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Secure and Active Learning in Three-Phase Power Systems

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Secure and Active Learning in Three-Phase Power Systems

Abstract

This paper presents an alternative approach for teaching undergraduate students about three-phase power systems that can be applied in a secure and active learning environment. The proposed method encompasses six lectures and two lab sessions and is designed for junior and senior students in the field of electrical engineering. Each lecture spans 50 minutes, while the lab sessions extend over 160 minutes. The teaching methodology includes hybrid traditional lectures on three-phase power, discussing wye-wye, wye-delta, and delta-delta connections for balanced and unbalanced systems, and providing online resources. Over two weeks, students engage in a series of assessments designed to evaluate their understanding and skills. These assessments include in-class quizzes, pre-laboratory quizzes, post-laboratory quizzes, and exams. Our experience shows that most students found analyzing three-phase systems more straightforward by transforming the delta into wye-wye connections and determining the delta's corresponding voltage and current values for further analysis.

One of the assessment tools is an in-class quiz administered at the end of each week, covering key topics such as three-phase phase-to-natural and line-to-line voltage, current, and power calculations that they learned in one week. After the in-class quiz, students complete online pre-lab quizzes to reinforce their understanding of practical and determinative power system analysis. During the lab session, students wire the three-phase circuit, measure voltage, current, and power, and participate in a post-lab quiz that examines the three-phase power's conceptual aspects. The final assessment stage evaluates three-phase systems by taking an exam and solving the engineering problem.

This paper introduces a brief methodology for teaching three-phase systems. It provides an alternative secure instructional laboratory approach for students to explore wiring a three-phase system comprising three-phase wye and delta load connected systems, with and without transmission line impedances, powered by a three-phase line-to-line 208 *Vrms* AC source. The lab experience enables students to wire three-phase systems and make the connection between the theory they learn in the classroom and the practical applications in the library. They observe the time and phasor domains of the three-phase balanced and unbalanced power system in a secure environment.

Introduction

Electrical Energy and Machines is an elective course offered within the Electrical Engineering program in the Electrical Engineering and Computing Department. It aims to provide essential content through engaging in-person instruction. One of the key contents of the course is three-phase power systems, which includes six lectures and two laboratory exercises. Weekly quizzes are designed to assess individual mastery of theoretical concepts, while pre-lab and post-lab quizzes highlight the application of theory to practical power systems. Additionally, an exam will evaluate students' understanding of critical topics specific to three-phase systems.

The primary objective of this paper is to outline a teaching methodology for three-phase power systems while providing a safe and effective laboratory environment for engaging with high-power systems. Designing a laboratory that effectively addresses the fundamental concepts of high-power systems poses unique challenges. To overcome these, this paper introduces innovative strategies integrating theoretical instruction with hands-on lab experiences, fostering a comprehensive understanding of three-phase power systems.

Numerous outstanding textbooks are available that delve into the fundamentals of electrical engineering circuits, electrical power systems, and electrical machinery [1], [2], [3], [4], [5], and [6]. These resources provide a comprehensive understanding of essential theoretical concepts. Furthermore, many universities globally have embraced laboratory-based software to enrich the educational experience in electrical machines and three-phase systems, fostering a more hands-on approach to learning. Sarkar et al. introduced a teaching model as a learning model, guiding learners to acquire knowledge, skills, and attitudes effectively [7]. This paper aims to design a successful instructional model with three phases: pre-learning, learning, and post-learning sessions [7]. Welch and Berry applied a locally designed unit that offers a safe, reliable, and cost-effective alternative to traditional high-voltage demonstration stations [8]. This approach to hands-on design enhanced student learning by allowing them to explore three-phase power systems, visualize key concepts like phase rotation and circuit connections, and reinforce power system fundamentals. Goulart and Consonni developed an automated system using LabVIEW software and an experimental setup that includes a digital oscilloscope with a general-purpose interface bus (GPIB) connection [9]. Cook et al. introduced a power quality course featuring an innovative approach to teaching power quality concepts [10]. The course incorporates an electric power laboratory specifically designed for undergraduate education. Hess et al. developed a hands-on training program that emphasized safety procedures, innovative testing methods, and collaborative improvements between the two universities [11].

The current paper introduces a brief methodology of teaching three-phase systems and an alternative secure instructional laboratory approach for students to explore wiring a three-phase system comprising three-phase wye and delta 25W and 60 W light bulbs as three-phase loads, with and without transmission line impedances, powered by a three-phase line-to-line 208 Vrms AC source. The lab experience enables students to observe the time and phasor domains of the three-phase balanced and unbalanced power system in a secure environment. Students demonstrate the ability to identify, formulate, and solve complex engineering problems by applying engineering, science, and mathematics principles. This achievement aligns with ABET Criterion 3, Student Outcome 1 [12].

