

Basics of Electricity

Transformer Theory

PJM State & Member Training Dept.

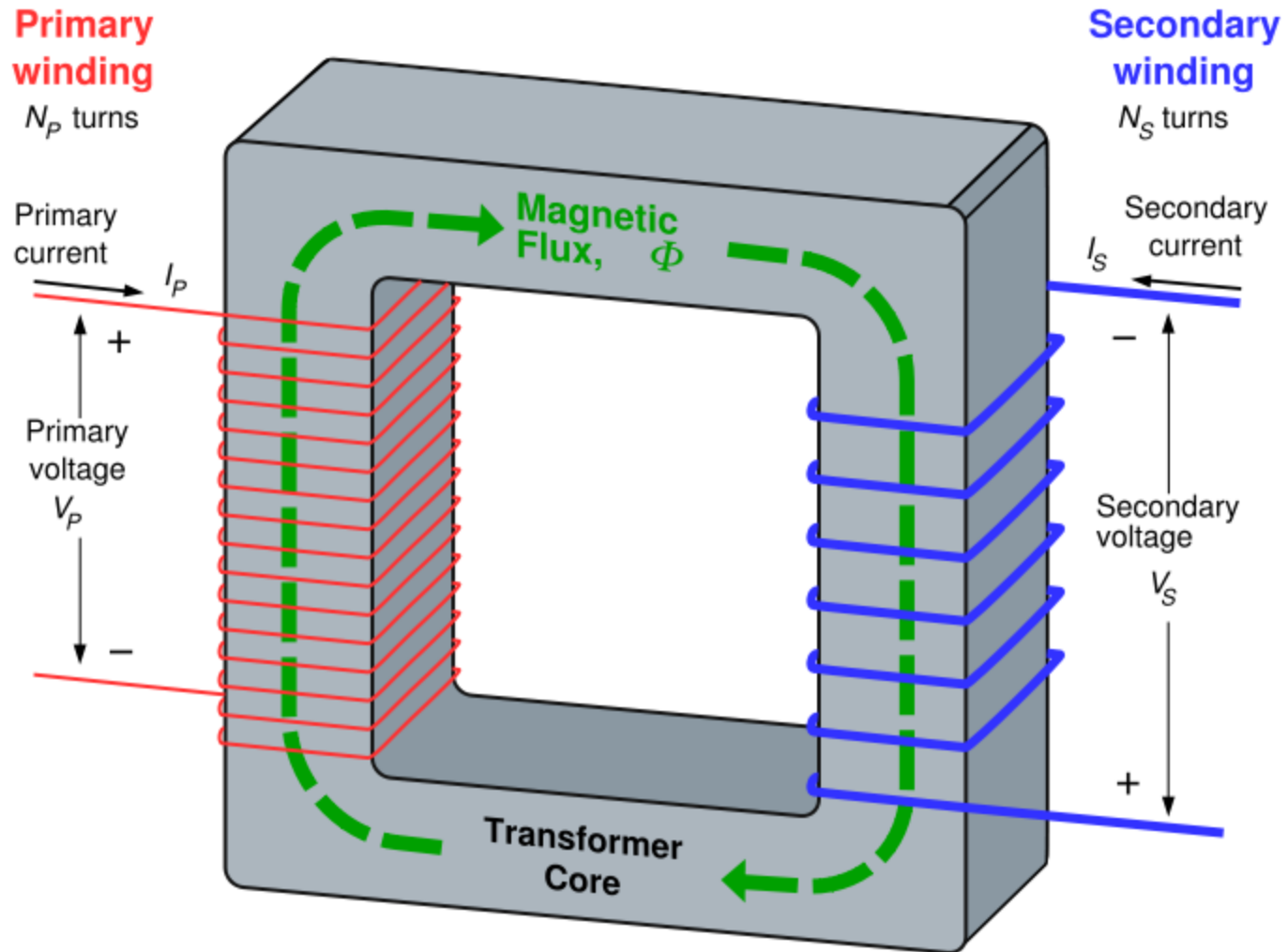
At the end of this presentation the Student will be able to:

- Describe the basic operational theory of transformers
- Interpret the formula for turns ratio
- Describe transformer efficiency and losses
- Describe transformer tap changers
- Classify the different types of transformers

Introduction

- A transformer is a static device that transfers electric energy from one circuit to another magnetically by the process of electromagnetic induction, or mutual induction
- Principle of electromagnetic induction:
 - An alternating magnetic flux is produced in the magnetic core of the transformer by passing an AC current through the primary winding
 - The magnetic flux circulates in the magnetic core passing through the secondary winding inducing an AC voltage
- Its function is to change electric system quantities, such as voltage and current, from one level to another

