Design and Pedagogical Validation of a Low-Cost Modular Three-Phase Educational Trainer

Solomon Benedict Ominyi[1*], Amarachi Modester Udefi[2]

[1]Department of Electrical Electronics Engineering Technology, Federal Polytechnic, Ngodo Isuoch, Nigeria

[2]Department of Computer Engineering Technology, Grundtvig Polytechnic, Oba, Nigeria

[*]Corresponding Author

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ABSTRACT

Hands-on laboratory experience is critical for effective teaching of three-phase power systems; however, many technical and vocational institutions in developing economies struggle with the high cost and limited flexibility of commercial training equipment. This paper presents the design, construction, and validation of a low-cost, modular three-phase educational trainer developed for resource-constrained environments. The proposed system supports both Star (Y) and Delta (Δ) configurations for balanced loads and features non-permanent patch-cord instrumentation, allowing seamless interchange between analog and digital measurement devices without structural modification. The trainer was built using off-the-shelf components at a total cost below USD 500. Technical performance was evaluated using the two-wattmeter method for both star and delta connections, achieving a mean percentage error of 3.8% ± 1.2%, which is acceptable for instructional laboratories. Pedagogical effectiveness was assessed through a one-group pre-test/post-test quasi-experimental study with 20 diploma-level students, showing a statistically significant improvement in conceptual understanding (mean scores increased from 56.3% to 80.9%, $t(19) = 8.91$, $p < 0.0001$, Cohen's $d = 2.24$). Complementary feedback was also obtained from 32 students. The results demonstrate that the proposed trainer offers a cost-effective, flexible, and pedagogically valuable solution for enhancing practical three-phase power systems education in resource-limited institutions. Limitations of the study, including the absence of a control group, are acknowledged.

Keywords: Three-phase power systems; Educational trainer; Two-wattmeter method; Modular instrumentation; Power systems laboratory; Engineering education.

INTRODUCTION

Three-phase power systems constitute a fundamental component of electrical and electronics engineering education, underpinning power generation, transmission, distribution, and numerous industrial applications. Effective instruction in this area requires not only strong theoretical grounding but also sustained hands-on laboratory experience that enables students to develop practical skills in circuit configuration, instrumentation, and power measurement [1].

In many technical and vocational institutions, particularly within developing economies, the provision of practical training remains constrained by under-resourced laboratories, inadequate equipment, and limited flexibility to support diverse instructional objectives. Commercial trainer systems and modern laboratory instruments are often expensive relative to institutional budgets, while outdated equipment further restricts hands-on learning opportunities [2, 3]. Consequently, instruction is frequently limited to theoretical lectures and software-based simulations. Although simulations are beneficial for conceptual understanding, they may not fully replicate real laboratory conditions or develop all industry-relevant competencies; they are most effective when complemented by practical laboratory experiences [4, 5].

In To address these challenges, several low-cost educational trainer boards and electrical training kits have been proposed in the literature to improve access to practical instruction [6, 7]. While these approaches reduce acquisition costs, many designs focus primarily on hardware implementation and acceptability rather than providing empirical evidence of pedagogical effectiveness [6, 8]. Comparative studies in technical education also indicate that simulation-only or hardware-only learning aids may not fully replicate real laboratory conditions or develop industry-relevant competencies, highlighting the need for rigorous validation of learning outcomes [9]. In resource-constrained institutions, where investments in laboratory infrastructure must be carefully justified, the absence of quantitative evidence on learning impact remains a significant gap in existing research.

This paper addresses this gap by presenting the design and validation of a low-cost, fully reconfigurable three-phase educational trainer that integrates modular hardware architecture with empirical pedagogical assessment. Unlike most existing low-cost trainers, the proposed system employs non-permanent patch-panel instrumentation, enabling seamless interchange between analog and digital measurement devices without soldering or structural modification. This approach supports progressive enhancement of laboratory capability while maintaining safety, affordability, and instructional completeness. Furthermore, the educational effectiveness of the trainer is quantitatively evaluated using a pre-test/post-test design, providing objective evidence of its impact on student learning outcomes [8]. Through this combined technical and pedagogical contribution, the work advances practical three-phase power systems education and offers a scalable solution tailored to the needs of resource-limited institutions.

The major contributions of this study are summarized as follows:

1. Development of a low-cost modular three-phase Star/Delta educational trainer for resource-constrained institutions.
2. Integration of reconfigurable patch-cord instrumentation that supports interchangeable analog and digital measurements.
3. Technical validation of the trainer using the two-wattmeter method.
4. Empirical evaluation of pedagogical effectiveness through a quasi-experimental pre-test/post-test study.

The remainder of the paper is organized as follows: Section II reviews related work on three-phase educational trainers and their limitations. Section III describes the design and construction of the proposed trainer. Section IV presents the technical and pedagogical results. Section V concludes the paper and suggests future research directions

LITERATURE REVIEW

Practical training in three-phase power systems remains a cornerstone of electrical engineering and engineering technology curricula. However, delivering effective hands-on laboratory experiences in resource-constrained environments, particularly in developing countries like Nigeria continues to present significant challenges. Commercial three-phase training systems are often prohibitively expensive, while many low-cost alternatives compromise on safety, flexibility, reconfigurability, or pedagogical effectiveness. In Nigerian polytechnics, for instance, issues such as unreliable electricity supply, overcrowded laboratories, and limited budgets exacerbate these problems, forcing reliance on theoretical instruction or simulations that fail to build essential wiring and troubleshooting skills [1]. Similar constraints are reported in Malaysian polytechnics, where three-phase system topics form part of the DET20033 Electrical Circuits course syllabus, yet laboratory facilities with three-phase supply sources are limited, and existing trainers used for practical work must be compatible with syllabus requirements and safety considerations [8].