Methodology of Teaching Three-Phase Power Systems

Understanding three-phase power systems is critical for engineering students to excel in power system analysis and design. This course's strategic sequence of topics ensures that students build a solid foundation before diving into the complexities of three-phase systems. Starting with an overview of power systems, energy sources, and electrical safety provides essential context while reviewing Alternating Current (AC) waveforms. Root Mean Square (RMS) values and power calculations reinforce key principles. Revisiting electromagnetic field concepts bridges prior knowledge from physics to real-world applications in electrical engineering. Students begin with the fundamentals of AC generators and transition to practical applications. They explore the production, advantages, and applications of three-phase power and various system configurations like wye and delta connections. Simplifying the analysis of balanced and unbalanced systems allows students to focus on critical problem-solving skills and active learning.

Visualizing time-domain signals and transitioning to phasor domain analysis enhances comprehension, making the subject approachable and engaging. A more effective approach to active learning begins by revisiting the concept of an electromagnetic field and electric machines from prior physics courses. Introducing the visual construction and operation of the electric machine, focusing on how the coils are positioned 120 degrees apart on the stator, provides a solid foundation. A brief review of rotating magnetic fields and the principles underlying generator operation further engages students, making the learning experience more interactive and practical. By incorporating active learning techniques, such as online animation videos of the electromagnetic fields and working electric and synchronous machines and rotating magnetic fields, students connect theoretical concepts to real-world engineering challenges. This approach strengthens their understanding of three-phase systems and prepares them for advanced topics in power engineering, aligning with industry needs and academic standards.

Creating schematics of the stator in synchronous machines, including wye and delta configurations, has proven highly effective in deepening understanding. Highlighting the role of neutral nodes in wye connections offers students a critical learning opportunity to observe and analyze the differences between these two wiring methods. For example, the stator can be illustrated as a wye connection in Figure 1 or as a delta connection in Figure 2. Such visual approaches enable students to connect theoretical knowledge to practical applications, fostering a more profound comprehension of three-phase power generation.

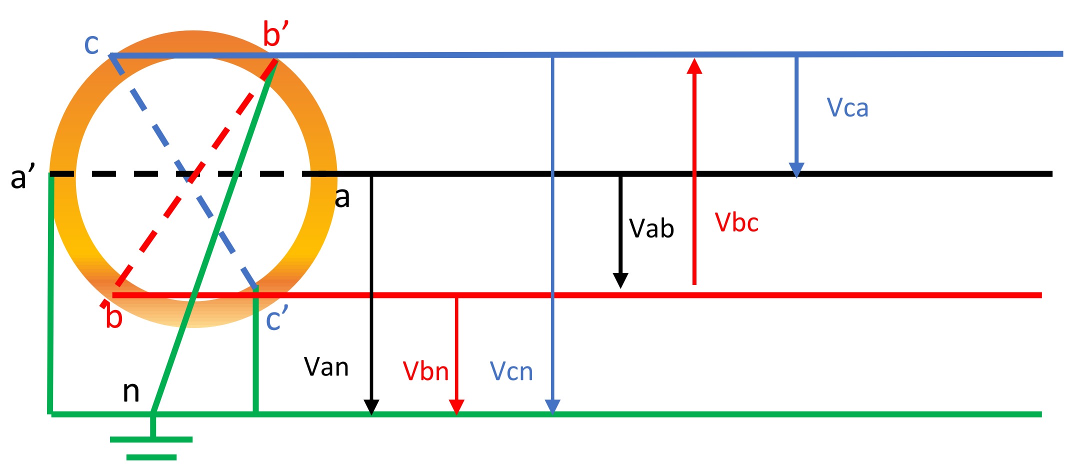

Figure 1. Schematic of a three-phase wye connection stator of a synchronous generator

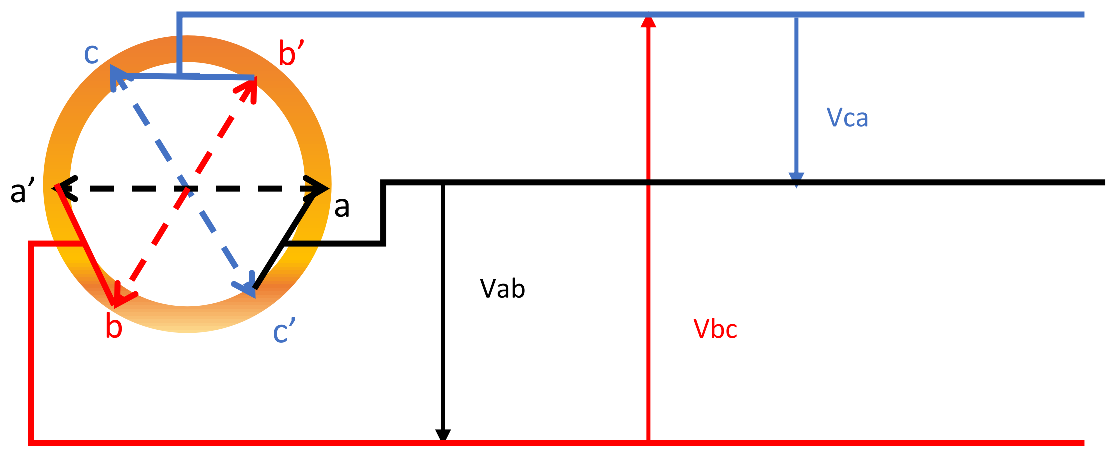

Figure 2. Schematic three-phase delta connection stator of a synchronous generator

