A. Fundamental Principles of Transformers

1. Purpose

   a. The purpose of a transformer is to transfer energy from one circuit to another. Transformers raise voltage to the very high levels required for transmission and lower voltage levels suitable for a variety of plant and customer needs. A transformer can process very small or very large amounts of power economically with very little power lost in the process.

   b. In the early days of the electrical power industry, central DC power plants were used and there was no known way to change voltage once it was generated. The power was generated at a voltage just a little higher than the 240/120 volts needed for home and industrial loads. A higher voltage was not used due to the insulation requirements for high voltage circuits. Because of voltage drop in transmission lines, the station could supply only those customers near the station. To see why, recall that it takes one volt to force one ampere through one ohm of any kind of opposition. Therefore, to deliver 1 kw at 100 vdc, 10 amperes must flow. For every ohm of opposition encountered 10 volts will be lost in transmission. Voltage had to remain fairly low, due to insulation difficulty. As a result, a higher load demand needed higher current flow in the transmission lines. As current flow in the transmission line doubled, power lost due to transmission resistance (I^2R) quadrupled. Thus, as electrical demand increased, many neighborhood DC generators had to be built. Power distribution was inefficient.

   c. Fortunately, the transformer was invented for AC power. With it, alternating electrical energy could be transferred from one circuit to another, raising or lowering voltage as necessary (Picture 1). Because most wire between a generating station and the system load carries high

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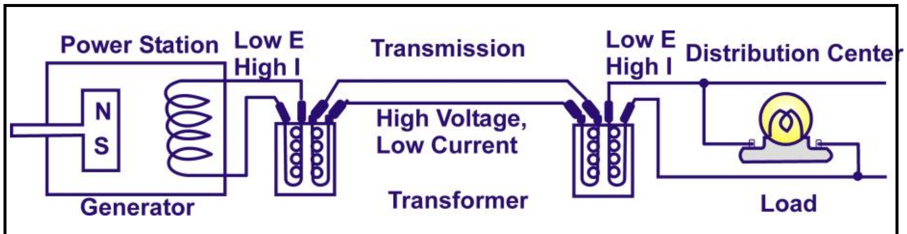
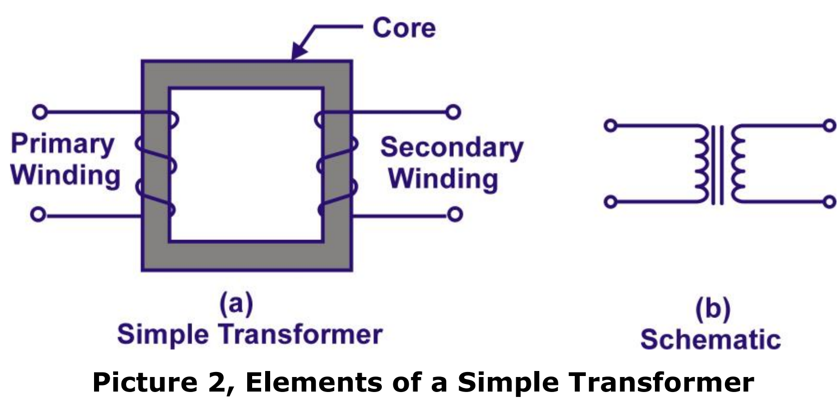
voltage and low current, I^2R losses are greatly reduced. Transformers can be made to economically handle very large amounts of power with very little power loss.



Picture 1, Basic AC Power Distribution

2. Basic Principles of Operation

   a. The operation of a transformer uses the principle of mutual electromagnetic induction. Changing magnetic field produced by alternating current in one inductor induces voltage in nearby inductors. The coil producing the original magnetic field is the primary winding, and the coil into which voltage is induced is the secondary winding. The windings are insulated from each other and may be wound around a common iron core. A simple transformer and its schematic symbol is shown in Picture 2.