Problem Statement: Existing trainers in many polytechnic laboratories, including those in resource-limited institutions in Nigeria often fall short of educational needs. For example, the three-phase star trainer used in the Electrical Engineering Department laboratory at Grundtvig Polytechnic Oba, Nigeria, is limited to star

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connections only and features permanently pre-wired setups, as shown in Figure 1. This design restricts students to basic observations without requiring them to perform connections themselves, thereby limiting the development of higher-level thinking skills. Additionally, it uses light bulbs as the sole load type, preventing experimentation with other loads, and requires a dedicated three-phase supply source, available in only a few laboratories—which complicates teaching and learning.

Similar issues persist in some Africa country, trainers are often constrained by cost, fixed instrumentation, and dependence on unreliable grid power, leading to suboptimal hands-on practice. These limitations result in products that are different from real-world applications and hinder student understanding, ultimately affecting lecturer effectiveness during practical sessions.

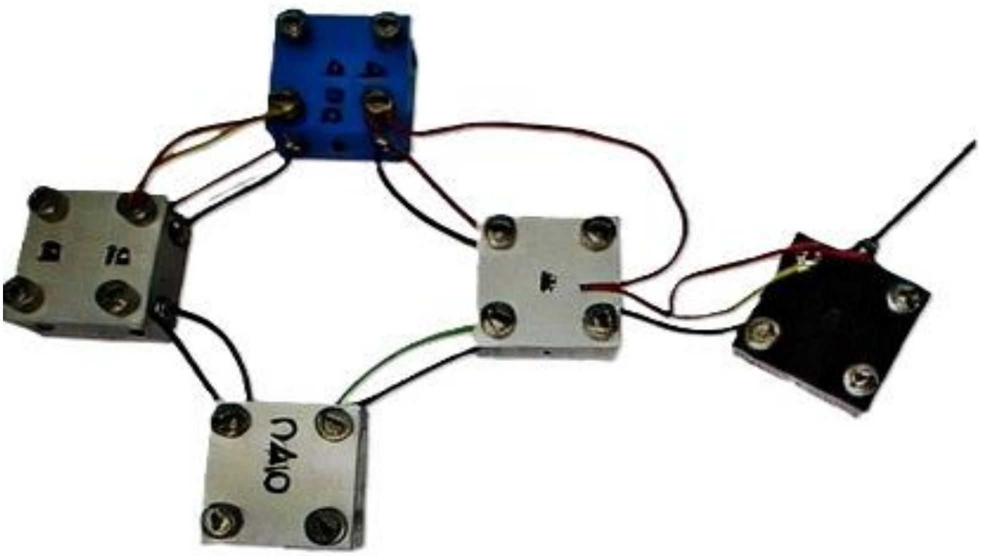

Figure 1: Existing three-phase Star (Y) trainer with fixed wiring configuration used for instructional demonstrations.

Three-Phase System Comparison: Several low-cost three-phase trainers have been developed in recent years to address the high cost and inflexibility of commercial systems. However, most still exhibit notable limitations in reconfigurability, instrumentation flexibility, supply compatibility, and empirical validation of learning outcomes.

[8] designed a compact Star/Delta Three Phase System Educational Trainer for Malaysian polytechnics. Their trainer supports both star and delta connections, can operate using either a three-phase or single-phase supply (via conversion), and allows basic wiring practice with multimeters. It is significantly smaller, more portable, and cheaper than market alternatives, addressing issues with fixed star-only trainers that limit student engagement. Nevertheless, the instrumentation remains largely fixed, and no quantitative pre/post-test evaluation of pedagogical impact was reported.

[6] developed and evaluated the acceptability of a low-cost Electro-Tech trainer board using locally available components. The design emphasized affordability and usability for basic electrical experiments in higher education settings in the Asia-Pacific region. While it received positive feedback on functionality and maintenance, it focused on general electrical training rather than full three-phase power measurement (e.g., two-wattmeter method) and offered limited reconfigurability.

[10] presented an educational Star-Delta Starter Trainer Kit with real-time inrush current monitoring using an ESP8266 microcontroller and current transformers. The kit incorporates industrial safety features (single-phase and overcurrent protection) and digital display for data validation. It is targeted at vocational students learning motor starting methods and provides good hands-on experience with modern monitoring. However, the design is more specialized toward motor control starters than general balanced-load power system experiments

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(star/delta configurations with resistive, inductive, and capacitive loads), and instrumentation is not fully modular for easy analog-to-digital swaps.

A 2025 study on the Development of an Electric Motor Control Trainer Board described a cost-effective board (~USD 500) that supports multiple motor control circuits, including Direct-On-Line (DOL) star and delta, forward-reverse, and dynamic braking [11]. It includes a single-phase to three-phase converter, making it suitable for laboratories with limited three-phase supply. The focus is on industrial relevance and troubleshooting skills, but like many others, it uses fixed or semi-fixed instrumentation and lacks rigorous quantitative assessment of student learning gains.