To enhance engagement, we encourage each group of students to conduct an in-class exercise investigating the foundation behind the two types of wiring configurations using online resources, such as YouTube and artificial intelligence tools. Students then share their findings with the class, fostering collaboration and discussion. Subsequently, the focus shifts to introducing schematic drawings and notations in three-phase systems, including phase voltages, phase currents, and line-to-line voltages. Based on our experience, starting with a wye-wye connection circuit with line impedance provides a straightforward entry point, as illustrated in Figure 3.

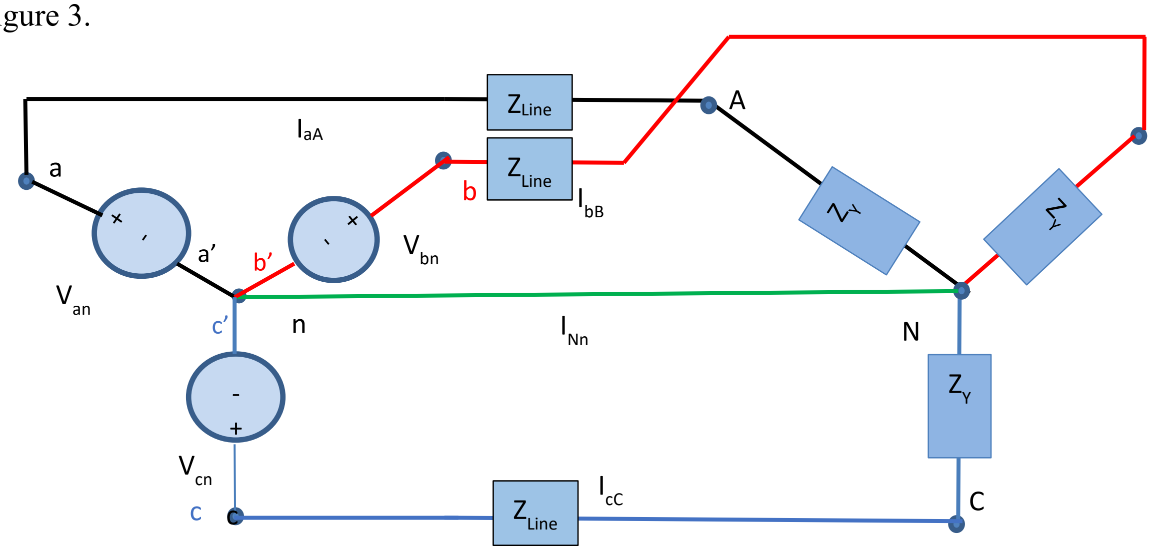

Figure 3. Schematic of a three-phase source and load wye-wye connection

The source phases (a, b, c) and load phases (A, B, C) notations are presented for a balanced and positive sequence configuration. The line impedances are shown as, Z_{Line}, in Figures 3 and 4. Circuit analysis is initially limited to the source-load loop (a−A−N−n), simplifying the process for students. After presenting this loop, students are asked to analyze a single loop, as shown in Figure 4. Then, a simple voltage division is applied to investigate the voltage and power in the line impedances and determine the load voltage. This step-by-step approach makes it easier for students to calculate the voltage, current, and power of the single circuit in Figure 4, building their confidence in analyzing more complex three-phase systems.

Assume that the voltage in phase (a) is at zero phase angle, and the current is at a positive phase angle of theta (θ) for the leading power factor or a negative angle for a lagging power factor system. The notations for Figure 3 and the equations (1), (2), (3) , and (4) are:

$\bar{V}_{an}$, $\bar{V}_{bn}$, $\bar{V}_{cn}$: source phase voltages

$\bar{V}_{AN}$, $\bar{V}_{BN}$, $\bar{V}_{CN}$: load phase voltages

V_{rms} and I_{rms}: the RMS value of the voltage and current

V_{max} and I_{max}: the maximum magnitude of the AC voltage and current

$\bar{I}_{aA}$, $\bar{I}_{bB}$, $\bar{I}_{cC}$: Line currents

$\bar{I}_{Nn}$: Neutral line current

$\bar{Z}_{Y}$ and $\bar{Z}_{\Delta}$: The load impedance of the wye and delta

$\bar{Z}_{Line}$: The line impedance

$\bar{V}_{Line}$: The line impedance voltage

ω: Electrical frequency in rad/second

θ: Phase angle between voltage and current at load

θ_s:Phase angle between voltage and current at source.

