6 | Transformers

Introduction to System Operations Course Outline

1. Introduction to WECC
2. Fundamentals of Electricity
3. Power System Overview
4. Principles of Generation
5. Substation Overview
6. Transformers
7. Power Transmission
8. System Protection
9. Principles of System Operation

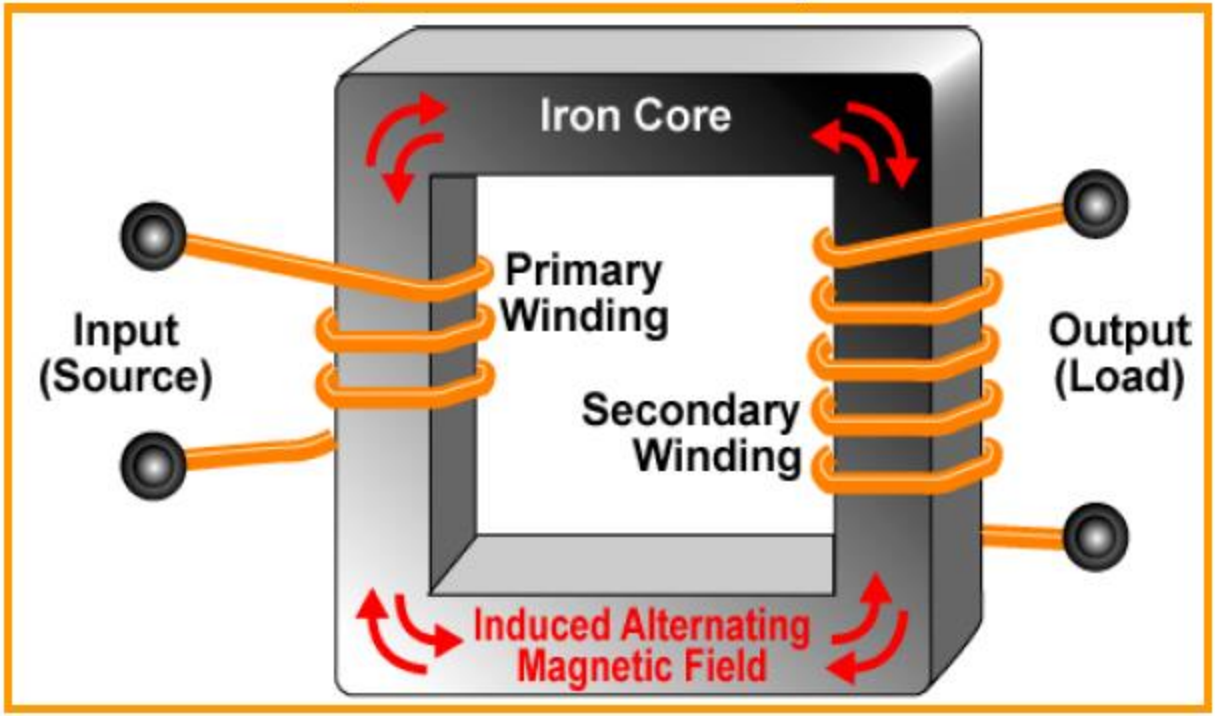
Module Overview

- This module presents the following topics:
- Principle of Operation
- Types of Transformers
- Operating Considerations and Limitations

Principle of Operation

- A ***transformer*** changes Voltage up or down and Current down or up.
- A transformer has two or more windings around a single steel core
- The winding conductors, are usually copper or aluminum.

Two-Winding Transformer



The primary winding is connected to the power source.
The secondary winding is connected to the output or load side.
There is no electrical connection between the primary and secondary windings.

Tertiary Winding

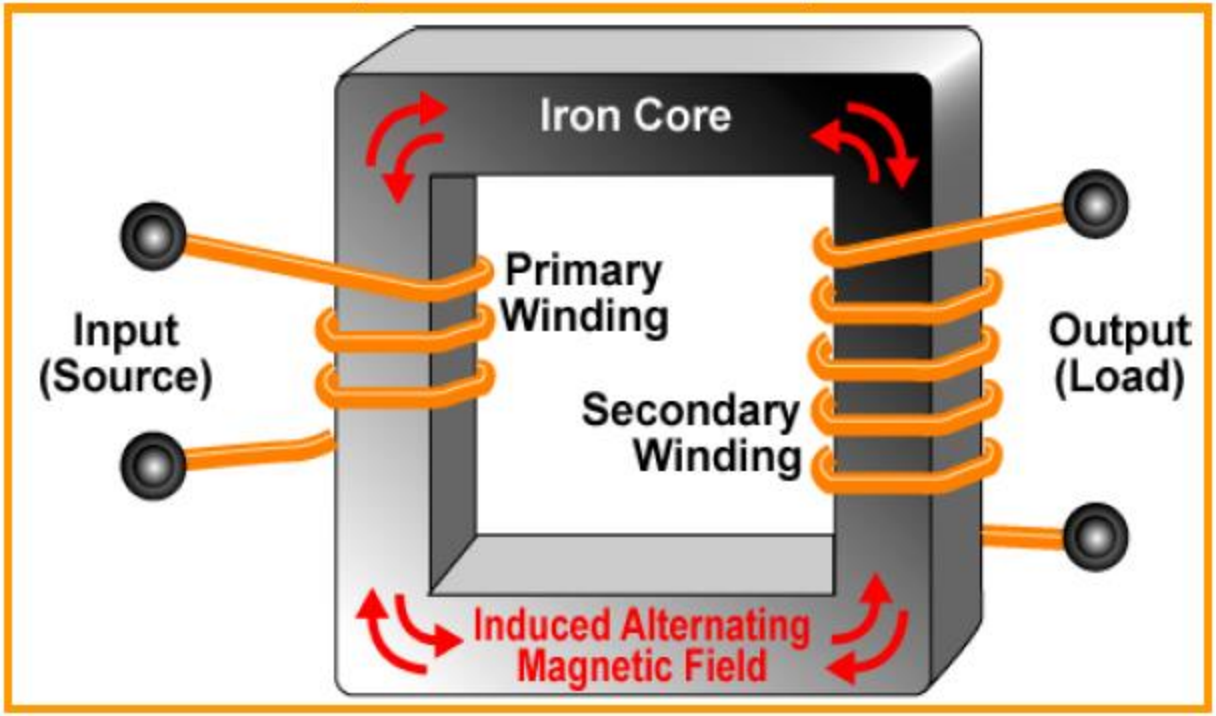
- A ***tertiary winding***, is sometimes present. It provides power to an auxiliary circuit or a reactor.
- The core and the windings are mounted in a steel tank filled with mineral oil.
- Insulated ***bushings***, mounted at the top of the tank, connect the windings to other power system equipment.

How do Transformers Work?

- An alternating current in the windings causes an alternating magnetic flux in the core.
- The magnetic flux in the core, passes through another coil (the secondary winding), inducing an alternating voltage in this coil.
- The amount of induced voltage depends on four factors:
  - 1) core composition and shape
  - 2) number of turns in primary coil or winding
  - 3) number of turns in the secondary coil or winding
  - 4) primary voltage

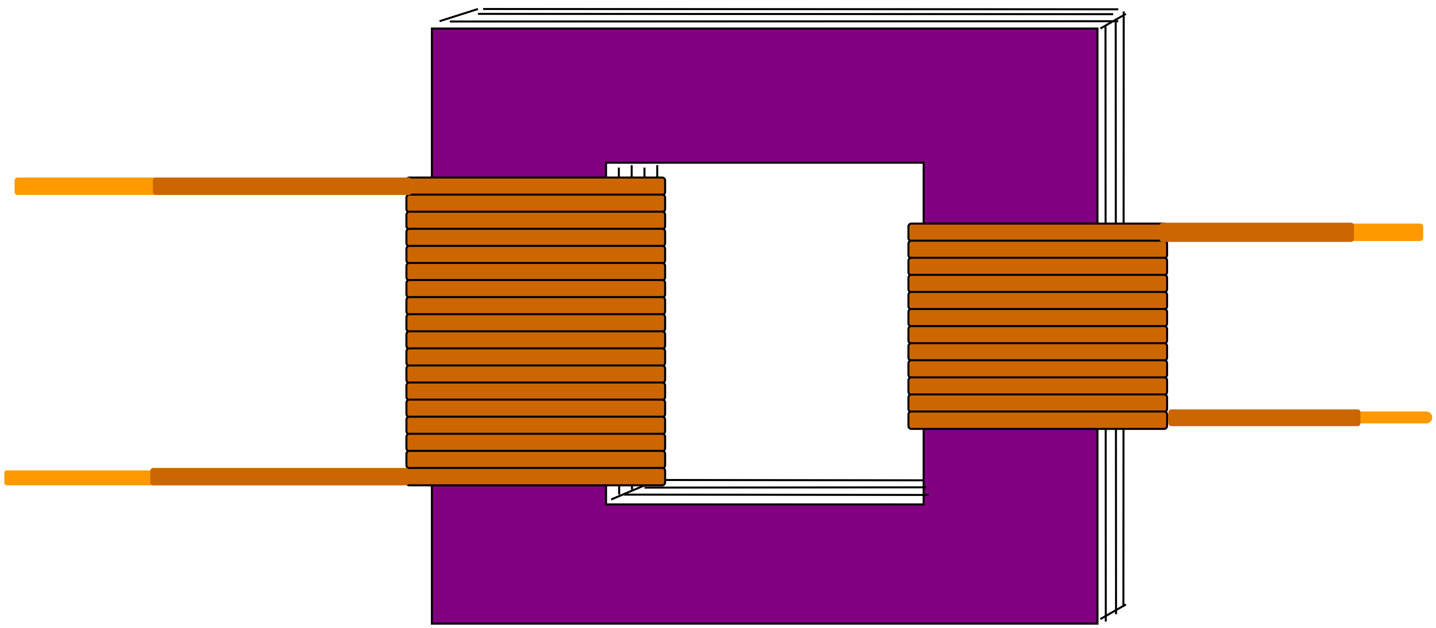
How do Transformers Work?

