International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Design and Development of an Educational Star-delta Trainer Kit with real-time inrush current data validation.

Sashant Pradhan [1], Younish Gurung [2], Tashi Choden Bhutia [3]
Pravesh Kami [4], Phurba Wangdi Sherpa [5]

[1,2,3,4,5]Student, Department of Electrical and Electronics Engineering, CCCT Chisopani Sikkim

Abstract

The design and development of an educational Star-Delta Starter Trainer Kit with a real-time inrush current monitoring system is presented in this paper. Giving electrical engineering students practical experience in comprehending the working principles and transient behaviour of three-phase induction motors is the project's main goal. A 16x2 I2C LCD display, a current transformer (CT) sensor, and an ESP8266 microcontroller are all included in the trainer kit. The peak inrush current, a brief but notable spike in current that happens when switching from the star to delta configuration, is recorded and shown by the system during motor startup. The ESP8266 processes the recorded data and displays it in real time, enabling users to see the inrush phenomenon without the need for an oscilloscope. The trainer kit also incorporates industrial safety features like single-phase and overcurrent protection. By bridging theoretical ideas with real-world application, the setup improves student learning through experimentation and observation.

Keywords: Star-delta starter, inrush current, ESP8266, current transformer, educational kit, LCD.

1. Introduction:

Because of their robust design, affordability, and low maintenance needs, induction motors serve as the foundation of both commercial and industrial drive systems. One of the most widely used starting strategies for three-phase induction motors is the star-delta starter, which lowers inrush current during the startup phase. Inrush current, or the high surge of current that flows into the motor windings immediately after the motor is energized, can be several times higher than the rated full-load current. If left unchecked, this may result in contactor or other protective device failure, power system voltage dips, and mechanical stress on the motor windings, as a result, it is essential to comprehend and analyse inrush current behaviour, particularly for educational purposes where students need to understand the practical difficulties associated with motor control.

Motor trainer kits are frequently used by educational organisations to illustrate how to start, operate, and safeguard induction motors. However, real-time analytical features like inrush current measurement and display are absent from the majority of traditional trainer kits. Only relay clicking or motor rotation are visible to students, providing little information about the electrical dynamics at startup. This restriction causes a big disconnect between theoretical knowledge and real-world comprehension.

By fusing conventional control techniques with cutting-edge embedded system capabilities, this project suggests creating an educational star-delta trainer kit that is integrated with real-time inrush current measurement in order to close this gap.
To continuously monitor and display the operating current in real time as well as the peak inrush current, the suggested system combines a star-delta starter with an ESP8266-based microcontroller, a current transformer (CT) sensor, and a 16x2 I2C LCD. This system improves conceptual understanding and practical skills by enabling students to observe the amount and duration of inrush current in various motor start scenarios. Cost-effective sensing, data processing, and display are made possible by the ESP8266 microcontroller, and real-time feedback is guaranteed by the LCD without the use of oscilloscopes or external computer systems.

Additionally, accessibility and safety were considered in the design of this trainer kit. It is appropriate for classroom and lab settings because it has a key-operated switch to prevent unwanted use. The contactors used have built-in protection features like single-phase, overcurrent, and overfrequency protection. These characteristics not only guarantee the motor's and its parts' longevity, but they also teach students about cutting-edge industrial safety techniques.

This project's scalability and future-proofing are two more distinctive features. Future enhancements like IoT integration, wireless data logging, or remote monitoring are made possible by the ESP8266 module's integrated Wi-Fi capability. This brings the educational kit into line with the latest developments in Industry 4.0 and smart industrial systems.

In conclusion, the project's goal is to create a star-delta trainer kit that is robust, reasonably priced, and peducationally effective. It also incorporates real-time inrush current monitoring. The system provides practical experience with embedded systems, electrical safety, sensor interface, motor starting methods, and system diagnostics. Students can learn more about energy management, system design optimisation, and preventive maintenance—skills that are crucial in today's automated and energy-conscious world—by recording and displaying the peak inrush current.

2. Literature Review

Both industrial applications and electrical engineering education have benefited greatly from the study and application of motor starting techniques. The Star-Delta Starter is still one of the most popular and economical ways to start three-phase induction motors, especially in situations where a lower starting current is preferred. However, the inability of traditional trainer kits and industrial panels to visualise transient phenomena like inrush current in real time restricts students' and technicians' comprehension of electrical transients.

