



Thesis on

Applications of Artificial Intelligence in Electrical Engineering Systems

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Abstract

The integration of Artificial Intelligence (AI) into modern domestic and commercial electrical infrastructures presents significant opportunities for enhancing sustainability, improving energy efficiency, and supporting the long-term reliability of power systems. As global energy demands continue to rise, the need for intelligent systems capable of optimizing power flow and minimizing wastage has become increasingly critical. This research investigates the role of load balancing within three-phase electrical distribution networks, highlighting how effective load redistribution directly contributes to higher operational efficiency, reduced power losses, and improved system stability. Achieving optimal load balance is not only beneficial for utility providers but also essential in promoting environmentally responsible energy management practices.

A key challenge in maintaining an efficient electrical power system lies in preventing excessive currents in overloaded conductors, which can lead to energy losses, voltage instability, and accelerated degradation of system components. One practical solution involves transferring excess current from heavily loaded phases to those with available capacity. By redistributing loads through controlled switching mechanisms or intelligent decision-making algorithms, the overall performance of the system can be significantly improved. Enhancements include better voltage regulation, reduced thermal stress on cables and transformers, and increased lifespan of critical infrastructure. These improvements ultimately benefit all stakeholders—end users, engineers, and utility operators—by ensuring safer, more reliable, and more cost-effective energy delivery.

To analyze these effects, an experimental setup utilizing a three-phase power supply system was designed and constructed under the supervision of a qualified electrical engineer (the researcher, serving as an electrical engineering lecturer). The study focused on scenarios where Phase L1 experienced disproportionately high demand compared to Phases L2 and L3. Through controlled experiments, portions of the load were systematically transferred from L1 to the under-utilized phases, enabling a detailed evaluation of both theoretical and practical outcomes. Results consistently demonstrated that strategic phase balancing reduces current disparities, minimizes energy losses, and enhances the overall stability and efficiency of the electrical network.

The findings of this research underscore the potential of AI-assisted load management systems as a transformative tool in modern power engineering. By enabling dynamic, real-time optimization of load distribution, AI technologies can support the transition toward more sustainable, resilient, and intelligent energy systems. This study therefore contributes valuable insights into the practical implementation of AI-enhanced load balancing and its role in shaping the future of efficient electrical power management.

Background and purpose of the research area or application

Energy efficiency plays a vital role in shaping a sustainable and resilient future. Within electrical power systems, achieving efficiency involves carefully managing and optimizing the various categories of loads that make up the overall demand. These include:

- Domestic or household loads
- Industrial loads
- Commercial and business-related loads
- Municipal and public infrastructure loads
- Irrigation and agricultural loads
- Traction loads used in rail, transport, and mobility systems [1]

From the perspective of an electrical engineer educated at both diploma and bachelor levels, one of the core principles we are trained to understand is the importance of proper load balancing—particularly when working with a three-phase power supply system. Three-phase systems are widely used because they deliver a stable, continuous, and more reliable form of electrical power. They also integrate seamlessly with single-phase systems, allowing single-phase loads to be distributed across the three available phases. This distribution helps reduce the stress on any individual phase conductor and ensures smoother and more efficient operation.

However, when a three-phase system becomes unbalanced, a number of operational issues emerge. Unequal load distribution forces the system to carry different current magnitudes in each phase, which may result in the need for:

- Higher-rated circuit breakers
- Cables with larger cross-sectional areas
- More robust and expensive protective devices

These requirements lead to increased installation costs and reduced overall system efficiency.

Balanced vs. Unbalanced Three-Phase Configurations

Figure 1 typically illustrates a balanced three-phase star (Y) configuration. Most residential and small commercial electrical supplies are tapped from the star connection because it provides a stable neutral point. The presence of this neutral conductor is essential for returning unbalanced current and enabling single-phase circuits to function correctly without affecting the integrity of the entire system.

Figure 2 shows a balanced three-phase delta (Δ) configuration, which does not have a neutral point. Delta connections are commonly found in industrial environments where high power is required and loads are predominantly three-phase in nature. One advantage of the delta arrangement is that the phase current is lower than the line current, which enhances system protection and reduces mechanical and thermal stress on electrical equipment.

3 phase balance supply (Y)

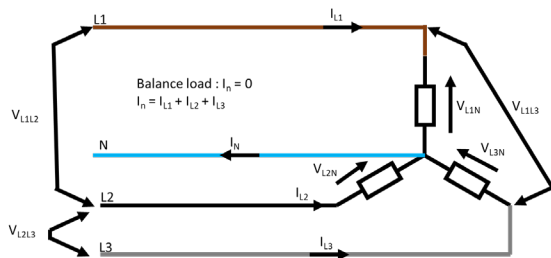


Figure 1 = Balance 3 phase star supply [2]

3 phase balance supply (Δ)

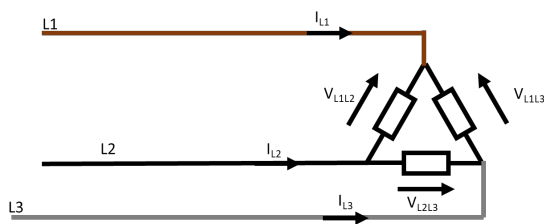


Figure 2 - Balance 3 phase Delta supply [2]

In real-world applications, achieving a perfectly balanced three-phase system is nearly impossible. Electrical loads switch on and off throughout the day, and their varying behavior introduces continuous imbalance. Despite this, engineers strive to distribute the loads as evenly as possible. Doing so minimizes neutral current flow, reduces power losses due to imbalance, and prevents the oversizing of conductors and protective devices.

Fundamental Relationships in Star (Y) and Delta (Δ) Systems

Understanding the basic voltage and current relationships within star and delta connections is essential for analysing system performance.

Star (Y) Connection

- Line Voltage:

$$V_L = \sqrt{3} \times V_{ph}$$

- Line Current equals Phase Current:

$$I_L = I_{ph}$$

Line Voltage	Phase Voltage
V_{L1L2}	$\sqrt{3} V_{L1N}$
V_{L2L3}	$\sqrt{3} V_{L2N}$
V_{L3L1}	$\sqrt{3} V_{L3N}$

Line Current	Phase Current
I_{L1}	I_{ph1}
I_{L2}	I_{ph2}
I_{L3}	I_{ph3}

Delta (Δ) Connection

- Line Voltage equals Phase Voltage:

$$V_L = V_{ph}$$

- Line Current:

$$I_L = \sqrt{3} \times I_{ph}$$

Line Voltage	Phase Voltage
V_{L1L2}	V_{ph1}
V_{L2L3}	V_{ph2}
V_{L3L1}	V_{ph3}

Line Current	Phase Current
I_{L1}	$\sqrt{3} I_{ph1}$
I_{L2}	$\sqrt{3} I_{ph2}$
I_{L3}	$\sqrt{3} I_{ph3}$

Interpreting Table 1: Balanced vs. Unbalanced Conditions

Table 1- Balance and unbalance system (from source)

Balance system (200A supply)				Unbalance system (200A supply)			
L1	L2	L3	N	L1	L2	L3	N
50.5A	57.56A	54.65A	6.15A	105.8A	58.47A	88.35A	44.98A
25.25%	28.78%	27.32A	3.08%	52.9%	29.24%	44.18%	22.49%

Balanced System:

The three phase currents (L1, L2, L3) are relatively close in magnitude, indicating symmetrical loading. As a result, the neutral current remains low (6.15 A), representing only 3.08% of the total. This small neutral current is expected when the load across all phases is nearly equal.

Unbalanced System:

In contrast, the unbalanced system shows a significant difference between the phase currents, particularly with L1 (105.8 A) and L3 (88.35 A) drawing substantially more current than L2. This uneven loading results in a much higher neutral current (44.98 A), approximately 22.49% of the total load current. The increased neutral current is a direct indicator of load imbalance within the system.

The data in Table 1 clearly illustrates the difference between balanced and unbalanced three-phase systems. In the balanced scenario, the currents in L1, L2, and L3 are close in magnitude, resulting in a very small neutral current. This is expected, as balanced phase currents naturally cancel out in the neutral conductor.

In contrast, the unbalanced system shows a significantly high current on L1 when compared with L2 and L3. This uneven distribution forces a large neutral current of 44.98 A—an indication of severe load imbalance. Such a situation can cause:

- Excessive heating of the L1 conductor
- Overloading of the neutral cable
- Voltage drops
- Reduced overall system efficiency

To rectify this, loads on L1 should be redistributed to L2 and L3. By re-allocating circuits more evenly, the system becomes more balanced, neutral current is minimized, and operational safety is improved.

Balanced three-phase systems therefore not only enhance electrical efficiency but also improve long-term system stability, safety, and equipment lifespan.

Towards an AI Driven Automatic Phase Changing System

Based on our engineering understanding and the operational challenges highlighted, we propose innovating an AI-driven automatic phase-changing solution. The concept is inspired by Singapore’s land transport system. When major expressways such as the Pan-Island Expressway (PIE) become congested, traffic is automatically diverted or rerouted through alternative paths so that commuters can still travel efficiently from Tuas to Changi.

A similar philosophy can be applied to electrical systems:
When a particular phase becomes overloaded, AI could intelligently reroute circuits to other phases in real time—restoring balance automatically.

(See Figure 3 – Expressways in Singapore [3].)



Figure 3- Expressway in Singapore [3]

To better illustrate this concept, consider how drivers in Singapore choose between multiple expressway routes depending on traffic conditions. A commuter traveling across the island has several possible pathways:

Route 1: Kranji Expressway (KJE) → Bukit Timah Expressway (BKE) → Seletar Expressway (SLE) → Tampines Expressway (TPE)

Route 2: Ayer Rajah Expressway (AYE) → Marina Coastal Expressway (MCE) → East Coast Parkway (ECP)

Route 3: West Coast Highway → MCE → Kallang-Paya Lebar Expressway (KPE) → TPE

When the primary route—such as the Pan Island Expressway (PIE)—becomes congested, drivers naturally divert to these alternative expressways. This flexibility helps distribute traffic more evenly across the transportation network, reducing bottlenecks and improving travel efficiency.

This real-world traffic management concept forms the foundation of our engineering approach. Just as vehicles can be re-routed to maintain smooth traffic flow, electrical loads can also be intelligently redirected across phases to maintain balance and optimize performance. Instead of allowing one phase to become overloaded while others remain underutilized, the system actively “re-routes” current flow to achieve a more even distribution.

AI-Driven Smart Phase Changing System

In our system model—represented in Figures 4, 5, and 6—we demonstrate how dynamic and intelligent phase changes can be implemented using an AI-based control strategy:

Figure 4 presents the overall structure of the Smart Phase Changing System designed for power re-routing.

Figure 5 shows a scenario where the load is predominantly concentrated on Phase L1, which is a common cause of imbalance and reduced efficiency in electrical installations.

Figure 6 illustrates how the system automatically redistributes loads across the three phases, achieving a more uniform distribution—similar to how alternative expressways relieve heavy traffic.

