

Electrical Theory

Transformer Theory

PJM State & Member Training Dept.

Objectives



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

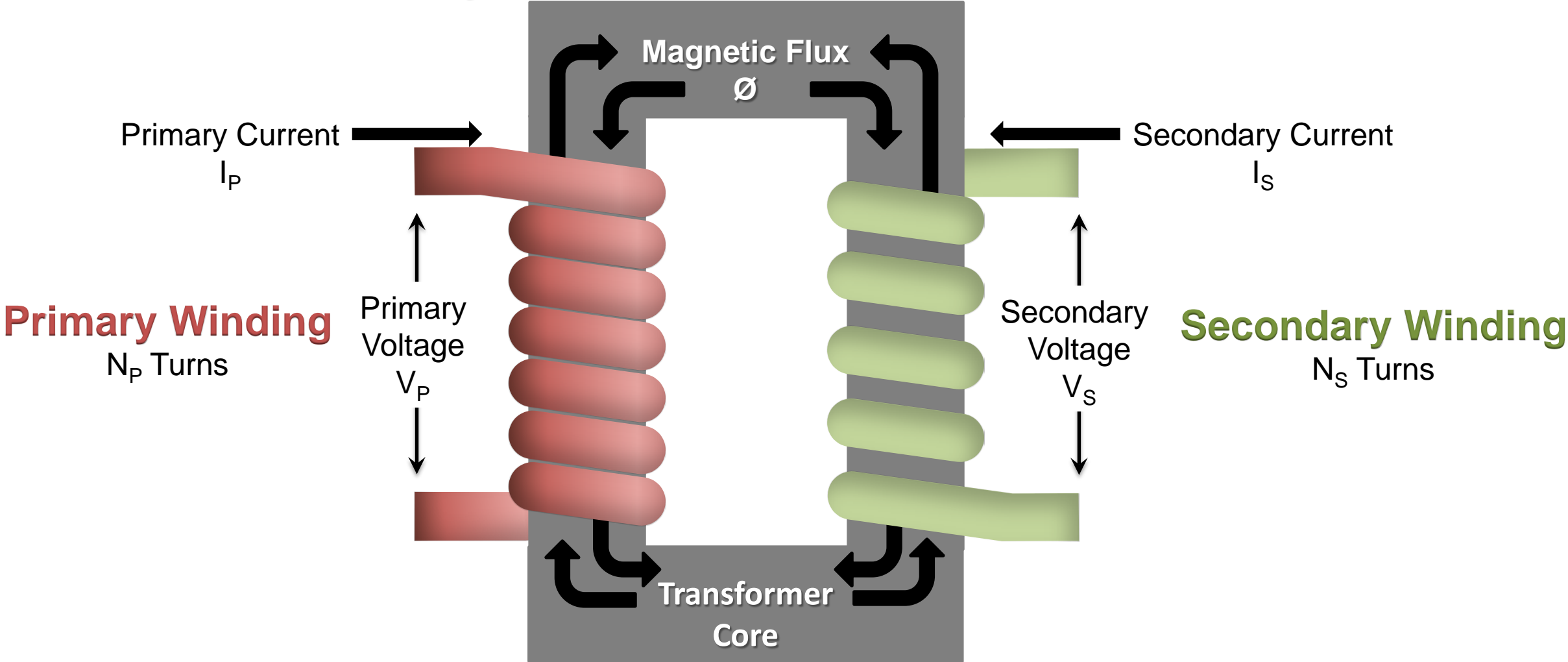
- Describe the basic operational theory of transformers
- Interpret the formula for turns ratio
- Describe transformer efficiency and losses
- Describe transformer tap changers
- Classify the different types of transformers

Transformer Theory

- **Transformer**

- Static device
- Used to convert high-voltage power to low-voltage power and vice versa
- Consists of two or more windings wound around a single magnetic core
 - Windings are insulated from each other and from ground
 - Primary winding - power source
 - Secondary winding - load side
 - Tertiary winding - provides power to auxiliary equipment
- Energy transfer is done via electromagnetic induction, or mutual induction