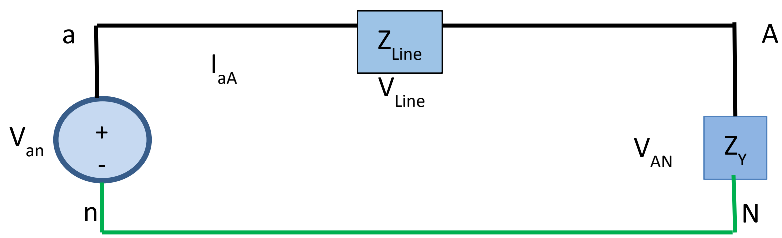

Figure 4. Schematic of phase **a** of the three-phase source and load wye-wye connection

Students find it easy to analyze the AC single-phase system shown in Figure 4, as this approach is commonly covered in various textbooks. They can effectively follow the equations in both the time and phasor domains.

$$"Phase\ a: \begin{cases} v_{an}(t) = V_{\max}\cos(\omega t) \\ \bar{V}_{an} = V_{\max}\angle 0° \Rightarrow \bar{V}_{an-rms} = \dfrac{V_{\max}}{\sqrt{2}}\angle 0° =: V_{rms}\angle 0° \\ I_{an}(t) = I_{\max}\cos\left(\omega t \pm \theta_s^{\circ}\right) \\ \bar{I}_{aA} = \bar{I}_{an} = I_{\max}\angle\left(\pm\theta_s°\right) \Rightarrow \bar{I}_{an-rms} = \dfrac{I_{\max}}{\sqrt{2}}\angle\left(\pm\theta_s°\right) =: I_{rms}\angle\left(\pm\theta_s°\right) \\ \bar{Z}_Y = \dfrac{\bar{V}_{AN}}{\bar{I}_{aA}}" \end{cases} \quad (1)$$

After that, the AC analysis of phase (b) in equations (2), and phase (c) in equations (3), in both time and phasor domains, for the positive sequence system.

$$"Phase\ b: \begin{cases} v_{bn}(t) = V_{\max}\cos(\omega t - 120^\circ) \\ \bar{V}_{bn} = V_{\max}\angle(-120°) \Rightarrow \bar{V}_{bn-rms} = \dfrac{V_{\max}}{\sqrt{2}}\angle(-120°) =: V_{rms}\angle(-120°) \\ I_{bn}(t) = I_{\max}\cos\left(\omega t - 120^\circ \pm \theta_s^\circ\right) \\ \bar{I}_{bB} = \bar{I}_{bn} = I_{\max}\angle\left(-120^\circ \pm \theta_s°\right) \Rightarrow \bar{I}_{bn-rms} = \dfrac{I_{\max}}{\sqrt{2}}\angle\left(-120^\circ \pm \theta_s°\right) =: I_{rms}\angle\left(-120^\circ \pm \theta_s°\right) \\ \bar{Z}_Y = \dfrac{\bar{V}_{BN}}{\bar{I}_{bB}}" \end{cases}$$

(2)

$$"Phase\ c: \begin{cases} v_{cn}(t) = V_{\max}\cos\left(\omega t + 120^\circ\right) =: V_{\max}\cos\left(\omega t - 240^\circ\right) \\ \bar{V}_{cn} = V_{\max}\angle 120° \Rightarrow \bar{V}_{cn-rms} = \dfrac{V_{\max}}{\sqrt{2}}\angle 120° =: V_{rms}\angle 120° \\ I_{cn}(t) = I_{\max}\cos\left(\omega t + 120^\circ \pm \theta_s^\circ\right) \\ \bar{I}_{cC} = \bar{I}_{cn} = I_{\max}\angle\left(120^\circ \pm \theta_s°\right) \Rightarrow \bar{I}_{cn-rms} = \dfrac{I_{\max}}{\sqrt{2}}\angle\left(120^\circ \pm \theta_s°\right) =: I_{rms}\angle\left(120^\circ \pm \theta_s°\right) \\ \bar{Z}_Y = \dfrac{\bar{V}_{CN}}{\bar{I}_{cC}}" \end{cases}$$

(3)

The final stage is to discuss balanced and unbalanced wye connections and introduce the line-neutral current from the load to the source in the equation (4) in phasor domains such as:

$$"\bar{I}_{Nn} = \bar{I}_{aA} + \bar{I}_{bB} + \bar{I}_{cC}" \tag{4}$$

After students were comfortable with one single phase, we introduced them to the load line-to-line voltage analysis by the following equations.

