DOE Fundamentals

ELECTRICAL SCIENCE

Module 13

Transformers

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REFERENCES

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OBJECTIVES

TERMINAL OBJECTIVE

1.0 Given the type of a transformer, **DESCRIBE** the operating characteristics and applications for that transformer type.

ENABLING OBJECTIVES

1.1 **DEFINE** the following terms as they pertain to transformers:

a. Mutual induction

b. Turns ratio

c. Impedance ratio

d. Efficiency

1.2 **DESCRIBE** the differences between a wye-connected and delta-connected transformer.

1.3 Given the type of connection and turns ratios for the primary and secondary of a transformer, **CALCULATE** voltage, current, and power for each of the following types:

a. Δ - Δ

b. Δ - Y

c. Y - Δ

d. Y - Y

1.4 **STATE** the applications of each of the following types of transformers:

a. Distribution

b. Power

c. Control

d. Auto

e. Isolation

f. Instrument potential

g. Instrument current

TRANSFORMER THEORY

Transformers are used extensively for AC power transmissions and for various control and indication circuits. Knowledge of the basic theory of how these components operate is necessary to understand the role transformers play in today's nuclear facilities.

EO 1.1 DEFINE the following terms as they pertain to transformers:

a. Mutual induction

b. Turns ratio

c. Impedance ratio

d. Efficiency

EO 1.2 DESCRIBE the differences between a wye-connected and delta-connected transformer.

EO 1.3 Given the type of connection and turns ratios for the primary and secondary of a transformer, CALCULATE voltage, current, and power for each of the following types:

a. Δ - Δ

b. Δ - Y

c. Y - Δ

d. Y - Y

Mutual Induction

If flux lines from the expanding and contracting magnetic field of one coil cut the windings of another nearby coil, a voltage will be induced in that coil. The inducing of an EMF in a coil by magnetic flux lines generated in another coil is called *mutual induction.* The amount of electromotive force (EMF) that is induced depends on the relative positions of the two coils.

Turns Ratio

Each winding of a transformer contains a certain number of turns of wire. The *turns ratio* is defined as the ratio of turns of wire in the primary winding to the number of turns of wire in the secondary winding. Turns ratio can be expressed using Equation (13-1).

$$\text{Turns Ratio} = \frac{N_P}{N_S} \tag{13-1}$$

where

N_P = number of turns on the primary coil

N_s = number of turns on the secondary coil

The coil of a transformer that is energized from an AC source is called the primary winding (coil), and the coil that delivers this AC to the load is called the secondary winding (coil) (Figure 1).

Impedance Ratio

Maximum power is transferred from one circuit to another through a transformer when the impedances are equal, or matched. A transformer winding constructed with a definite turns ratio can perform an impedance matching function. The turns ratio will establish the proper relationship between the primary and secondary winding impedances. The ratio between the two impedances is referred to as the *impedance ratio* and is expressed by using Equation (13-2).

$$\left(\frac{N_P}{N_S}\right)^2 = \frac{Z_P}{Z_S} \tag{13-2}$$

Another way to express the impedance ratio is to take the square root of both sides of Equation (13-2). This puts the ratio in terms of the turns ratio, which is always given for a transformer.

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}}$$

where

N_P = number of turns in the primary

N_S = number of turns in the secondary

Z_P = impedance of primary

Z_S = impedance of secondary

Efficiency

Efficiency of a transformer is the ratio of the power output to the power input, as illustrated by Equation (13-3).

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}} = \frac{P_S}{P_P} \text{ X } 100 \qquad (13\text{-}3)$$

where

P_S = power of secondary

P_P = power of primary

Theory of Operation

A transformer works on the principle that energy can be transferred by magnetic induction from one set of coils to another set by means of a varying magnetic flux. The magnetic flux is produced by an AC source.

The coil of a transformer that is energized from an AC source is called the primary winding (coil), and the coil that delivers this AC to the load is called the secondary winding (coil) (Figure 1).

In Figure 1, the primary and secondary coils are shown on separate legs of the magnetic circuit so that we can easily understand how the transformer works. Actually, half of the primary and secondary coils are wound on each of the two legs, with sufficient insulation between the two coils and the core to properly insulate the windings from one another and the core. A transformer wound, such as in Figure 1, will operate at a greatly reduced efficiency due to the magnetic leakage. Magnetic leakage is the part of the magnetic flux that passes through either one of the coils, but not through both. The larger the distance between the primary and secondary windings, the longer the magnetic circuit and the greater the leakage.