Transformer Theory



<http://www.ustudy.in/ece/eci/u3>

Transformer Theory

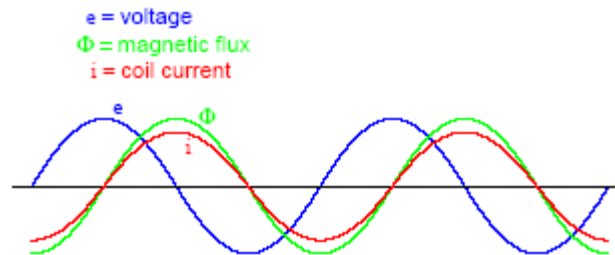
- A transformer is made up of two or more windings wound around a single magnetic core
- Windings are insulated from each other and from ground except in an autotransformer
 - Primary winding is connected to the power source
 - Secondary winding is connected to the load side
 - Tertiary winding is utilized to provide power to an auxiliary circuit or a reactor

Transformer Theory

- Magnetic flux is comparable to current through a conductor
- In electric circuits, the motivating force is electromotive force or emf
- In magnetic circuits, the motivating force is magnetomotive force or mmf
- Magnetomotive force and magnetic flux are related to each other by the magnetic property of reluctance
- Reluctance in a magnetic circuit is similar to resistance in an electrical circuit

Transformer Theory

- The mmf required to produce the changing magnetic flux is supplied by a changing current through the coil
- Magnetic flux, current, and mmf are all directly proportional; current is in-phase with the magnetic flux wave
- Current is required to produce a changing magnetic flux which produces an opposing voltage in-phase with the applied voltage



Transformer Theory

- The amount of induced voltage in a transformer depends on:
 - Core composition and shape
 - Number of primary turns
 - Number of secondary turns
 - Primary voltage
- Relationship between flux and inductance:
 - Increasing current flow increases flux magnitude
 - Increasing turns increases flux concentration
 - Increasing flux concentration increases induction
 - Inductance causes current to lag the voltage by a maximum of 90°

Transformer Turns Ratio

- The amount a quantity changes in a transformer is determined by the:

$$\text{Turns Ratio} = \frac{N_P}{N_S}$$

- Transformer Equation:

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

where,

- V_P and V_S are the primary and secondary no-load voltages
- N_P and N_S are the number of turns in the primary and secondary windings

Transformer Turns Ratio

- **Step-Up Transformer** transfers energy from a low-voltage to a high-voltage circuit ($N_s > N_p$)
 - A turns ratio of $1/8$ (1:8) implies that the secondary coil has eight times more turns as the primary coil
- **Step-Down Transformer** transfers energy from a high-voltage to a low-voltage circuit ($N_p > N_s$)
 - A turns ratio of $8/1$ (8:1) means that the primary coil has eight times more turns than the secondary coil

Transformer Turns Ratio

- As voltage is stepped up, current is stepped down by the same ratio
- As voltage is stepped down, current is stepped up by the same ratio
- Energy is neither created nor destroyed by a transformer
- Average power (P_p) delivered to the primary coil is equal to the average power (P_s) delivered to the secondary coil

$$P_p = P_s$$

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Question #1

- A step-up transformer has 50 turns in the primary coil and 1250 turns in the secondary coil. The primary current is 10,000 amps and the secondary voltage is 230 kV. Find (a) the primary voltage (b) the secondary current and (c) the average power delivered to the load

$$N = \frac{50}{1250} = \frac{1}{25}$$

1 : 25 turns ratio

$$\text{a) } \frac{N_P}{N_S} = \frac{V_P}{V_S} \text{ so } \frac{1}{25} = \frac{V_P}{230 \text{ kV}} \text{ so } V_P = \frac{230 \text{ kV}}{25} = 9200 \text{ volts}$$

$$\text{b) } \frac{I_S}{I_P} = \frac{N_P}{N_S} \text{ so } \frac{I_S}{10,000 \text{ amps}} = \frac{1}{25} \text{ so } I_S = \frac{10,000 \text{ amps}}{25} = 400 \text{ amps}$$

$$\text{c) } P_{\text{AVG}} = (400 \text{ amps})(230,000 \text{ volts}) = 92 \text{ MW}$$

Transformer Efficiency/Losses

- Transformer efficiency is the ratio of the output power to the input power:

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} \times 100$$

- Most transformers have an efficiency of 97% to 99%
- Power consumed by a transformer (losses) is caused by:
 - Hysteresis losses (core)
 - Eddy current losses (core)
 - Copper losses (winding)

Transformer Efficiency/Losses

- **Hysteresis loss** is due to residual magnetism which remains after the magnetizing force is removed
- Occurring every half-cycle, hysteresis loss is the energy required to reduce the residual magnetism to zero
- **Eddy current** flows in the transformer's core and results from the induced voltage in the core caused by the primary winding
- Voltage is induced in the core and converted to heat
- Eddy current can be reduced by laminating the core with a higher resistance material