In a transformer there are two or more coils linked together by a common core conducting the magnetic flux. Flux from one coil (the primary winding) passes through the other coil (the secondary winding), inducing a voltage in the secondary winding. Mutual induction links the two windings.



Basic Transformer

Laminated Steel Core



Source Side = Primary Winding

Secondary Winding = Load Side

How do Transformers Work?

- A transformer core is made from carefully stacked pieces of steel sheet metal.
- Magnetic flux travels through (permeates) the steel hundreds of times easier than through air.
- The core is shaped to allow the maximum steel path for the flux to flow through, with minimum air-gaps.
- Individual sheets of steel reduce eddy-currents between sheets.

Stacked Steel Transformer Core

- Windings may be assembled on a hollow tube before being placed over a core leg.
- Individual strands are carefully transposed to balance un-even induced current.
- When windings are in place, core steel is interleaved together to complete the core.
- Final assembly is braced in anticipation of strong electromagnetic forces while operating.

How do Transformers Work?

Turns Ratio

- Voltage changes in the transformer are determined by the ***turns ratio*** or windings ratio.
- The magnetic flux links the turns of the primary and secondary windings.
- The Flux induces the same voltage in each turn.
- Total voltage of the winding is the sum of the induced voltages in each of its turns.

Turns Ratio

- The total voltage in each winding is proportional to the number of turns in that winding:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \text{ or } V_1 = \frac{N_1}{N_2} * V_2$$

Where:

- V_1 and V_2 are the voltages in the primary and secondary windings, respectively.
- N_1 and N_2 are the number of turns in the primary and secondary windings, respectively.

Turns Ratio

- Current changes in the transformer are also determined by the ***turns ratio***
- The same magnetic flux links the turns of the primary and secondary windings.
- The Flux is proportional to the total Amp-Turns.
- The winding with fewer turns requires more amps.

Turns Ratio

- The total current in each winding is inversely proportional to the number of turns in that winding:

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \quad \text{or} \quad I_1 = \frac{N_2}{N_1} * I_2$$

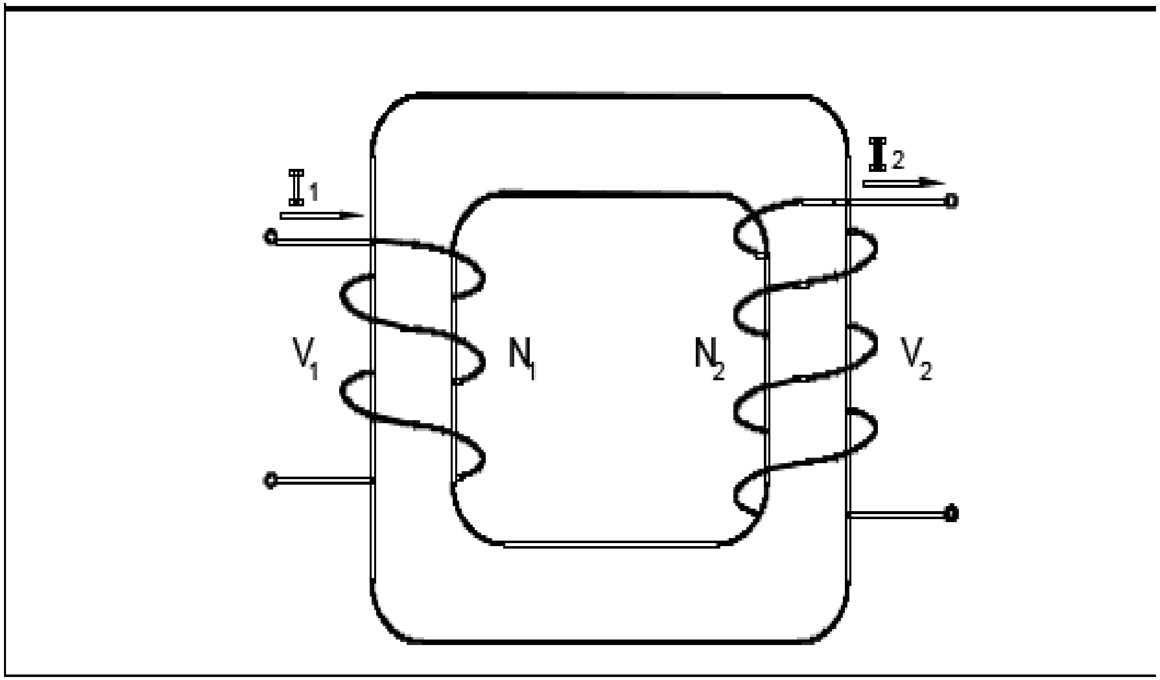
Where:

- I_1 and I_2 are the Currents in the primary and secondary windings.
- N_1 and N_2 are the number of turns in the primary and secondary windings., respectively.

Turns Ratio

- The windings have inductance which opposes changes in current.
- As current increases, magnetic flux increases in the core.
- The changing magnetic flux opposes the change in current.
- This causes a time lag or phase angle shift of up to 90° (if the transformer is not loaded)

Turns Ratio



$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \text{ and } \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