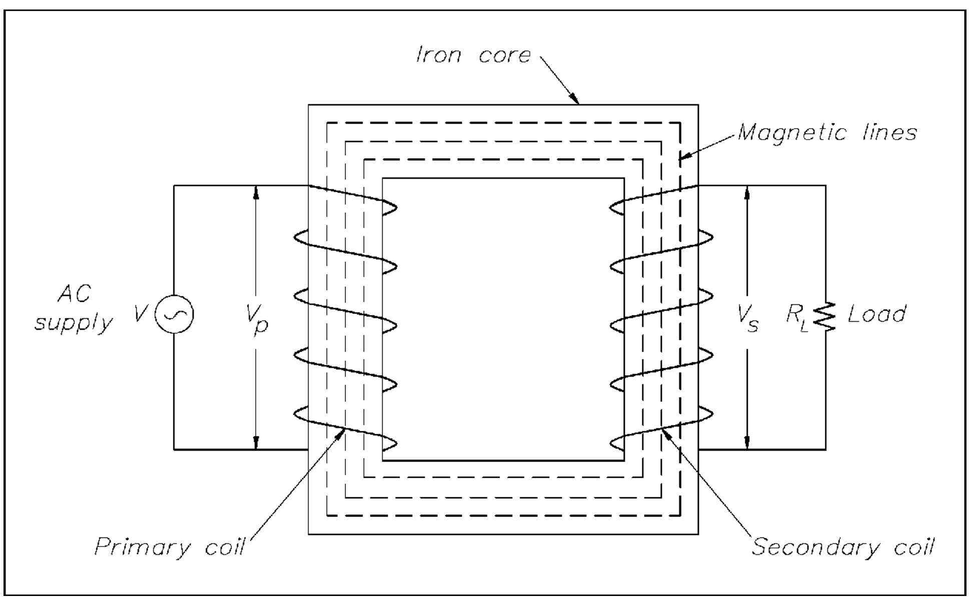

Figure 1 Core-Type Transformer

When alternating voltage is applied to the primary winding, an alternating current will flow that will magnetize the magnetic core, first in one direction and then in the other direction. This alternating flux flowing around the entire length of the magnetic circuit induces a voltage in both the primary and secondary windings. Since both windings are linked by the same flux, the voltage induced per turn of the primary and secondary windings must be the same value and same direction. This voltage opposes the voltage applied to the primary winding and is called counter-electromotive force (CEMF).

Voltage Ratio

The voltage of the windings in a transformer is directly proportional to the number of turns on the coils. This relationship is expressed in Equation (13-4).

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \qquad (13\text{-}4)$$

where

V_P = voltage on primary coil

V_S = voltage on secondary coil

N_P = number of turns on the primary coil

N_S = number of turns on the secondary coil

The ratio of primary voltage to secondary voltage is known as the *voltage ratio* (VR). As mentioned previously, the ratio of primary turns of wire to secondary turns of wire is known as the turns ratio (TR). By substituting into the Equation (13-4), we find that the voltage ratio is equal to the turns ratio.

VR = TR

A voltage ratio of 1:5 means that for each volt on the primary, there will be 5 volts on the secondary. If the secondary voltage of a transformer is greater than the primary voltage, the transformer is referred to as a "step-up" transformer. A ratio of 5:1 means that for every 5 volts on the primary, there will only be 1 volt on the secondary. When secondary voltage is less than primary voltage, the transformer is referred to as a "step-down" transformer.

Example 1: A transformer (Figure 2) reduces voltage from 120 volts in the primary to 6 volts in the secondary. If the primary winding has 300 turns and the secondary has 15 turns, find the voltage and turns ratio.

Solution:

$$VR = \frac{V_P}{V_S} = \frac{120}{6} = \frac{20}{1} = 20:1$$

$$TR = \frac{N_P}{N_S} = \frac{300}{15} = \frac{20}{1} = 20:1$$

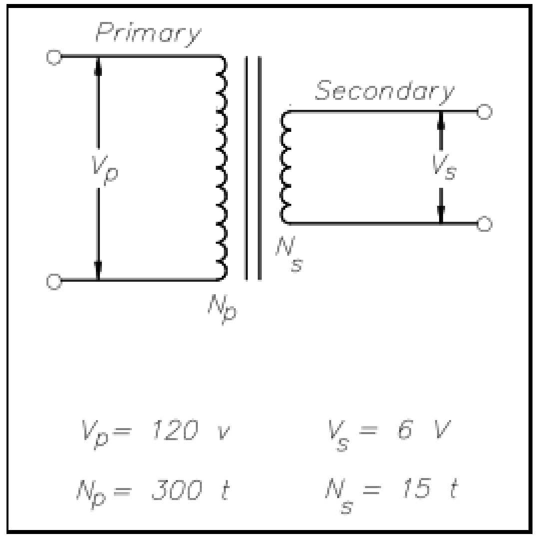

Figure 2 Example 1 Transformer

Example 2: An iron core transformer with a primary voltage of 240 volts has 250 turns in the primary and 50 turns in the secondary. Find the secondary voltage.