Transformer Efficiency/Losses

- **Copper loss** is power dissipated in the transformer windings
- Copper loss is due to the resistance of the windings
- Using larger conductors for the transformer windings, which is restricted by the core openings, helps to reduce copper loss

Transformer Taps

- Tap is a connection at some point on a primary or secondary winding which permits changing the turns ratio which alters the secondary voltage and current
 - No load de-energized tap changers
 - Load tap changers
- Tap changer is motor-operated in response to a relay setting to hold voltage at a pre-determined level
- LTC transformers change taps automatically, remote via SCADA, or manually while the transformer is energized

Question #2

- An ideal transformer serves a 50 MVA load. The primary voltage is 138 kV and the secondary current is 2174 amps. Find (a) the primary current (b) the secondary voltage and (c) the turns ratio

$$a) I_P = \frac{50 \text{ MVA}}{138 \text{ kV}} = 362.32 \text{ amps}$$

$$b) V_S = \frac{50 \text{ MVA}}{2174 \text{ amps}} = 22.999 \text{ kV or } 23 \text{ kV}$$

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

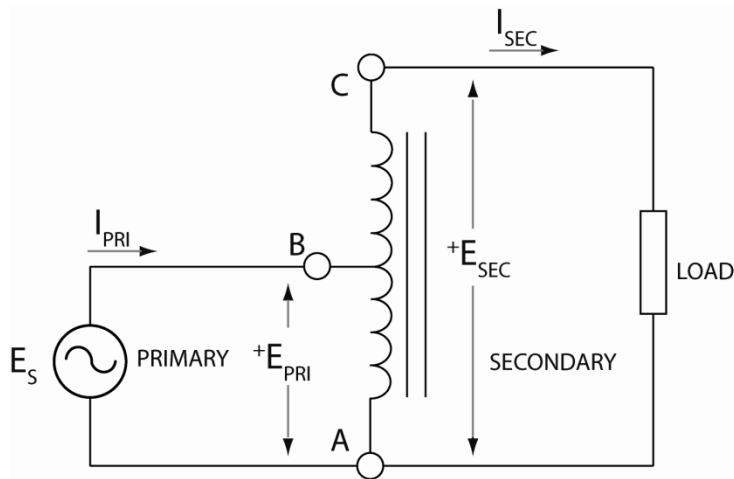
$$\frac{138 \text{ kV}}{23 \text{ kV}} = \frac{6}{1} \text{ Turns ratio is } 6:1$$

Power Transformer

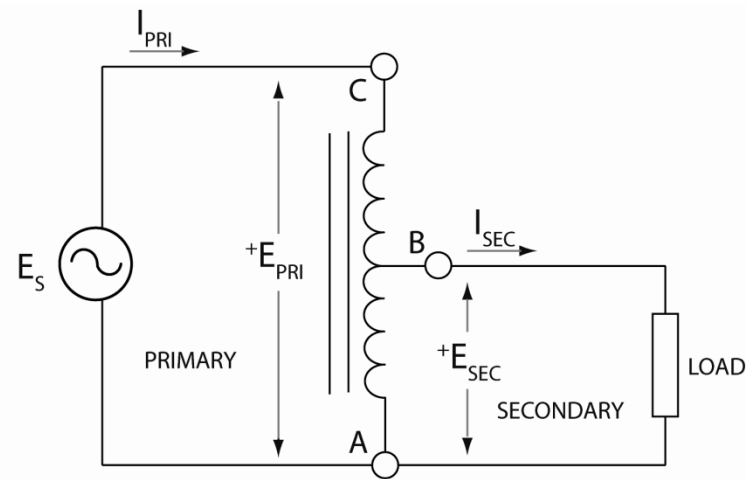
- **Power Transformer** is a term given to a transformer used to transfer power for voltages usually higher than 69kV
- Most power transformers are three-phase
- Power transformers can step-up or step-down the voltage
- Other capabilities, such as tap changing equipment can be added to a step-up or step-down transformer

Autotransformer

- **Autotransformer** is a single-winding transformer with a terminal dividing the winding into two sections
- Autotransformers are simply constructed and cost relatively little in comparison