Commercial and semi-commercial three-phase trainers (e.g., NV7001 Three Phase Lab or similar low-voltage star-delta setups) as shown in Figure 2 often provide safe, low-voltage operation for studying phase/line relationships and balanced loads. They are compact and relatively affordable for basic experiments but typically feature permanently wired or fixed metering, limited load variety (frequently bulbs or motors only), and no support for seamless upgrades to digital or IoT-based measurement.

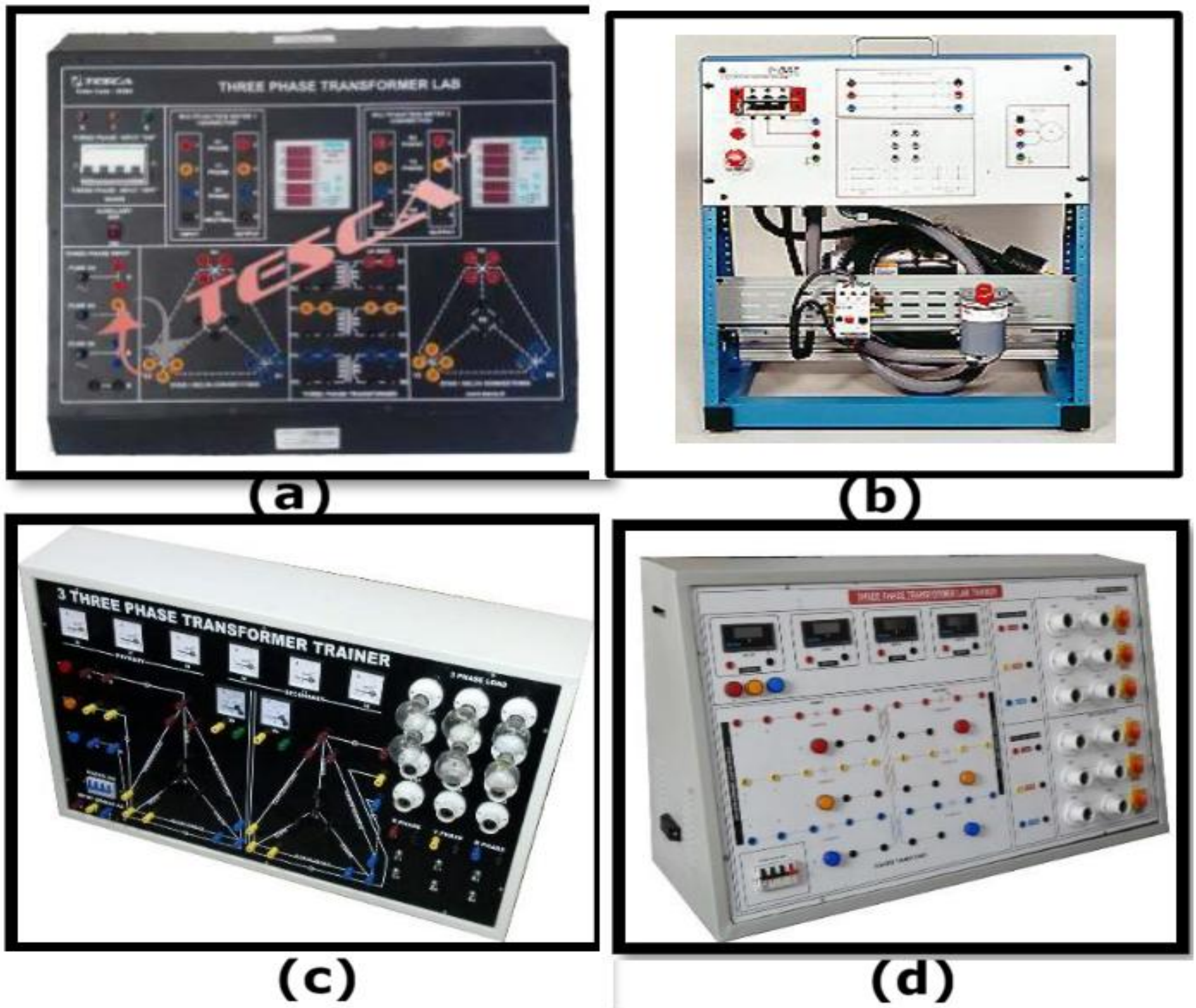

Figure 2: Examples of commercial and reported three-phase educational trainers. (a) Modular three-phase Star/Delta trainer with contactor switching (b) Three-phase motor trainer for star connection (c) Three-phase star connection trainer (d) Three-phase transformer trainer.

Across these designs and commercial offerings, recurring limitations include:

- Fixed instrumentation — making upgrades (analog to digital meters or future sensors) difficult without major rework.

- Restricted flexibility — dependence on dedicated three-phase supplies or limited load types.
- Insufficient pedagogical validation — most rely on qualitative feedback or hardware acceptability rather than statistical pre/post-test analysis.
- Higher effective cost for full functionality when safety enclosures, varies, and load banks are considered.

