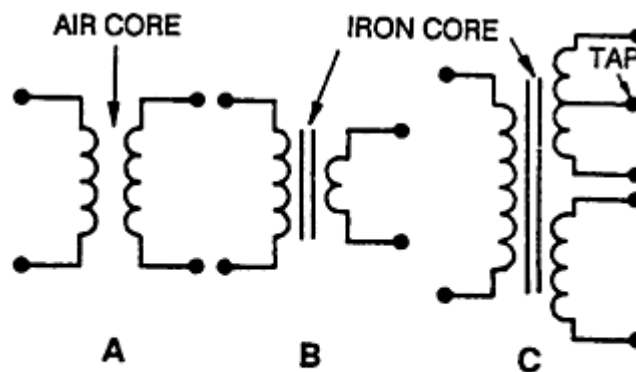


FIGURE 8-11. Schematic Symbols for Various Types of Transformers.

NO-LOAD CONDITION

A transformer can supply voltages that are usually higher or lower than the source voltage. This is done through mutual induction, which takes place when the changing magnetic field produced by the primary voltage cuts the secondary winding.

A no-load condition exists when a voltage is applied to the primary, but no load is connected to the secondary (Figure 8-12). Because of the open switch, there is no current flowing in the secondary winding. With the switch open and an AC voltage applied to the primary, there is, however, a very small amount of current, called exciting current, flowing in the primary. The exciting current "excites" the winding of the primary to create a magnetic field.

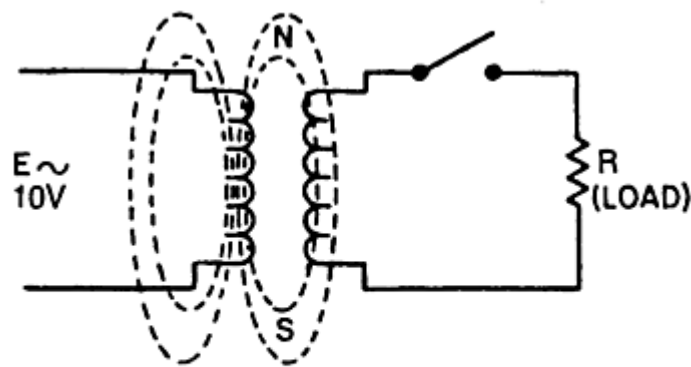


FIGURE 8-12. Transformer Under No-Load Conditions.

The amount of the exciting current is determined by three factors, which are all controlled by transformer action:

- The amount of voltage applied.
- The resistance of the primary winding's wire and core losses.
- The inductive reactance which depends on the frequency of the exciting current.

This very small amount of exciting current serves two functions:

- Most of the exciting energy is used to support the magnetic field of the primary.
- A small amount of energy is used to overcome the resistance of the wire and core. This is dissipated in the form of heat (power loss).

Exciting current will flow in the primary winding at all times to maintain this magnetic field, but no transfer of energy will take place as long as the secondary circuit is open.

WARNING

The open secondary leads provide a potential hazard to personnel. Should a path between the secondary leads develop, current will result. The soldier should never come in contact with the exposed secondary leads when the primary leads are energized.

COUNTER ELECTROMOTIVE FORCE

When an AC flows through a primary winding, a magnetic field is established around the winding. As the lines of flux expand outward, relative motion is present, and a counter EMF is induced in the winding. Flux leaves the primary at the north pole and enters the primary at the south pole. The CEMF induced in the primary has a polarity that opposes the applied voltage, thus opposing the flow of current in the primary. It is the CEMF that limits the exciting current to a very low value.

VOLTAGE IN THE SECONDARY

[Figure 8-12](#) shows a voltage is induced into the secondary winding of a transformer. As the exciting current flows through the primary, magnetic lines of force are generated. During this time, while current is increasing in the primary, magnetic lines of force expand outward from the primary and cut the secondary. A voltage is induced into a winding when magnetic lines cut across it. Therefore, the voltage across the primary causes a voltage to be induced across the secondary.

TURNS AND VOLTAGE RATIOS

The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary. [Figure 8-13 view A](#) shows a transformer whose primary consists of 10 turns of wire and whose secondary consists of a single turn of wire. As lines of flux generated by the primary expand and collapse, they cut both the 10 turns of the primary and the single turn of the secondary. Since the length of the wire in the secondary is about the same as the length of the wire in each turn of the primary, CEMF induced into the secondary will be the same as the EMF induced into each turn in the primary. This means that if the voltage applied to the primary winding is 10 volts, the CEMF in the primary is almost 10 volts. Thus, each turn in the primary will have an induced CEMF of about 1/10th of the total applied voltage, or 1 volt. Since the same flux lines cut the turns in both the secondary and the primary, each turn will have an EMF of 1 volt induced into it. The transformer in [Figure 8-13 view A](#) has only one turn in the secondary thus, the EMF across the secondary is 1 volt.