Solution:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

Next, solve for V_S.

$$V_S = \frac{N_S}{N_P} V_P$$

$$V_S = \frac{50}{250} 240 \text{ volts}$$

$$V_S = 48 \text{ volts}$$

Example 3: A power transformer has a turns ratio of 1:4. If the secondary coil has 5000 turns and secondary voltage is 60 volts, find the voltage ratio, V_P, and N.

Solution:

$$VR = TR$$

$$VR = 1:4$$

$$\frac{V_P}{V_S} = VR = 1:4 = \frac{1}{4}$$

$$V_P = \frac{1}{4} V_S = \frac{60}{4} = 15 \text{ volts}$$

$$TR = \frac{N_P}{N_S} = \frac{1}{4}$$

$$N_P = \frac{1}{4} N_S = \frac{5000}{4} = 1250 \text{ turns}$$

Current Ratio

The current in the windings of a transformer is inversely proportional to the voltage in the windings. This relationship is expressed in Equation (13-5).

$$\frac{V_P}{V_S} = \frac{I_S}{I_P} \qquad (13\text{-}5)$$

where

I_P = primary coil current

I_S = secondary coil current

Since the voltage ratio is equal to the turns ratio, we can express the current ratio in terms of the turns ratio, as in Equation (13-6).

$$\frac{N_P}{N_S} = \frac{I_S}{I_P} \qquad (13\text{-}6)$$

Example 1: When operated at 120 V in the primary of an iron core transformer, the current in the primary is 4 amps. Find the current in the secondary if the voltage is stepped up to 500 V.

Solution:

$$\frac{V_P}{V_S} = \frac{I_S}{I_P}$$

Next, we solve for I_s

$$I_S = \frac{V_P}{V_S} I_P$$

$$I_S = \frac{120}{500}\ 4\ \text{amps}$$

$$I_S = 0.96\ \text{amps}$$

Example 2: A transformer with 480 turns on the primary and 60 turns on the secondary draws 0.6 amps from a 120 V line. Find I_s.

Solution:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$I_S = \frac{N_P}{N_S} I_P$$

$$I_S = \frac{480}{60}\ 0.6\ \text{amps}$$

$$I_S = 4.8\ \text{amps}$$

The student should note from the previous examples that a transformer that "steps-up" voltage, "steps-down" the current proportionally.

Three-Phase Transformer Connections

So far, our discussion has dealt with the operation of single-phase transformers. Three-phase transformer operation is identical except that three single-phase windings are used. These windings may be connected in wye, delta, or any combination of the two.

Delta Connection

In the delta connection, all three phases are connected in series to form a closed loop (Figure 3).

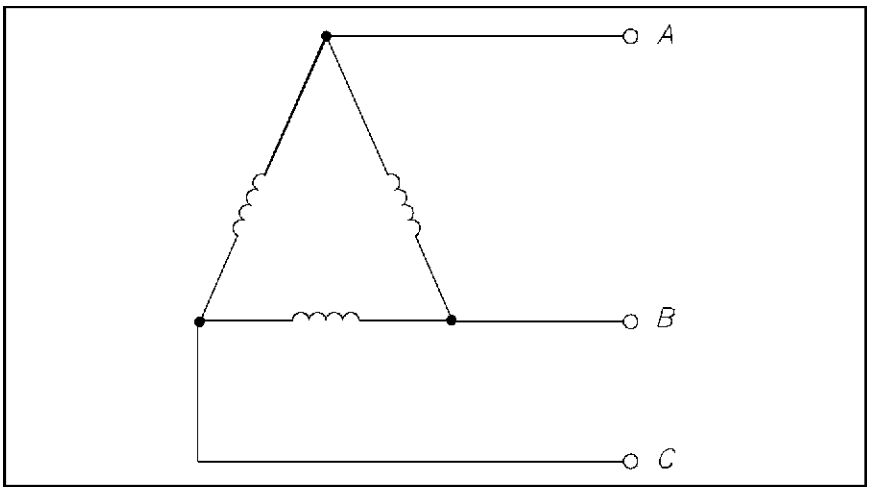

Figure 3 Delta Connection

Wye Connection

In the wye connection, three common ends of each phase are connected together at a common terminal (marked "N" for neutral), and the other three ends are connected to a three-phase line (Figure 4).