$$\text{Assume: } "\left|\bar{V}_{AN}\right| = \left|\bar{V}_{BN}\right| = \left|\bar{V}_{CN}\right| = V" \tag{5}$$

$$"\bar{V}_{AB} = \bar{V}_{AN} - \bar{V}_{BN} = \left(V\angle 0°\right) - \left(V\angle -120°\right) = \sqrt{3}\ V\ \angle 30°" \tag{6}$$

$$"\bar{V}_{BC} = \bar{V}_{BN} - \bar{V}_{CN} = \left(V\angle(-120°)\right) - \left(V\angle 120°\right) = \sqrt{3}\ V\ \angle(-90°)" \tag{7}$$

$$"\bar{V}_{CA} = \bar{V}_{CN} - \bar{V}_{AN} = \left(V\angle 120°\right) - \left(V\angle 0°\right) = \sqrt{3}\ V\ \angle 150°" \tag{8}$$

Where: $\bar{V}_{AB}$, $\bar{V}_{BC}$, $\bar{V}_{CA}$ are the phasor domain of load line-to-line voltages for phases A, B, and C. As long as students are comfortable with a balanced wye connection, talking and updating the equations for an unbalanced wye-wye connection system won't be challenging. Students also visualize it in practice in the lab.

The next lecturer on three-phase power concentrates on the mixed connection of the wye source and delta load connections. The concept is how to transform wye load connections to delta loads. Figure 5 is a simple analysis.

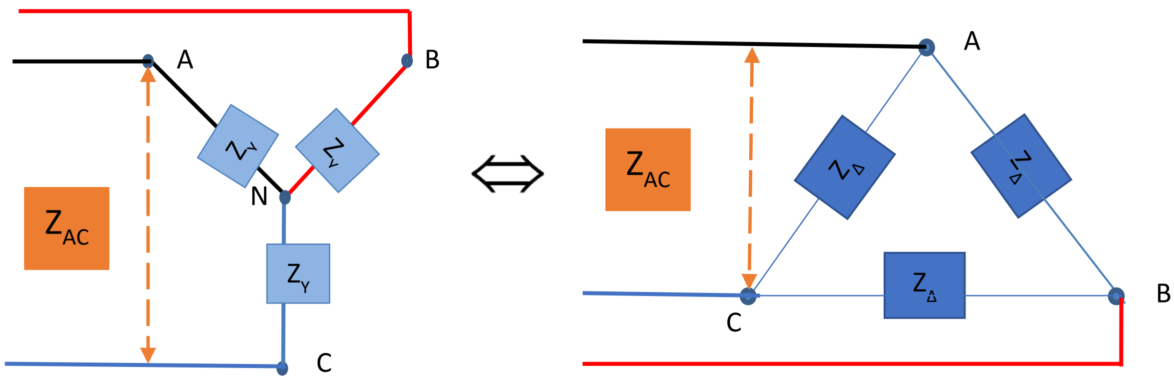

Figure 5. Transformation of wye load and delta connection loads

Students can easily find the transformation of load impedance in wye, $\overline{Z}_Y$, and into load impedance in delta, $\overline{Z}_\Delta$, in Figure 5, such as:

$$Wye\ Connection: "\overline{Z}_{AC} = 2\overline{Z}_Y" \tag{9}$$

$$Delta\ Connection: "\overline{Z}_{AC} = 2\overline{Z}_\Delta \,||\, \overline{Z}_\Delta \Rightarrow \overline{Z}_{AC} = \frac{2}{3}\overline{Z}_\Delta" \tag{10}$$

From the equation (9) and (10) the relationship between wye and delta load is:

$$"\overline{Z}_{AC} = \frac{2}{3}\overline{Z}_\Delta = 2\overline{Z}_Y \Rightarrow \overline{Z}_\Delta = 3\overline{Z}_Y" \tag{11}$$

Figures 6 and 7 introduced mixed wye-delta and delta-delta connections. To analyze these circuits, students transform each circuit into a wye-wye connection. Then, they use corresponding equations to find source and load phase voltages and current from the corresponding source and load line-to-line voltages. As students determine the delta phase voltages, they can use a simple Ohm's law to find the corresponding phase currents in delta connections. After students learned about the determinations and analysis of voltages in either of Figures 6 and 7, we introduced the delta load phase currents, $\overline{I}_{AB}, \overline{I}_{BC}, \overline{I}_{CA}$, determination in the phasor domain, and the direction of current inside the loop of the phase delta connection, such as:

$$\text{Assume:}\quad "\left|\overline{I}_{AB}\right| = \left|\overline{I}_{BC}\right| = \left|\overline{I}_{CA}\right| = I" \tag{12}$$

$$\begin{aligned} &"\overline{I}_{AB} = \frac{\overline{V}_{AB}}{\overline{Z}_\Delta} \\ &\overline{I}_{aA} = \overline{I}_{AB} - \overline{I}_{CA} = \left(I\angle 0^\circ\right) - \left(I\angle(120^\circ)\right) =: \sqrt{3}\,\overline{I}_{AB}\ \angle(-30^\circ)" \end{aligned} \tag{13}$$