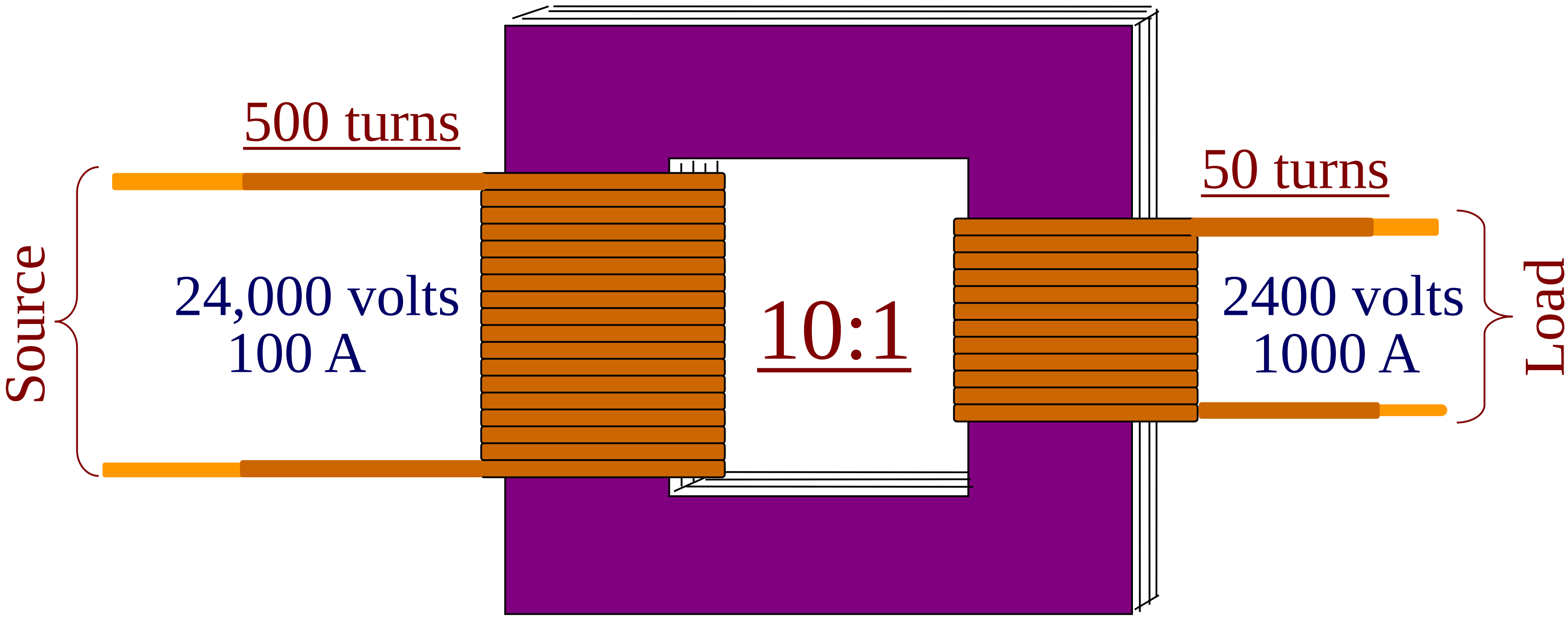
Turns Ratio

- In an ideal transformer, Power-In equals Power-Out. P_1=P_2

- Doing the math….
- $P_1 = V_1 * I_1 = \frac{N_1}{N_2} * V_2 * \frac{N_2}{N_1} * I_2 = V_2 * I_2 = P_2$
- In other words…Voltage goes up, Current goes down, Power stays the same.

Turns Ratio

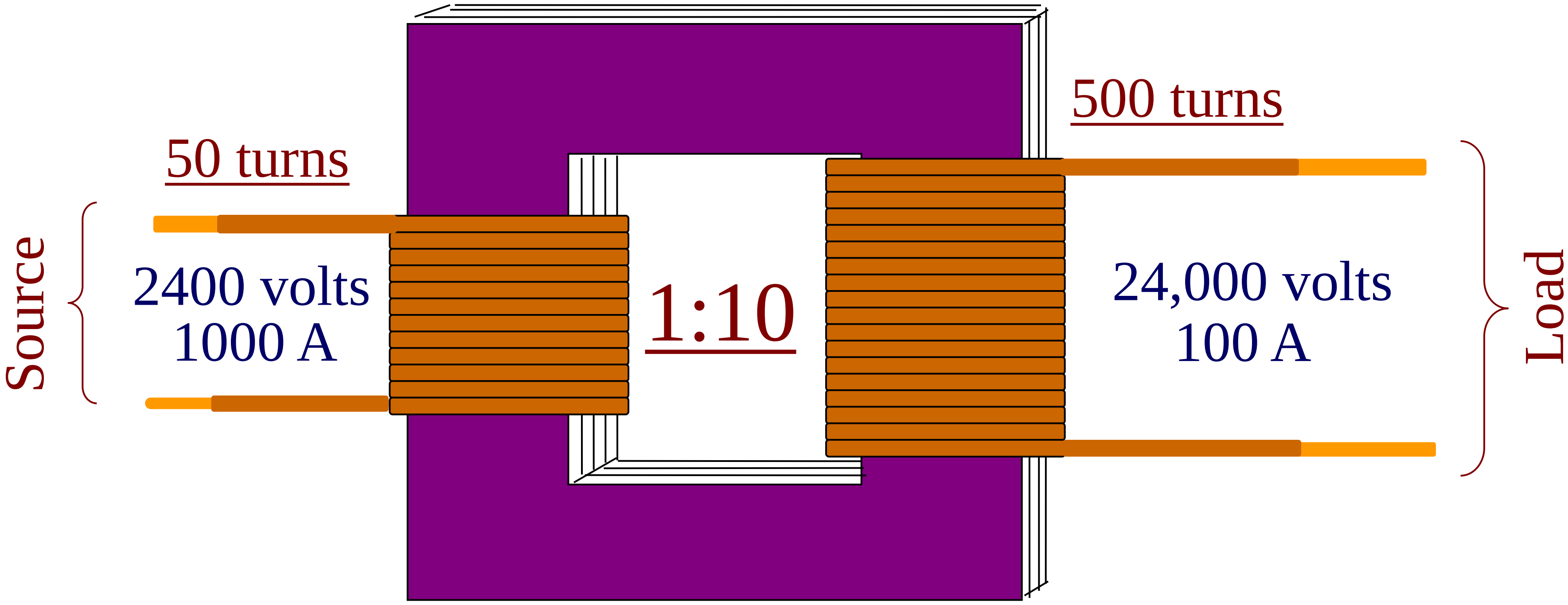
Step-Down Transformer



$$\frac{N_P}{N_S} = \frac{500}{50} = \frac{10}{1} \qquad \frac{10}{1} = \frac{V_P}{V_S} \qquad \frac{10}{1} = \frac{I_S}{I_P}$$

Turns Ratio

Step-Up Transformer



$$\frac{N_P}{N_S} = \frac{50}{500} = \frac{1}{10} \qquad \frac{1}{10} = \frac{V_P}{V_S} \qquad \frac{1}{10} = \frac{I_S}{I_P}$$

Check Your Knowledge:
Determining Power: Turns Ratio

A transformer has 300 turns on its primary winding and 600 turns on its secondary winding. The input voltage is 120 volts.

The given quantities are:

- V_1 = 120 volts
- N_1 = 300 turns
- N_2 = 600 turns

1. What is the Output Voltage?

Check Your Knowledge:

Determining Power: Turns Ratio

A transformer has 300 turns on its primary winding and 600 turns on its secondary winding. The input voltage is 120 volts.

The given quantities are:

- V_1 = 120 volts
- N_1 = 300 turns
- N_2 = 600 turns

1. What is the Output Voltage?

Answer: $V_2 = 120V * \frac{600}{300} = 240V$

Check Your Knowledge:
Determining Power: Turns Ratio

2. Given I_1= 800 Amps what is the secondary current, I_2?

Check Your Knowledge:
Determining Power: Turns Ratio

2. Given I_1= 800 Amps what is the secondary current, I_2?

Answer: I_2=800 Amps*$\frac{300}{600}$ = 400 Amps

Check Your Knowledge:
Determining Power: Turns Ratio

Check to see that the power is the same on both sides of the transformer.

$P_1 = V_1 \times I_1 = 120V * 800A = 96{,}000\ W$

$P_2 = 240V \times 400A = 96{,}000\ W$

√ Check!

Determining Power

- Example – continued:
- Check to see that the power is the same on both sides of the transformer.
- $P_1 = V_1 \times I_1 = 120V * 800A = 96,000\ W$
- $P_2 = 240V \times 400A = 96,000\ W$
- √ Check!

Step-Up/Step-Down Transformer

- Power can flow either direction through a transformer
- …stepping-up or stepping-down the voltage
- …depending on which way you look at it.

Step-Up/Step-Down Transformer

- Whatever happens to the voltage through the transformer, the opposite happens to the current.
  - If the voltage is stepped down, current is stepped up by the same ratio.
  - Likewise, when voltage is stepped up, current is stepped down by the same ratio.
- Transformers do not produce electricity. They only transform it from one level to another; i.e., step the voltage or current up or down.

Step-Up/Step-Down Transformer

For a given level of power, the higher the voltage, the lower the current. Using lower current decreases losses.

- This is why transmission systems use high voltage.
- A Generator Step-up transformer Unit (GSU) raises the generator output voltage.

Losses

- While the transformer is operating, some electrical energy is converted into heat.
- Any heat the transformer produces is an energy loss and represents inefficiency.

Transformer Efficiency

- The efficiency of a transformer is the ratio of the output power to the input power.

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

- In an ideal transformer, power-in equals power-out.
- In reality, the transformer consumes some of the power.
- Most transformers have an efficiency of 97% to 99%.