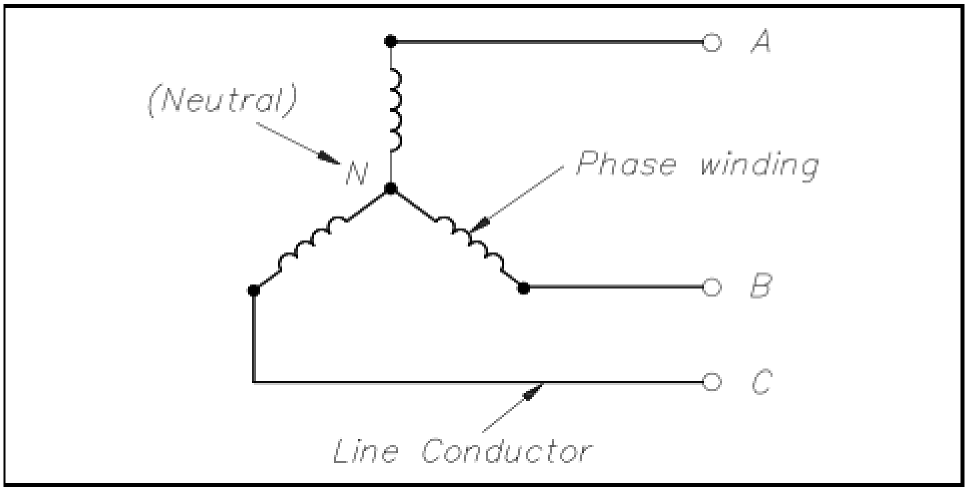

Figure 4 Wye Connection

Combinations of Delta and Wye Transformer Connections

A three-phase transformer may have three separate but identical single-phase (4) transformers or a single 34 unit containing three-phase windings. The transformer windings may be connected to form a 34 bank in any of four different ways (Figure 5).

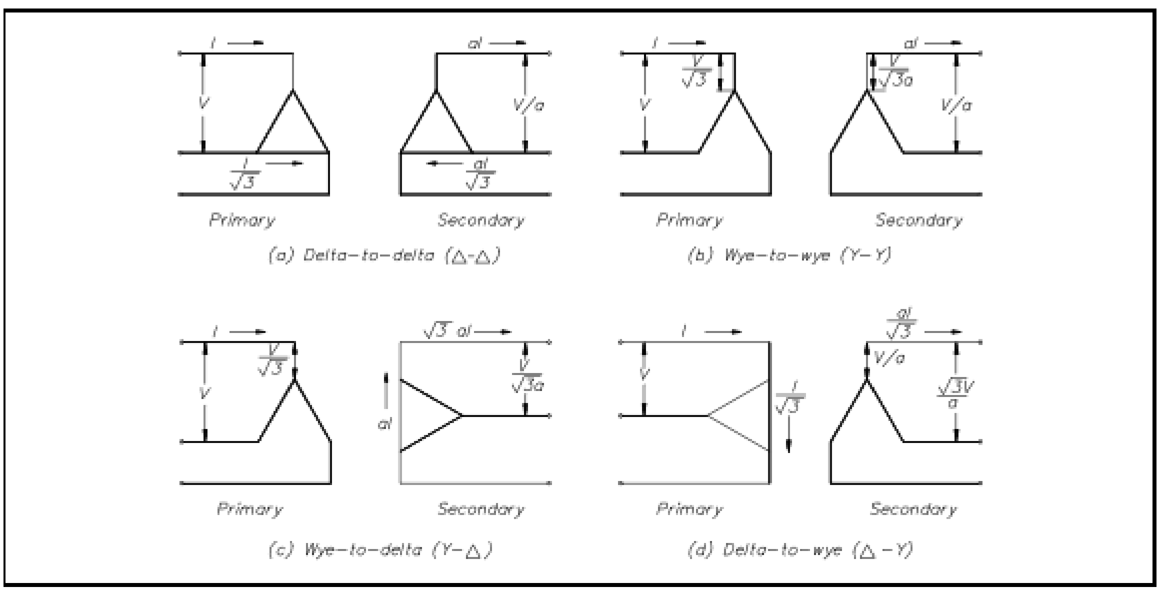

Figure 5: 3Φ Transformer Connections

Figure 5 shows the voltages and currents in terms of applied line voltage (V) and line current (I), where the turns ratio (a) is equal to one. Voltage and current ratings of the individual transformers depend on the connections (Figure 5) and are indicated by Table 1 for convenience of calculations.

TABLE 1: Voltage and Current Ratings of Transformers

Transformer Connection (Primary to Secondary)	Primary				Secondary			
	Line		Phase		Line		Phase	
	Volt.	Current	Volt.	Current	Volt. *	Current	Volt.	Current
Δ-Δ	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{V}{a}$	aI	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$
Y-Y	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{a}$	aI	$\frac{V}{\sqrt{3}\,a}$	aI
Y-Δ	V	I	$\frac{V}{\sqrt{3}}$	I	$\frac{V}{\sqrt{3}\,a}$	$\sqrt{3}\,aI$	$\frac{V}{\sqrt{3}\,a}$	aI
Δ-Y	V	I	V	$\frac{I}{\sqrt{3}}$	$\frac{\sqrt{3}\,V}{a}$	$\frac{aI}{\sqrt{3}}$	$\frac{V}{a}$	$\frac{aI}{\sqrt{3}}$