Smart Phase Changing System

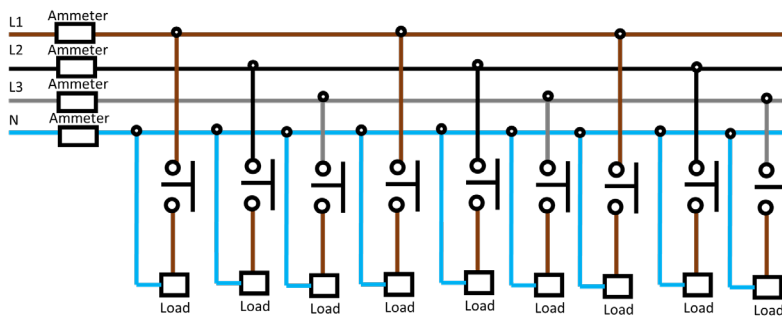


Figure 4- Smart Phase Changing System for Power re-routing

Smart Phase Changing System (biased @ L1)

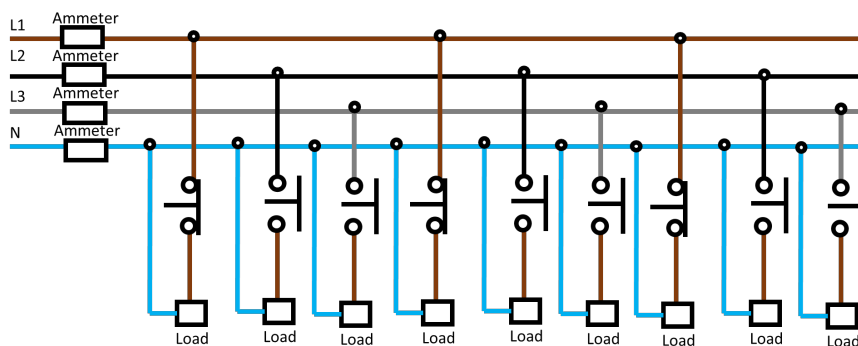


Figure 5- load biased at L1

Smart Phase Changing System (load balancing)

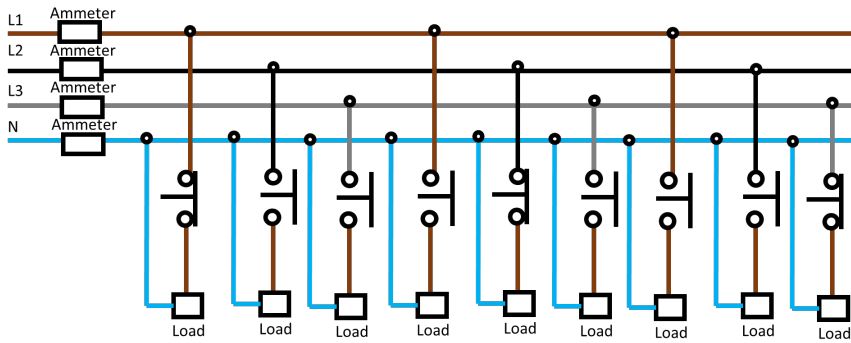


Figure 6 - Loading balance

By integrating artificial intelligence into the control mechanism, the system continuously evaluates the loading conditions on each phase. When imbalances arise, the AI makes real-time decisions to allocate loads to phases that have spare capacity. This results in:

- Maximized utilization of the available power
- Lower risk of phase overloading
- Improved overall stability of the electrical network

The parallel with expressway re-routing is clear: just as traffic is shifted from congested roads to smoother ones, electrical demand can be shifted from overloaded phases to healthier phases.

Operation of smart phase changing system

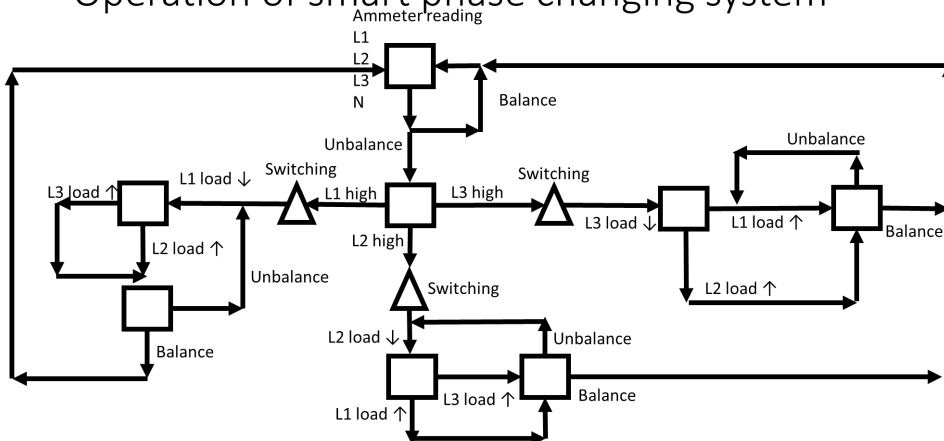


Figure 7 - The operation of smart phase change system

Figure 7 – Operation of the Smart Phase Changing System

The functional operation of the system, illustrated in Figure 7, relies on a combination of continuous monitoring and intelligent switching:

Real-Time Current Measurement:

An ammeter constantly tracks the current flowing through each phase (L1, L2, and L3). These measurements feed directly into the controller.

Assessment of Load Conditions:

The controller analyses the incoming data to determine whether the phase currents remain within an acceptable balance. Any significant deviation signals a potential imbalance.

Automatic Switching:

When an imbalance is identified—such as one phase drawing substantially higher current—the system automatically activates the switching mechanism.

This mechanism reassigns the connected loads to different phases, distributing them as evenly as possible.

Restoration of System Stability:

By balancing the load, the smart phase change system helps maintain better power quality, reduces the chances of thermal stress or overheating on heavily loaded conductors, and increases the overall efficiency and reliability of the electrical network.

In essence, this innovative approach brings together transportation-inspired logic and electrical engineering principles. Through continuous monitoring and intelligent re-routing, the system ensures that the electrical “traffic flow” remains smooth, balanced, and optimized—supporting both safety and long-term sustainability.

Analysis of Balanced and Unbalanced Three-Phase Systems

Research and Experiment

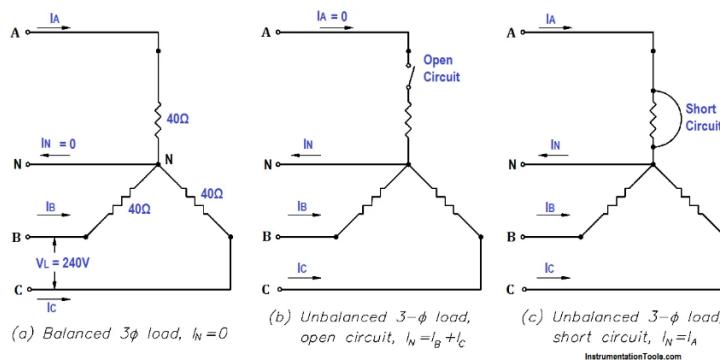


Figure 8 – balance and unbalance three phase system [4]

Figure 8 – Balanced and Unbalanced Three-Phase System [4]

Referring to the behaviour illustrated in Figure 8, the characteristics of the neutral current under faulted conditions become clearly evident. When an open-circuit fault occurs on Phase A, the current in that phase becomes zero. As a result, the neutral conductor must carry the vector sum of the remaining phase currents, meaning the neutral current is determined entirely by the combined effects of Phase B and Phase C.

Conversely, during a short-circuit fault on Phase A, a large surge of current flows through that phase. Under this condition, the neutral conductor carries a current essentially equal to the full magnitude of the current in Phase A. This behaviour follows directly from the foundational principles of three-phase system theory, where the neutral conductor always carries the resultant of the three phase currents whenever the system becomes unbalanced. To properly simulate, control, and investigate these conditions, the experiment incorporates a programmable logic controller (PLC) paired with a suitable relay arrangement. This configuration enables controlled energisation and de-energisation of individual phases, thereby allowing safe replication of both open-circuit and short-circuit scenarios. The PLC-relay setup also ensures switching accuracy, prevents accidental faults, and provides a reliable platform for demonstration and analysis.

Experimental Methods and Results

This section presents the experimental design, procedures, and the findings obtained from testing a three-phase system under both balanced and unbalanced loading conditions. The primary objective is to observe how load imbalance influences:

Phase current magnitudes

Neutral current behaviour

System efficiency and stability

Mathematical calculations and measured results are used to verify theoretical expectations.

Experimental Setup

To ensure a safe and controlled test environment, several electrical appliances were connected to a three-phase 20 A supply. All experiments were performed under strict electrical safety practices. The equipment used for creating the loads is summarised below.

Table 2 – Items Used in the Experiment

Table 2 – Equipment used with wattage labelled

Item Used	Wattage
Bread Toaster	1000 W
Compact Fluorescent Lamp (CFL)	25 W

Balanced Load Simulation

To simulate a balanced load condition, identical loads were carefully distributed across all three phases. The test setup consisted of:

Three bread toasters, and

Six CFL lamps

Each phase received the same combination of appliances:

L1: 1 toaster + 2 CFLs

L2: 1 toaster + 2 CFLs

L3: 1 toaster + 2 CFLs

This arrangement ensures that each phase draws approximately the same current. In an ideal balanced three-phase system, the neutral current should be zero. Although a perfectly balanced condition is difficult to achieve in practical scenarios, this configuration provides a stable reference point for comparison with unbalanced conditions.

Measurements taken in this phase serve as the baseline for understanding how current distribution changes when imbalance is introduced.

Unbalanced Load Simulation

To observe the effects of uneven load distribution, the appliances were rearranged—while keeping the total number of appliances the same—to create a deliberately unbalanced scenario:

L1: 2 toasters + 2 CFLs

L2: 1 toaster

L3: 4 CFLs

This arrangement reflects realistic situations in residential, commercial, or workshop settings where appliances are rarely distributed evenly across phases.

Under this unbalanced configuration:

Phase currents differ significantly

The neutral conductor carries the imbalance current

Voltage stability may be affected

Monitoring these parameters provides insight into how improper load distribution can lead to inefficiencies and thermal stress in a three-phase system.

Summary of Experimental Intent

The experiment serves to highlight several key principles:

Balanced loads minimise neutral current, ensuring optimum system efficiency

Unbalanced loads increase the neutral current, potentially causing heating and voltage shifts

Load placement and phase management directly impact system safety and performance

The results obtained validate the theoretical behaviour of three-phase circuits and deepen understanding of load balancing practices.

Experimental Switching Logic and Circuit Configuration

To allow precise control over appliance activation, six selector switches (SS1 to SS6) were used. Each switch corresponds to one appliance, and each appliance can be assigned to any of the three phases or turned OFF for safety.

Before energising the system, all switches were placed in the OFF position.

A total of seven clamp-on multimeters were used to measure:

Phase currents

Neutral current

Redundant measurements for accuracy verification

Balanced Configuration – Selector Switch Assignments

Table 3 – Selector Switch Energisation (Balanced)

Selector Switch	Equipment	Energised Phase
SS1	Toaster 1	L1
SS2	Toaster 2	L2
SS3	Toaster 3	L3
SS4	CFL 1	L1
SS5	CFL 2	L2
SS6	CFL 3	L3

Figure 9 and Figure 10 illustrate the OFF-mode wiring for the toaster and CFL circuits.

From the design, each selector switch directly controls one appliance. This setup enables quick and repeatable switching of phases without the need to physically unplug and reconnect appliances—a process that would be time-consuming and physically demanding. The use of selector switches therefore significantly reduces manual effort and prevents unnecessary fatigue and loss of man-hours.

Figures 11 and 12 show the ON-mode configuration, where the balanced loads are energised as per Table 3.

Unbalanced Configuration – Selector Switch Assignments

To create the unbalanced scenario, the selector switches were set as follows:

Table 4 – Selector Switch Energisation (Unbalanced)

Selector Switch	Equipment	Energised Phase
SS1	Toaster 1	L1
SS2	Toaster 2	L1
SS3	Toaster 3	L2
SS4	CFL 1	L1
SS5	CFL 2	L3
SS6	CFL 3	L3

Figures 13 and 14 illustrate the ON-mode wiring for both toaster and CFL circuits in the unbalanced configuration.