$$"\overline{I}_{BC} = \frac{\overline{V}_{BC}}{\overline{Z}_{\Delta}} \tag{14}$$
$$\overline{I}_{bB} = \overline{I}_{BC} - \overline{I}_{AB} = \left(I \angle(-120^{\circ}) \right) - \left(I \angle 0^{\circ} \right) =: \sqrt{3}\ \overline{I}_{BC} \angle(-30^{\circ})"$$

$$"\overline{I}_{CA} = \frac{\overline{V}_{CA}}{\overline{Z}_{\Delta}} \tag{15}$$
$$\overline{I}_{cC} = \overline{I}_{CA} - \overline{I}_{BC} = \left(I \angle(120^{\circ}) \right) - \left(I \angle(-120^{\circ}) \right) =: \sqrt{3}\ \overline{I}_{CA} \angle(-30^{\circ})"$$

Most students found the analysis of three-phase systems to be more straightforward by transforming the delta connections into in wye-wye connections.

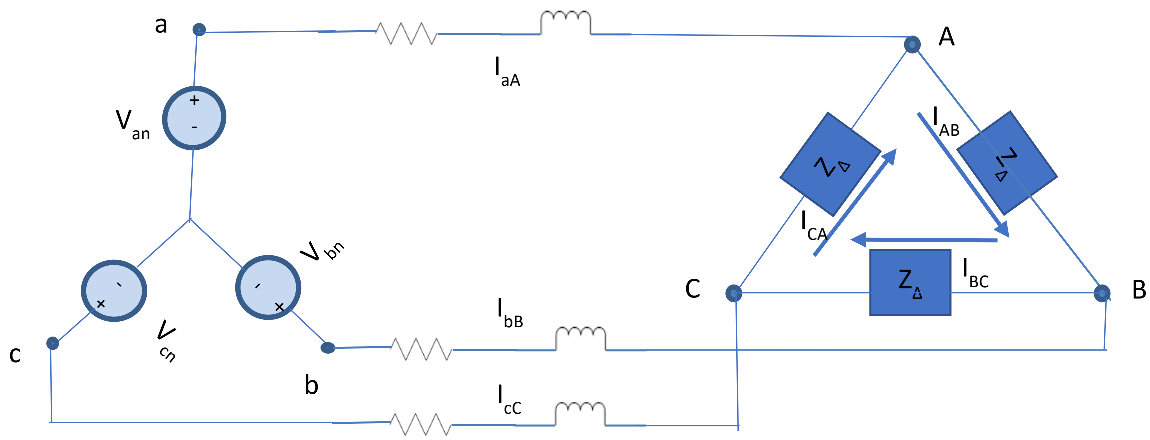

Figure 6. Mixed wye-delta connection

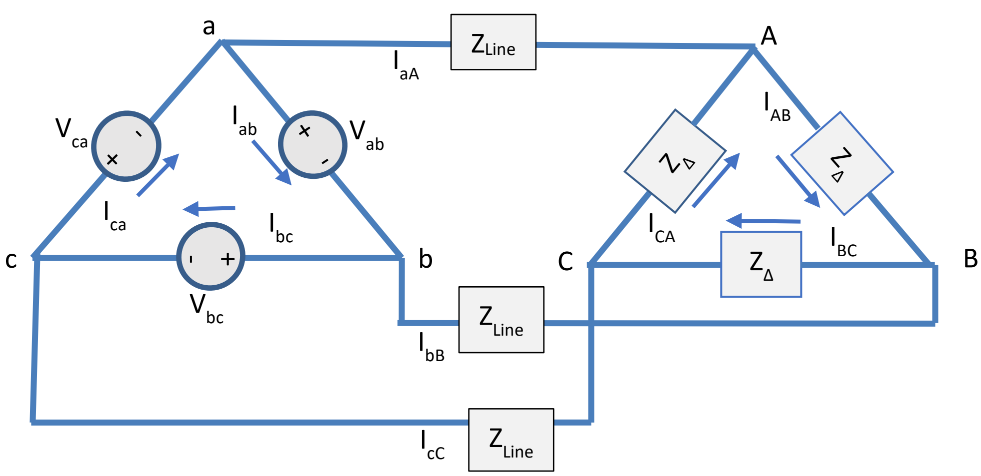

Figure 7. Delta- delta connection

Laboratory

Three-Phase Wye-Wye Connected Circuits

This lab aims to provide a thorough understanding of the wiring and operational principles of three-phase wye-wye connected circuits. Students will analyze balanced and unbalanced configurations and a balanced wye-wye system connected to a complex load.