*$a = N_1/N_2$; $\sqrt{3} = 1.73$

Example 1: If line voltage is 440 V to a 34 transformer bank, find the voltage across each primary winding for all four types of transformer connections.

$$\Delta - \Delta\text{: primary voltage} = V = 440\text{ volts}$$

$$Y - Y\text{: primary voltage} = \frac{V}{\sqrt{3}} = \frac{440}{1.73} = 254.3\text{ volts}$$

$$Y - \Delta\text{: primary voltage} = \frac{V}{\sqrt{3}} = \frac{440}{1.73} = 254.3\text{ volts}$$

$$\Delta - Y\text{: primary voltage} = V = 440\text{ volts}$$

Example 2: If line current is 10.4 A in a 3Φ transformer connection, find the primary phase current.

$$\Delta - \Delta\text{: primary phase current} = \frac{I}{\sqrt{3}} = \frac{10.4}{1.73} = 6\text{ amps}$$

$$Y - Y\text{: primary phase current} = I = 10.4\text{ amps}$$

$$Y - \Delta\text{: primary phase current} = I = 10.4\text{ amps}$$

$$\Delta - Y\text{: primary phase current} = \frac{I}{\sqrt{3}} = \frac{10.4}{1.73} = 6\text{ amps}$$

Example 3: Find the secondary line current and phase current for each type of transformer connection, if primary line current is 20 amps, and the turns ratio is 4:1.

$$\Delta - \Delta\text{: } \mathit{secondary\ line\ current} = 4\,(20) = 80\ \mathit{amps}$$

$$\text{secondary phase current} = \frac{\text{aI}}{\sqrt{3}} = \frac{4\,(20)}{1.73} = 46.2\ \text{amps}$$

$$\text{Y} - \text{Y: secondary line current} = \text{aI} = 4\,(20) = 80\ \text{amps}$$

$$\text{secondary phase current} = \text{aI} = 4\,(20) = 80\ \text{amps}$$

$$\text{Y} - \Delta\text{: secondary line current} = \sqrt{3}\,\text{aI} = (1.73)(4)(20) = 138.4\ \text{amps}$$

$$\text{secondary phase current} = \text{aI} = (4)(20) = 80\ \text{amps}$$

$$\Delta - \text{Y: secondary line current} = \frac{\text{aI}}{\sqrt{3}} = \frac{4\,(20)}{1.73} = 46.2\ \text{amps}$$

$$\text{secondary phase current} = \frac{\text{aI}}{\sqrt{3}} = \frac{4\,(20)}{1.73} = 46.2\ \text{amps}$$

Transformer Losses and Efficiency

All transformers have copper and core losses. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the windings. Copper loss, in watts, can be found using Equation (13-7).

$$\text{Copper Loss} = I_P^2 R_P + I_S^2 R_s \qquad (13\text{-}7)$$

where

I_P = primary current

I_s = secondary current

R_p = primary winding resistance

R_s = secondary winding resistance

Core losses are caused by two factors: hysteresis and eddy current losses. Hysteresis loss is that energy lost by reversing the magnetic field in the core as the magnetizing AC rises and falls and reverses direction. Eddy current loss is a result of induced currents circulating in the core.

The efficiency of a transformer can be calculated using Equations (13-8), (13-9), and (13-10).

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}} = \frac{P_S}{P_P} \times 100 \qquad (13\text{-}8)$$

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Output} + \text{Copper Loss} + \text{Core Loss}} \text{ x } 100 \qquad (13\text{-}9)$$

$$\text{Efficiency} = \frac{V_S I_S \text{ x PF}}{(V_S I_S \text{ x PF}) + \text{Copper Loss} + \text{Core Loss}} \text{ x } 100 \qquad (13\text{-}10)$$

where

PF = power factor of the load

Example 1: A 5:1 step-down transformer has a full-load secondary current of 20 amps. A short circuit test for copper loss at full load gives a wattmeter reading of 100 W. If $R_P = 0.3\Omega$, find R_s and power loss in the secondary.

Solution:

Copper Loss = $I_P^2 R_P + I_s R_s$ = 100 W

To find I_P:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$I_S = \frac{N_P}{N_S} I_P = \frac{1}{5} \text{ x } 20 = 4 \text{ amps}$$

To find R_s:

$$I_S^2 R_S = 100 - I_P^2 R_P$$

$$R_S = \frac{100 - I_P^2 R_P}{I_S^2} = \frac{100 - 0.3\,(4)^2}{20^2} = 0.24\,\Omega$$

$$\text{Power loss in secondary} = I_S^2 R_S = (20)^2 (0.24) = 96 \text{ W}$$

Example 2: An open circuit test for core losses in a 10 kVA transformer [Example (1)] gives a reading of 70 W. If the PF of the load is 90%, find efficiency at full load.