Here:

L1 carries the highest load (2 toasters + 1 CFL)

L2 carries a moderate load (1 toaster)

L3 carries a light load (2 CFLs)

This uneven distribution produces measurable differences in phase current and a significantly higher neutral current, which aligns with theoretical predictions.

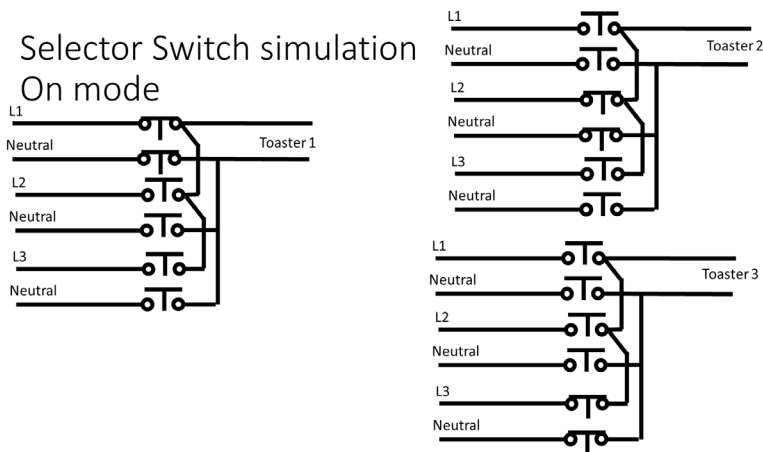


Figure 11 – Three phase loading to equipment for testing (Toaster circuit) (ON mode) |Balance

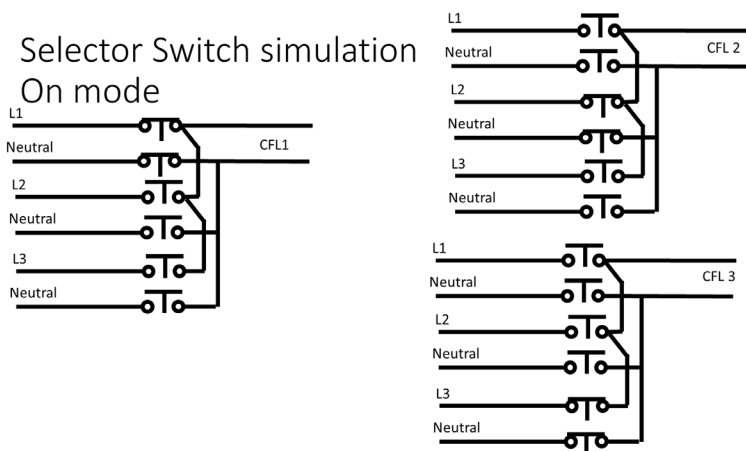


Figure 12 – Three phase loading to equipment for testing (CFL circuit) (ON mode) |Balance

Now going to into the unbalance phase experiment. The selector switch energizes of the equipment as tableted as shown in Table 7,

Table 4 – The selector switch energize position of equipment (Unbalance)

Selector Switch	Equipment	Energise phase
SS1	Toaster 1	L1
SS2	Toaster 2	L1
SS3	Toaster 3	L2
SS4	CFL 1	L1
SS5	CFL 2	L3
SS6	CFL 3	L3

From the Figure 11 and Figure 12 circuit connection, each selector switch is connected to one phase by equipment. Line 1 (L1) supply current to the toaster 1. Line 1 (L1) supply current to the toaster 2. Line 2 (L2) supply current to the toaster 3. While the supplies to CFL Line 1 (L1) supply current to the CFL 1. Line 3 (L3) supply current to the CFL 2. Line 3 (L3) supply current to the CFL 3. The result from this experiment is tableted as Table 6 previously.

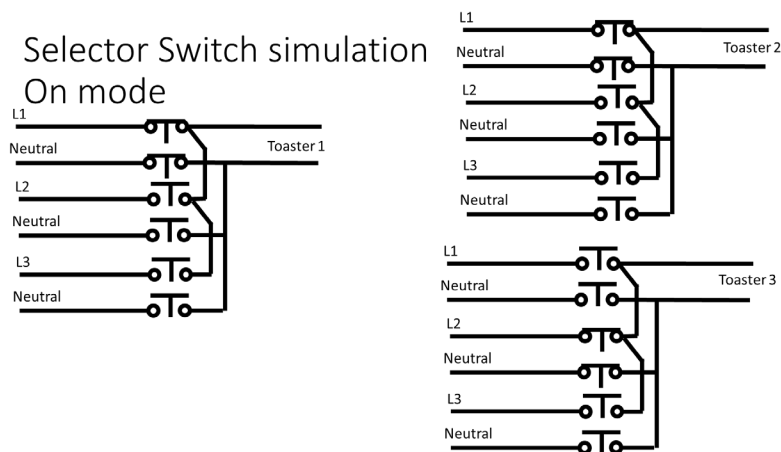


Figure 13 – Three phase loading to equipment for testing (Toaster circuit) (ON mode) |Unbalance

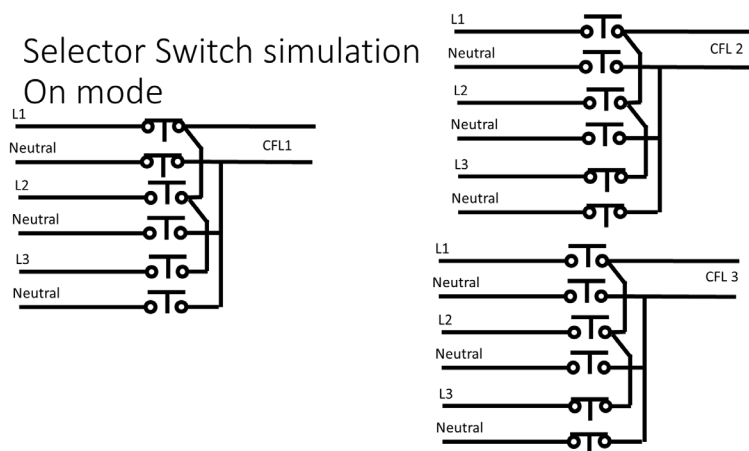


Figure 14 – Three phase loading to equipment for testing (CFL circuit) (ON mode) |Unbalance

Following the successful completion of the manual phase-switching experiment—conducted through real-time, on-site testing—the next phase of the development involves transitioning the system into a fully automated platform. This automation process will be implemented using a Programmable Logic Controller (PLC). Additional components, including current sensors and an analog-to-digital (A/D) converter, will be incorporated to capture real-time current measurements and translate them into digital data for processing by the PLC. To enable automatic phase switching, the mathematical relationships governing three-phase currents must be integrated into the PLC program. These calculations will form the decision-making logic that determines when phases should be switched based on the sensor feedback.

Power and Sensor Conversion Assumptions

Table 8 – Current-to-Analog Conversion Reference

Actual Current (A)	Percentage (%)	Output of A/D Converter (mA)
4 A	0%	4 mA
8 A	25%	8 mA
12 A	50%	12 mA
16 A	75%	16 mA
20 A	100%	20 mA

This linear scaling assumes a proportional relationship between actual load current and its A/D converter output. The 4–20 mA range is widely used in industrial systems due to its noise immunity and reliability in long-distance signal transmission.

Current Sensor Placement

Table 9 – Current Sensor Assignment

Current Sensor	Measurement Position	Connected Load
CS1	Main Supply L1	–
CS2	Main Supply L2	–
CS3	Main Supply L3	–
CS4	Neutral	–
CS5	Load on L1	Toaster 1
CS6	Load on L2	Toaster 2
CS7	Load on L3	Toaster 3
CS8	Load on L1	CFL 1
CS9	Load on L2	CFL 2
CS10	Load on L3	CFL 3

Mathematical Formulation of Neutral Current

The neutral current is calculated using the vector sum of the three phase currents:

$$I_N = I_{L1} + I_{L2} + I_{L3}$$

To analyse the system using complex numbers (phasors), each phase current is decomposed into its real and imaginary components:

The mathematic equation:

$$I_N = I_{L1} + I_{L2} + I_{L3}$$

The measure current will be label:

$$\begin{aligned}I_{L1} &= A \cos 0 \\I_{jL1} &= A \sin 0 \\I_{L2} &= B \cos 120 \\I_{jL2} &= B \sin 120 \\I_{L3} &= C \cos -120 \\I_{jL3} &= C \sin -120\end{aligned}$$

The total neutral components are then:

$$I_N = I_{L1} + I_{L2} + I_{L3}$$

$$I_{jN} = I_{jL1} + I_{jL2} + I_{jL3}$$

If both the real and imaginary neutral components equal zero, the system is perfectly balanced.

In practical terms, tradesmen often refer to imaginary numbers using the “j-operator” instead of “i” to avoid confusion with electrical current denoted by I.

PLC Input and Output Assignments

To support automation, all sensors, switches, relays, and internal bits are mapped as follows.

Analog Inputs (Current Sensors)

Analog Input Assignments

- CS1 – Current sensor for main supply L1
- CS2 – Current sensor for main supply L2
- CS3 – Current sensor for main supply L3
- CS4 – Current sensor for Neutral
- CS5 – Current sensor for Toaster Load 1
- CS6 – Current sensor for Toaster Load 2
- CS7 – Current sensor for Toaster Load 3
- CS8 – Current sensor for CFL Load 1
- CS9 – Current sensor for CFL Load 2
- CS10 – Current sensor for CFL Load 3

Digital Input Assignments

Switch Inputs for Phase Control

- SW11 – Switch for L1
- SW12 – Switch for L2
- SW13 – Switch for L3

Second Switch Set

- SW21 – Switch for L1
- SW22 – Switch for L2
- SW23 – Switch for L3

Third Switch Set

- SW31 – Switch for L1
- SW32 – Switch for L2
- SW33 – Switch for L3

Fourth Switch Set

- SW41 – Switch for L1
- SW42 – Switch for L2
- SW43 – Switch for L3

Fifth Switch Set

- SW51 – Switch for L1
- SW52 – Switch for L2
- SW53 – Switch for L3

Sixth Switch Set

- SW61 – Switch for L1
- SW62 – Switch for L2
- SW63 – Switch for L3

Digital Output Assignments

Relay Outputs

- CR1 – Relay for Toaster 1
- CR2 – Relay for Toaster 2
- CR3 – Relay for Toaster 3
- CR4 – Relay for CFL 1
- CR5 – Relay for CFL 2
- CR6 – Relay for CFL 3

Bit-Controlled Relay Outputs

- X11, X12, X13 – Relay control bits, Group 1
- X21, X22, X23 – Relay control bits, Group 2
- X31, X32, X33 – Relay control bits, Group 3
- X41, X42, X43 – Relay control bits, Group 4
- X51, X52, X53 – Relay control bits, Group 5
- X61, X62, X63 – Relay control bits, Group 6

Internal Bit Assignments

- BO11, BO12, BO13 – Internal control bits, Group 1
- BO21, BO22, BO23 – Internal control bits, Group 2
- BO31, BO32, BO33 – Internal control bits, Group 3
- BO41, BO42, BO43 – Internal control bits, Group 4
- BO51, BO52, BO53 – Internal control bits, Group 5
- BO61, BO62, BO63 – Internal control bits, Group 6

Each relay is controlled by internal bits X11–X63, which determine the phase selection for each load.

Internal Bits (Control Logic and Safety)

Internal bits BO11–BO63 are used to:

Prevent parallel phase connections

Enforce safe switching sequences

Isolate contact paths during transitions

Serve as logical flags for decision-making

These internal contacts ensure that only one phase can be assigned to one load at any time, preventing dangerous back-feeding between phases.

Integration with Contactor and Relay System

The PLC operates at 24 VDC, which energizes 24 VDC coil relays.