Before the lab, students will complete a pre-lab quiz, which includes sketching a three-phase positive sequence with a wye-connected source supplying a three-phase 25 W lamp circuit at a line-to-line source voltage of 208 Vrms. They will also predict the relationship between the source and load line-to-neutral voltages in a balanced system, analyze three-phase currents and voltages, and estimate power at both the source and load.
During the lab, students wire the circuits, measure key parameters using the Hampden workbench, Fluke 435 power meter, digital multimeters, and resistive loads, and compare experimental results with theoretical calculations to identify discrepancies. Hands-on activities include wiring and testing circuits, taking precise measurements, and evaluating results against theoretical expectations. Figure 8 illustrates the measurement setup for a balanced wye-wye system with inductive impedance. The Hampden digital sensor records line-to-line voltage, and the Fluke 435 measures phase voltages, currents, and power. Figure 9 presents the three-phase source current measurement in the phasor domain, showing a lagging power factor due to inductive impedance. One 25-W light bulb is replaced with a 60-W bulb to create an unbalanced system, and the resulting measurements are analyzed.

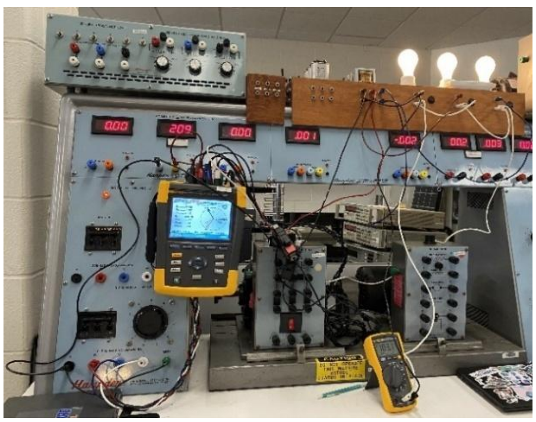
Figure 8. Balanced wye-wye connections

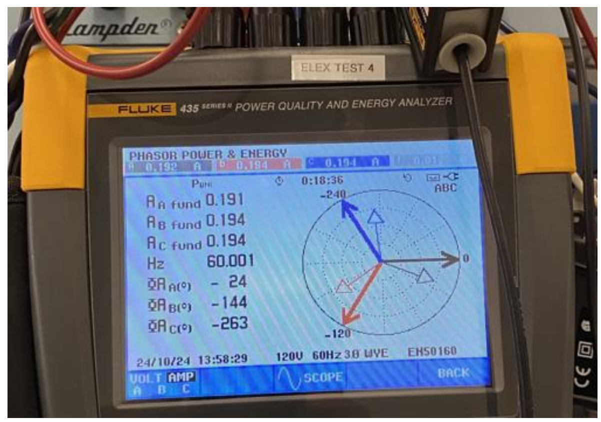

Figure 9. The current measurement in the phasor domain

<u>Three-Phase Wye-Delta Connected Circuits</u>
This lab aims to construct and analyze three-phase wye-delta connections, focusing on understanding their wiring configurations and operational principles. Specifically, students will examine balanced wye-delta connections, unbalanced delta load connections, and balanced delta load connections with line impedances.

To prepare for the lab, students will complete a pre-lab quiz similar to the one for the wye-wye connection. This includes sketching circuit diagrams, labeling components, and solving for key electrical parameters such as currents, voltages, and power relationships within wye-delta configurations. By engaging in these preparatory exercises, students will develop a foundational understanding of the theoretical aspects before conducting practical experiments. The set point for the three-phase source line-to-natural voltage of about 69 Vrms supplies power to a three-phase 25 W lamp circuit.

Students wire the circuits during the lab, perform measurements, and analyze their findings. The experimental procedures closely resemble those used in the wye-wye connection lab but are adapted explicitly for wye-delta configurations. This hands-on approach reinforces theoretical knowledge by allowing students to compare expected outcomes with real-world measurements.

The experiment utilizes the same equipment as previous labs, ensuring continuity and familiarity in the experimental process. The measurement setup, illustrated in Figure 10, includes a Hampden digital sensor to record the source phase voltage and a Fluke 435 power meter to measure source phase voltages, currents, and power. A Fluke 117 is also used to measure the delta load phase voltage, while its current is recorded using the Fluke 435. When a resistive load is introduced to the transmission line, the objective is to maintain a delta load phase voltage of 120 V, as depicted in Figure 11. Students will observe that line currents exceed load phase currents by a factor of the square root of three ($\sqrt{3}$), resulting in a lagging power factor from the source's perspective. Through these analyses, students gain valuable insights into the behavior of three-phase wye-delta systems, enhancing their ability to troubleshoot and optimize such circuits in practical applications.