Solution:

$$\text{Efficiency} = \frac{V_S I_S \text{ x PF}}{(V_S I_S \text{ x PF}) + \text{Copper Loss} + \text{Core Loss}} \text{ x } 100$$

$$V_S I_S = \text{Transformer Rating} = 10 \text{ kVA} = 10{,}000 \text{ VA}$$

$$\text{PF} = 0.90;\ \text{Copper Loss} = 100 \text{ W};\ \text{Core Loss} = 70 \text{ W}$$

$$\text{Eff.} = \frac{10{,}000\,(0.90)}{10{,}000\,(0.90) + 100 + 70} \text{ x } 100 = \frac{9000}{9170} \text{ x } 100 = 98.2\%$$

Transformer Operation Under No-Load

If the secondary of a transformer is left open-circuited (Figure 6), primary current is very low and is called the *no-load current.* No-load current produces the magnetic flux and supplies the hysteresis and eddy current losses in the core. The no-load current (I_E) consists of two components: the magnetizing current (I_m) and the core loss (I_H). Magnetizing current lags applied voltage by 90°, while core loss is in phase with the applied voltage (Figure 6b). V_P and V_S are shown 180° out of phase. $\mathbf{I_H}$ is very small in comparison with I_m, and I_m is nearly equal to $\mathbf{I_E}$**.** No-load current, I_E is also referred to as exciting current.

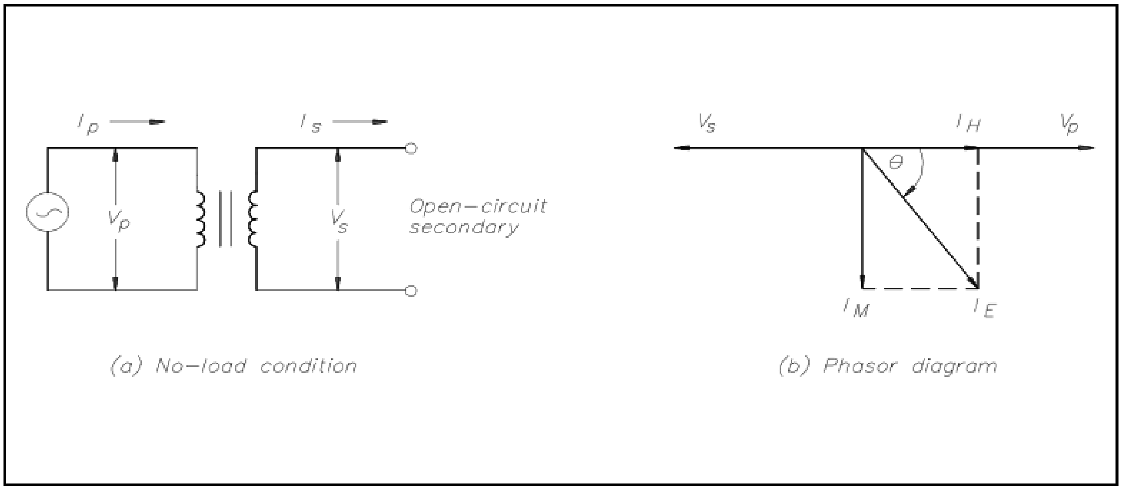

Figure 6 Open-Circuit Secondary

Example: When the secondary of a 120/440 V transformer is open, primary current is 0.2 amps at a PF of 0.3. The transformer is a 5 kVA transformer. Find: (a) I_P, (b) I_E (c) I_H, and (d) I_M.

(a) $\text{Full Load Current} = \frac{\text{kVA Rating}}{V_P}$

(b) I_P at no − load is equal to I_E $\quad I_E = 0.2\ \text{amp}$

(c) $I_H = I_E \cos\Theta = I_E\ \text{PF} = 0.2\ (0.3) = 0.06\ \text{amp}$

(d) $I_M = I_E \sin\Theta$

$$\Theta = \arccos 0.3 = 72.5^o$$

$$I_M = (0.2) \sin 72.5^o = (0.2)(0.95) = 0.19\ \text{amp}$$

Coil Polarity

The symbol for a transformer gives no indication of the phase of the voltage across the secondary. The phase of that voltage depends on the direction of the windings around the core. In order to solve this problem, polarity dots are used to show the phase of primary and secondary signals. The voltages are either in phase (Figure 7a) or 180° out of phase with respect to primary voltage (Figure 7b).

