



MAKERERE

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**DEVELOPMENT OF A SINGLE-PHASE POWER QUALITY MONITORING  
SYSTEM**

**BY**

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**A Dissertation submitted to the Directorate of Research and Graduate Training in  
partial fulfilment of the requirements for the Award of the Degree of Master of Science  
in Technology Innovation and Industrial Development of Makerere University**

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**Kampala. Uganda.**

## DECLARATION

I, Kalema Ansty Ezra declare that this thesis is my original work and has not been submitted to any college, university, or institution for any academic award.

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## **ABSTRACT**

Electricity is crucial for the social, cultural, and overall well-being of Uganda. However, the absence of real-time monitoring and reporting on single-phase electricity networks exacerbates downtime and power instability, resulting in reduced productivity, equipment damage, and revenue loss. The existing call center structure, which depends on social media feedback and phone calls to the Supervisory control and data acquisition (SCADA), is susceptible to human error, process delays, and is labor-intensive in managing reference numbers. This study aimed to develop a prototype of an automated voltage quality reporting system with location updates. The conceptual framework was employed to visually represent the relationships between various concepts and variables.

A comprehensive literature review of related studies and system development life cycle (SDLC) models was conducted to inform and guide the research. Methods were developed to address the research questions and to guide activities to fulfill the objectives' requirements. Data were gathered using measurement instruments from a sample area of single-phase households, with a focus on shops for ease of accessibility. The findings were subsequently employed to benchmark the study's test setup. The data collected from the sample area closely aligned with the test bench results, exhibiting only minor deviations, which indicated that the trends observed in the test bench were consistent with those in the sample area.

The hardware and software were assembled and calibrated, resulting in a functional single-phase power quality monitoring system, with reports and alerts accessible online and on mobile devices. The developed prototype exhibited hardware and software configurations analogous to those documented in comparable studies. The study recommended integrating the system with an existing power meter for regular power supply to prevent misreporting of power failures when customer units are depleted. Further research recommends embedding of algorithms and AI tools for designing power distribution topologies, promoting continuous improvement within the energy sector.

Keywords: Automated, SCADA system, Single phase.

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## LIST OF ACRONYMS

AC	Alternating Current
AI	Artificial Intelligence
AVR	Automatic Voltage Regulator
BS	British Standard
ERA	Electricity Regulatory Authority
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HV	High Voltage
ISO	International Organization for Standardization
LV	Low Voltage
MV	Medium Voltage
MVP	Minimum Viable Product
RMS	Root Mean Square
RX	Receive
SCADA	Supervisory Control and Data Acquisition
SDLC	System Development Life Cycle
SRSD	System Requirements Specification Document
TX	Transmit
UART	Universal Asynchronous Receiver/Transmitter
UEDCL	Uganda Electricity Distribution Company Limited
UEGCL	Uganda Electricity Generation Company Limited
V	Volt
WENRECO	West Nile Rural Electrification Company

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## CHAPTER ONE: INTRODUCTION

### 1.1 Background

Electricity is fundamental to the functioning and transformation of social, economic, and cultural systems. In Uganda, the electricity sector is governed by policy guidelines issued by the Electricity Regulatory Authority (ERA) under the Ministry of Energy and Mineral Development, which aim to promote efficiency, reliability, and continuous improvement in electricity service delivery (Onyoin & Bovis, 2021). The establishment of the ERA has contributed to increased access to electricity for domestic single-phase consumers and industrial users, thereby expanding connectivity to the national electricity grid. Despite these developments, adequate attention has not been given to power quality assurance, particularly at the end-user level (Kayima et al., 2023).

Although the energy sector, especially electricity distribution, has experienced significant growth, the implementation of systematic quality of service monitoring at the consumer level remains limited. End users frequently experience voltage fluctuations, with recorded levels falling below the acceptable lower limit of 216 V and exceeding the upper limit of 253 V, as stipulated in the British Standard BS 7671. Empirical observations indicate that undervoltage conditions commonly occur during peak demand periods between 6:00 pm and 11:00 pm, while overvoltage conditions are more prevalent during off-peak hours, particularly between 11:00 pm and 5:00 am. These challenges are further compounded by prolonged and often uncommunicated power outages.