The present study addresses these gaps by designing a low-cost, fully reconfigurable three-phase educational trainer. The proposed system employs non-permanent patch-cord instrumentation using standard 4 mm shrouded banana connectors, enabling seamless interchange between analog and digital measurement devices without soldering or structural modification. It supports both Star (Y) and Delta (Δ) configurations under balanced load conditions and incorporates essential safety features, including miniature circuit breakers (MCBs), contactors, and thermal overload protection. The system is constructed entirely from off-the-shelf components, with a total material cost below USD 800. Importantly, the trainer's effectiveness is validated both technically, using the two-wattmeter method, and pedagogically through a quasi-experimental pre-test/post-test study involving 20 diploma-level students.

METHODOLOGY

This study adopted a combined engineering design and quasi-experimental research methodology to develop and validate a low-cost, reconfigurable three-phase educational trainer and to evaluate its technical performance and pedagogical effectiveness. The methodology consisted of four main stages: system design and construction, technical validation, pedagogical evaluation, and data analysis.

System Design and Construction: The trainer was designed to support instructional delivery of three-phase power system concepts through direct hands-on experimentation. A modular design philosophy was adopted to ensure flexibility, and cost efficiency. All electrical and measurement components were interconnected using 4 mm shrouded banana sockets and heavy-duty patch cords, eliminating permanently soldered instrumentation. This approach allows rapid reconfiguration of circuit topologies and seamless interchange between analog and digital measurement devices without structural modification to the trainer.

The overall system architecture, including the power supply unit, protection elements, connection panel, measurement

Table 1: Comparison of t Star (Y)three-Phase Educational Trainers

Ref	System Type	Key Features	Limitations	Identified Gap
[6]	Hands-on laboratory framework	Emphasizes experimental learning and practical skill development	Requires physical lab infrastructure; limited accessibility	Accessibility constraints
[7]	Active learning-based instruction	Improves engagement and conceptual understanding	Not hardware-specific	Lack of practical implementation focus
[11]	Instructional laboratory design framework	Defines objectives for effective lab learning	No actual trainer hardware	Absence of system design
[12]	Remote/virtual laboratory systems	Flexible and scalable access	No physical interaction	Limited hands-on experience
[13]	Remote laboratory platforms	Supports distance learning	Lacks real wiring practice	No psychomotor skill development
[14]	Power system simulation tools	Supports analysis and visualization	Cannot replicate real systems	Lack of practical exposure

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[15]	Electrical machines laboratory	Structured experiments with real equipment	High cost; limited flexibility	Cost and adaptability issues
[16]	Engineering laboratory development studies	Improves learning outcomes	Limited modularity	Lack of reconfigurability
This Work	Modular three-phase Star/Delta educational trainer	Low-cost (< USD 500); reconfigurable patch-cord instrumentation; supports Star (Y) and Delta (Δ); interchangeable analog/digital meters; integrated safety (MCB, contactors, overload protection); validated technically and pedagogically	Requires initial setup and instructor guidance	Addresses cost, flexibility, modularity, and lack of empirical validation

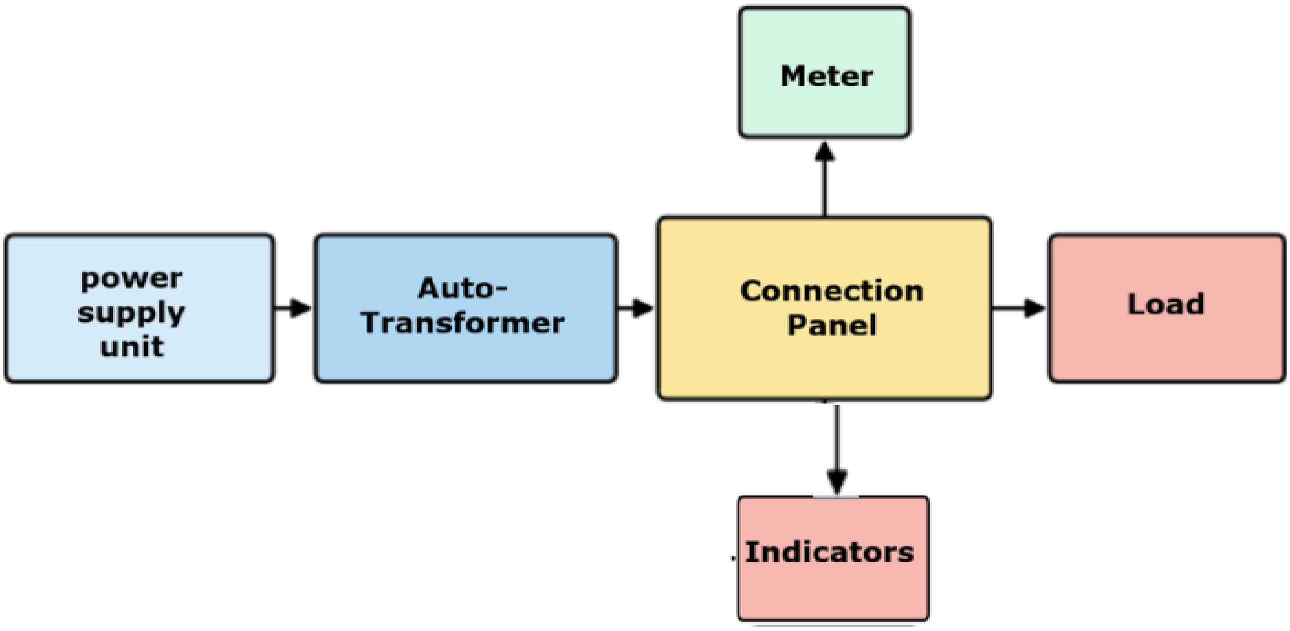

Figure 3: System block diagram

instruments, load banks, and autotransformer, is illustrated in Figure 3, which presents the functional block diagram of the trainer.