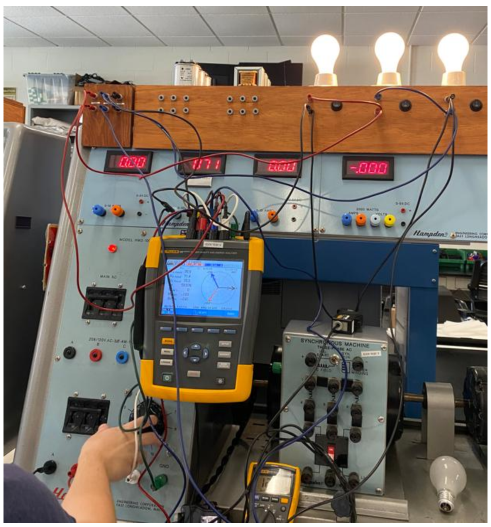

Figure 10. Balanced wye-delta connections

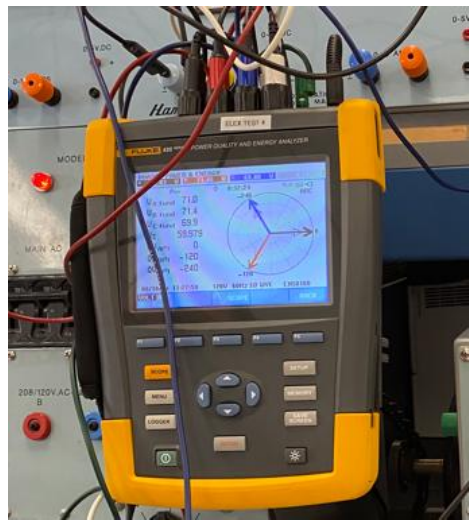

Figure 11. Voltage measurements in the phasor domain

Figure 12 shows the measurement results of an unbalanced three-phase load. The set point for the source phase voltages for the unbalanced system was about 69V. Figure 12 also shows the current measurement of the currents and voltages of the source phase of the phasor domain.

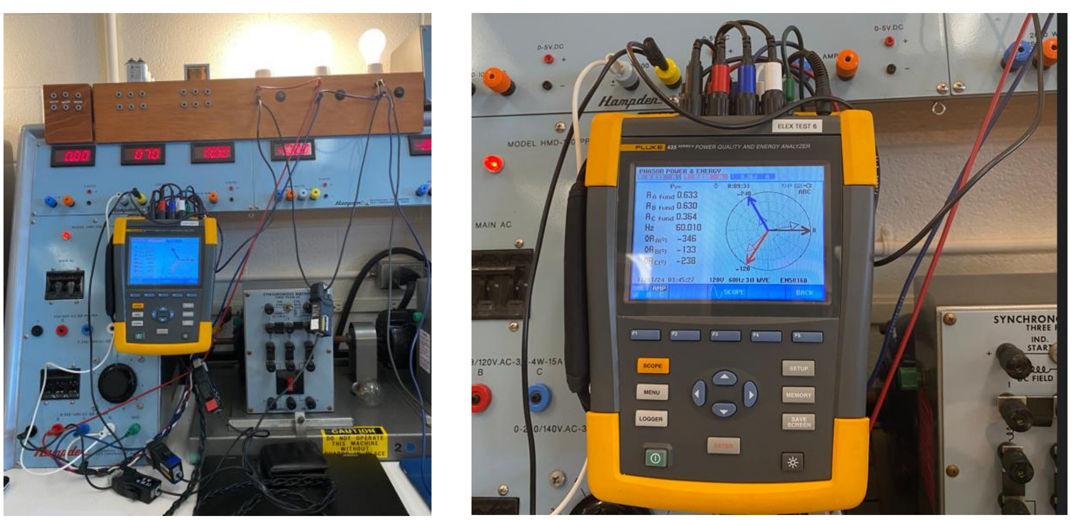

Figure 12. The phasor domain of an unbalanced three-phase wye-delta connection

Conclusions

This paper combined theoretical learning with hands-on experimentation, deepening students' understanding of three-phase power systems. Students reinforced foundational concepts while sharpening critical thinking and problem-solving skills essential for real-world engineering challenges. The structured progression from wye-wye to more advanced wye-delta and delta-delta systems provided a clear learning pathway, enabling students to develop their expertise systematically. This step-by-step approach aligned with ABET Criterion 3, Student Outcome 1, equipping students with the ability to identify, analyze, and solve complex engineering problems.

In a controlled laboratory environment, students worked with a line-to-line 208 Vrms AC three-phase source to analyze wye and delta-connected loads using 25 W and 60 W light bulbs. They measured and evaluated supply voltages and currents under balanced and unbalanced conditions, with and without transmission line impedance. Observing power systems in both time and phasor domains provides a comprehensive understanding of system behavior and performance.

This hands-on approach bridged the gap between theory and practice, reinforcing engineering principles while emphasizing safety and analytical rigor. By integrating experimentation with real-world applications, students gained practical insights into three-phase system operations, preparing them for the challenges of modern engineering practice.

Acknowledgment

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