Picture 2, Elements of a Simple Transformer

   b. When current flows in the primary winding, it generates a magnetic field. Because the applied alternating current is constantly building up,

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collapsing, and changing direction, the magnetic field of the primary winding is constantly changing. The effect is relative motion between the magnetic field and the secondary winding. This induces voltage in the secondary winding. If the secondary circuit is closed, current will flow due to induced voltage.

c. When the primary windings of a transformer are energized, an opposition voltage is induced in the windings equal to the applied voltage. The voltage induced in each primary winding is the induced voltage divided by the number of windings, or E_p/N_p. Because the same magnetic flux cutting the primary windings also cuts the secondary windings, the same voltage is induced in each secondary winding. The total induced secondary voltage would be the induced voltage per winding (E_p/N_p) times the number of secondary windings (N_s). This is shown in the equation below.

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

OR

$$\frac{E}{N_P} = \frac{E_S}{N_S}$$

Where:

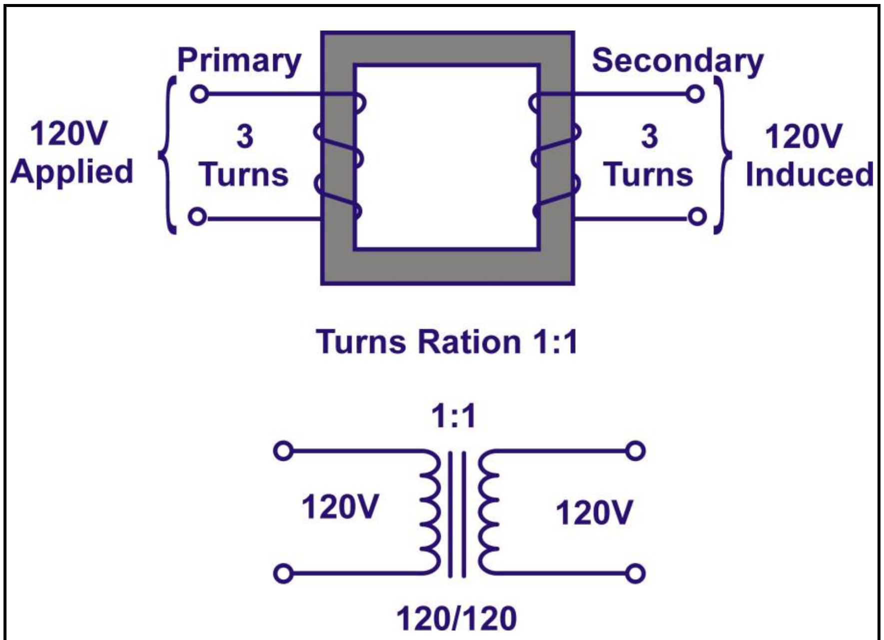
E_p is the voltage applied to the primary

N_p is the number of turns in the primary winding

E_s is the induced secondary voltage

N_s is the number of turns in the secondary winding.

d. If the transformer has the same number of turns on the primary and secondary windings, the induced secondary voltage will be the same as the applied primary voltage (Picture 3). The transformer shown has a turns ratio of one to one. The first number always refers to the primary and second number refers to the secondary. This type of transformer is commonly referred to as an isolation transformer, as the voltage characteristics are not changed but secondary circuit problems (e.g., grounds) are not reflected in the primary circuit. Observe that both windings are of equal voltage in an isolation transformer.