The system supports both Star (Y) and Delta (Δ) configurations for balanced three-phase loads. A three-phase, 415 V, 50 Hz supply was interfaced through a four-pole miniature circuit breaker, contactors, and a thermal overload relay to ensure electrical safety. A three-phase autotransformer was incorporated to enable controlled voltage variation during experiments. Resistive, inductive, and capacitive load banks were included to facilitate power factor studies under different loading conditions. Reserved terminals and mounting space were provided to allow future integration of digital sensors or network-based monitoring modules.

The experimental procedure involved recording line voltages, line currents, and wattmeter readings under steady-state conditions. The total three-phase power was computed as the algebraic sum of the two wattmeter readings. Experimental results were compared with theoretical values derived from measured electrical parameters. Percentage error was computed for each test case, and the mean error and standard deviation were used as indicators of measurement accuracy.

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A picture of the completed trainer, highlighting the patch-cord-based instrumentation and modular layout, is shown in Figure 4.

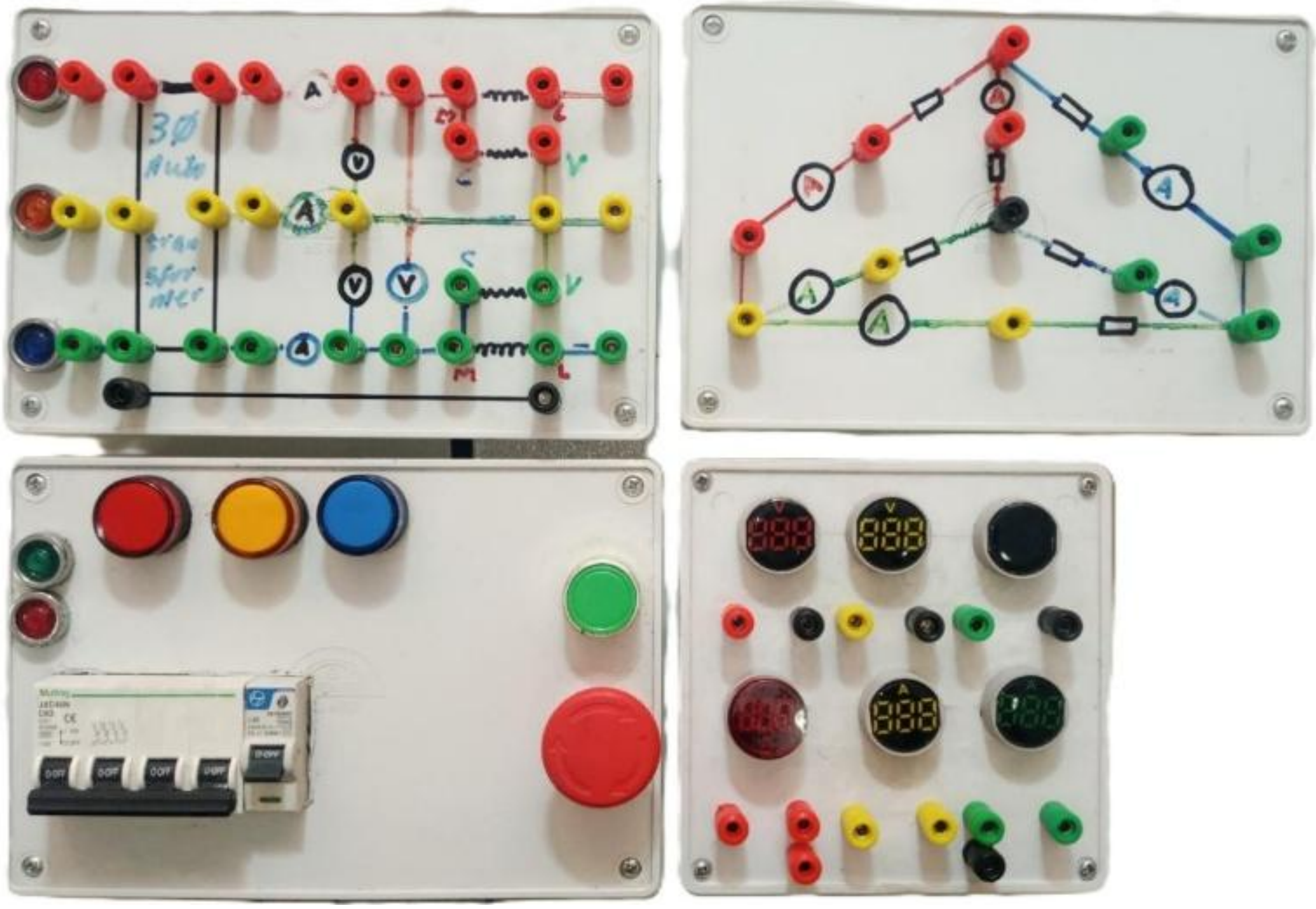

Figure 4: Completed trainer showing patch-cord instrumentation and modular connection points

Instrumentation and Measurement Configuration: The trainer supports both Star (Y) and Delta (Δ) configurations for balanced three-phase loads. For a balanced star-connected system, the relationship between line voltage V_L and phase voltage V_{ph} is given by

$$V_L = \sqrt{3}V_{ph} \qquad (1)$$

Similarly, for a balanced delta-connected system, the line voltage is equal to the phase voltage:

$$V_L = V_{ph} \qquad (2)$$

For both configurations, the three-phase real power $P_{3\emptyset}$ can be expressed as

$$P_{3\emptyset} = \sqrt{3}V_L I_L \cos\phi \qquad (3)$$

where I_L is the line current and cosϕ is the power factor of the load.