Voltage instability poses significant risks to electrical equipment used in households, commercial establishments, and industrial facilities. However, there is currently no clearly defined framework through which affected consumers can substantiate compensation claims with electricity distribution companies, insurance providers, or the ERA. This gap underscores the need for verifiable, real-time evidence to support power quality-related claims. Consequently, the present study was motivated by the need to improve electricity service quality monitoring.

The domestic single-phase electricity market, which constitutes the largest proportion of consumers under the Uganda Electricity Distribution Company Limited (UEDCL), presents an appropriate focus for such an intervention, as highlighted in the 2023 Annual Report.

Electricity distribution in Uganda is predominantly managed by UEDCL across most regions, with the West Nile Rural Electricity Company (WENRECO) and other licensed subcontractors operating in specific areas. The distribution network complies with the British Standard BS 7671. With population growth, the distribution grid has expanded in both coverage and length, increasing operational complexity (Jensen et al., 2021).

Voltage regulation is achieved through step-down transformers that reduce medium-voltage levels of approximately 11 kV to 415 V in a three-phase system. Following transformation, electricity is primarily distributed to consumers using a radial network topology (Ibrahim et al., 2025). Currently, fault detection beyond the substation level is largely manual and relies heavily on customer reports received through branch offices, telephone calls, and social media platforms, as well as on visible physical damage to distribution infrastructure. This approach often results in delayed fault identification and inefficient fault localization.

To address this limitation, the study aimed to design and develop a prototype capable of monitoring and reporting single-phase voltage supply trends in real time, incorporating location data transmitted via a General Packet Radio Services (GPRS) network. In addition, the prototype was designed to provide protective functionality by disconnecting the load under extreme voltage conditions to safeguard end-user equipment (IJMSRT, 2025). The study focused specifically on the single-phase live-to-neutral low-voltage segment of the distribution network at the consumer premises (Asoh & Chia, 2022).

## **1.2 Problem Statement**

Single-phase electricity consumers in Uganda frequently experience unplanned power outages and voltage fluctuations that are often not detected by the Supervisory Control and Data Acquisition (SCADA) system. These disturbances typically occur at the household level of the distribution network, thereby necessitating consumer-initiated fault reporting. The identification and resolution of such faults largely depend on consumers reporting issues through phone calls, WhatsApp messages, or other social media platforms. Consequently, response times are prolonged, and fault localization becomes inefficient. Furthermore, voltage fluctuations and power interruptions frequently result in damage to consumer property.

The compensation claims against electricity distribution companies or insurance providers are often unsubstantiated due to the absence of verifiable and documented evidence. In light of the increasing demand for electricity and expanding grid connectivity, there is a critical need for

systematic monitoring of the electricity distribution network to ensure power quality assurance at the end-user level.

### **1.3 Objectives**

#### **1.3.1 Main Objective**

To develop a single-phase power quality monitoring system

#### **1.3.2 Specific Objectives**

- i. To determine the design specifications required for a single-phase electricity monitoring system.
- ii. To develop a functional prototype based on the identified design specifications.
- iii. To evaluate the performance, effectiveness, and reporting capabilities of the developed system.

### **1.4 Research Questions**

The following questions guided the research:

- i. What functional, technical, and operational requirements are necessary for designing a system capable of monitoring and reporting single-phase voltage levels?
- ii. Which methodologies and tools are appropriate for the development of the proposed single-phase power quality monitoring system?
- iii. How can the performance and output of the developed prototype be evaluated to determine its effectiveness?

### **1.5 Justification**

This study is of considerable significance as it contributes to the existing body of knowledge on real-time monitoring and reporting of single-phase power quality. The integration and deployment of the proposed system within current single-phase electricity distribution networks offer electricity regulatory authorities and other key stakeholders a practical reference framework for evaluating the quality of service delivered by power distribution companies to end users. Furthermore, the system facilitates the generation of verifiable accountability records, which may be accessed by stakeholders upon request or disseminated through periodic reports. In addition, the developed system can serve as a performance monitoring and benchmarking tool for single-phase distribution networks, thereby supporting informed decision-making and fostering continuous improvement within the power distribution sector.