These relays then drive 230 V contactors that control:

400 V (line-to-line), or

230 V (phase-to-neutral)

The arrangement is shown in Figure 15 – Sample Circuit Connection, ensuring full electrical isolation between low-voltage control signals and high-voltage power circuits.

PLC Operational Logic

Primary Current Monitoring

CS1, CS2, CS3 measure currents in L1, L2, L3

CS4 monitors neutral current

A CS4 reading of approximately zero indicates a balanced condition.

Secondary Load Monitoring

CS5–CS10 measure individual appliance currents. These values are summed and compared against the respective main supply sensors:

$CS5 + CS8 \approx CS1$

$CS6 + CS9 \approx CS2$

$CS7 + CS10 \approx CS3$

If the values match, phase currents are balanced and no switching is required.

Automatic Unbalance Detection

When:

CS4 \neq 0 (neutral current present)

OR any main phase sensor shows excessive current

OR load distribution does not match expected patterns

The PLC activates a timer which initiates phase switching.

Automatic Phase Diversion Example

If L1 is heavily loaded:

Timer triggers

Internal bit BO21 opens

BO22 closes

Load previously on L1 is diverted to L2

Similarly, if L2 is overloaded:

BO42 opens

BO41 closes

Load is reassigned back to L1

This mimics a real-time “traffic-diversion” strategy for electrical loads.

Balanced Operation Example

- X11 → CR1 energises Toaster 1 on L1
- X22 → CR2 energises Toaster 2 on L2
- X33 → CR3 energises Toaster 3 on L3
- X41 → CR4 energises CFL 1 on L1
- X52 → CR5 energises CFL 2 on L2
- X63 → CR6 energises CFL 3 on L3

Neutral current is near zero → no switching action is taken.

Unbalanced Operation Example

- X11 → CR1 energises Toaster 1 on L1
- X21 → CR2 energises Toaster 2 on L1
- X33 → CR3 energises Toaster 3 on L3
- X42 → CR4 energises CFL 1 on L2
- X52 → CR5 energises CFL 2 on L2
- X63 → CR6 energises CFL 3 on L3
- CS1 and CS4 increase → PLC triggers rebalancing sequence.

Ladder Logic and Block Diagram Representation

Figure 15 – PLC Output to Relay (Sample of Circuit Connection)

Figure 16 – PLC Ladder Diagram (Mathematical Operation – Sample)

Figure 17 – PLC Ladder Diagram (Timer Function – Sample)

Figure 18 – PLC Ladder Diagram (Switch and Interlock Control – Sample)

Figure 19 – Block Diagram

These diagrams collectively illustrate the logical sequencing, system isolation, and fail-safe mechanisms that govern the automatic phase-switching process. They provide a clear visual representation of how various PLC functions—such as mathematical operations, timing control, interlocking, and relay activation—are systematically integrated to ensure reliable system performance. In addition, the diagrams help demonstrate the steps and methodologies used in conducting the experiment, offering insight into both the control logic design and the operational workflow of the overall system.

PLC out to Relay and driving Relay

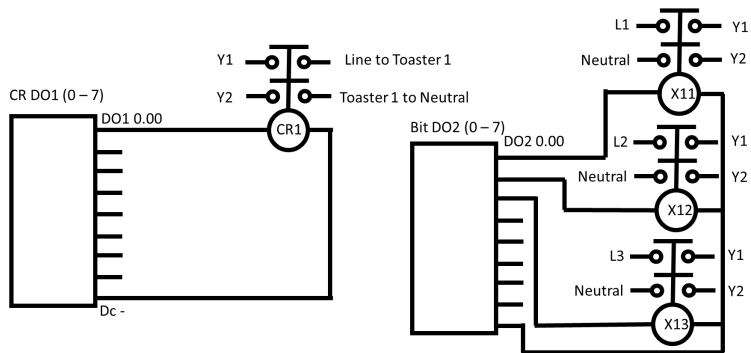


Figure15 – PLC Digital out to relay (“sample of circuit connection”)

Mathematic (part of PLC) 1

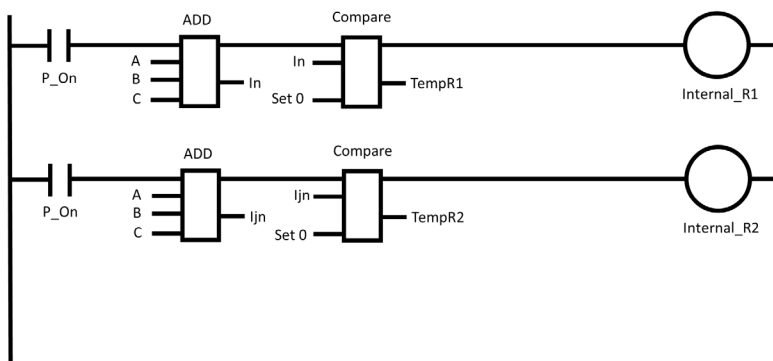


Figure16 – PLC Digital out to relay (“sample of circuit connection”)

Timer (part of PLC) 2

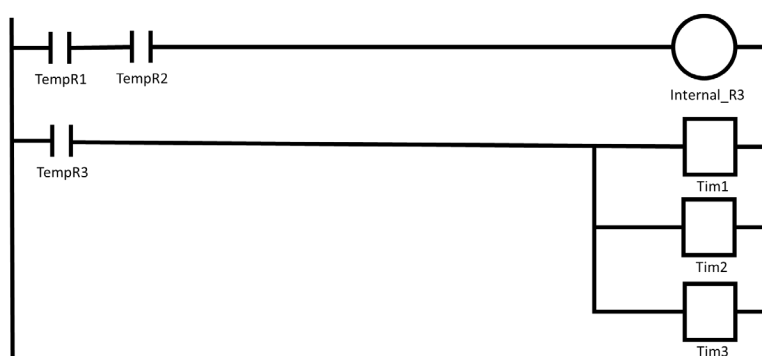


Figure17 – PLC Digital out to relay (“sample of circuit connection”)

Switching and interlock (part of PLC) 3

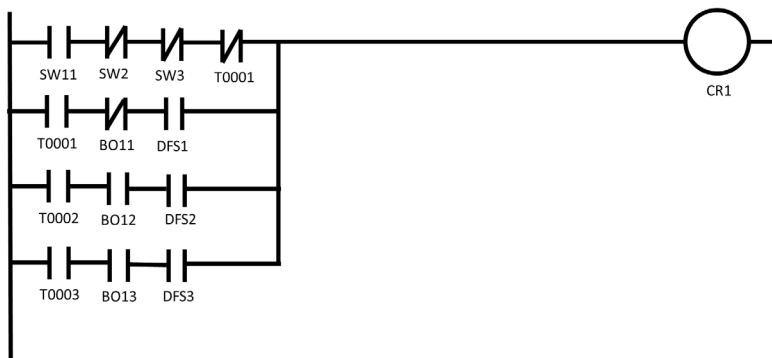


Figure18 – PLC Digital out to relay (“sample of circuit connection”)

Block diagram of the experiment

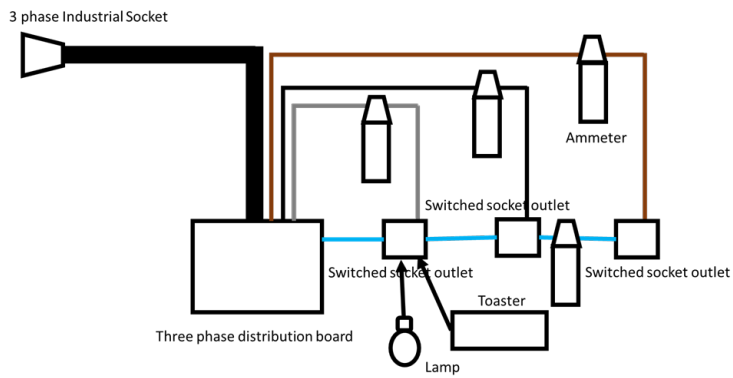


Figure 19 –The block diagram of the experiment

Power Assumption Analysis and 200A simulation

Using the current readings obtained from the 20 A supply experiment, a proportional scaling method was applied to estimate the behaviour of a full-scale 200 A three-phase electrical installation. This approach allows us to visualise how commercial or industrial-level systems would respond under both balanced and unbalanced load conditions. By scaling up the measured values, we can better understand the practical impact of load imbalance, neutral current magnitude, and the effectiveness of corrective actions such as load redistribution.

Table 10 – Power Assumption Results

Table 10 – power assumption

Condition	L1	L2	L3	N
Balanced System	120.5 A	115.68 A	123.57 A	6.92 A
Balanced (%)	60.25%	57.80%	61.50%	3.46%
Unbalanced System	160.52 A	80.56 A	120.45 A	69.32 A
Unbalanced (%)	80.26%	40.28%	60.23%	34.66%
Adjusted Redistribution	125.36 A	115.47 A	120.45 A	8.58 A
Adjusted (%)	62.68%	57.74%	60.23%	4.29%

Interpretation of Table 10

The data clearly demonstrates the influence of load redistribution on system behaviour. In the unbalanced state, L1 carries a substantially higher load than L2 and L3, which forces the neutral conductor to carry a much larger return current. After transferring some of the load from L1 to L2, the currents across the three phases become significantly more even. As a direct result, the neutral current drops from 69.32 A to 8.58 A, showing how effective even minor load adjustments can be in restoring system balance.

This reduction in imbalance is important because an overloaded phase places mechanical and thermal stress on the distribution system. From an engineering standpoint, elevated current levels produce higher losses according to $P = I^2R$. Excessive heat can:

- accelerate the aging of cable insulation,
- cause deformation of conductor materials,
- shorten the operational life of protective devices, and
- decrease overall system energy efficiency.

Balancing the load ensures that each phase shares the electrical demand more evenly, reducing unnecessary stress on the wiring and ensuring stable, efficient, and safe operation of the power system.

Procedures, Safety Measures, and Data Collection Methods

Because the experiment involved a live 400 V three-phase installation, strict safety procedures were implemented from setup to shutdown.

Safety Measures

- All personnel on site wore full personal protective equipment (PPE), including insulated gloves, safety boots, and face shields.
- The experimental setup utilised an industrial-grade three-phase socket connected to a distribution board containing appropriately rated circuit breakers.
- All wiring, load banks, and connection points were inspected and verified by both the engineering lecturer and the supervising mentor before energising the system.

These precautions ensured that no exposed conductors, loose terminations, or incorrect phase assignments were present before testing began.

Procedure Overview

1. Confirm all selector switches are in the OFF position.
2. Energise the three-phase supply using the distribution board.
3. Apply the loads one phase at a time using the selector switches.
4. Measure the current on each phase and the neutral using clamp-on multimeters.
5. Record all readings in a structured table for later comparison and analysis.
6. Repeat the entire sequence for both the balanced and unbalanced configurations.

This structured approach ensures data consistency and allows for a clear comparison between different load conditions.

Risk Awareness and Control Measures

Working on high-current systems always carries inherent hazards such as electric shock, arc flash, short circuits, or unintended energisation of equipment. Despite these risks, the experiment was completed safely due to:

- continuous supervision by qualified instructors,
- adherence to safety protocols,
- use of proper tools and insulating equipment, and
- disciplined behaviour by all participants.

This reinforces the importance of engineering professionalism and a strong safety culture when operating real-world electrical installations.