Picture 3, Isolation Transformer

e. If the number of secondary windings is more than the number of primary windings, the lines of flux will cut more coils in the secondary. Therefore, higher voltage will be induced into secondary windings. This type of arrangement has higher turns ratio than the isolation transformer and is called a Step-up Transformer. The transformer shown in Picture 4 has 3 turns in its primary winding and 6 turns in its secondary, resulting in a

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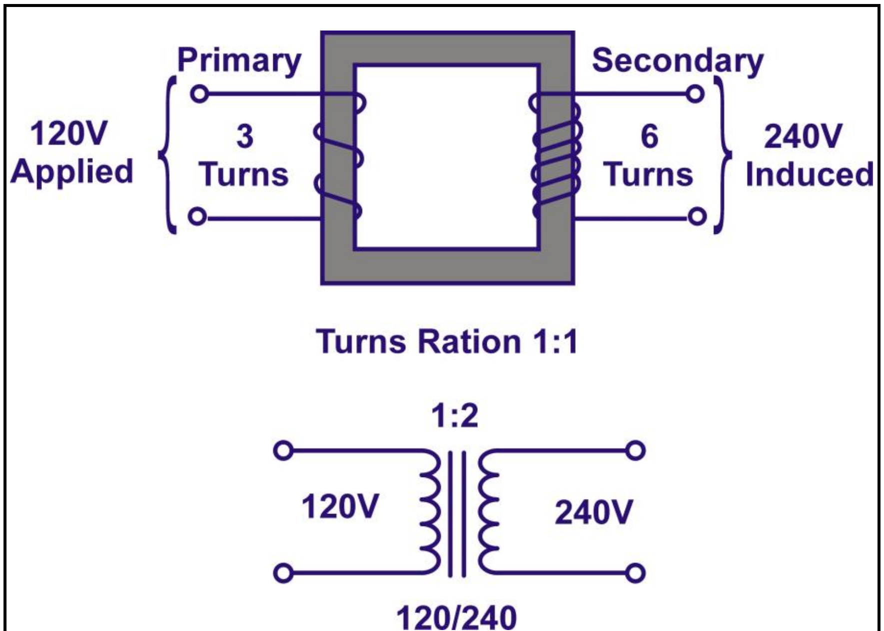
turns ratio of 1 to 2. Notice that the induced secondary voltage is twice that of primary input voltage.



Picture 4, Step-Up Transformer

f. Example: An AC generator applies 18,000 volts to the primary of its output transformer. The transformer has 200 turns in its primary winding and is supposed to step up the voltage to 345,000 volts. Find the number of turns required in the secondary winding.

g. Answer:

$$\frac{18{,}000}{200} = \frac{345{,}000}{N_S}$$

$$N_S = \frac{345{,}000 \text{ x } 200}{18{,}000}$$

$$N_S = 3833 \text{ turns}$$

h. Conversely, if there are fewer secondary windings than primary windings, less voltage will be induced than is applied. A transformer with a turns ratio greater than one is called a step-down transformer (Picture 5).

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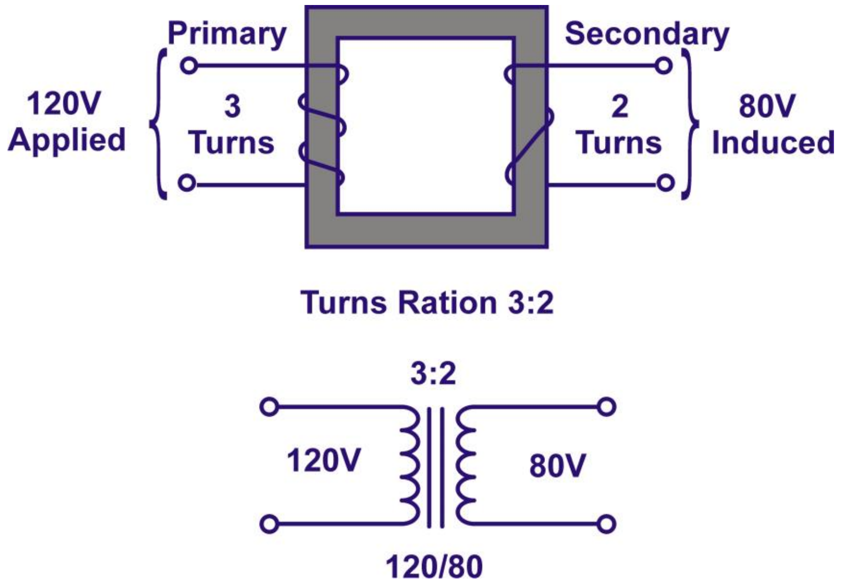