Losses

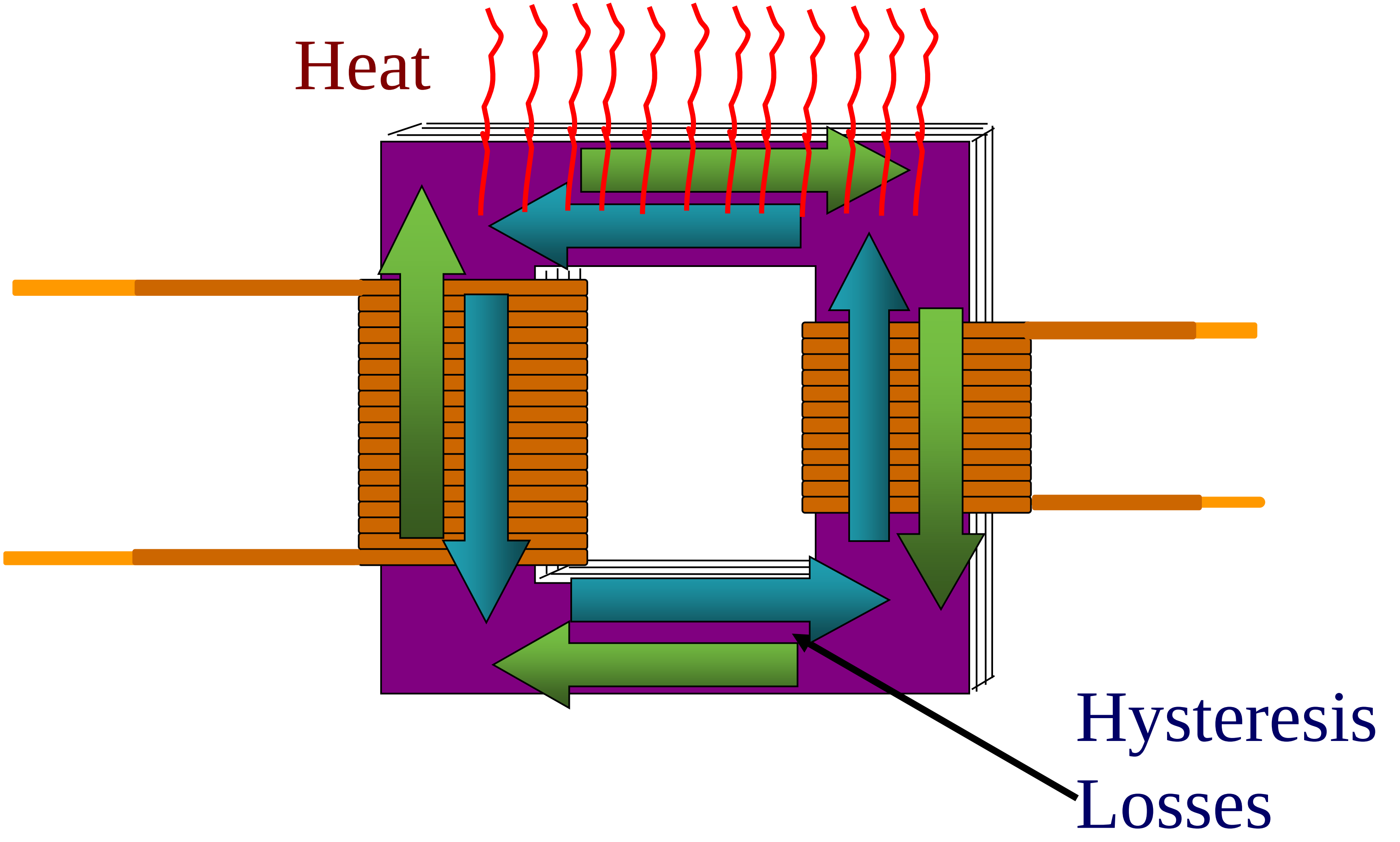
- The power consumed is called *power loss. It is caused by the following:*
  - hysteresis losses
  - eddy current losses
  - copper (I^2R) losses
- Hysteresis and eddy current losses occur in the transformer's core.
- Copper losses occur in the windings.
- All three loss types convert electrical energy into heat.
- These losses can over-heat the transformer during overload periods.

Residual Magnetism

- Hysteresis loss is due to ***residual magnetism,*** that remains in a material after the magnetizing force is removed.
- The transformer core reverses magnetic polarity each time the primary current reverses direction.
- The residual magnetism of the previous polarity has to be overcome.
- This produces heat.

Transformer Losses

(Core Losses)

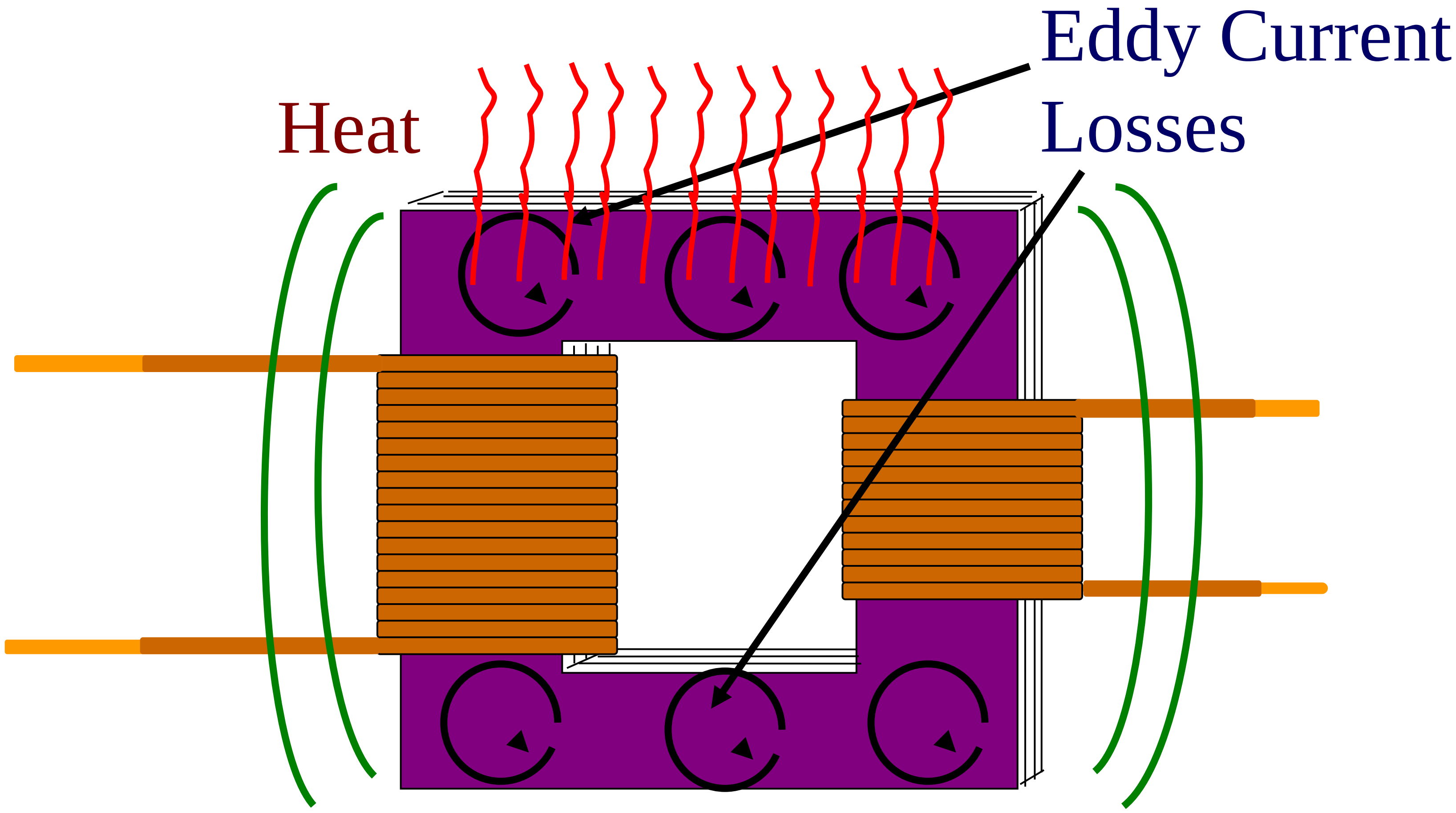


Eddy Currents

- ***Eddy currents*** are the result of voltage induced in the core by the changing magnetic flux.
- The primary coil creates a changing magnetic flux that induces a voltage in the secondary coil.
- The flux also induces voltages and currents in the steel core which is itself a conductor.
- The current flowing through the resistance of the steel is converted to heat.
- Eddy current can be reduced by laminating the transformer's core, using higher resistance silicon steel, and laser etching of the steel surface.