Table 11 – Power Assumption Results

Balanced System (200 A supply)	Unbalanced System (200 A supply)
L1: 120.5 A	L1: 160.52 A
L2: 115.68 A	L2: 80.56 A
L3: 123.57 A	L3: 120.45 A
N: 6.92 A	N: 69.32 A
60.25%	80.26%
57.80%	40.28%
61.50%	60.23%
3.46%	34.66%

Adjusted (After Redistribution):

- L1: 125.36 A
- L2: 115.47 A
- L3: 120.45 A
- N: 8.58 A
- (62.68%, 57.74%, 60.23%, 4.29%)

Interpretation of Table 11

The redistribution of load from L1 to L2 visibly reduces the current imbalance. In the unbalanced case, L1's high loading leads to large neutral current. Once the load is redistributed, current sharing between phases becomes more uniform, and the neutral current almost returns to its balanced-state value.

This correction not only prevents overheating but also:

- improves voltage stability across the phases,
- reduces copper losses,
- minimises energy wastage, and
- enhances the overall resilience of the electrical system.

Proper phase balancing is therefore an essential practice in large-scale installations such as factories, workshops, and commercial buildings.

Conclusion

The collected measurements were then analysed to evaluate the degree of imbalance and the effectiveness of corrective actions. This involved comparing current values across all phases, calculating percentage loading, and assessing how load shifting influenced system performance.

Through the experiment conducted under my guidance, the involved students were able to deepen their understanding of fundamental electrical engineering concepts, particularly in the areas of circuit analysis, load behaviour, and three-phase system characteristics. The hands-on experience allowed students to apply theoretical knowledge in a practical setting, which significantly strengthened their conceptual grasp.

One of the most valuable aspects of this experiment was learning how to safely energize a 400V line-to-line supply under partial loading. This is a procedure that many of my students' peers have not yet encountered and mastering it has enhanced our confidence in handling real-world industrial electrical systems. During the tests, we also observed that the neutral current decreases significantly when the phase currents in L1, L2, and L3 are nearly identical—directly illustrating the concept of load balancing in a three-phase system. This real-time observation reinforced the theoretical principle that balanced loads reduce neutral conductor stress and improve system stability.

Additionally, our measurements revealed that the actual power consumption of connected equipment can differ from its nameplate rating. This is largely due to Singapore's nominal supply of $230V \pm 6\%$, which causes fluctuations in operating voltage. The current values predicted by theoretical calculations did not always match our measured values, highlighting the influence of practical factors such as voltage drop, cable sizing, transmission losses, and internal component tolerances. These differences provided us with a realistic understanding of why design calculations must always account for real-world deviations.

The insights gained from this experiment directly support the development of our project prototype: a smart phase-change system. By automatically shifting loads from heavily loaded phases to lighter ones, the system aims to improve load distribution, enhance electrical efficiency, and reduce the risks associated with phase overloading. This innovation reflects our growing appreciation for the importance of phase balancing in modern electrical networks.

Overall, this learning experience has not only sharpened the technical skills but also broadened the engineering perspective. It has shown us how theoretical knowledge, practical experimentation, and real-world problem-solving come together in electrical engineering. As with progression in the further into the working prototype, that better equipped to approach design tasks with both analytical understanding and practical awareness.

Acknowledgement

I would like to extend my deepest appreciation to my organization for providing the invaluable opportunity and necessary permission to conduct the extra-low-current simulations and testing that form the foundation of this research paper. The support and trust granted by the management were essential in enabling the successful planning, execution, and completion of the experimental work. Their willingness to facilitate access to the laboratory facilities, as well as to allow the use of the required electrical infrastructure, made it possible to explore the technical aspects presented in this study in a safe and controlled environment.

All phases of the experimental procedures—especially those involving cable configurations, connection setups, and system simulation—were carried out under my direct supervision. I carefully oversaw every stage of the energizing process to ensure that all safety protocols were strictly followed. Given the potential hazards associated with electrical energization and live testing, my students were not exposed to any dangerous aspects of the experiment. I assumed full responsibility for handling all energized components to maintain the highest standard of safety for everyone involved.

I would also like to express my sincere gratitude to my students, whose commitment, enthusiasm, and technical assistance contributed significantly to the engineering aspects of the project. Their support in preparing the cable assemblies, assisting with data collection procedures, and participating in various stages of the non-hazardous portions of the experiment was invaluable. Their willingness to learn and contribute meaningfully greatly strengthened the overall quality of the work.

Furthermore, I am deeply thankful to the management of my organization for their ongoing encouragement and for allowing me the flexibility to carry out this experimental study as part of my research efforts. Their approval to utilize the three-phase supply and the 20A socket-outlet assemblies for experimental purposes was essential for generating accurate, real-world test conditions. This access enabled the research to achieve a level of authenticity and technical depth that would not have been possible otherwise.

In summary, this research is the result of the combined support, trust, and collaboration of my organization, its management team, and my dedicated students. Their contributions, both direct and indirect, have played a crucial role in the completion of this study. I am sincerely grateful for their guidance, involvement, and continued support.

Abbreviation

CFL – Compact Fluorescent Lamp

PLC – Programmable Logic Controller

References

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[Unbalanced 3 Phase Loads - Inst Tools \(instrumentationtools.com\)](#)

Appendices

Figure 1

3 phase balance supply (Y)

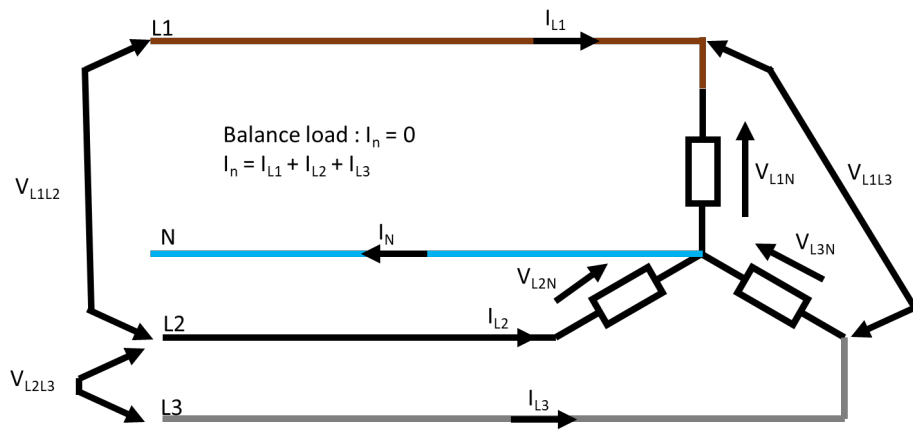


Figure 2

3 phase balance supply (Δ)

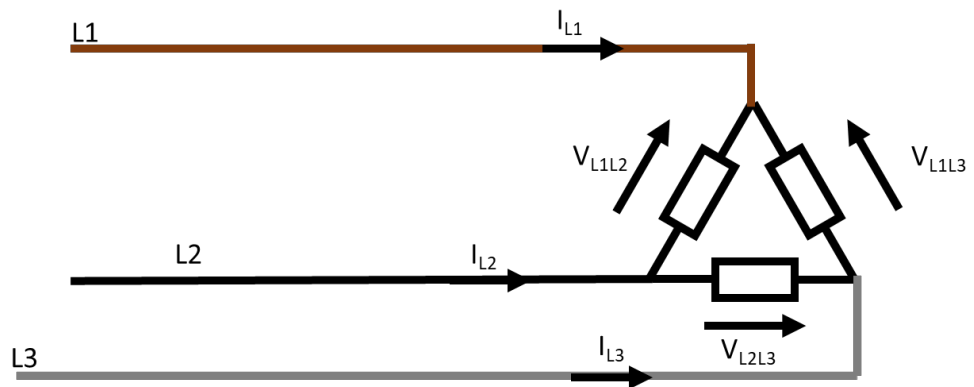


Figure 3



Figure 4

Smart Phase Changing System

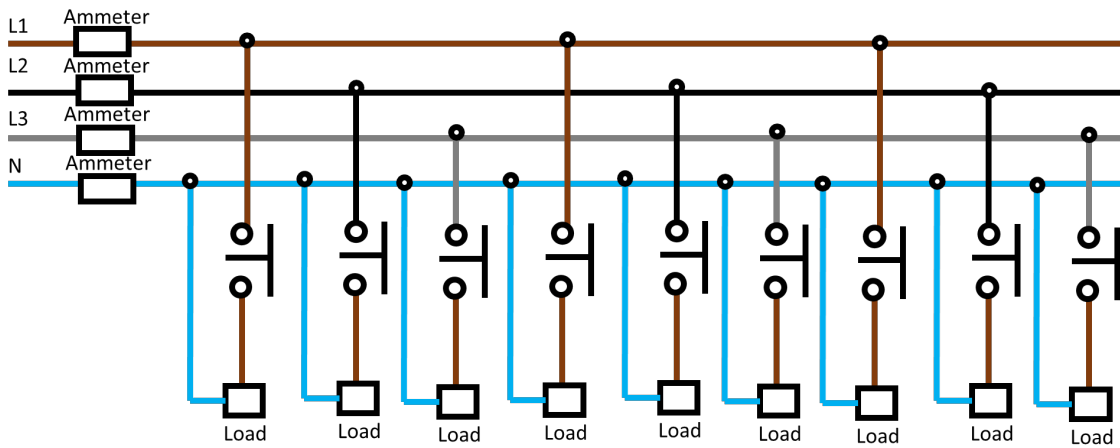


Figure 5

Smart Phase Changing System (biased @ L1)

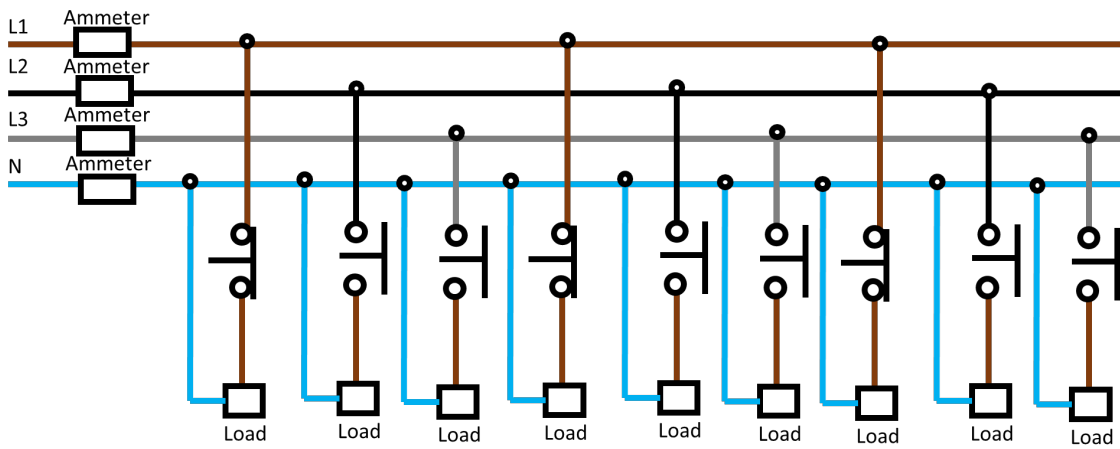


Figure 6

Smart Phase Changing System (load balancing)