(a) STEP-UP CONFIGURATION



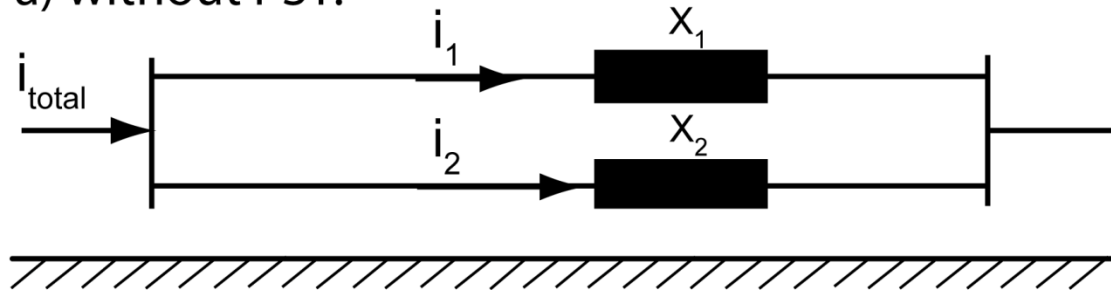
(b) STEP-DOWN CONFIGURATION

Phase Shifting Transformer

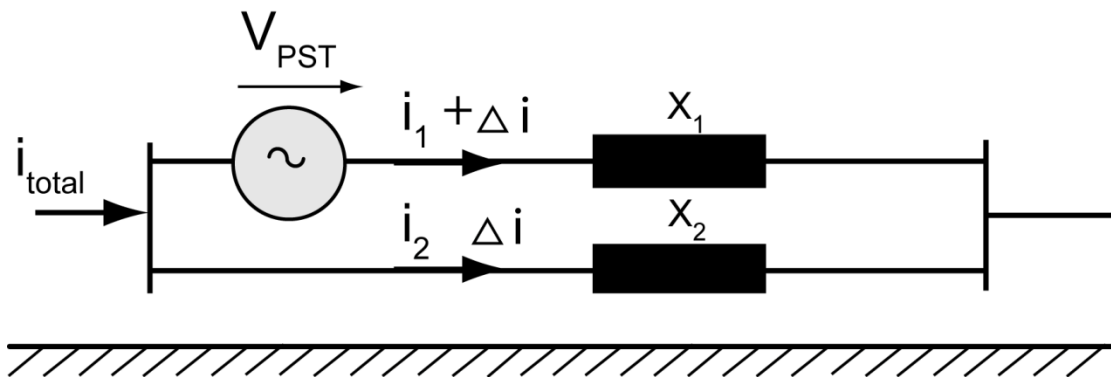
- **Phase Shift Transformer**, or phase angle regulator, controls power flow over parallel lines by adjusting the voltage phase angle at one end of the line
- The interconnection of the windings within the transformer creates the phase shift similar to the operation of power transformers

Phase Shifting Transformer

a) without PST:



b) with PST:



Distribution Transformer

- **Distribution Transformer** is used to reduce voltage to a level which is usable by customers
- Distribution transformers are mounted on poles, concrete pads, or in underground vaults
- Operation is similar to power transformers

Question #3

- A generating station is producing power that is feeding a 5000 kW resistive load located several miles away. Find (a) the current flow if the power is transmitted at 5 kV (b) the current flow if a 1:46 step-up transformer is used to raise the voltage before the power is transmitted; and (c) how many MWs the generator has to produce in each case

Question #3 Answer

a) 5000 Volts :

$$I_{\text{Total}} = \frac{5000 \text{ kW}}{5 \text{ kV}} = 1000 \text{ amps}$$

$$P_{\text{Losses}} = (1000 \text{ amps})^2 (0.5 \Omega) = 500 \text{ kW}$$

Total Generation = 5500 kW or 5.5 MW

b) Stepup Transformer

$$V_{\text{New}} = (46)(5000 \text{ volts}) = 230 \text{ kV}$$

$$I_{\text{Total}} = \frac{5000 \text{ kW}}{230 \text{ kV}} = 21.7 \text{ amps}$$

$$P_{\text{Losses}} = (21.7 \text{ amps})^2 (0.5 \Omega) = 236.3 \text{ watts}$$

Total Generation = 5,000,236.3 watts or 5000.236 kW

Lab Volt Exercises

- Do LabVolt exercises 7.1, 8.1, 9.1 and 9.2

Summary

- Discussed the basic theories associated with transformer operation
- Described and applied the formula for calculating transformer turns ratio
- Examined transformer efficiency and losses
- Described the operation of transformer tap changers
- Explained the different types of transformers and their uses

Questions?

Disclaimer:

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<http://www.pjm.com/documents/agreements/pjm-agreements.aspx>

For additional detailed information on any of the topics discussed, please refer to the appropriate PJM manual which can be found by accessing:

<http://www.pjm.com/documents/manuals.aspx>

Resources and References

- Rustebakke, H. (1983). *Electric Utility Systems and Practices*. New York: John Wiley and Sons
- Miller, R. & Malinowski, J. (1993). *Power System Operation*. New York: McGraw-Hill Inc.