Transformer Theory



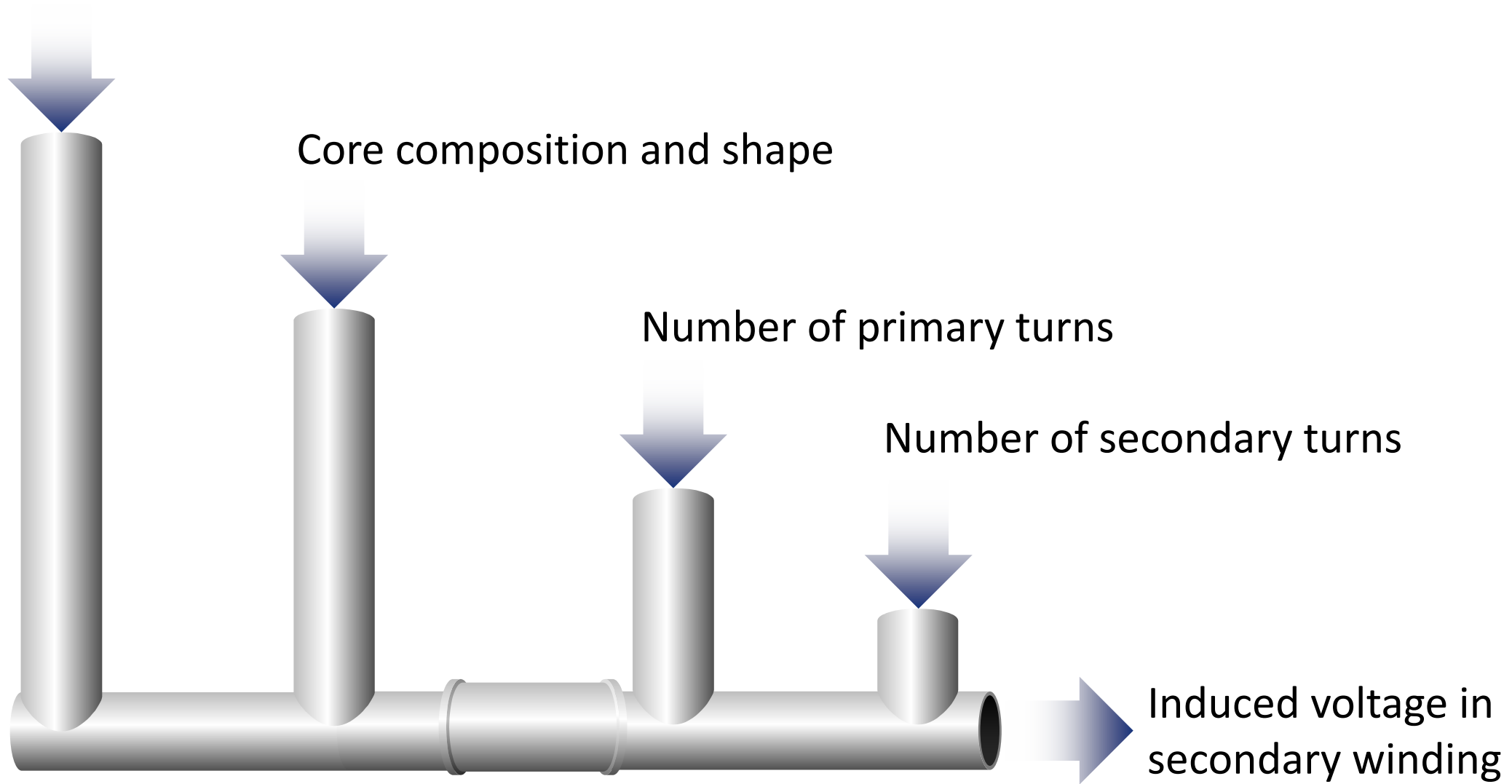
Transformer Theory

“How’d they do that?”

- Transformers work by combining two physical laws:
 - Current flowing in a wire produces a magnetic field
 - Voltage is produced in any conductor in a changing magnetic field
- Current flowing in the coil on one side of the transformer induces a voltage in the coil on the other side
 - Coils are coupled by the magnetic field (mutual induction)

Transformer Theory

Primary Voltage



Transformer Turns Ratio

- The amount voltage and current changes in a transformer is determined by the: $\textit{Turns Ratio} = \frac{N_P}{N_S}$

- Transformer Equation: $\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$

where,

- N_p and N_s = number of turns in the primary and secondary windings
- V_p and V_s = primary and secondary no-load voltages
- I_p and I_s = primary and secondary amps