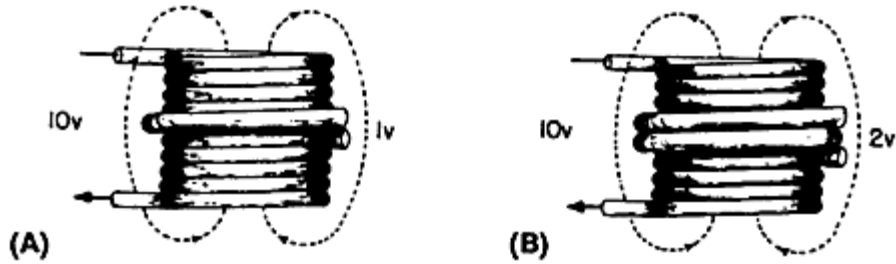


FIGURE 8-13. Transformer Turns and Voltage Ratios.

The transformer in [view B](#) has a 10-turn primary and a 2-turn secondary. Since the flux induces 1 volt per turn, the total voltage across the secondary is 2 volts. The volts per turn are the same for both the primary and secondary windings. Since the CEMF in the primary is equal (or almost equal) to the applied voltage, a proportion may be set up to express the value of the voltage induced in terms of the voltage applied to the primary and the number of turns in each winding. This proportion also shows the relationship between the number of turns in each winding and the voltage across each winding.

This proportion is expressed by the following equation:

$$\frac{E_s}{E_p} = \frac{N_s}{N_p}$$

Where: N_p = number of turns in the primary

E_p = voltage applied to the primary

E_s = voltage induced in the secondary

N_s = number of turns in the secondary

The [equation](#) shows that the ratio of secondary voltage to primary voltage equals the ratio of secondary turns to primary turns. The equation can be written as --

$$(E_p) \times (N_s) = (E_s) \times (N_p)$$

The following formulas are derived from the above [equation](#):

Transposing for E_s : $E_s = \frac{(E_p) \times (N_s)}{N_p}$

Transposing for E_p : $E_p = \frac{(E_s) \times (N_p)}{N_s}$

If any three quantities in the above [formulas](#) are known, the fourth quantity can be calculated.

Example: A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary. What is the voltage across the secondary (Es)?

Given:

$$N_p = 200 \text{ turns}$$

$$N_s = 50 \text{ turns}$$

$$E_p = 120 \text{ volts}$$

$$E_s = ?$$

Solution:

$$E_s = \frac{(E_p) \times (N_s)}{N_p}$$

Substitution:

$$E_s = \frac{(120 \text{ volts}) \times (50 \text{ turns})}{200 \text{ turns}}$$

$$E_s = 30 \text{ volts}$$

The transformer in the above [problem](#) has fewer turns in the secondary than the primary. As a result, there is less voltage across the secondary than across the primary. A transformer in which the voltage across the secondary is less than the voltage across the primary is called a step-down transformer. The ratio of a four-to-one step-down transformer is written 4:1. A transformer that has fewer turns in the primary than in the secondary will produce a greater voltage across the secondary than the voltage applied to the primary. A transformer in which the voltage across the secondary is greater than the voltage applied to the primary is called a step-up transformer. The ratio of a one-to-four step-up transformer is written as 1:4. In the two ratios, the value of the primary winding is always stated first.

EFFECT OF A LOAD

When an electrical load is connected across the secondary winding of a transformer, current flows through the secondary and the load. The magnetic field produced by the current in the secondary interacts with the magnetic field produced by the current in the

primary. This interaction results from the mutual inductance between the primary and secondary windings.

POWER RELATIONSHIP BETWEEN PRIMARY AND SECONDARY WINDINGS

The turns ratio of a transformer affects current as well as voltage. If voltage is doubled in the secondary, current is halved in the secondary. Conversely, if voltage is halved in the secondary, current is doubled in the secondary. In this manner, all the power delivered to the primary by the source is also delivered to the load by the secondary (minus whatever power is consumed by the transformer in the form of losses). In the transformer shown in [Figure 8-14](#), the turns ratio is 20:1. If the input to the primary is 10 amperes at 450 volts, the power in the primary is 4,500 watts ($P = I \times E$). If the transformer has no losses, 4,500 watts is delivered to the secondary. The secondary steps down the voltage to 22.5 volts and will increase the current to 200 amperes. Thus, the power delivered to the load by the secondary is $P = E \times I = 22.5 \text{ volts} \times 200 \text{ amps} = 4,500 \text{ watts}$.