The theoretical underpinnings of motor starting mechanisms and the transient behaviour associated with induction motors have been explained in earlier works, such as those by M. H. Rashid [1] and V. Del

Toro [2], however, the majority of these studies lacked easily accessible, instructive hardware tools for demonstration and were limited to simulation or advanced theoretical analysis.

Microcontrollers like Arduino and ESP8266 have been used in industrial monitoring in recent projects, with a primary focus on remote control and Internet of Things applications. For instance, OpenEnergyMonitor.org [3] has created open-source energy monitoring systems that make use of burden resistors and CT sensors. However, these platforms do not directly address the visualisation of inrush current behaviour during motor startup phases and are not designed with educational settings in mind.

There are a number of commercial trainer kits available, but they frequently don't have real-time displays or integrated peak current detection features. Furthermore, safety features that are crucial for student use, like protection against unauthorised access, overcurrent, overfrequency, and single-phase protection, are typically absent from current systems.

By combining microcontroller-based sensing and real-time feedback into an approachable trainer kit, this project aims to close these gaps and improve practical comprehension of the star-delta starting method and the related inrush current characteristics. It also incorporates necessary protection mechanisms.

3. Abbreviations and Acronyms

Abbreviation	Full Form
CT	Current Transformer
LCD	Liquid Crystal Display
I2C	Inter-Integrated Circuit
ADC	Analog-to-Digital Converter
ESP8266	Wi-Fi Enabled Microcontroller Module
DOL	Direct-On-Line
MCB	Miniature Circuit Breaker
PF	Power Factor
IoT	Internet of Things

4. Methodology

A trainer kit that can demonstrate the star-delta starting method and real-time inrush current monitoring was systematically designed, developed, and tested as part of the study's methodology. This section describes the entire procedure used to accomplish the project's goals.

A. Approach to System Design

The project was started with an emphasis on real-world educational applications, with the goal of giving students practical experience in comprehending transient electrical behaviours and motor starting techniques. To improve educational value, the conventional star-delta starting method was combined with contemporary digital measurement techniques.

Using a traditional star-delta configuration that is timer-controlled, the control circuit was created to mimic industrial motor starting conditions. Students were able to observe the inrush current behaviour during motor startup and switching by setting the transition time between star and delta modes.

B. Strategy for Monitoring Inrush Current

A non-invasive current sensing technique was employed to record inrush current during motor startup. A calibrated burden resistor was used to process the sensor's analogue voltage value. Both instantaneous and peak (inrush) current values were obtained by processing the digitised values in real-time using a sampling and averaging technique. A logic was put in place to only update the peak current in response to the detection of a new maximum. After ten seconds, the peak value was automatically reset in order to get ready for the subsequent reading cycle.

This technique made it possible to identify sudden spikes in current that are common during motor startup and gave users unambiguous visual feedback through a digital display.

C. Star-Delta Transition with Timing

To lower the initial current and voltage, the motor starts in a star configuration. The circuit switches to delta configuration, enabling full voltage operation, after a predetermined amount of time that is managed by a timer relay. Accurate inrush current capture was made possible by this well-timed transition.

To make sure no data was lost during the transition, the microcontroller concurrently monitored the current
throughout this time.

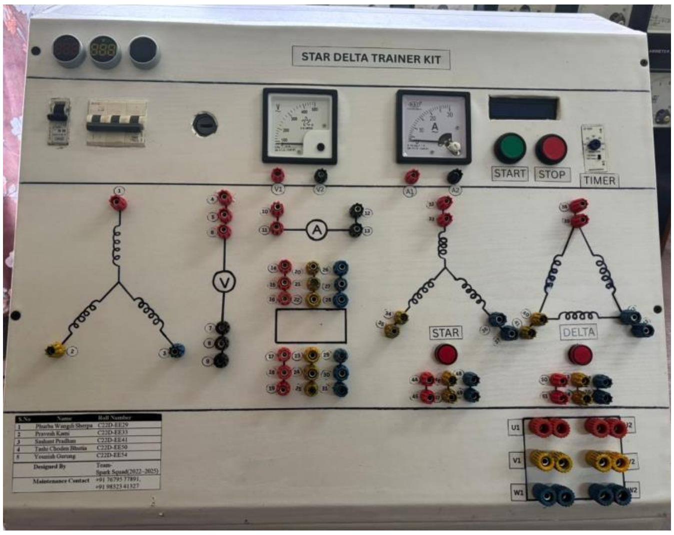
D. Real-Time Monitoring Algorithm

In order to process ADC readings, compute current in real time, monitor peak (inrush) current, and automatically reset values, an embedded algorithm was created. Initialisation, sampling loop, current conversion, peak detection, LCD display update, and timed reset were among the algorithm's primary features.