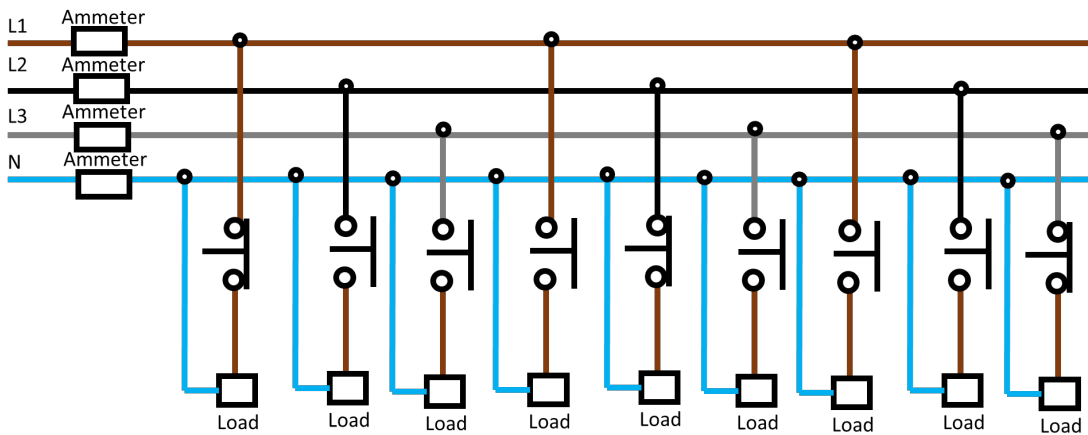


Figure 7

Operation of smart phase changing system

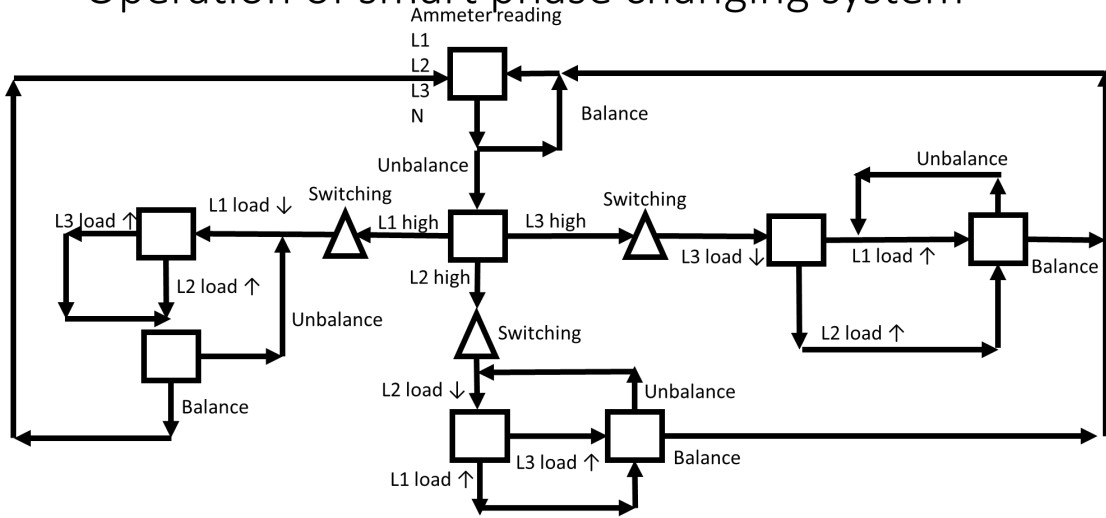


Figure 8

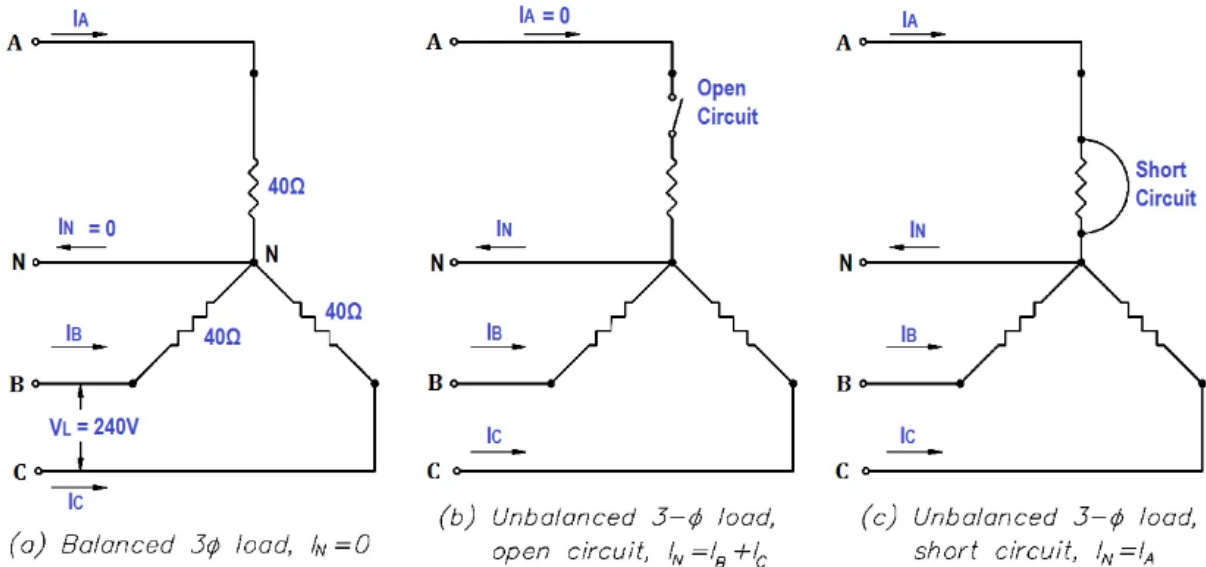


Figure 9

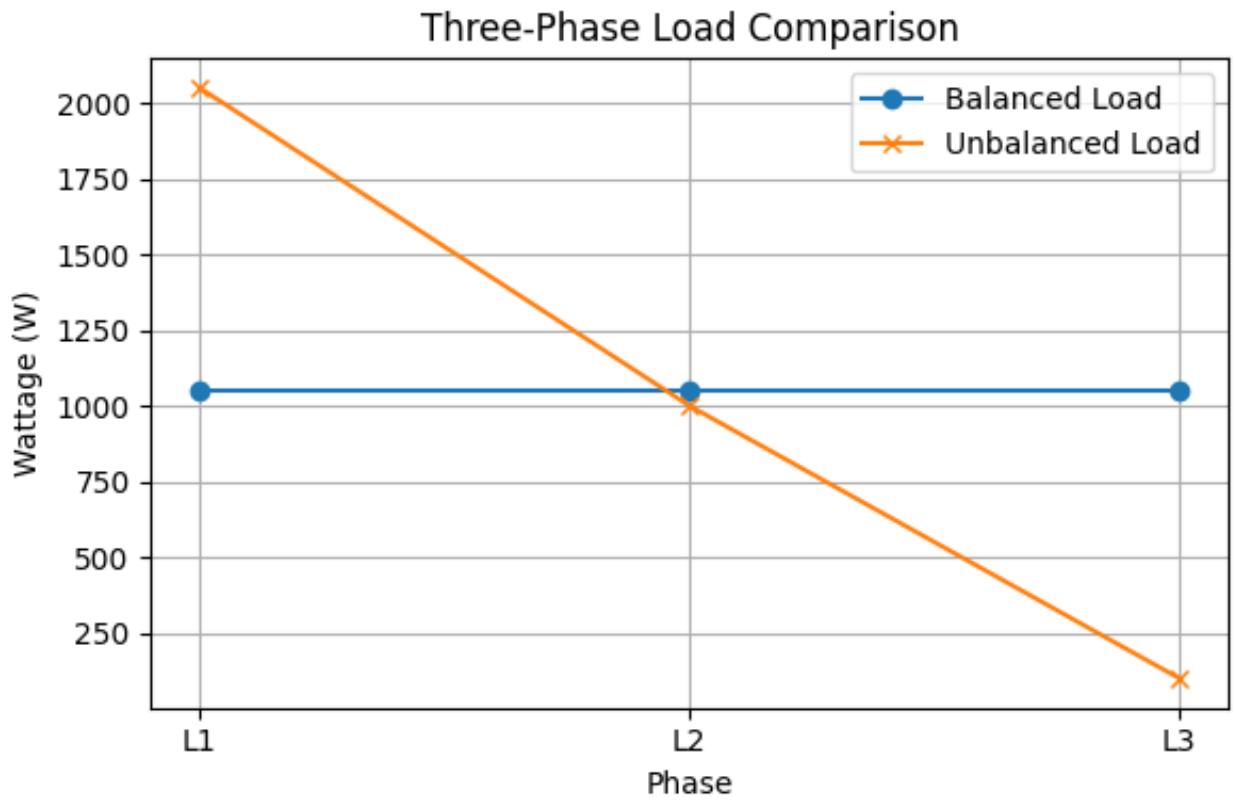


Figure 10

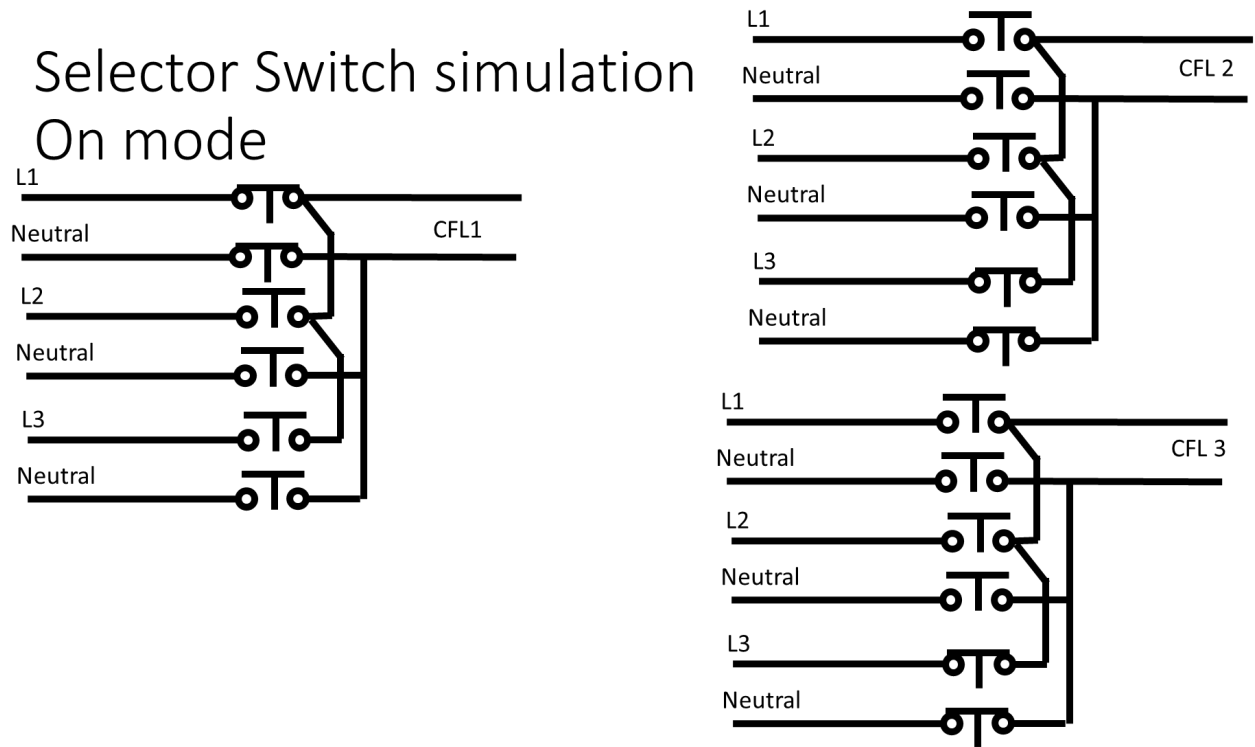


Figure 11

Selector Switch simulation Off mode

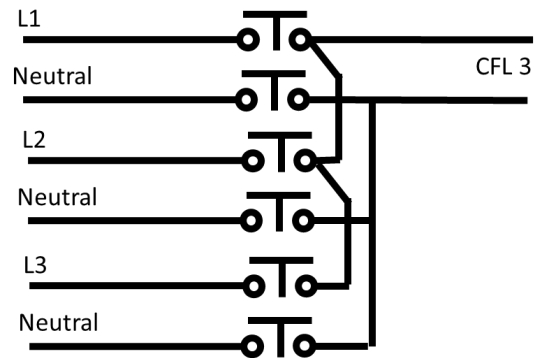
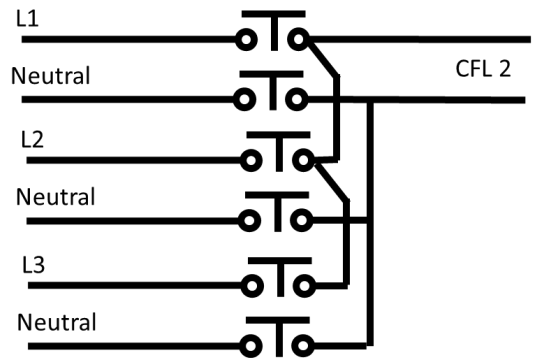
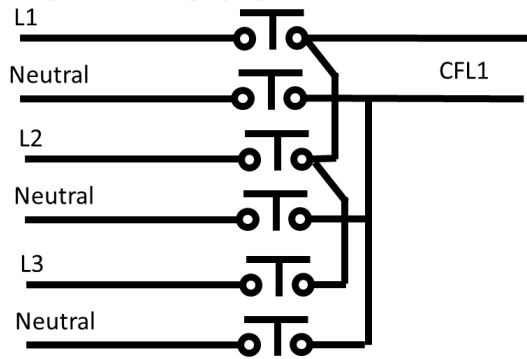


