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

• The purpose of a transformer is to change an electric system quantity (e.g., voltage or current) from one level to another.

• A transformer is made up of two or more conductors wound around a single magnetic core, usually iron. The wound conductors, usually copper, are called **windings**.
Two-Winding Transformer

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

- Sometimes a third winding, the *tertiary winding*, is present. A tertiary winding provides power to an auxiliary circuit or a reactor.
- The core and the windings are mounted in a steel tank filled with mineral oil or some other liquid suitable for insulating and cooling. Insulated bushings, usually mounted at the top of the tank, connect the windings to other power system equipment.
How do Transformers Work?

• Passing an alternating current through a coil causes an alternating magnetic flux in the magnetic core.
• The magnetic flux circulates in the magnetic core, passing through another coil (the secondary winding), inducing an alternating voltage in this coil.
• The amount of induced voltage depends upon 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
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.
At the beginning of this section, we state that the transformer's purpose is to change an electric system quantity from one level to another. The amount a quantity changes is determined by the **turns ratio**, which is the ratio of the number of turns in the two windings.

The magnetic flux links the turns of the primary and secondary windings. This induces a voltage in each winding. Since the same flux cuts both windings, the same voltage is induced in each turn of both windings.
Turns Ratio

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

\[ \frac{V_1}{V_2} = \frac{N_1}{N_2} \]

- \(V_1\) 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.
We know from Module 2 that inductance is the electrical circuit property that opposes the change of current. The following statements describe the relationship between flux and inductance:

- Increasing the current flow increases the magnitude of the flux.
- Increasing the turns in the conductor increases the concentration of flux.
- Increasing the flux concentration increases induction.
- Inductance causes the current to lag the voltage. The current may lag the voltage in a transformer by a maximum of 90°.
There is one additional relationship we must consider – the relationship between $P_1$ and $P_2$. In an ideal transformer, the power into the transformer is equal to the power out of the transformer. In other words, there are no losses.

Therefore, the following relationship exists: $P_1 = P_2$

Using the relationships, we can determine the changes across a transformer.
Step-Down Transformer

Source

24,000 volts
100 A

500 turns

Load

2400 volts
1000 A

50 turns

\[ \frac{N_P}{N_S} = \frac{500}{50} = \frac{10}{1} \]

\[ 10 \quad = \quad \frac{E_P}{E_S} \]

\[ 10 \quad = \quad \frac{I_S}{I_P} \]
Step-Up Transformer

\[ \frac{N_P}{N_S} = \frac{50}{500} = \frac{1}{10} \]

\[ \frac{1}{10} = \frac{E_P}{E_S} \]

\[ \frac{1}{10} = \frac{I_S}{I_P} \]
Determining Output Voltage

• Let's apply these relationships to an example:
• A transformer has 300 turns on its primary winding and 600 turns on its secondary winding. The input voltage is 120 volts. What is the output voltage?
• The given quantities are:
  • V1 = 120 volts
  • N1 = 300 turns
  • N2 = 600 turns
Determining Output Current

- If we are given \( I_1 \), we can determine the secondary current, \( I_2 \), by using the following equation:

\[
\frac{I_1}{I_2} = \frac{N_2}{N_1}
\]

If \( I_1 = 800 \) amps, by substituting the given values into the equation we have:

\[
\frac{800}{I_2} = \frac{600}{300}
\]
Determining Power

• Remember, the power remains the same across the transformer. So, let's check to make sure the power into the transformer is the same as the power coming out of the transformer. (For purposes of this example, assume a resistive load; therefore, \( \cos \theta = 1 \))

• \( P_1 = V_1 \times I_1 \times \cos \theta \)
• \( P_1 = 120 \text{ V} \times 800 \text{ A} \times 1 \)
• \( P_1 = 96,000 \text{ Watts} \)
• \( P_1 = 96 \text{ kW} \)
Determining Power