## **1.6 Scope**

This study focused on the development of a system designed to monitor and detect voltage fluctuations, with the capability to automatically disconnect the power supply upon detection of undervoltage, overvoltage, or complete loss of mains supply. In addition, the system was designed to capture location information and transmit voltage data to a remote database for storage and analysis. The study involved continuous voltage monitoring over a period of 21 days at a selected single-phase domestic residence, which served as the primary test point. The experimental phase was conducted over a three-week period, and due to financial constraints, the researchers developed and deployed only one functional prototype. The geographical scope of the study was limited to a residence within the selected sample space in Wakiso district, specifically, the Kira–Kimwanyi Division, alongside supporting field voltage measurements taken within the same locality.

## **1.7 Conceptual Framework**

Referring to (Figure 1.1), the input variables consist of regulatory, operational, and technical factors that inform the system design. These include Electricity Regulatory Authority (ERA) guidelines, operational requirements of power distribution companies, relevant IEEE and British Standards, existing literature, expert technical advice, and identified power quality challenges. Additionally, system-specific data inputs such as single-phase line-to-neutral voltage, time of occurrence, GPS location, and consumer meter identification number provide the foundational data required for system operation.

Process variables represent the intervening activities through which the inputs are transformed into a functional system. These processes include system analysis and design, during which functional requirements, hardware components, software specifications, and system architecture are determined. This is followed by system development involving hardware assembly and software programming. Testing, calibration, and validation are then conducted using standard reference instruments to ensure accuracy, reliability, and compliance with established power quality measurement standards. Data analysis and documentation are also undertaken to evaluate system performance and record findings.

Output variables comprise the tangible deliverables resulting from the system development process. These include a fully implemented and calibrated single-phase power quality monitoring system, power quality reports, real-time data transmission to an online platform (ThingSpeak), SMS alerts for abnormal events, and a user manual to guide system operation.

The outcomes of the system are reflected in improved access to real-time power quality information, enhanced detection and localization of power quality disturbances through GPS integration, and increased protection of consumer equipment.



Figure 1.1: Conceptual Framework

The framework illustrates the relationship between system inputs, development processes, system outputs, and the resulting outcomes in the implementation of a single-phase power quality monitoring system.

## **1.8 The Report Structure**

Chapter 2 presents the review and analysis of the related literature, as well as other studies that presented similar monitoring systems. It also includes a discussion of the standards related to electricity, distribution topologies, and methodologies used in system development. Chapter 3 explains the methods, tools, and resources used to meet the study's goals. Chapter 4 presents the findings, providing an analysis of these results. Chapter 5 presents the discussion of the results, limitations, and similar studies. Chapter 6 presents the conclusions and recommendations for the future work. The rest of the document contains the references and appendices.

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Transmission and Distribution

The Ugandan transmission network predominantly comprises of 132 kV lines that facilitate the transfer of electricity from generation sites to various substations, where the voltage is stepped down and subsequently distributed to the 11 kV and 33 kV distribution networks. The primary transmission infrastructure extends from the Jinja, Karuma, and Bujagali hydropower plants to numerous substations throughout the country, as illustrated in Figure 2.1. Monitoring is conducted up to the 11 kV and 33 kV substations. Beyond the 11 kV/400 V step-down transformer, the distribution system is not subject to monitoring (Living et al., 2023).