Picture 5, Step-Down Transformer

i. Example: A transformer has 4000 volts applied to its primary and a turns ratio of 50 to 3. What is the secondary voltage of the transformer?

j. Answer:

$$E_S = \frac{E_P N_S}{N_P}$$

$$E_S = \frac{40,000 \text{ x } 3}{50}$$

$$E_S = 240 \text{ volts}$$

3. Power and Efficiency

a. To transmit a given amount of power, less current is required at a high voltage than a low voltage. Energy may be transmitted with less I^2R (or line) loss when high transmission voltages are used. In order to obtain high transmission voltage (e.g., 345,000 or 765,000 volts), step-up transformers are used at the generating stations. Generators are not designed to produce voltages this high due to enormous insulation requirements. At points where electricity is used, step-down

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transformers are installed to reduce the high transmission voltage to safe, usable values. Since transformer efficiency is high, 98% to 99% at full load and larger sizes, the energy produced by the generator has been economically transmitted over a long distance.

4. Rating

a. Transformer capacity is rated in apparent power (volt-amperes). An output rating for a transformer is based on the maximum current the transformer can carry without exceeding design temperature limits. Because power in an AC circuit depends on the power factor of the load as well as real current flowing, the output rating in watts would have to be at some specified power factor. Power factor changes continuously as a consequence of changing the system load profile. For this reason, transformers, and AC machines in general, are rated in volt-amperes, independent of power factor.

b. Data other than KVA ratings commonly found on transformer name plates include voltage ratings of both the primary and secondary windings, rated frequency, impedance drop expressed as a percentage of rated voltage, and a connection diagram.

B. Types of Transformers

1. Two Types of Transformer in Common Use

a. When the magnetic circuit takes the form of a single ring encircled by two or more groups of primary and secondary windings distributed around the periphery of the ring, the transformer is termed a “core-type transformer”. When the primary and secondary windings take the form of a common ring which is encircled by two or more rings of magnetic material distributed around it’s periphery, the transformer is termed a “shell-type transformer”.

b. Actually, “core-type” (or “core-form”) in US power-transformer engineering usage means that the coils are cylindrical and concentric (the outer winding over the inner) whereas “shell-type” (or “form”) denotes large pancake coils which are stacked or interleaved to make primary-secondary (P-S) groups.

2. Power Transformers

a. A power transformer is used when transmission of electrical energy is required with a minimum loss of power. This type of transformer can be quite large with ratings in the hundreds of thousands of volt-amperes. The step up and step down transformers previously discussed are examples of power transformers.

3. Instrument Transformers

a. To safely connect instruments, meters, and control devices directly to high-voltage and/or high current circuits, an instrument transformer is used. Instrument transformers are universally used to reduce high voltages and currents to safe and usable values. These transformers perform two functions. They act as ratio devices, making possible the use of standardized low-voltage and low- current meters and instruments used in control rooms, load dispatch offices, and other places. They also act as insulating devices to protect instruments and operating personnel from high voltages. Two kinds of instrument transformers are potential and current transformers. Picture 6 shows a potential transformer (PT) and a current transformer (CT) connected to a high voltage circuit. Together they feed a watt meter (Wm).

b. Potential transformers supply voltage to meters, instruments, or control devices which have a definite ratio to line voltage. The potential transformer operates on the same principle as a power transformer. When the primary winding is connected across a voltage, a current sets