- P2 should be the same. Let's see.
- \[ P2 = V_2 \times I_2 \times \cos \theta \]
- \[ P2 = 240 \, \text{V} \times 400 \, \text{A} \times 1 \]
- \[ P2 = 96,000 \, \text{Watts} \]
- \[ P2 = 96 \, \text{kW} \]
- These calculations show that the power on the primary side of the transformer equals the power on the secondary side of the transformer.
Step-Up/Step-Down Transformer

• In the example, the transformer changed the primary-side voltage from 120 V to a secondary voltage of 240 V to decrease the current on the secondary side. This is an example of a step-up transformer; the voltage was stepped up from 120 V to 240 V. Conversely, a transformer in which the energy transfer is from a high-voltage circuit to a low-voltage circuit is a step-down transformer.
Step-Up/Step-Down Transformer

- We can see from the example that 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.

- Some important concepts to remember about transformers include:
  - 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

- Although transformers take certain levels of voltage and current and change them to other levels, the total amount of power does not change from one side of the transformer to the other, if losses are ignored.

- The power on the primary side equals the power on the secondary side, if the transformer is without losses. In reality, transformers experience some losses. We discuss losses later in this module.
For a given value of power, the higher the voltage, the lower the current for use by the transmission system. Using lower current decreases losses.

- This is why transmission systems use high voltage. In *Module 3: Power System Overview*, we discussed the step-up transformers at generating stations (GSU). These transformers raise the generator output voltage.
While the transformer is operating, some electrical energy is converted into heat. But we know the purpose of the transformer is not to provide heat. The purpose is to transfer electrical energy from the primary to the secondary winding. Therefore, any heat the transformer produces is an energy loss and represents inefficiency.
The efficiency of a transformer is the ratio of the output power to the input power. The formula for efficiency is:

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

But we stated earlier that the power into a transformer is equal to the power out of the transformer, therefore the efficiency equals 100%. This is the ideal case. In reality, the transformer consumes some of the power. Most transformers have an efficiency of between 97% and 99%. 

Losses

• The power consumed is called *power loss*. *It is caused by the following:*
  – hysteresis losses
  – eddy current losses
  – copper (I²R) losses

• Hysteresis and eddy current losses occur in the transformer's core.

• Copper losses occur in the windings.

• All three loss types involve the conversion of electrical energy into heat energy.
Residual Magnetism

Hysteresis loss is due to *residual magnetism*, which is the 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. Every time the magnetic polarity reverses, the residual magnetism of the previous polarity has to be overcome. This produces heat. Hysteresis loss is the energy required to reduce the residual magnetism to zero and occurs every half cycle just before the core is re-magnetized in the opposite direction.
Transformer Losses

Heat

Hysteresis Losses
Eddy Currents

- **Eddy current** is the current that flows in the transformer's core and results from the voltage that is induced in the core by the primary winding. We know that the primary coil creates a flux that induces a voltage in the secondary coil. The flux also cuts the core, and we know that when a varying flux passes through a conductor it induces voltage. The core is itself a conductor. So a voltage is induced in the core as well as in the secondary winding. In the core, the energy is converted to heat. Eddy current can be reduced by laminating the transformer's core with a higher resistance material.
Transformer Losses

Eddy Current Losses

Heat
Copper Loss (I^2R Losses)

- **Copper loss** is the power dissipated in the transformer windings. Using larger conductors for the transformer windings reduces the copper loss, but the conductor size is limited by the openings in the core into which the winding must fit. However, larger conductors may be required to sustain higher currents.
Transformer Losses

Copper Losses

Heat

I$^2$R Losses

Current

Heat
Voltage Control

• Most high-voltage transformers contain taps on the windings for changing the transformer's turns ratio. A *tap* is a connection at some point on a primary or secondary winding which permits changing the turns ratio. Changing the turns ratio alters the secondary voltage and current.