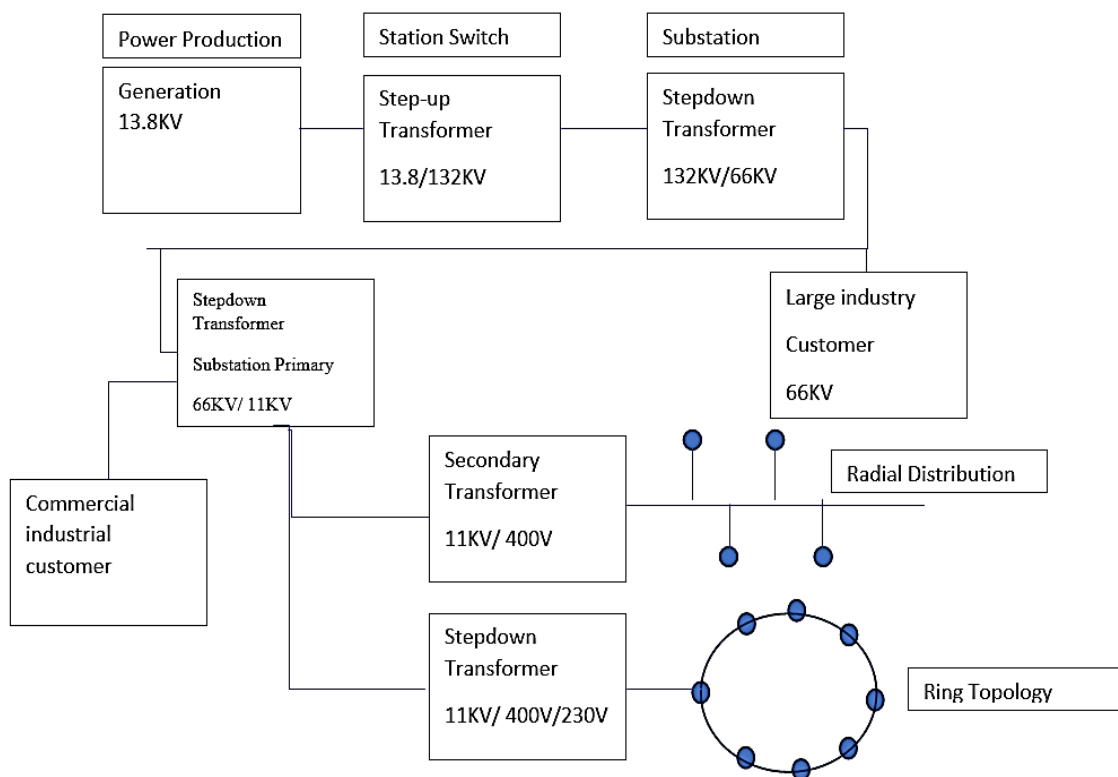


Figure 2.1: Distribution topology types

Source of figure (Akbar et al., 2023)

Figure 2.1 shows the breakdown and the different topologies used to distribute power to the single-phase end users. The study was carried out at the three phase four wire networks.

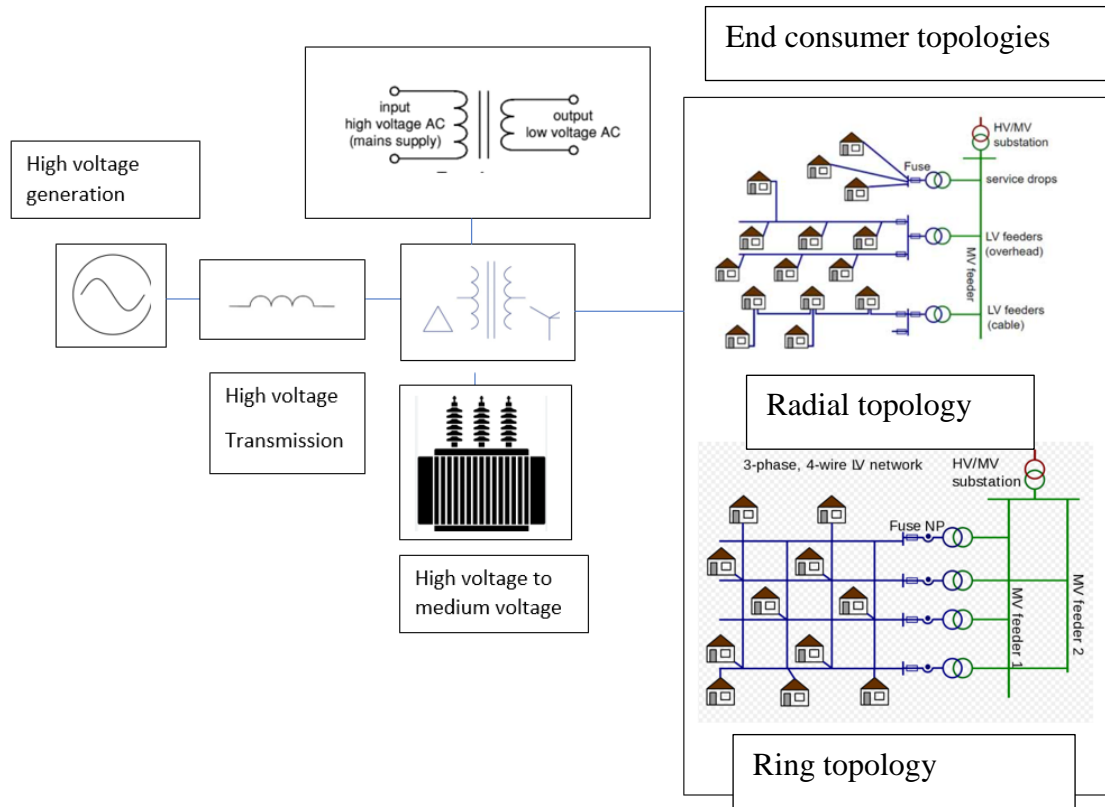


Figure 2.2: Low voltage distribution topology

Source (Limpraptono et al., 2021)