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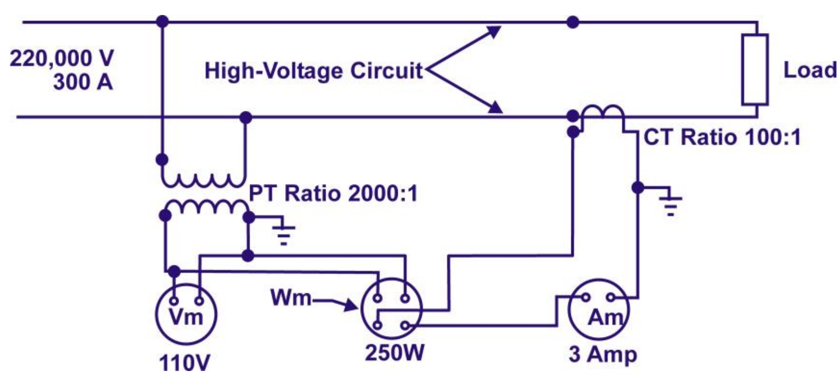
up flux in the core. Flux linking the secondary winding induces an emf that is proportional to the ratio of primary to secondary turns. Potential transformers usually have a rated secondary voltage of 115 or 120 v. Most meters are rated for those voltages. A voltage as high as 765 Kv is applied to the primary winding. Since the amount of load supplied by the potential transformer is small (a couple of voltage meters and maybe a watt meter), volt-ampere ratings are small, normally between 50 and 200 VA. Picture 6 shows a potential transformer with a turns ratio of 2000:1 supplying a voltmeter and a watt meter. Meter faces indicate the high voltage and power of the high voltage circuit even though a smaller proportional value is applied to the meter.

c. A current transformer reduces line current to values that may be used to operate standard low- current measuring and control devices. These devices must be completely insulated from the main circuits. If a current meter (ammeter) were to be connected directly to the circuit, it would have to be inserted in-series with the high voltage circuit. This means that all of the current in the circuit would have to pass through the ammeter. In high power lines this could mean thousands of amperes, which would require large conductors with sufficient cooling to be routed to the meter. This would be impractical for control room or other remote ammeters. The current transformer is used in conjunction with current measuring devices such as ammeters. The primary winding is designed to be connected in series with the high power line. It is, therefore, necessary that the impedance of the primary winding be made as low as possible. This is done by using a few turns of low resistance wire (the bus bar is the primary winding for many installations) capable of carrying rated line current.

d. Because a current transformer is used to decrease current, the secondary contains more turns than the primary. Ratio of primary to secondary current is inversely proportional to ratio of primary to secondary turns. Picture 6 shows a current transformer connected to a high voltage circuit. Because impedance of the primary is very low, very little voltage will be dropped across the primary. Thus, induced current in the secondary will be low and voltage drop in the high voltage circuit line be negligible.



Picture 6, Instrument Transformer Connection

C. In Summary

a. The basic transformer consists of a highly permeable core with a primary and secondary coil wrapped around it. When alternating current is passed through the primary winding, an alternating magnetic field is established around the winding. This magnetic field is concentrated by the core such that most of the field cuts across the windings of the secondary coil. This induced voltage varies with the ration of turns between the primary and secondary windings.

b. An ideal transformer has 100% transfer of power (no losses). The apparent power of the primary is equal to the apparent power of the secondary. Most transformers are rated in apparent power since it is total current flow (both real and reactive) that produces heat in a transformer.

c. Transformers are very efficient with some larger transformers approaching 98% efficiency. However, due to magnitude of power involved in a large power transformer, even small losses result in large quantities of heat. The transformer is designed to minimize losses.

d. Transformers play a key role in distribution and use of electrical energy produced by generators. Transformers are unique in that they require very little maintenance or operator action. Normally the transformer, results could be far reaching and costly.

PRACTICE:

1 What is the basic principle of operation of a transformer?

2. The primary of a transformer has 500 turns and an input voltage of 100 vac. The secondary has 2000 turns. What is the output voltage of the secondary?

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