The measurement configurations for the two-wattmeter method applied to star- and delta-connected loads are shown in Figures 5 and 6, respectively.

Technical Validation Procedure: Technical validation was carried out using the two-wattmeter method under balanced

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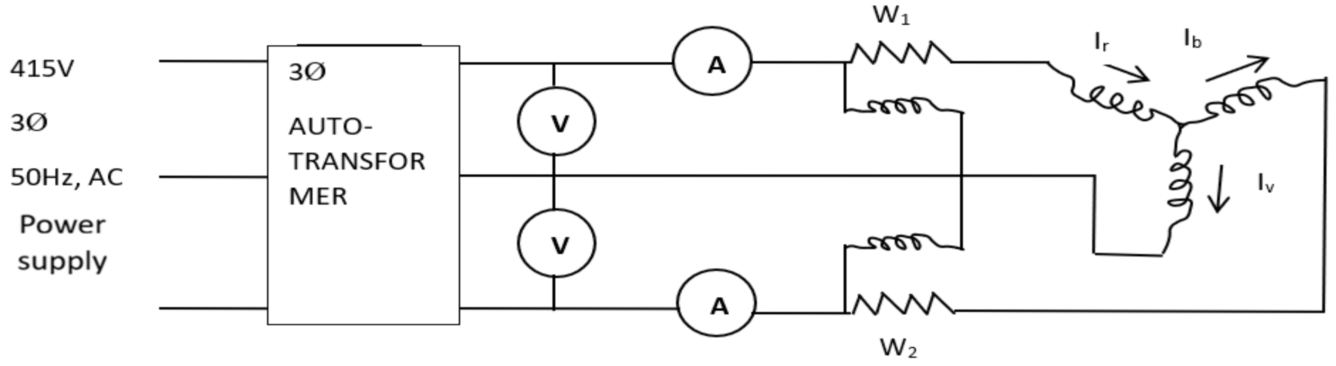

Figure 5: Two-wattmeter schematic – Star (Y) connection

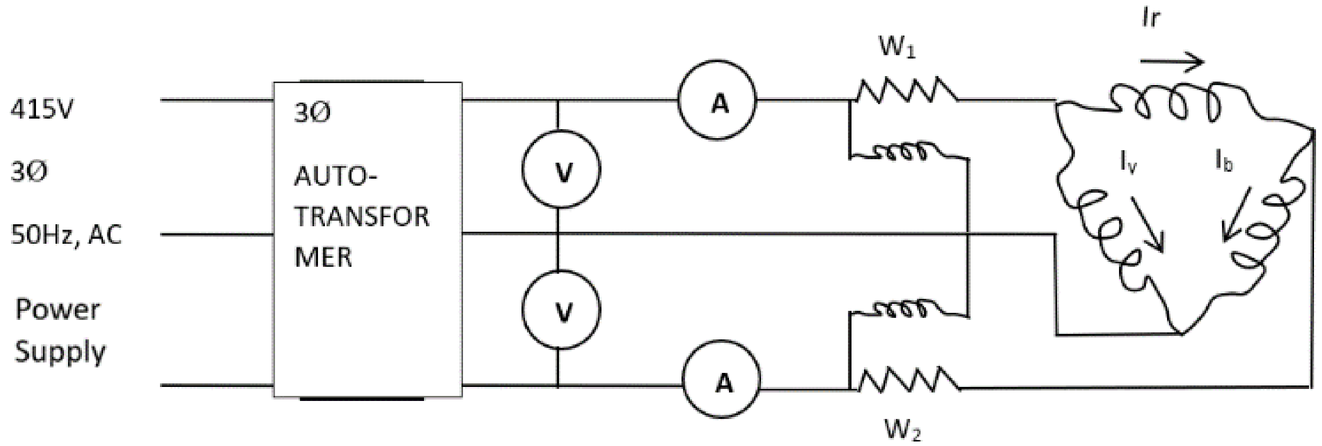

Figure 6: Two-wattmeter schematic – Delta (Δ) connection

load conditions. The total three-phase power was obtained from the algebraic sum of the two wattmeter readings:

$$P_{3\emptyset} = W_1 + W_2 \qquad (4)$$

Where $P_{3\emptyset}$ = total power and $W_1 + W_2$ = wattmeter readings.