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

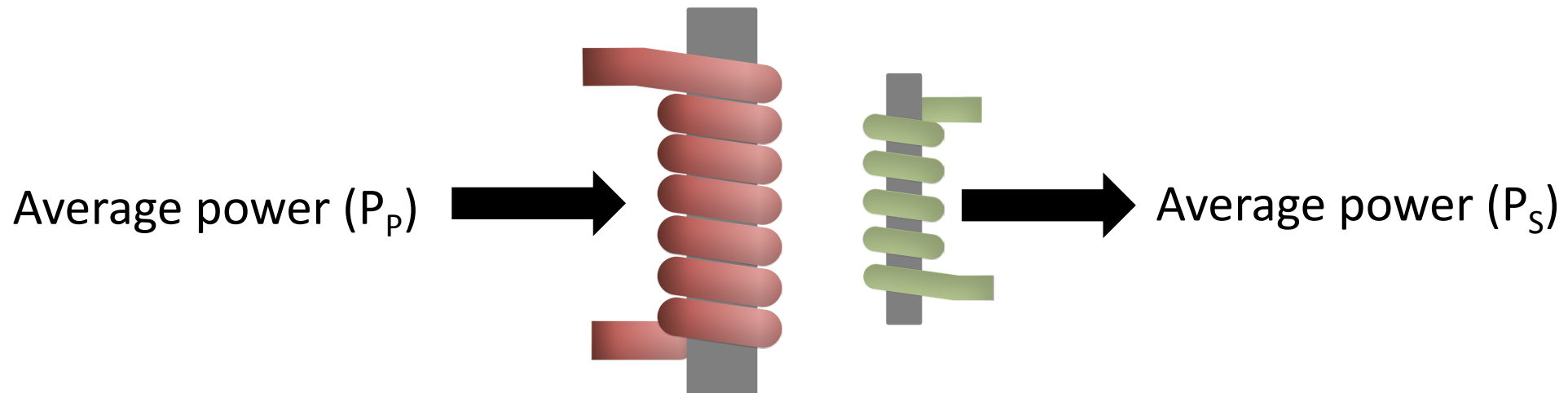
- **Step-Down Transformer**

- 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 , current  by the same ratio
- As voltage , current  by the same ratio

Energy is neither created nor destroyed by a transformer



Answer Question 1

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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

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

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

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

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**

- 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 is caused by the induced voltage in the core from 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**

- 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

- Connections on a primary or secondary winding
 - Permits changing the turns ratio to alter the primary and/or secondary voltage
 - Two types:
 - 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

Answer Question 2

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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

$$a) I_P = \frac{50 \text{ MVA}}{138 \text{ kV}} = 362 \text{ amps}$$

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

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

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

Types of Transformers

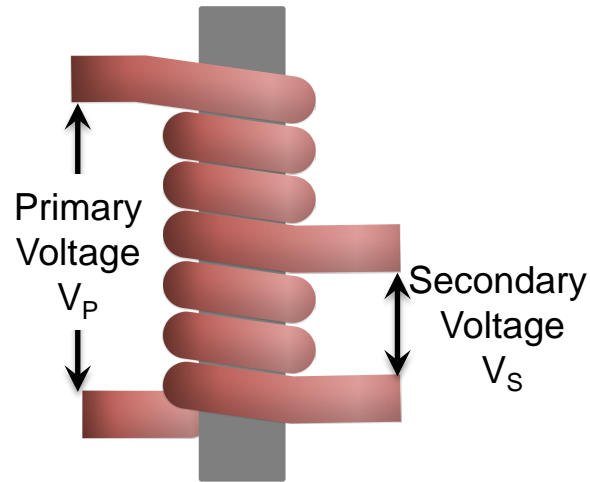
- **Power Transformer**

- 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

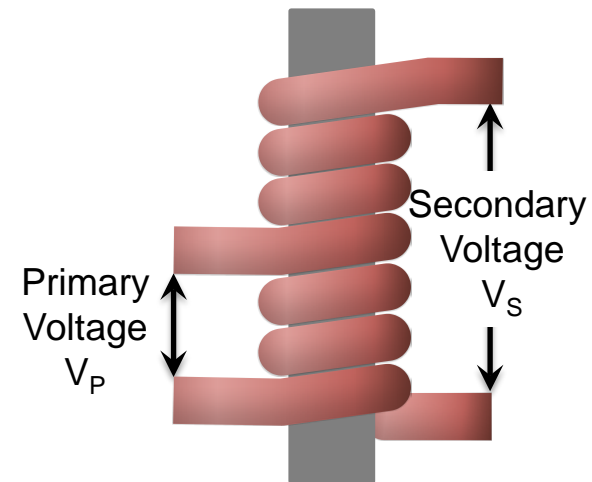
Types of Transformers

- **Autotransformer**

- Single-winding transformer with a terminal dividing the winding into two sections
- Simply constructed and cost relatively little in comparison