Transformer Losses

(Core Losses)

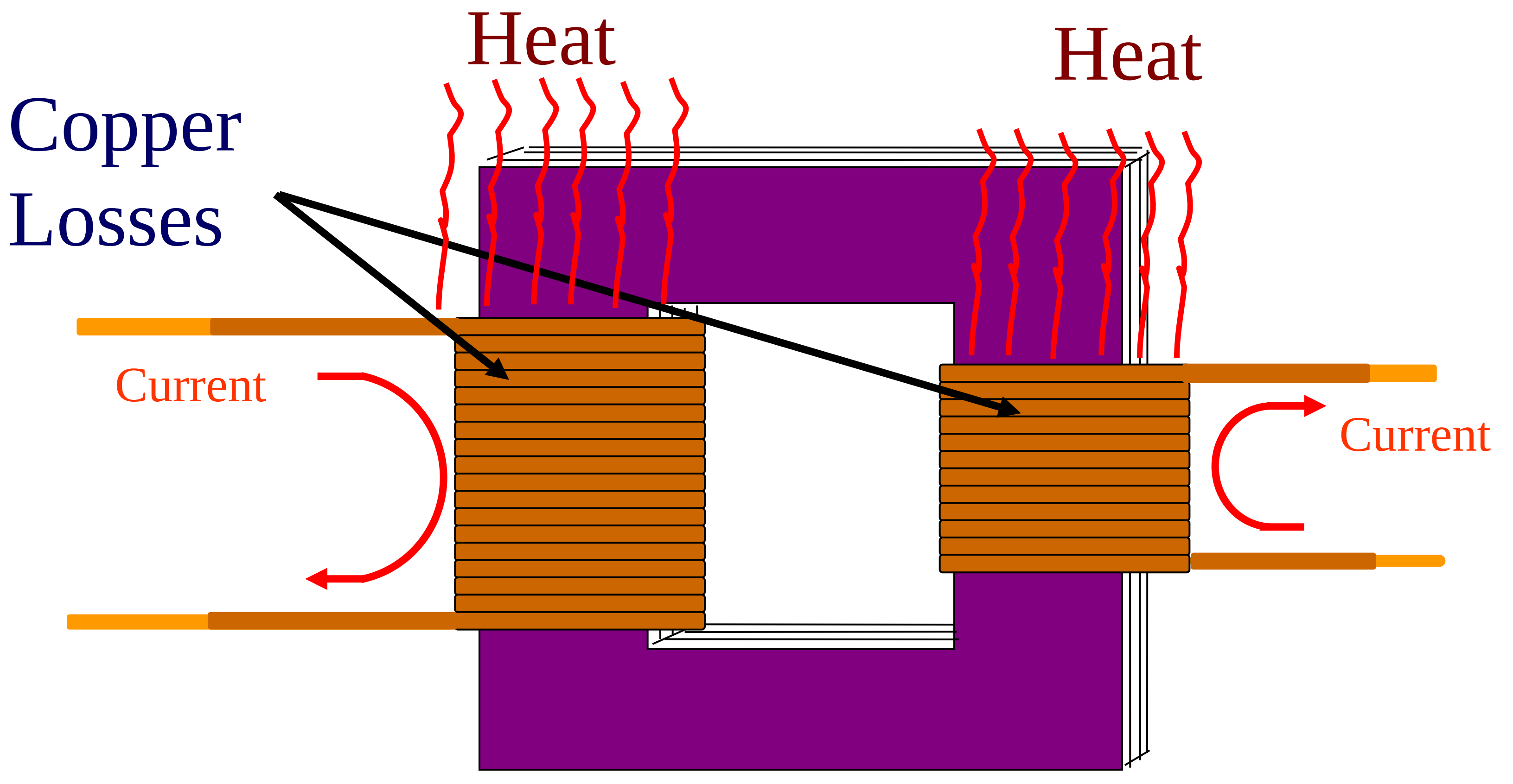


Copper Loss (I^2R Losses)

- ***Copper Loss (or I^2R Loss)*** is energy converted to heat due to current flowing through the resistance of the windings.
- Using larger conductors for the transformer windings reduces the copper loss.

Transformer Losses

(I^2R Losses)



Transformer Losses

- Users of Large Transformers quantify cost of the losses and let the manufactures know the cost.
- Manufacturers design a transformer that will minimize their costs for steel, copper and aluminum -
- While minimizing the purchaser's total cost of ownership including losses.

Transformer Losses

- Losses are characterized as:
  - Load Losses – proportional to the Square of the Load (mostly copper losses)
  - No-load Losses – that are being consumed anytime the transformer is energized (mostly core losses)
- Users calculate a cost factor for each type of Loss
  - Cost per watt for Load Losses is K1
  - Cost per watt loss for No-load Losses is K2

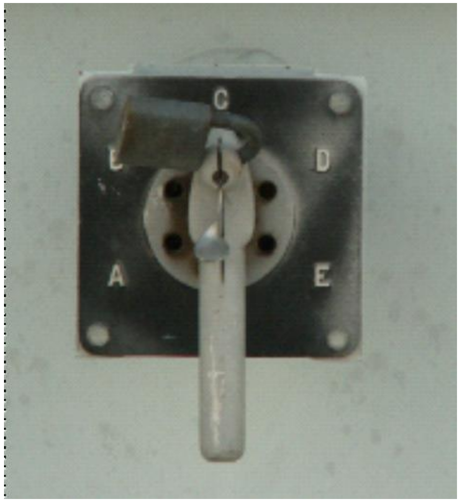
Transformer Losses

- Users may evaluate bids by calculating a Total Owning Cost (TOC) for different transformers.
- TOC = Purchase Price + No Load Loss * K1 + Load Loss * K2

Voltage Control

- Most high-voltage transformers contain many taps.
- A ***tap*** is a connection at some point on a transformer winding which permits changing the turns ratio.
- Changing the turns ratio alters the secondary voltage and current.
- For infrequent adjustments (e.g., for load growth or seasonal variations), utilities use ***no load de-energized tap changers***.

Tap Changers



Load Tap Changer

- Where frequent voltage adjustments are necessary, or where the transformer cannot be de-energized, utilities use ***Load-tap-changing (LTC)*** transformers.
- LTC transformers, are sometimes called ***tap-changing under load (TCUL)*** transformers.
- ***LTC*** transformers can be operated automatically, by local or remote control.

Load Tap Changer

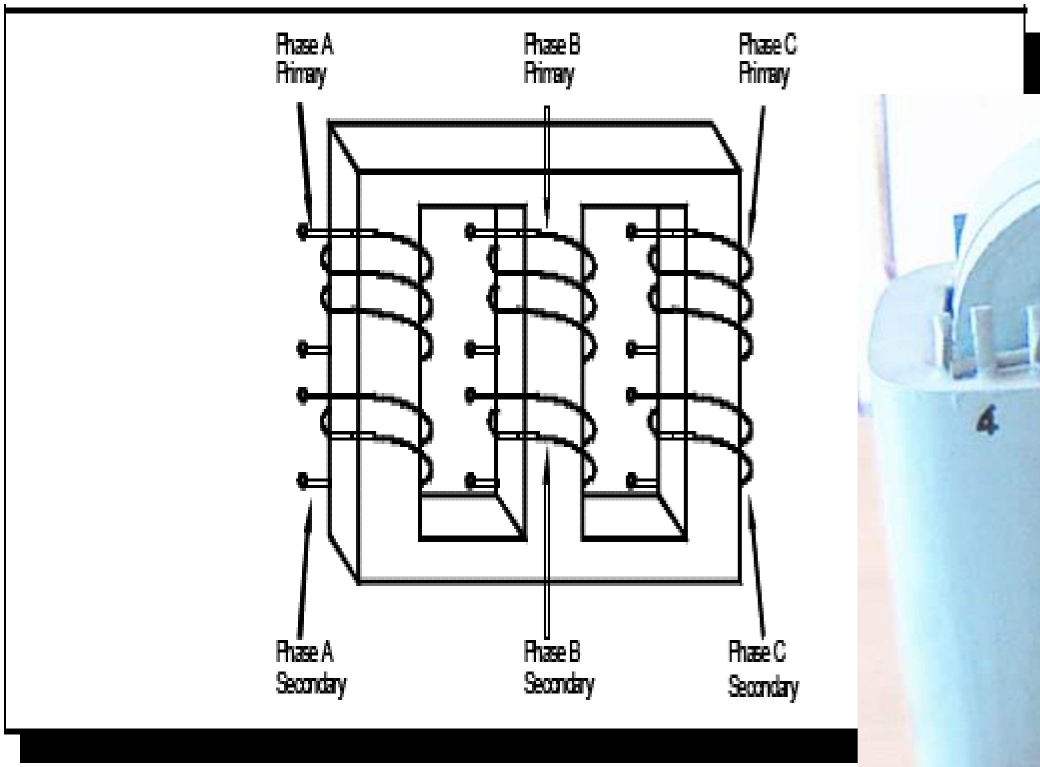
- The tap changer is operated by a motor that responds to relay settings to hold the voltage at a pre-determined level.
- Special circuits allow the tap to be changed without interrupting current.
- LTC equipment is usually housed in a separate compartment on the side of the transformer.