The power factor of the load was computed from the wattmeter readings using

$$tan\,\theta = \sqrt{3}\frac{W_1 - W_2}{W_1 + W_2} \qquad (5)$$

$$\cos\phi = \cos(\tan - 1(\tan\phi)) \qquad (6)$$

For each test case, experimental power values were compared with theoretical values calculated using Eq. (3). The percentage error ε was determined as

$$\varepsilon(\%) = \left|\frac{P_{exp} - P_{theory}}{P_{theory}}\right| \qquad (7)$$

The mean error $\bar{\varepsilon}$ and standard deviation σ across all test conditions were computed to assess overall measurement accuracy.

Pedagogical Evaluation Design: The pedagogical effectiveness of the trainer was evaluated using a one-group pre-test/post-test quasi-experimental design. Twenty diploma-level students participated in a supervised two-hour laboratory session during which they configured star and delta connections, performed voltage and current

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measurements, and applied the two-wattmeter method. An example of student interaction with the trainer is shown in Figure 7.

Data Analysis: Student learning gains were evaluated by comparing pre-test and post-test scores. The mean score μ was computed as

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (8)$$

Figure 7. Students interchanging analog and digital meters during a practical session

where x_i represents an individual student's score and N is the number of participants.

The paired-sample t-statistic was calculated using

$$t = \frac{\bar{d}}{s_d\sqrt{N}} \qquad (9)$$

where $\bar{d}$ is the mean difference between post-test and pre-test scores and s_d is the standard deviation of the differences.

The effect size was computed using Cohen's d:

$$d = \frac{\bar{d}}{s_d} \qquad (10)$$

Statistical significance was evaluated at a 95% confidence level.

Ethical Considerations: The study involved routine educational activities with no collection of personally identifiable information. Participation was voluntary, and all assessment data were anonymized prior to analysis. Given the minimal-risk nature of the study, formal ethical approval was not required.

RESULTS AND DISCUSSION

Technical Performance of the Trainer: The technical performance of the developed three-phase trainer was evaluated using balanced star-connected and delta-connected loads comprising resistive, inductive, and capacitive elements. Detailed measured values for the Star (Y) connection are presented in Table 2.

Although the trainer fully supports both star and delta configurations (as shown in Figures 5 and 6), only star-connection results are presented in detail in this paper. This is because the two-wattmeter method and measurement procedure are fundamentally the same for both configurations under balanced load conditions, and the star connection is the most commonly used reference in instructional laboratories. Testing confirmed that the trainer performs equally well in the Delta (Δ) configuration, with comparable phase balance, voltage and current stability, and measurement accuracy (mean percentage error remaining below 4.5%).

For the star connection, the trainer produced stable balanced operation across all load types. The calculated power factors were 1.000 (resistive), 0.988 (inductive), and 0.745 (capacitive), with total power readings as shown in Table 2.

Measurement Accuracy and Error Analysis: The power factor values shown in Table 2 were derived from the two wattmeter readings using the standard formulas presented in Figure 5 and 6.

The mean percentage error in total active power measurement for the star connection was 3.8% ± 1.2%. Independent tests conducted on the delta connection yielded a very similar accuracy (mean error ≈ 4.1% ± 1.4%). Both results fall comfortably within the acceptable tolerance of ±5% for educational laboratory equipment

The close similarity in performance between the two configurations validates the trainer's reconfigurability and its suitability for teaching both star and delta connections. The non-permanent patch-cord instrumentation maintained consistent accuracy in both setups without introducing additional errors

Pedagogical Effectiveness: To evaluate the instructional effectiveness of the developed trainer, a quasi-experimental pre-test/post-test assessment was conducted involving 20 diploma-level students. The assessment measured students' understanding of three-phase Star/Delta connections, line and phase quantities, and power measurement procedures before and after the laboratory sessions.

The mean pre-test score increased from 56.3% to 80.9% in the post-test assessment, indicating substantial improvement in conceptual understanding and practical competence. A paired-sample t-test revealed that the improvement was statistically significant $t(19) = 8.91, p < 0.0001$). (In addition, the calculated Cohen's d value of 2.24 indicates a very large effect size, suggesting that the hands-on laboratory experience had a strong positive impact on student learning outcomes.

Table 2. Raw Measured Values (Star-Connected Balanced Loads)

Load Type	**Line Voltages (V)** **V_RY**	**Line Voltages (V)** **V_YB**	**Line Voltages (V)** **V_BR**	**Line Currents (A)** **I_R**	**Line Currents (A)** **I_Y**	**Line Currents (A)** **I_B**	**Power Factor (cos φ)**	**Wattmeter Readings (W)** **W_1**	**Wattmeter Readings (W)** **W_2**	**Total Power (W)**
Resistive	338	347	350	2.9	3.0	3.0	1.000	1000	870	1870
Inductive	330	332	333	0.9	1.0	1.0	0.988	200	240	440
Capacitive	189	187	191	1.7	1.8	1.7	0.745	70	220	290

These results indicate a substantial improvement in students' conceptual understanding after hands-on sessions with the trainer.

These findings demonstrate that the proposed trainer not only satisfies technical laboratory requirements but also provides a scalable and cost-effective solution for improving practical understanding and student engagement in three-phase power systems education.

Comparison with Existing Trainers: Table 3 presents a comparison between the developed trainer, the existing system currently used at POLISAS, and two representative commercial trainers (with specifications obtained from supplier catalogues and laboratory inspection, 2022).