Step Down Autotransformer



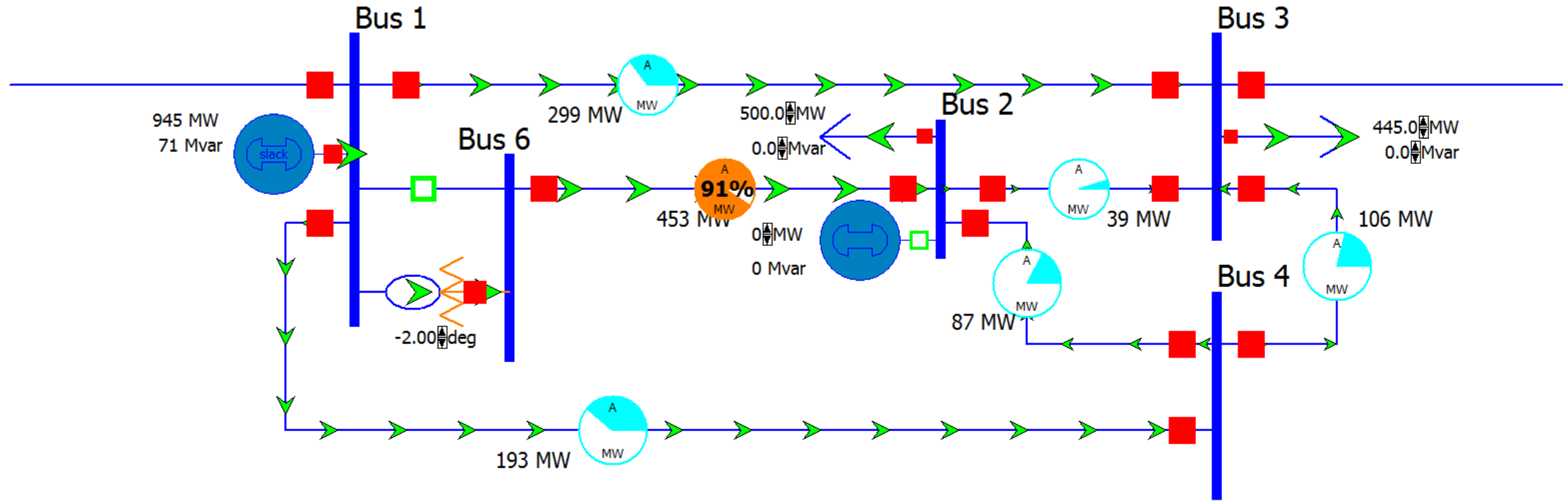
Step Down Autotransformer

Types of Transformers

- **Phase Shift Transformer (PAR)**

- Controls power flow over parallel lines by adjusting the voltage phase angle at one end of the line
- Interconnection of the windings within the transformer creates the phase shift similar to the operation of power transformers

Types of Transformers



Types of Transformers

- **Distribution Transformer**

- Used to reduce voltage to a level which is usable by customers
- Mounted on poles, concrete pads, or in underground vaults
- Operation is similar to power transformers

Answer Question 3

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Question #3

- A generating station is producing power that is feeding a 5000 kW resistive load across a line with 0.5 ohms of resistance. 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
 - c) How many MWs the generator has to produce in each case

Question #3 Answer

a) 5000 volts:

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

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

$$Total \text{ Generation} = 5500 \text{ kW or } 5.5 \text{ MW}$$

b) Step – up Transformer

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

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

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

$$Total \text{ Generation} = 5000.236 \text{ kW or } 5.000236 \text{ MW}$$

Lab Volt Exercises

- Do LabVolt exercises **7.1 and 8.1**

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?

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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.
- Blume, S. *Electric Power System Basics For the Nonelectrical Professional*. New York: John Wiley and Sons