Load Tap Changer

Three Phase Transformer

- In three-phase transformers there are three primary windings and three secondary windings.
- Some three-phase transformers include windings for all three phases in one tank.
- A three phase transformer may have a single core with 3 or 5 legs.
- Other three-phase transformers have three single-phase transformers connected together.

Three Phase Transformer



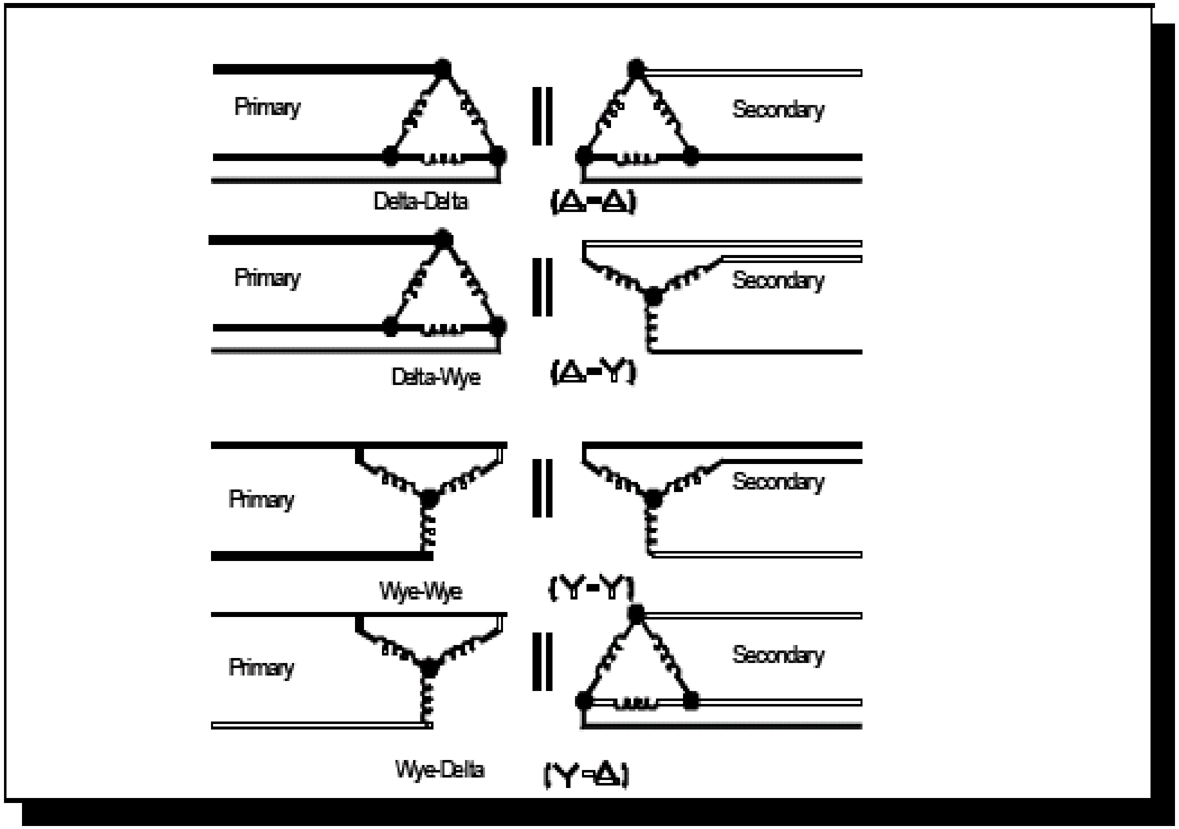
Three Phase Transformer

Transformer Bank

- A ***transformer bank*** is two or more single-phase transformers connected as a unit.
- The most common methods for connecting the windings are:
  - **Wye** or Y (sometimes called star) connection
  - **Delta** connection
- Some connections result in a ***phase shift***
- The primary and secondary windings need not have the same connection.

Transformer Bank

Transformer Connections



In some transformers, the neutral point in the Y connection is grounded.

Transformer Connections

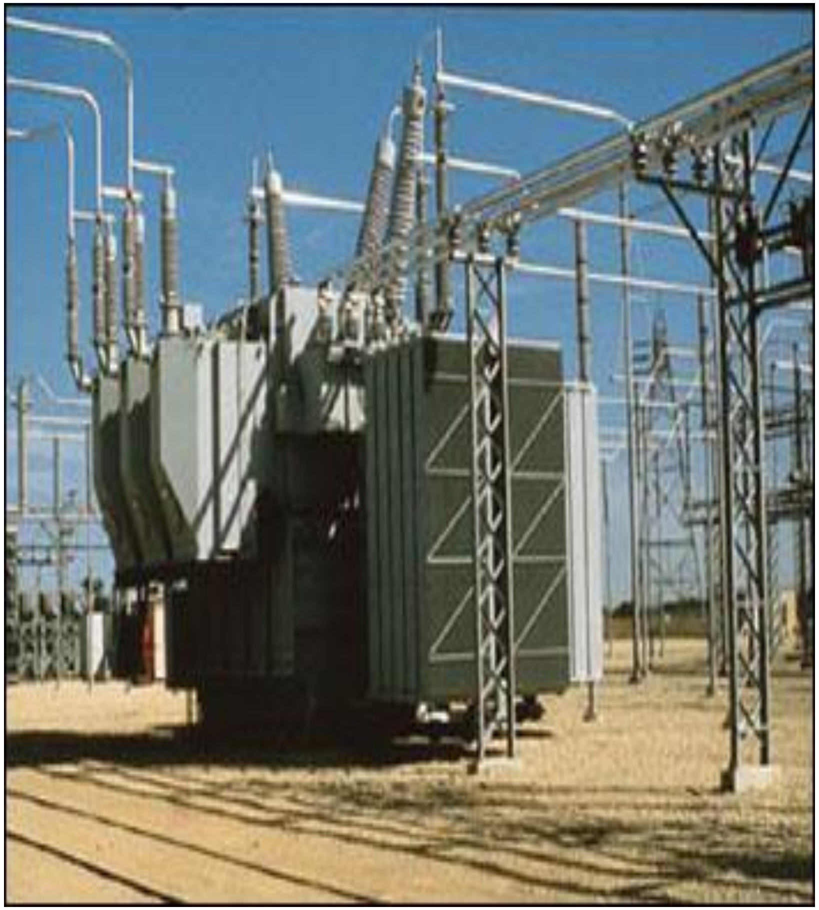
- Consider the phase shifts before tying circuits together if they are fed through different types of transformers.
- For example: connecting a circuit fed by a Wye-Delta bank to a circuit fed by a Wye-Wye bank results in excessive current flow because of the 30º phase difference.

Types of Transformers

- Power Transformers
- Autotransformers
- Phase Shifting Transformers
- Instrument Transformers
- Distribution Transformers