• If the need for voltage adjustments is infrequent (e.g., adjustments are made for load growth or seasonal variations), utilities use no load de-energized tap changers. As the name implies, the transformer is de-energized prior to changing taps.
Tap Settings
Load Tap Changer

• Where frequent voltage adjustments are necessary, or in cases of a transformer that cannot be de-energized without jeopardizing customer service, utilities use load-tap-changing (LTC) transformers. LTC transformers, sometimes called tap-changing under load (TCUL) transformers, change transformer taps automatically, remote manually via SCADA, or manually by local control, while the transformer is energized.
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.

The load-tap changing equipment is usually housed in a separate compartment on the side of the transformer. Load-tap changing equipment is used on power transformers, autotransformers, and distribution transformers.
Load Tap Changer
Load Tap Changer (LTC)
How Transformer Taps Adjust Voltage

Changing taps adjusts the turns-ratio between windings
Up to this point we have been discussing single-phase transformers.

Three-phase transformers operate using the same principles: passing an alternating current through a primary winding causes an alternating magnetic flux in the core, which induces an alternating voltage in the secondary winding.

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.

Other three-phase transformers have three single-phase transformers connected together.
Three Phase Transformer
Three Phase Transformer
Transformer Bank

• The connection of two or more single-phase transformers as a unit is called a *transformer bank*. The most common methods for connecting the windings are:
  – Wye or Y (sometimes called star) connection
  – Delta connection

• We discussed the Wye and Delta connections in *Module 2: Fundamentals of Electricity*. Some methods of connecting the windings result in a voltage phase difference between the primary and the secondary windings. This is called a phase shift. The primary and secondary windings need not have the same configuration.
Transformer Bank
Transformer Connections

Note: In some transformers, the neutral point in the Y connection is grounded.
Transformer Connections

• We must consider these phase shifts before tying together circuits 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 30° phase difference.
Types of Transformers

• Power Transformers
• Autotransformers
• Phase Shifting Transformers
• Instrument Transformers
• Distribution Transformers
Power Transformers

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

- **Phase shifting transformers**, sometimes called 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. Inserting a phase shifting transformer on a transmission line changes the power flow over the line by changing the phase angle between locations thus redistributing the power flow.
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 120° (or 60° 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. We must scale down the values for use by meters and relays. Instrument transformers perform this function.

• Instrument transformers include current transformers (CTs) and potential transformers (PTs) (sometimes called voltage transformers [VTs]). Both of these transformers reduce system current and voltage to lower values for use by the relays and control circuitry. We discuss CTs and PTs in more detail in Module 8: System Protection.
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. Their operation is similar to a power transformer.
Transformer Cooling Systems

• Excessive heating in the transformer causes the insulation to deteriorate; therefore, it is important to prevent overheating. The technology for this is based on the idea that oil cools the core and windings. Transformer manufacturers equip transformers with cooling systems that prevent the permissible temperature rise of the insulating oil from exceeding specifications.
Cooling systems for large power transformers typically include:

- radiators in which outside air cools the transformer oil that circulates by convection through the radiators
- pumps to increase the circulation rate 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. While some heating is unavoidable, excessive heating can cause rapid deterioration and breakdown of the transformer insulating materials.

• The **transformer rating** is the maximum power that the transformer can safely carry without exceeding a temperature limit and is expressed in MVA. Transformers typically have more than one rating depending on the portion of the transformer cooling system that is operating.
Transformer Ratings

• The **forced-oil and air (FOA)** rating is the maximum rating that applies when oil pumps and cooling fans are operating.

• 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 **oil to air (OA)** rating applies when neither the fans nor the oil pumps are running. This is approximately 60% of maximum rating.
It is important to detect faults in the transformer windings before damage occurs. Major problems that cause extensive damage in transformers usually start out as small short-circuits between turns. These short circuits usually develop into an arc, which produces large volumes of gas by chemically decomposing the insulating oil.
• 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.
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.
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 to determine whether a short circuit has occurred between turns.
• 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.
So what happens when you exceed those transformer ratings?
Salem and Hope Creek Nuclear Power Stations, Hancock’s Bridge NJ
Whoops! Wrong kind of transformers.
QUIZ TIME