## 2.2 Distribution Topology

Ring topology has both link and open loop which is mostly used in 11 kV and 33 kV networks to provide more secure supply. The open end is located between two radial feeders to ensure the radial operation for each feeder as well enforce isolation of a faulty section refer to figure 2.2 ring topology is a ring circuit where power distribution takes both directions and will read the same voltage at any point measured in the ring circuit. This was observed only in the medium power transmission section of the grid. The radial topology is used in LV distribution networks in Uganda because of ease of implementation however it is more prone to faults, and one fault affects multiple customers for example a single break in the line which is not the case with the ring topology. This is where the study is based, this type of network is widely used in Uganda for power distribution (Joshua et al., 2023).

### 2.3 Low Voltage Distribution Networks

Based on the British standards BS 7671, LV has a maximum limit of voltage level of 1 kV. World over, the most common voltage levels are within the range of 120-240 V single phase i.e., phase to neutral, 208 - 415 three phases three or four wires. Based on the international standard recommendation (IEC 60038), the voltage level of 3 phase - 4 wire is 230/ 400 V (Figure 2.5). The LV network is the last stage of the power network, which is connected directly to the single-phase customer and supplies many dispersed small-scale loads. It has the characteristics of small individual loads, but a massive number of nodes. Due to the low voltage level, the LV feeders require lower financing compared with higher voltage feeders such as MV and HV. The huge number of LV feeders requires a significant amount of work, third party contractors are assigned the job to further the distribution as the topology grows. This creates an unending line of distribution attached to the last low voltage transformer in sight or closer to the consumer, (Figure 2.3) specifies the voltage per stage (Olojede et al., 2025).