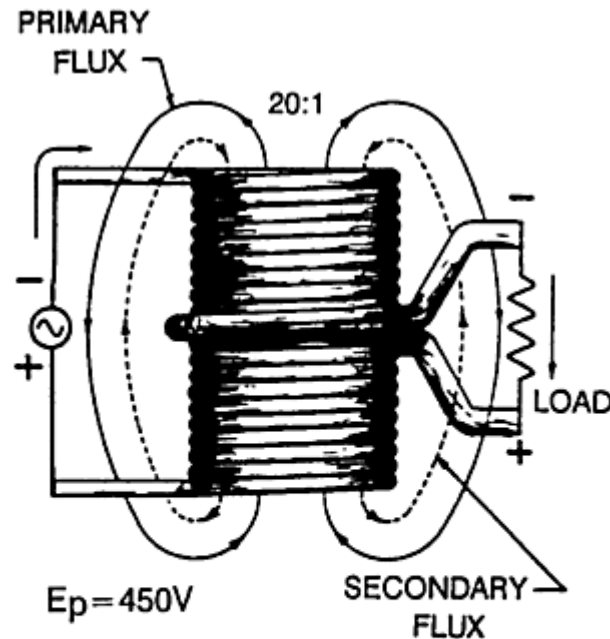


FIGURE 8-14. Simple Transformer Indicating Primary and Secondary Winding Flux Relationship.

The reason for this is that when the number of turns in the secondary is decreased, the opposition to the flow of the current is also decreased. Hence, more current will flow in the secondary. If the turns ratio of the transformer is increased to 1:2 (step up), the number of turns on the secondary is twice the number of turns on the primary. This means the opposition to current is doubled. Thus, voltage is doubled, but current is

halved due to the increased opposition to current in the secondary. With the exception of the power consumed within the transformer, all power delivered to the primary by the source will be delivered to the load. The form of the power may change, but the power in the secondary almost always equals the power in the primary. This can be expressed in the formula:

$$P_s = P_p - P_1$$

Where: P_s = power delivered to the load by the secondary

P_p = power delivered to the primary by the source

P_1 = power losses in the transformer

ACTUAL TRANSFORMER LOSSES

Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used with electrical components have an 80 to 90 percent efficiency range, while large distribution system transformers may have efficiencies exceeding 98 percent.

The total power loss in a transformer is a combination of losses. One loss is due to the resistance in the conductors of the primary and secondary windings. This loss is called copper loss or I^2R loss. As current increases through the resistance of the conductor, there is a drop in voltage proportional to the increase in current flow. This phenomenon is found wherever there is a resistance. Ohm's Law shows this.

Example: The initial electrical load demands 10 amperes. The resistance in the transformer winding conductor is .4 ohms. The voltage drop across the winding conductor is 4 volts.

$$E = I \times R$$

$$E = 10 \text{ amps} \times .4 \text{ ohms}$$

$$E = 4 \text{ volts}$$

If the electrical demand is increased and a current of 70 amperes is now required, the voltage drop across the winding conductor will increase.

$$E = I \times R$$

$$E = 70 \text{ amps} \times .4 \text{ ohms}$$

$$E = 28 \text{ volts}$$

As current flow increases, there is a resulting increase in heat. The resistance of copper increases as current and temperature increase. This further affects the voltage drop. This makes secondary voltage decrease as load is applied.

Whenever current flows in a conductor, power is dissipated in the resistance of the conductor in the form of heat. The amount of power dissipated by the conductor is directly proportional to the resistance of the wire and to the square of the current through it.

The greater the value of either the current or the resistance, the greater the power dissipated.

$$P = I \times E$$

$$P = 70 \text{ amps} \times 28 \text{ volts}$$

$$P = 1,960 \text{ watts}$$

or

$$P = I^2 \times R$$

$$P = 70^2 \text{ amps} \times .4 \text{ ohms}$$

$$P = 4,900 \text{ amps} \times .4 \text{ ohms}$$

$$P = 1,960 \text{ watts}$$

This is the power consumed or lost due to the resistance of the conductor.

The resistance of a given conductor or winding is a function of the diameter of the conductor and its length. Large diameter, lower resistance wire is required for high-current-carrying applications whereas small diameter, higher resistance wire can be used for low-current-carrying applications.

Two other losses are due to eddy currents and hysteresis in the core of the transformer. Copper loss, eddy current loss, and hysteresis loss result in undesirable conversion of electrical energy to heat energy.

Eddy Current Loss

The core of a transformer is usually constructed of some type of ferromagnetic material because it is a good conductor of magnetic lines of flux.

Whenever the primary of an iron-core transformer is energized by an AC source, a fluctuating magnetic field is produced. This magnetic field cuts the conducting core