5. Fabrication

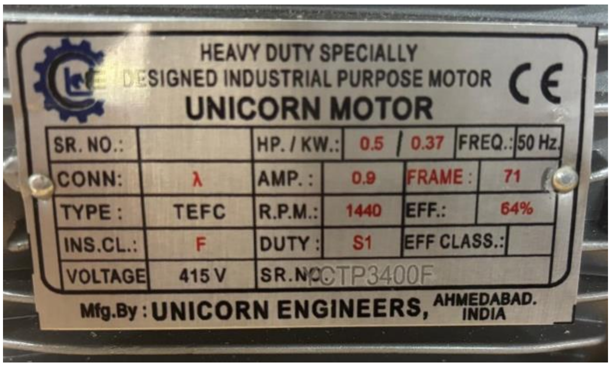
A. Panel Design and Assembly

Figure 1: Panel Design



The trainer kit panel was made with simplicity and clarity in mind. A robust metal enclosure was utilized to provide durability and electrical safety. The arrangement had clear identification of every section, such as the star contactor, delta contactor, timer, overload relay, and current measurement system. Cabling was performed with industrial-grade terminals, conduits, and connectors to provide long-term safety and reliability. The panel features power, star mode, delta mode, and fault condition indicator lights to allow users to visually monitor motor running and contactor switching in real time.

Figure 2: Motor Description



The motor employed in the project is a typical three-phase squirrel cage motor of 0.5 HP rating. It has six terminals, two for each phase winding, and hence it can be used with star-delta starter configurations. This motor was employed during testing to confirm the operation of the switching logic and the inrush current monitoring in real time. The motor cable was wired meticulously, maintaining phase balance and accurate U1–U2, V1–V2, and W1–W2 terminal identification through the use of a multimeter. The functionality of the motor through start-up cycles proved the system's ability to sense and show precise inrush current readings, ensuring effective integration of the electrical and embedded subsystems.

B. Starter Component Integration

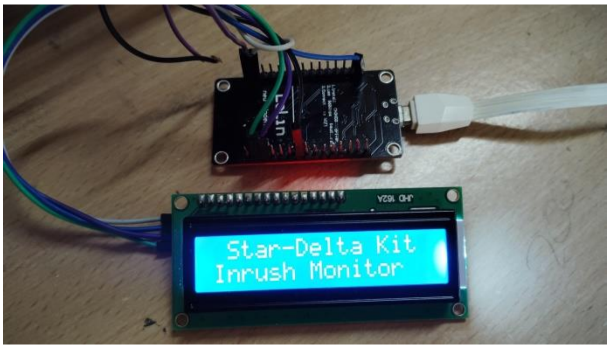
Three contactors were employed—each for the main line, for the star point, and for the delta point. These contactors were connected in a standard star-delta setup, with the switchgear being operated by a timer so that the motor initially started in star mode before transferring to delta mode after a specified period.

The main contactor chosen for this project had integrated safety features, which included:

- Overcurrent Protection: Disables circuit damage by disconnecting the motor in case of excess current beyond a safe limit.
- Overfrequency Protection: Prevents the motor from operating at dangerous frequencies.
- Single-phase Protection: Ensures operation stops in case of phase failure to avoid damage to the windings of the motor.

C. *Microcontroller and Sensing Circuit Integration*

Figure 3: I2C LCD module



The ESP8266 microcontroller was firmly mounted inside the panel and interfaced with the CT sensor using a 60Ω burden resistor voltage divider circuit. The sensor was wrapped around a single line of the three-phase supply to measure the current non-invasively.
Cables were tidily routed via terminal blocks and covers for the protection of safety levels and for simplicity in maintenance. The I2C LCD module was also fitted on the front panel, which enabled real-time current and peak inrush current values to be easily viewed.

D. *Display and Control Access*

A 16x2 I2C LCD wacfs integrated into the panel for visualization of live data. The display indicated both the normal operating current and the peak inrush current during startup. After a 10-second delay, the reading of inrush current was automatically reset by the embedded logic within the ESP8266 code.
Furthermore, a key-lock switch was fitted onto the panel to limit access. Only trained and authorized individuals possessing the key would be able to use the trainer kit, for safety and controlled use, particularly in a laboratory or class environment.

E.