Power Transformers

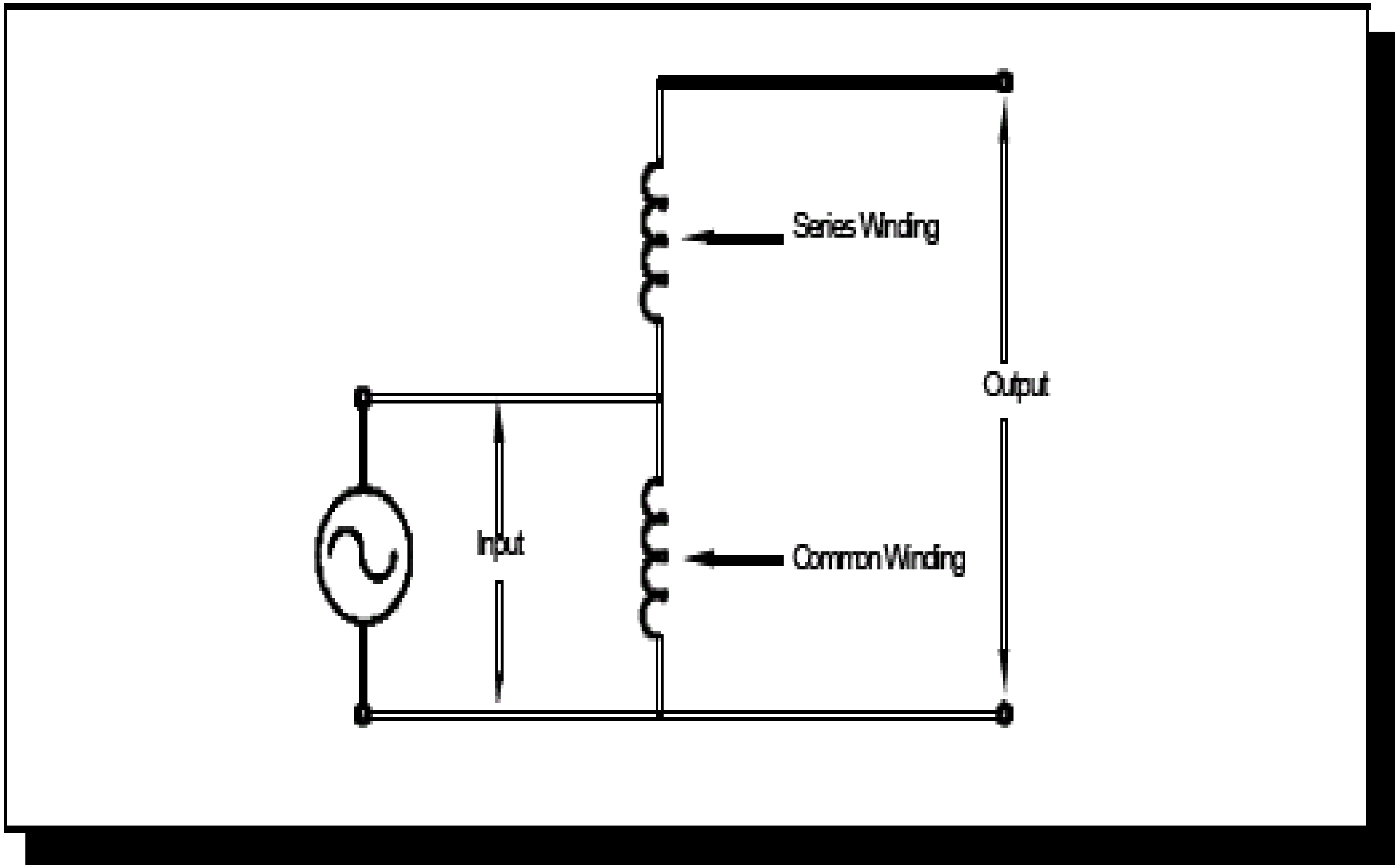
- A ***Power transformer*** is for voltages higher than 69 kV.
- Most power transformers are three-phase.
- Power transformers may include tap changing equipment.



Autotransformers

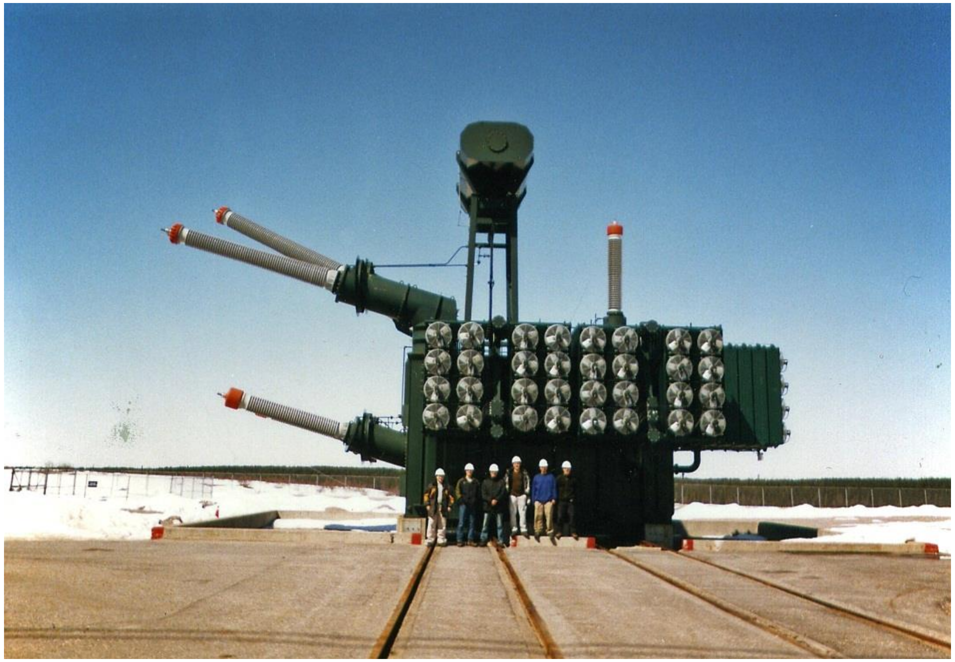
- An ***autotransformer*** is a single-winding transformer with a terminal that divides the winding into two sections.
- Autotransformers are useful because they are simply constructed and cost relatively little compared with multi-winding transformers.
- Autotransformers are variously designed to raise or lower the voltage at
- ± 5%, ± 7.5%, or ± 10 % ranges.

Autotransformers

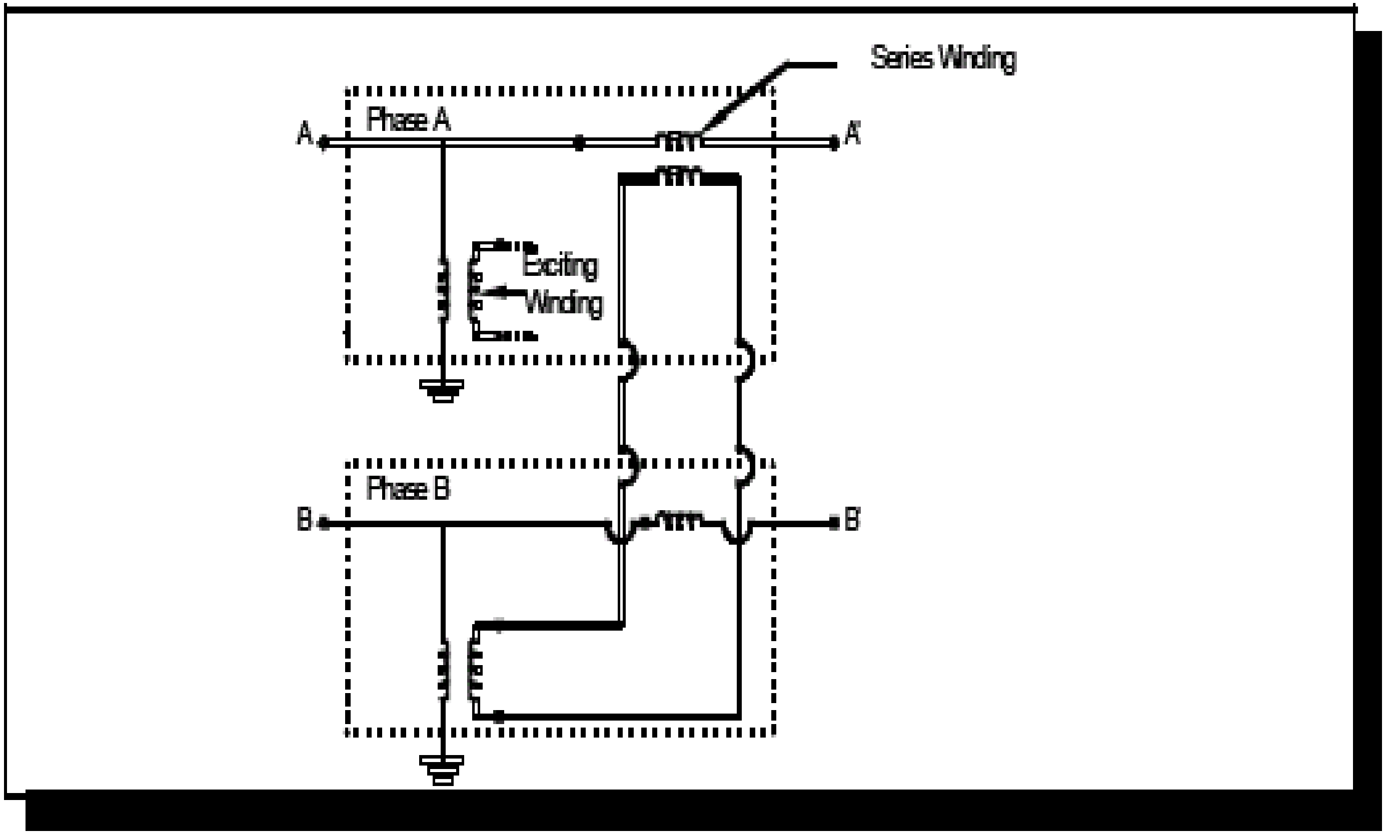


Phase Shifting Transformers

- ***Phase shifting transformers,*** or phase angle regulators (PARS), control power flow over parallel lines by adjusting the voltage phase angle at one end of the line.
- Phase shifting transformers increase or decrease the phase angle differences between buses.
- Power flow on a line is a function of the phase angle.