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Table 3. Comparison of three-phase Star/Delta trainer

Feature	**Existing POLISAS Trainer**	**Commercial Trainer A**	**Commercial Trainer B**	**Developed Trainer**
Connection flexibility (Star/Delta)	Star only	Yes	Yes	Yes
Student wiring practice	No (pre-wired)	Partial	Yes	Yes
Load variety	Bulbs only	Bulbs + motor	Bulbs + inductors	Bulbs, inductors, capacitors
Supply flexibility (3-φ / 1-φ)	3-phase only	3-phase only	3-phase only	3-phase or 1-phase
Measurement flexibility	Fixed	Fixed	Fixed + portable	Fully flexible
Approximate cost (USD)	~$1,333	~$2,252 – $3,556	~$1,926	~$830
Suitability for low-resource labs	Low	Low	Moderate	High

The results indicate that the proposed trainer offers clear advantages in terms of cost, supply flexibility, and support for hands-on learning. These features are particularly important for polytechnic laboratories operating under limited budgets and inconsistent access to three-phase power, where affordability, adaptability, and active student engagement are essential for effective practical instruction.

Student Feedback and Learning Effectiveness: Student perceptions of the trainer were evaluated using a structured feedback form and an observation checklist administered to 32 second-semester EEC 433 students after four laboratory sessions (two star-connection experiments and two delta-connection experiments). The summarized responses are presented in Table 4.

A large majority of the students (84.4%) reported an improvement in their conceptual understanding of three-phase systems after using the trainer. Students frequently identified the ability to physically wire the circuits and immediately observe line and phase voltages and currents as the most beneficial aspect of the practical sessions.

Classroom observations by the instructors further supported these findings. The following trends were noted during the sessions:

Table 4. Student feedback summary (n = 32)

Statement	**Strongly Agree / Agree (%)**	**Neutral (%)**	**Disagree / Strongly Disagree (%)**
The trainer helped me understand Star and Delta connections better	84.4%	12.5%	3.1%
I could confidently make the connections myself	78.1%	15.6%	6.3%
The trainer is easy to use and safe	90.6%	6.3%	3.1%
I prefer this trainer over the previous fixed-wiring trainer	85.0%	8.7%	6.3%

- Reduced time spent correcting incorrect wiring compared to simulation-only laboratory sessions.
- Increased student engagement and peer discussion during practical activities.
- Improved performance in wiring-related questions in the end-of-topic assessment.

These qualitative and quantitative observations align with previous studies that emphasize the importance of hands-on, psychomotor learning in electrical engineering practical courses [8].

Discussion of Key Findings: The experimental results confirm the technical viability and instructional value of the proposed low-cost modular three-phase trainer. Three main findings emerge from this study.

First, the trainer maintained stable and balanced operation across resistive, inductive, and capacitive loads. The mean error in total active power measurement using the two-wattmeter method was 3.8% ± 1.2%, which falls within acceptable limits for educational laboratories. Although the actual power factors achieved were higher than the intended nominal value of 0.5 (0.988 lagging for the inductive load and 0.745 leading for the capacitive load) due to the available reactive components, the trainer accurately measured the real electrical quantities.

Second, the non-permanent patch-cord instrumentation architecture performed effectively, allowing seamless interchange between analog and digital meters without affecting measurement accuracy. This represents a clear advantage over the fixed-instrumentation designs prevalent in most existing low-cost trainers.

Third, the pedagogical evaluation revealed significant improvements in student performance. However, because a control group was not included, these gains should be interpreted as resulting from the overall instructional experience that incorporated the new trainer rather than the trainer in isolation. Future studies could strengthen causal claims by employing a control group or randomized design. Despite this limitation, the large effect size (Cohen's $d = 2.24$) and highly positive student feedback ($n=32$) suggest that the modular trainer meaningfully contributes to hands-on learning in three-phase power systems.

Overall, the results demonstrate that the developed trainer offers reliable technical performance and significant educational benefits in resource-constrained environments. The deviation in achieved power factors from the initial target further highlights the practical realities of laboratory experimentation and the importance of transparent reporting of actual measured values.

CONCLUSION

This paper presented a low-cost, modular three-phase educational trainer designed for resource-constrained engineering laboratories. The system employs off-the-shelf components and a non-permanent, patch-cord-based instrumentation architecture to ensure flexibility and ease of reconfiguration.

Experimental validation using the two-wattmeter method confirmed stable operation under balanced resistive, inductive, and capacitive load conditions, with a mean measurement error of 3.8% ± 1.2%, which is acceptable for instructional laboratories. Pedagogical evaluation demonstrated a statistically significant improvement in student performance, with mean scores increasing from 56.3% to 80.9%, supported by a large effect size and positive student feedback.

Overall, the results indicate that the proposed trainer provides an accurate, cost-effective, and pedagogically effective platform for teaching three-phase power systems. Its modular architecture also supports incremental upgrades, making it suitable for long-term use in resource-limited institutions. Despite the promising results, the study was limited by the relatively small sample size and evaluation within a single institution

Future research will focus on extending the capabilities of the trainer through the integration of digital sensors, data acquisition modules, and network-based monitoring features. This will enable real-time data logging, remote laboratory access, and the exploration of data-driven diagnostic techniques. Also, future versions of the trainer may incorporate fault simulation modules and advanced load configurations to support a wider range of power systems experiments.

Authorship Contributions

Authors equally contributed to this work.

Conflict Of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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