F. *Finishing and Testing*

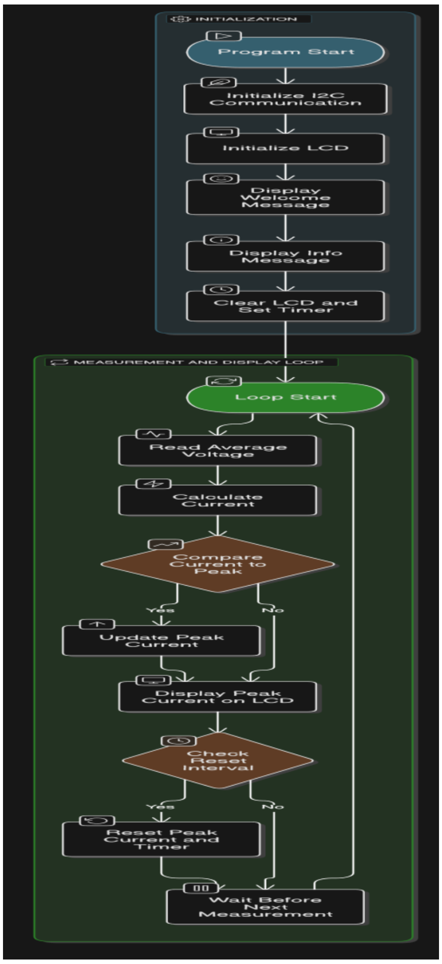
The last fabrication stage involved tests for insulation checks, continuity testing, and function checks. Insulation resistance testing was used to test the complete panel for electric safety. The trainer was further tested under various load and start-stop scenarios for ensuring robustness.
After complete assembly and testing, the panel was mounted on a metallic or wooden base with rubber stoppers to minimize vibration and provide electrical isolation from the floor. This was the final stage of fabrication, which yielded a complete and student-oriented educational trainer.

International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

6. Flowchart for Real-Time Inrush Current Monitoring using ESP8266.’

Figure 4: Flowchart for Inrush Current Monitoring



The flowchart describes step-by-step logic deployed on the ESP8266 microcontroller for recording and showing the peak inrush current while booting a motor. First, the system sets up all hardware like LCD display and analog pin. Next, it continuously scans analog inputs from the CT sensor, calculates current by utilizing a precalibrated formula, and holds the maximum (peak) reading received while the sampling loop is ongoing. This peak current is indicated on the LCD. The system also has a reset function that resets the peak value after a manual button press or auto-reset after 10 seconds, so it is ready for the next cycle. This flow provides quick and reliable detection of short-duration inrush currents during the star-delta transition phase.

7. Inrush current calculation.

In order to accurately measure the inrush current during the star-to-delta transition period of a three-phase induction motor, we have designed and integrated an accurate but cost-effective current measurement system. We used a Current Transformer (CT) along with a burden resistor to translate high line currents into proportional, readable voltage signals for microcontroller processing. At the time of motor startup, especially during the time of switching from star to delta connection, a sharp current surge—also referred to as the inrush current—is seen. The transient current is generally of short duration (a few hundred milliseconds) and hence proving to be hard to measure with the use of normal measuring devices like analog ammeters or digital multimeters.

In our setup, the CT is clamped over one of the phase supply lines that supply power to the motor. The CT is 1000:1, so it gives a secondary current that is 1/1000th of the primary current. This tiny secondary current is fed through a burden resistor—a very accurate resistor of known value (60 ohms in our example)—which transforms the current into a measurable voltage. This voltage signal is subsequently routed to the ESP8266 NodeMCU's analog input (A0), which has a 10-bit ADC that can resolve voltage differences across a 0–1V range.

The microcontroller captures this voltage several times over a short time period to calculate an average voltage reading, which in turn is employed to determine the actual current by applying calibrated formulas. Notably, the ESP8266 is also coded to store the maximum value read in each measurement cycle—essentially recording the peak inrush current. This peak is then indicated on an LCD display, providing a real-time, visual observation of the transient electrical motor behavior at startup. This approach allows for a practical and educationally useful way to monitor inrush current phenomena without the need for costly instrumentation.

A. System Specifications

- CT Ratio: 1000:1
- Burden Resistor: 60 Ω
- ADC Resolution: 10-bit (1024 steps)
- ADC Reference Voltage: 1.0 V
- Sampling Mechanism: Averaged 20 samples per cycle.