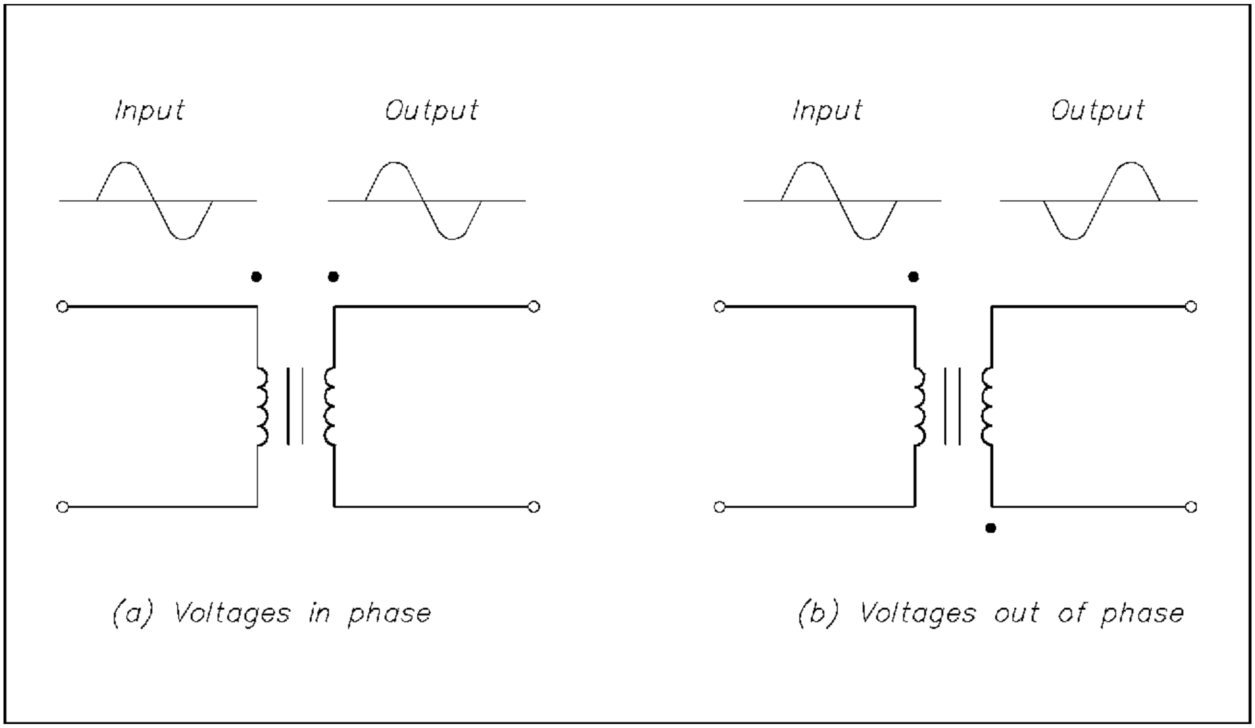

Figure 7 Polarity of Transformer Coils

Summary

The important information covered in this chapter is summarized below.

Transformer Theory Summary

- The induction of an EMF in a coil by magnetic flux lines generated in another coil is called mutual induction.
- The turns ratio is defined as the ratio of turns of wire in the primary winding to the number of turns of wire in the secondary winding.
- The ratio between the primary and secondary impedances is referred to as the impedance ratio.
- Efficiency of a transformer is the ratio of the power output to the power input.
- In a delta connection, all three phases are connected in series to form a closed loop.
- In a wye connection, three common ends of each phase are connected together at a common terminal, and the other three ends are connected to a three-phase line.
- In a Δ connected transformer:

$$V_L = V_\Phi$$

$$I_L = \sqrt{3}\, I_\Phi$$

- In a Y connected transformer:

$$I_L = \sqrt{3}\, V_\Phi$$

$$I_L = I_\Phi$$

TRANSFORMER TYPES

Transformers can be constructed so that they are designed to perform a specific function. A basic understanding of the various types of transformers is necessary to understand the role transformers play in today's nuclear facilities.

EO 1.4 **STATE** the applications of each of the following types of transformers:

a. Distribution
b. Power
c. Control
d. Auto
e. Isolation
f. Instrument potential
g. Instrument current

Types of Transformers

Transformers are constructed so that their characteristics match the application for which they are intended. The differences in construction may involve the size of the windings or the relationship between the primary and secondary windings. Transformer types are also designated by the function the transformer serves in a circuit, such as an isolation transformer.

Distribution Transformer

Distribution transformers are generally used in electrical power distribution and transmission systems. This class of transformer has the highest power, or volt-ampere ratings, and the highest continuous voltage rating. The power rating is normally determined by the type of cooling methods the transformer may use. Some commonly-used methods of cooling are by using oil or some other heat-conducting material. Ampere rating is increased in a distribution transformer by increasing the size of the primary and secondary windings; voltage ratings are increased by increasing the voltage rating of the insulation used in making the transformer.