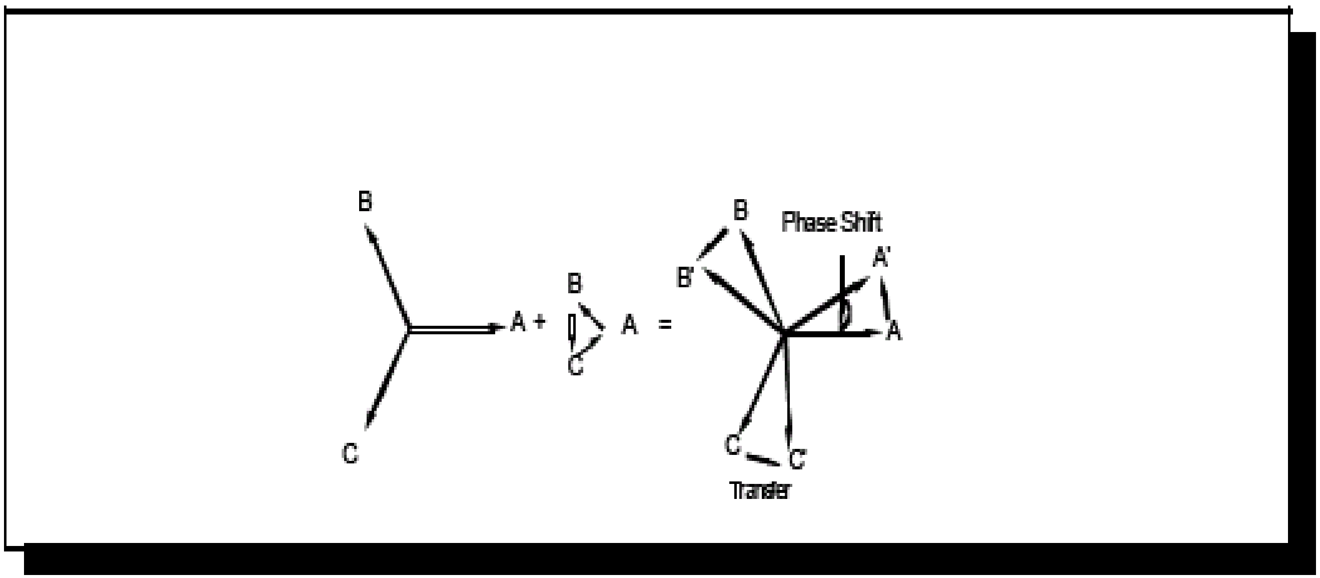


Phase Shifting Transformers



Phase Shifting Transformers

- The Phase A series winding's secondary is connected to Phase B's exciting winding.
- Phase B's voltage lags Phase A's voltage by 120º (or 60º leading if the polarity is reversed).
- The Phase B exciting winding induces a voltage in the Phase A series secondary winding. This small out-of-phase voltage advances the supply voltage



Instrument Transformers

- In high-voltage systems, direct measurement of voltage or current is not practical.
- ***Instrument transformers*** scale down the values for use by meters and relays.
- Instrument transformers include current transformers (***CT***s) and potential transformers (***PT***s) (sometimes called voltage transformers [***VT***s]).

Distribution Transformers

- A ***distribution transformer*** reduces voltage to a level that is usable by customers. Distribution transformers are mounted on poles, on concrete pads, or in underground vaults.

Transformer Cooling Systems

- Excessive heating in a transformer causes the insulation to deteriorate; therefore, it is important to prevent overheating.
- Insulating oil carries heat away from the transformer core to the outer walls and the radiator fins to dissipate heat.
- Transformers are equipped with cooling systems that prevent temperature rise from exceeding specifications.

Transformer Cooling Systems

- Cooling systems for large power transformers typically include:
  - radiators in which outside air cools the transformer oil
  - pumps to increase the oil circulation when additional cooling is needed
  - fans that blow air on the radiators for added cooling

Transformer Cooling Systems

Transformer Ratings

- Heat generated within the transformer tank causes the transformer insulation to deteriorate gradually.
- Excessive heating can cause rapid deterioration of the transformer insulation.
- The ***transformer rating*** is the maximum power it can carry without exceeding a temperature limit.
- Transformers typically have more than one rating depending on the portion of the cooling system that is operating.

Transformer Ratings

- The ***oil to air (OA)*** rating applies when neither the fans nor the oil pumps are running. This is approximately 60% of maximum rating.
- The ***forced air (FA***) rating applies when the fans are running but the oil pumps are not running (oil is flowing by natural circulation). This is approximately 80% of the maximum rating.
- The ***forced-oil and air (FOA)*** rating is the maximum rating that applies when oil pumps and cooling fans are operating (100 % of rating).

Transformer Ratings

- The ***oil to air (OA)*** New nomenclature is ***ONAN*** (meaning: Oil – Natural Circulation, Air – Natural Circulation)
- The ***forced air (FA***) New nomenclature is ***ONAF*** (meaning: Oil – Natural Circulation, Air – Forced Circulation)

- The ***forced-oil and air (FOA)*** New nomenclature is ***OFAF*** (meaning: Oil – Forced Circulation, Air – Forced Circulation)

Transformer Ratings

- It is important to detect faults in the transformer windings before damage occurs.
- Major problems usually start out as small short-circuits between turns.
- These short circuits usually develop into an arc, which produces large volumes of gas by evaporating and chemically decomposing the insulating oil.

Transformer Ratings

- Relays that detect rising internal gas pressure in the tank are able to detect such faults while they are still relatively minor.
- However, these relays cannot be too sensitive, or they operate needlessly for pressure surges caused by sudden changes in current flow, such as those caused by external faults.

Transformer Ratings

- It is important to be able to determine:
  - whether a transformer relay operated incorrectly, in which case the operator should restore the transformer to service.
  - whether there is a minor internal fault that should be repaired prior to re-energizing the transformer to prevent more extensive damage.
- Following a transformer relay operation, substation personnel typically perform inspections to determine whether an internal short circuit is present.

Transformer Ratings

They may:

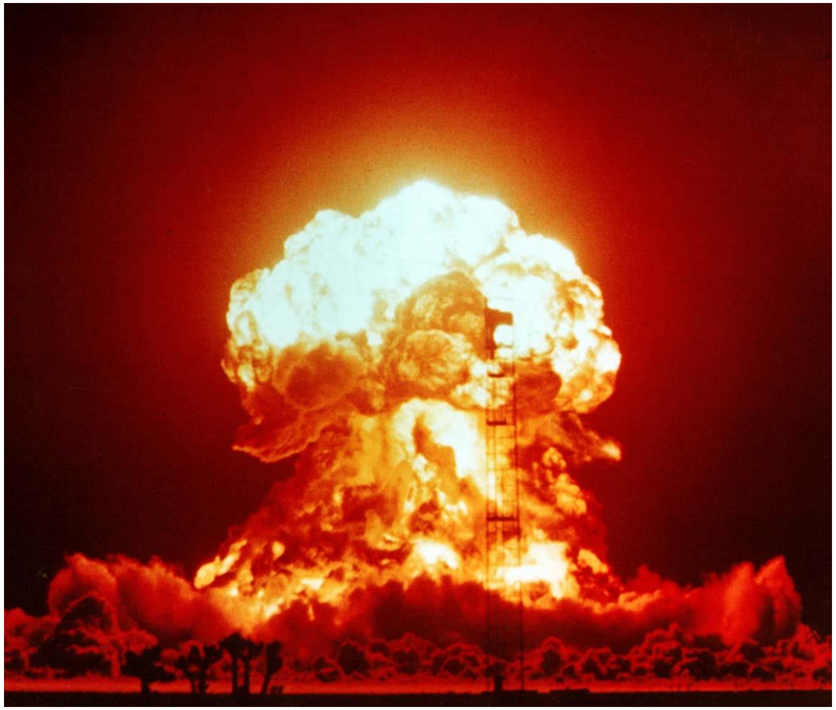
- Perform a resistance check to determine whether normally energized parts have come in contact with normally non-energized parts.
- Draw gas and oil samples from the tank and have the samples analyzed to determine whether excessive decomposition due to arcing has occurred.
- Measure the turns ratio (TTR) to determine whether a short circuit has occurred between turns.

Transformer Ratings

- If test results indicate that no internal fault exists, the transformer can be re-energized.
- As a preventive measure, utilities periodically inspect transformers to identify possible problems.
- Most transformers include gauges for reading transformer loading, oil levels and temperatures, and gas pressures and temperatures to assist in performing these inspections.

Transformer Ratings

So what happens when you exceed those transformer ratings???



No, not that bad!

Whoops! Wrong kind of transformers

Check Your Knowledge:

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