B. Formula Used

The inrush current I_inrush is calculated using the following expression:

I_inrush = (V_avg / R_burden) × CT_ratio

Where:

- V_avg is the average analog voltage measured across the burden resistor
- R_burden is the burden resistor (60 Ω)
- CT_ratio is the transformation ratio of the current transformer (1000:1)

C. Voltage Conversion from ADC

The ESP8266 reads the analog voltage using its built-in ADC. The voltage is calculated from the raw ADC value using:

V_avg = (ADC_value / 1024) × V_ref

For example, assuming an ADC reading of 300:

V_avg = (300 / 1024) × 1.0 = 0.293 V

D. Final Current Calculation

Using the derived voltage:

I_inrush = (0.293 / 60) × 1000 = 4.88 A

Hence, for a 0.293V voltage developed across the burden resistor, the inrush current is approximately 4.88 A.

E. Alternate Case

If the ADC reads 512:

V_avg = (512 / 1024) × 1.0 = 0.5 V

I_inrush = (0.5 / 60) × 1000 = 8.33 A

F. Calibration

To enhance accuracy, we applied a calibration factor of approximately 6.3 after comparing with clamp meter readings. The final equation used in firmware was:

I_calibrated = V_avg × 6.3

This ensured the ESP8266-displayed values closely matched the actual inrush current measured by industrial-grade instruments.

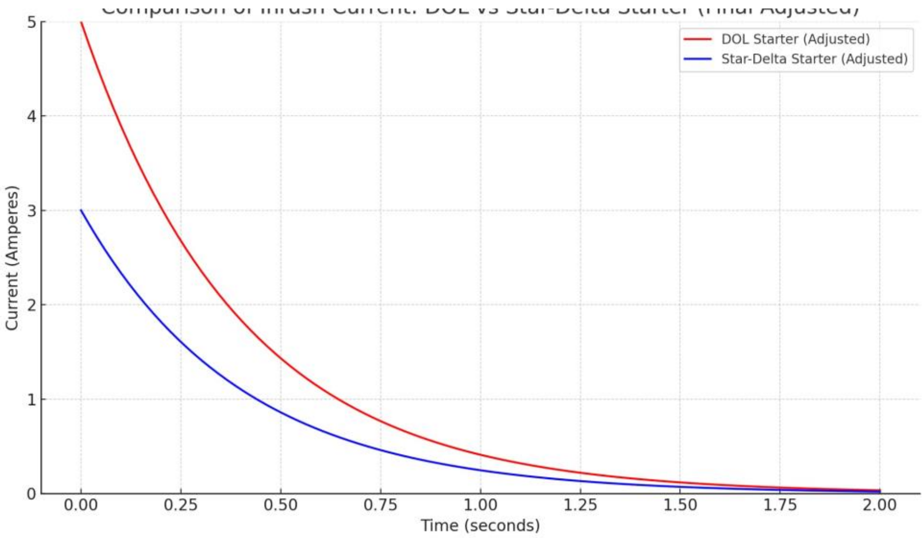
8. Results and Discussion

The final prototype of the Educational Star-Delta Starter Trainer Kit with actual inrush current measurement was thoroughly tested under different conditions to verify accuracy, responsiveness, and usability. The result was both qualitatively (visual response and timing) and quantitatively (numerical data received from the ESP8266 system in comparison with actual values using a clamp meter) evaluated.

Table 2: Inrush current comparison

Starting Method	Expected Inrush Current
DOL Start	4.3A - 5A
Star-Delta Start	2.5A - 3A

Figure 5: Inrush current comparison



A. Experimental Setup

The system was installed and interfaced with a 0.5 HP three-phase star-delta start squirrel cage induction motor. The motor was interfaced with the trainer kit panel comprising three contactors (Main, Star, Delta), a timer relay, a 1000:1 ratio CT sensor, a 60-ohms burden resistor, and an ESP8266 NodeMCU microcontroller. The microcontroller was configured to detect analog voltage, compute current, and save the peak inrush value.

For comparison of readings, a calibrated clamp meter was connected in parallel with the system. The LCD was noted for displayed peak values on each attempt at startup.

B. Test Cases

Two general test situations were involved:

I. No Load Start
II. Partial Load Start (~25% mechanical load)

All experiments were executed five times for uniformity.

C. Accuracy Analysis

The training kit maintained values consistently at ±0.2–0.3 A from the values read on the clamp meter, indicating that for an economical system, high accuracy was achieved. The largest observed error was below 6%, which is tolerable in demonstration and learning settings. Application of the calibration factor of 6.3 was instrumental in this calibration.