Figure 12

Selector Switch simulation On mode

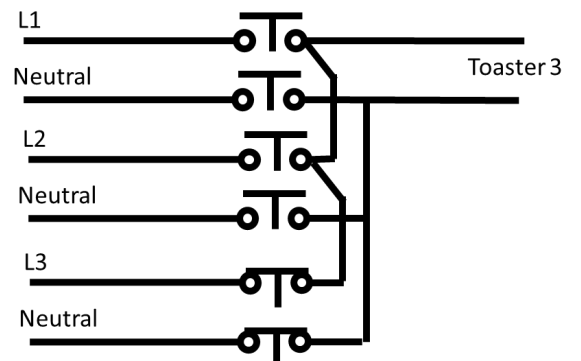
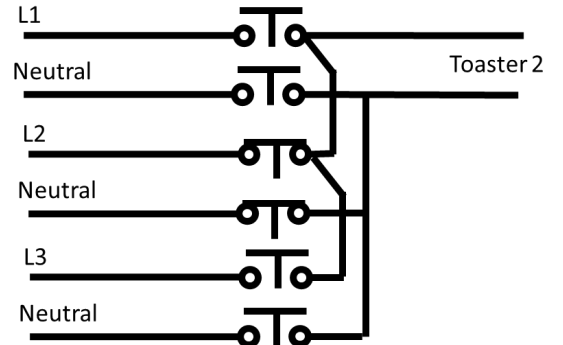
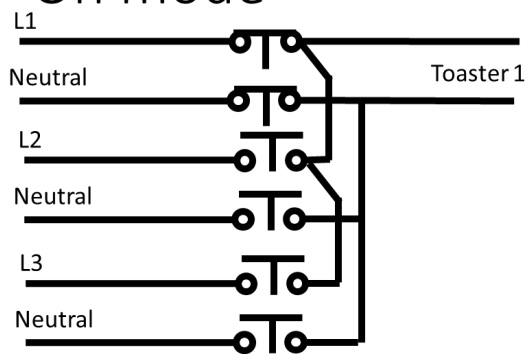