Power Transformer

Power transformers are used in electronic circuits and come in many different types and applications. Electronics or power transformers are sometimes considered to be those with ratings of 300 volt-amperes and below. These transformers normally provide power to the power supply of an electronic device, such as in power amplifiers in audio receivers.

Control Transformer

Control transformers are generally used in electronic circuits that require constant voltage or constant current with a low power or volt-amp rating. Various filtering devices, such as capacitors, are used to minimize the variations in the output. This results in a more constant voltage or current.

Auto Transformer

The auto transformer is generally used in low power applications where a variable voltage is required. The auto transformer is a special type of power transformer. It consists of only one winding. By tapping or connecting at certain points along the winding, different voltages can be obtained (Figure 8).

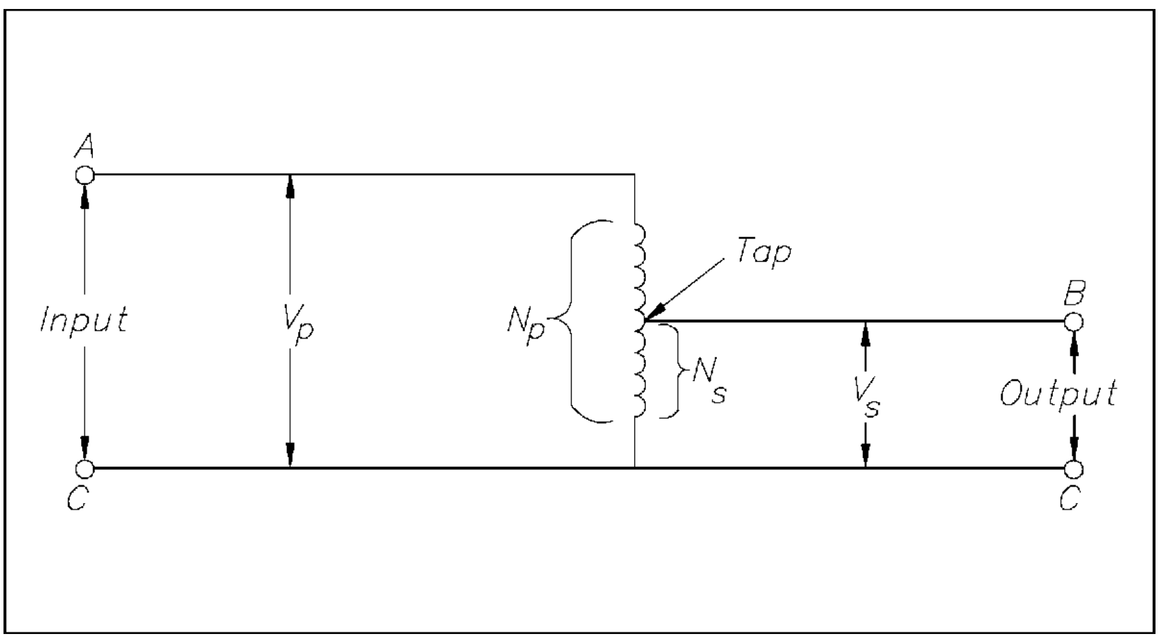

Figure 8 Auto Transformer Schematic

Isolation Transformer

Isolation transformers are normally low power transformers used to isolate noise from or to ground electronic circuits. Since a transformer cannot pass DC voltage from primary to secondary, any DC voltage (such as noise) cannot be passed, and the transformer acts to isolate this noise.

Instrument Potential Transformer

The instrument potential transformer (PT) steps down voltage of a circuit to a low value that can be effectively and safely used for operation of instruments such as ammeters, voltmeters, watt meters, and relays used for various protective purposes.

Instrument Current Transformer

The instrument current transformer (CT) steps down the current of a circuit to a lower value and is used in the same types of equipment as a potential transformer. This is done by constructing the secondary coil consisting of many turns of wire, around the primary coil, which contains only a few turns of wire. In this manner, measurements of high values of current can be obtained.

A current transformer should always be short-circuited when not connected to an external load. Because the magnetic circuit of a current transformer is designed for low magnetizing current when under load, this large increase in magnetizing current will build up a large flux in the magnetic circuit and cause the transformer to act as a step-up transformer, inducing an excessively high voltage in the secondary when under no load.

Summary

The important information covered in this chapter is summarized below.

Transformer Types Summary

- Distribution transformers are generally used in power distribution and transmission systems.
- Power transformers are used in electronic circuits and come in many different types and applications.
- Control transformers are generally used in circuits that require constant voltage or constant current with a low power or volt-amp rating.
- Auto transformers are generally used in low power applications where a variable voltage is required.
- Isolation transformers are normally low power transformers used to isolate noise from or to ground electronic circuits.
- Instrument potential and instrument current transformers are used for operation of instruments such as ammeters, voltmeters, watt meters, and relays used for various protective purposes.