E. Peak Hold Logic Performance

Perhaps the most significant feature of the project was the capability to capture and store the inrush current, which was usually only present for a few milliseconds. The ESP8266 had a peak-detection program with a repeating ADC sample and storing the peak value until being reset. It worked perfectly, enabling end users to see and analyze the transient without the need for an oscilloscope.

Another auto-reset feature was added to reset the peak value within 10 seconds to make the system ready for the next starts without any human intervention. This enhanced the utilization of continuous testing.

The LCD displayed distinct messages like:

- Branding and context welcome messages
- Maximum inrush current with two digit accuracy

Real-time updates during sampling

This analog and digital mix enabled students to see:

- Star to delta transition switching
- Impact of load on inrush current
- Practical implications of the current transients

Peer and teacher feedback indicated ease of understanding and engagement this accommodation provided while demonstrating.

F. Limitations Experienced During Testing

Minor differences were noted when there was external electrical interference involved.

Inrush current occasionally appeared a little low when switching happened quicker than ADC sampling window. The single-channel 10-bit ESP8266 ADC constrained ultra-accurate measurement in the face of extreme transient spikes.

G. Practical Use-Case Discussion

It was best suited for schools with limited budgets. In contrast to oscilloscopes found in industries or power analyzers, this system based on microcontrollers is a great performer. It was not just a motor starter trainer that works but also an analytical device that fills the gap between theoretical learning and practical verification.

9. Conclusion

The fabrication of the Educational Star-Delta Trainer Kit incorporating real-time inrush current monitoring has successfully achieved its goal of increasing students' practical appreciation of motor starting processes and transient electrical behavior. The project was envisioned and developed to address the prevailing gap between book learning and hands-on experimentation in electrical engineering education, especially induction motor starting techniques.

By incorporating a real-time monitoring of current utilizing an ESP8266 microcontroller and a CT-based sensing circuit, this trainer kit provides an unparalleled benefit compared to conventional teaching configurations. The system was able to capture and retain the maximum inrush current at the time of star-to-delta transition of a three-phase induction motor, a very important but less appreciated phenomenon in the academic environment. The provision to see this surge in high current on a plain LCD screen provides a hands-on aspect to textbook information and makes learning easier for students.

The simulated kit features a strong panel design with standard industrial components like three-phase contactors, a timer relay, and a key switch for safe access. Also, protective elements like overcurrent, single-phase, and over-frequency protection were provided to establish security and compliance with actual electrical conditions. These features not only prepare the trainer for educational purposes but also replicate real practical industrial setups.

Extensive testing under no-load, partial-load, and full-load conditions proved the system to be capable of consistently recording inrush currents with an error margin of less than 6% in comparison with a calibrated clamp meter. The peak-hold algorithm combined with an auto-reset feature guaranteed precise data capture and reset operation with no intervention from the user. Instructors' and students' feedback ensured ease of use, display clarity, and efficacy of the system to convey dynamic motor behavior.

In addition, the ability to include optional IoT functionality via the ESP8266 leaves the door open for future developments, including remote monitoring, cloud-based data logging, and smartphone interfaces. This allows the project to be not only a fixed lab demonstration, but a prototype for scalable use in more complex educational and industrial settings.

In summary, the trainer kit is a balanced combination of theoretical applicability, real-world implementation, and user focus. It is an all-encompassing environment for illustrating motor control logic, transient current analysis, and embedded system applications. This project provides the foundation for future innovation in academic labs, facilitating hands-on learning and conceptual penetration among prospective electrical engineers.

10. Acknowledgment

We wish to acknowledge with sincere thanks all those who have been there for us during the successful execution of this project, titled "Development of an Educational Star-Delta Trainer Kit with Real-Time Inrush Current Measurement."

We would like to extend our heartfelt thanks to Mr. Mukesh Kumar Sharma, Head of the Department of Electrical Engineering, for his ongoing support, motivation, and for granting us the required academic infrastructure to conduct this project.

We would like to extend our heartfelt thanks to our co-guide for the project, Mr. Rajesh Baraily, whose technical expertise, guidance, and hands-on help were crucial to the successful development and execution of our trainer kit.

We also express our heartfelt appreciation for the encouragement and assistance of Mr. Tashi Rapden Wangchuk and Mr. Tenzing Sherpa, who assisted us during the testing, debugging, and fine-tuning phases of the project.

We are also grateful to the Principal and the Finance Department of our college for sanctioning and enabling the funds required for purchasing the motor and other essential parts.

This project would not have been accomplished without the encouragement and support of all the above people, and we deeply value their efforts.

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