Figure 13

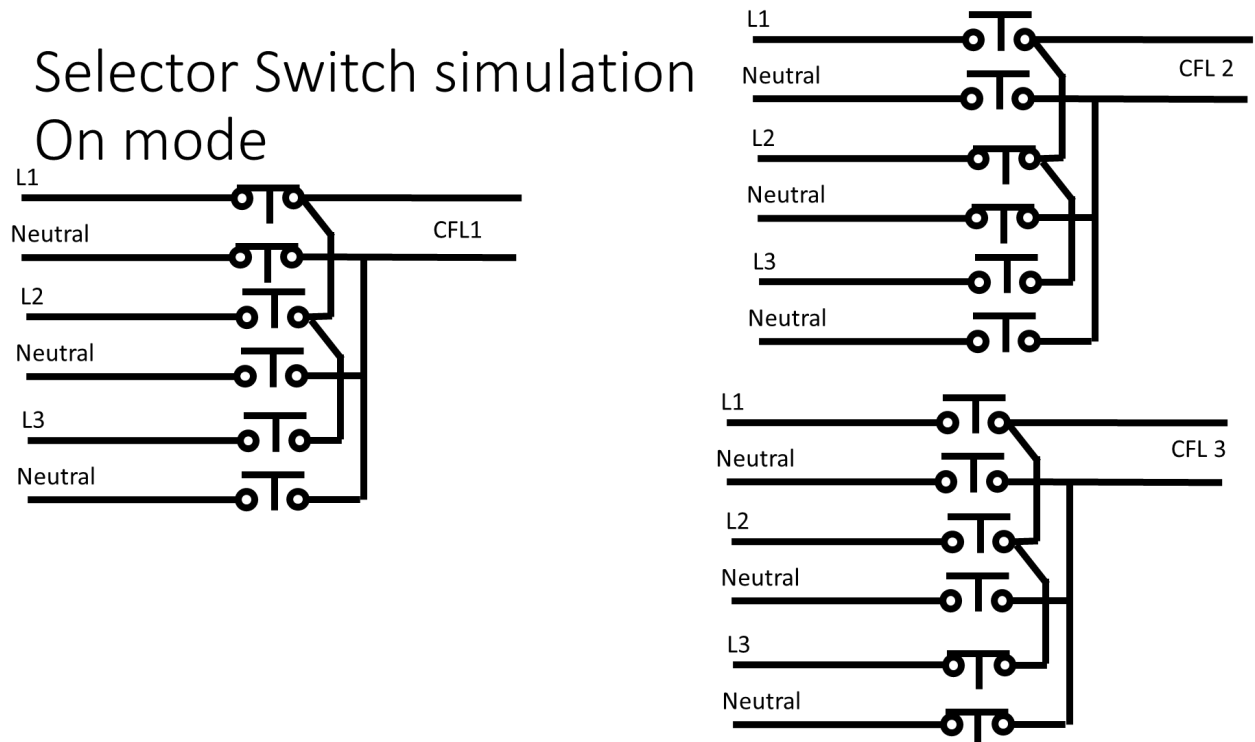


Figure 14

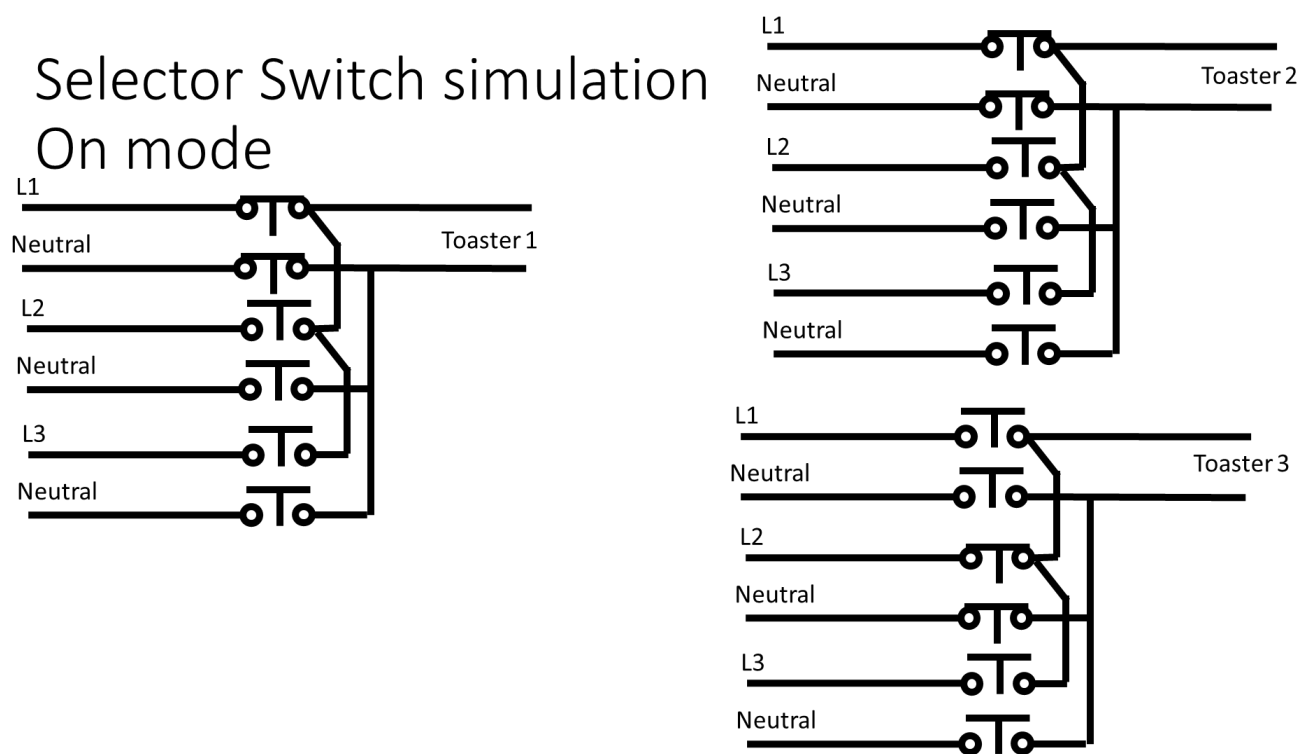


Figure 15

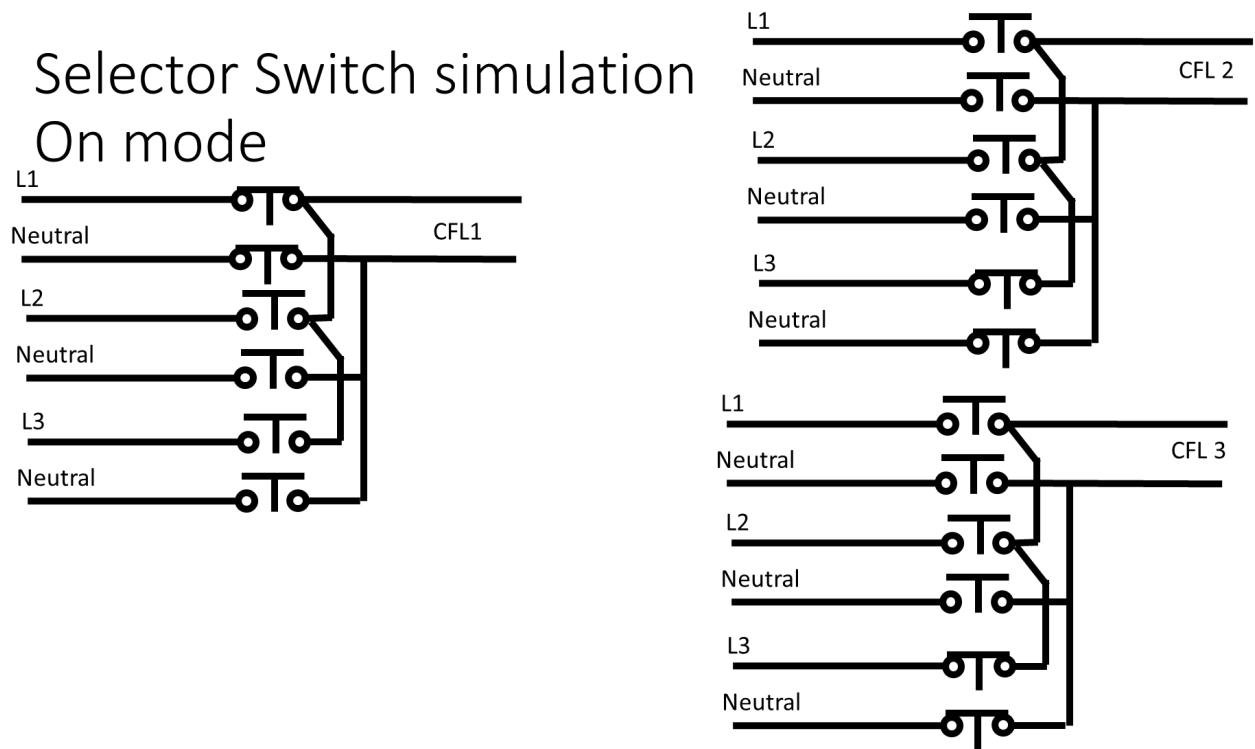


Figure 16

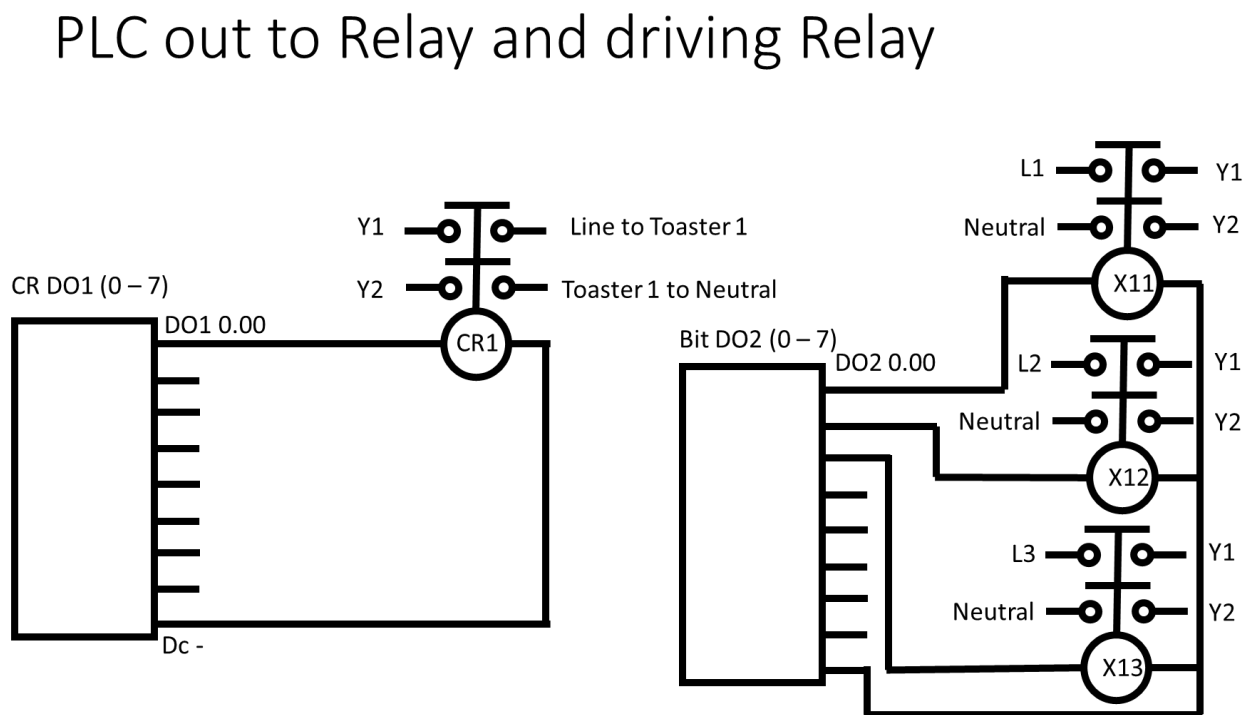


Figure - 16

Mathematic (part of PLC) 1

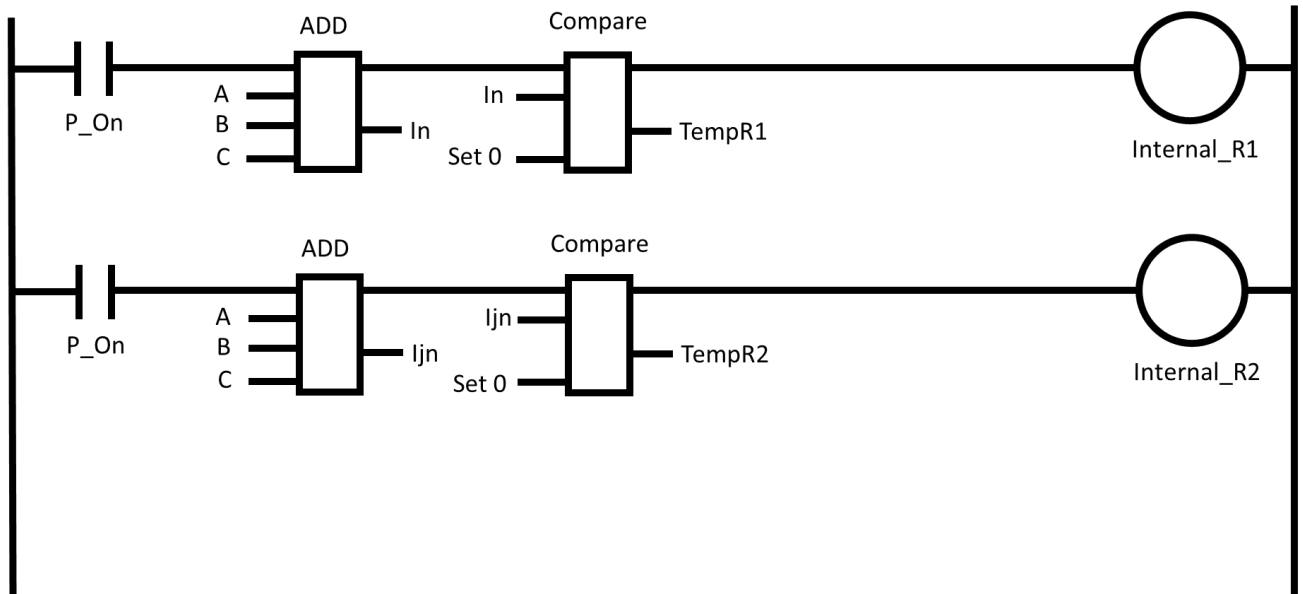


Figure17

Timer (part of PLC) 2

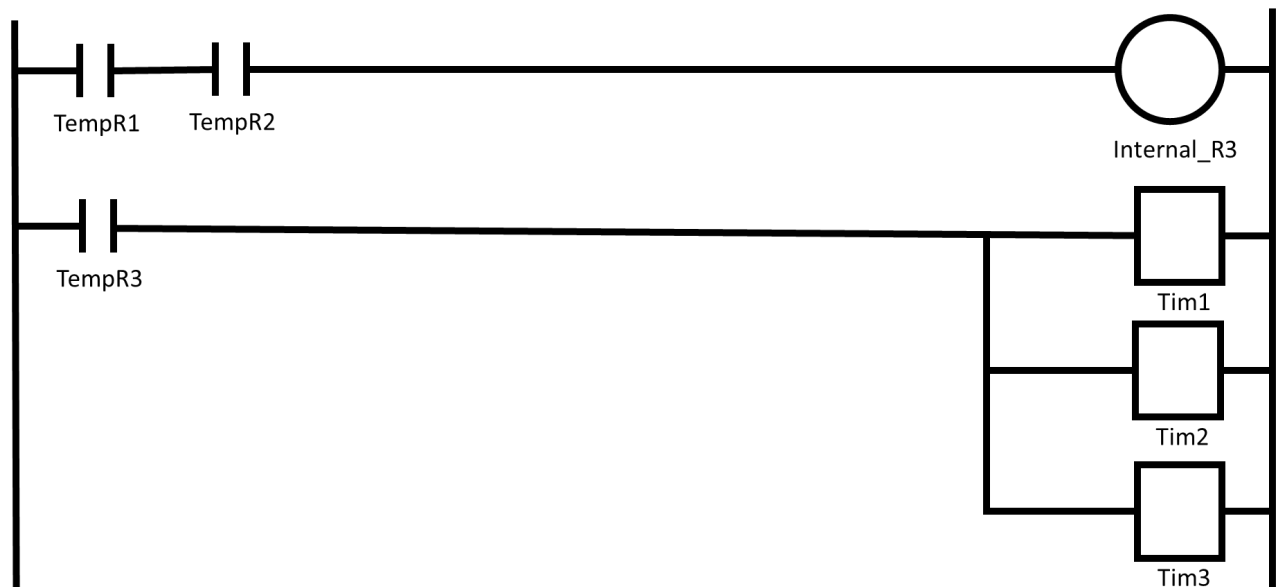


Figure18

Switching and interlock (part of PLC) 3

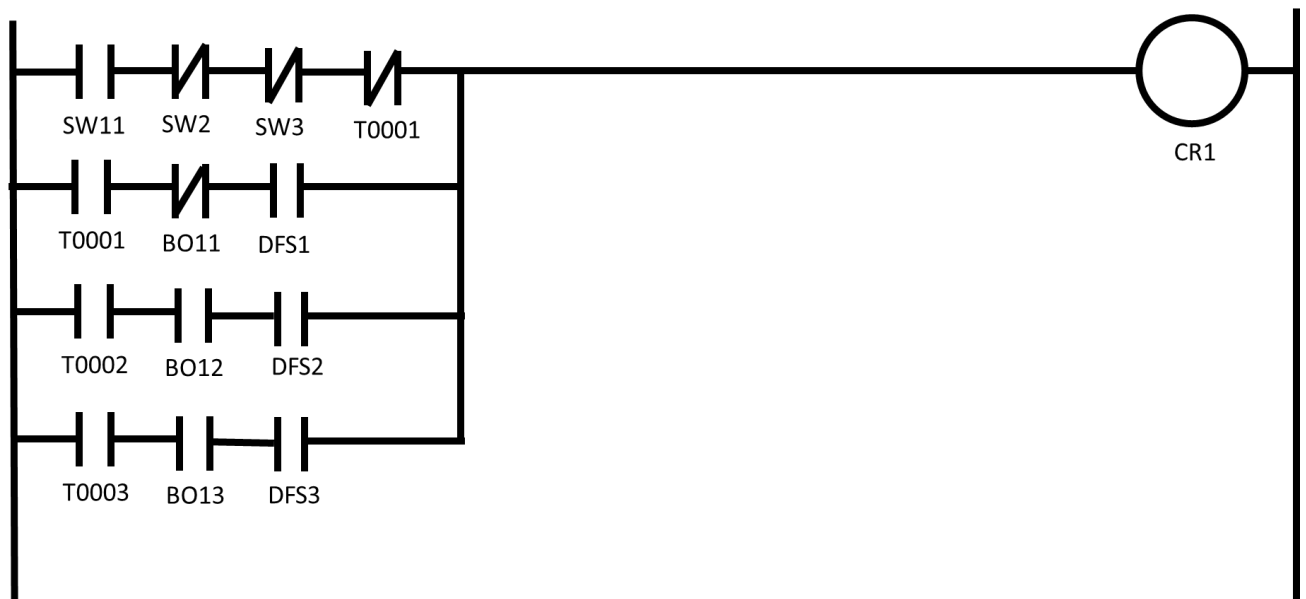


Figure 19

Block diagram of the experiment

3 phase Industrial Socket