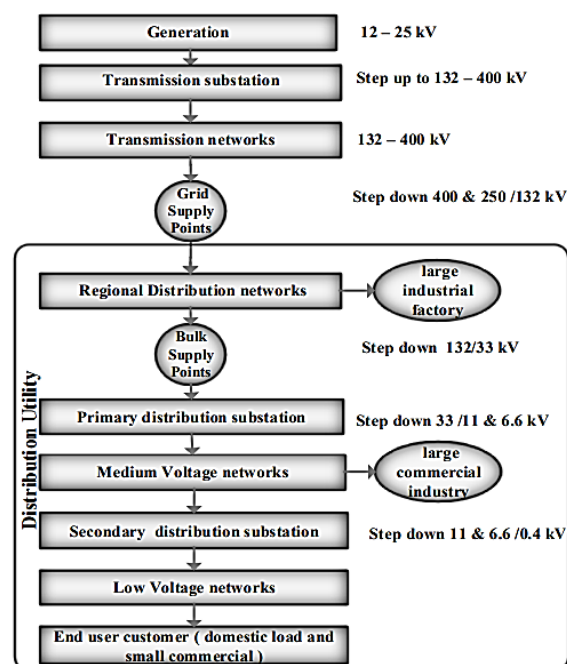


Figure 2.3: Uganda Electricity Grid system

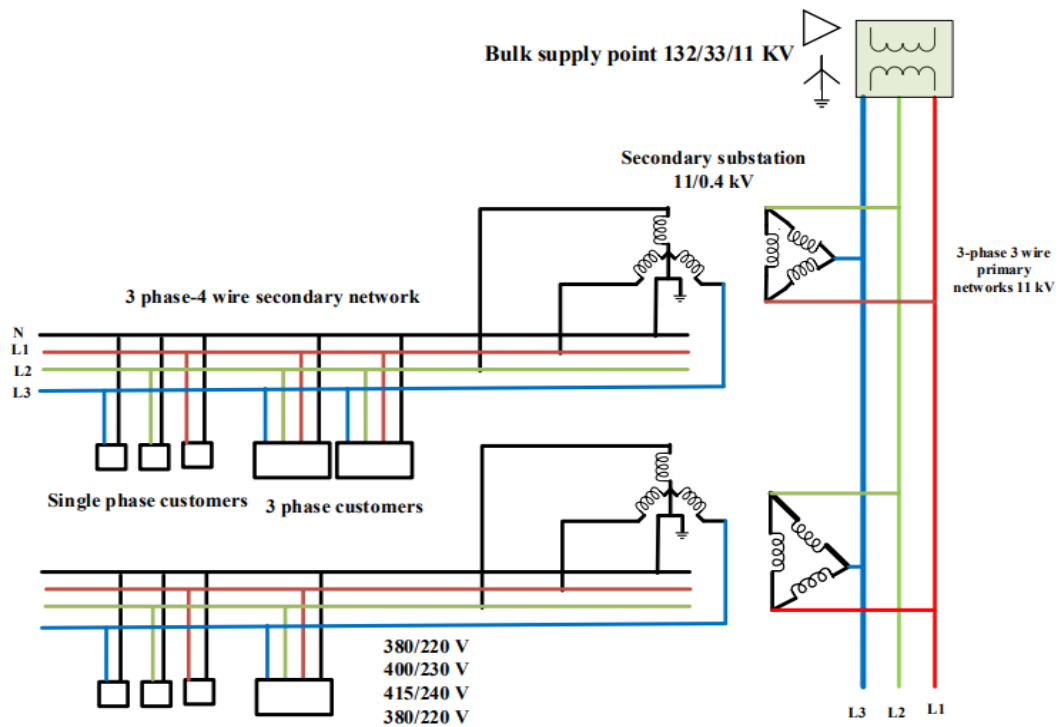


Figure 2.4: Uganda power grid HV to LV

Uganda’s national grid is like the British power grid (figure 2.4), the block diagram has been given in (Figure 2.4). A UK based study was conducted to monitor current usage and power failures on the national grid. In the current system setup in Uganda, voltage monitoring at the end user is nonexistent, monitoring is done at substation level dropping off a ring topology. End-users are connected to a radial topology that spirals endlessly where a connection to the grid is upon request to the nearby power service pole (Olojede et al., 2025).

Fault location is time-consuming, which affects the turnaround time for fault resolution. Another problem is that in small grids, there is no automatic protection device along the feeder. In this area of study, several authors have performed different approaches to create an efficient monitoring system for the detection and location of the faults in electric power grid. Basing on measurements of voltage magnitude and phase angle at a small number of lines to detect and locate failures, observing the behavior of the three power lines over time, using tools like the Hilbert transform, fuzzy classifier to achieve successful detection but can be a more complex and not easy to maintain system (Damanjani et al., 2022).

Utilizing input samples of current and voltage, the detector is constructed with four distinct connections corresponding to each phase, in addition to one for the ground. Failures associated with atmospheric conditions necessitate the design of an environmental monitoring device for transmission lines in real time, to differentiate between weather-related changes and actual faults. Related work includes a team in India that detected power grid synchronization failures by sensing frequency, voltage, and deviations beyond the acceptable range.

The system was designed to identify synchronization issues of any external supply to the power grid by detecting anomalies in frequency and voltage. The generating units were required to supply power in accordance with grid-specific regulations. These regulations necessitated maintaining voltage and frequency variations within specified limits. In the event of any deviation, the grid line would automatically disconnect. This prevented brown out or black out of the grid power. It was preferable to warn the grid in advance so that alternate options are kept on standby to avoid total failure. The system was based on a microcontroller of 8051 family. The system monitored the under/ over voltage derived from a set of comparators.

To ensure efficient supply of safe electricity and to reduce power outages, UEDCL Ltd introduced the SCADA system in 2009. It is based at Lugogo Substation. The system promptly detects faults on the high voltage grid for quick rectifications. It is also used to monitor all equipment on the electricity grid such as transformers and switches up to the substation.

The company reports that power losses stood at 33.5% before the introduction of SCADA in 2009 and that they had reduced to 16.5% by end of 2017 (ERA report 2016). This approach focuses on only three phase energy metering infrastructure and the substation. The primary goal of the study was to design a power quality monitoring system at a single-phase consumer side which is not covered by the current SCADA system.

There are contributions to the development of energy monitoring systems under IOT, these include the use of energy monitors for efficiency improvement and current usage monitoring (Varela–Aldás et al., 2022). Varela proposed a two-channel electrical power monitoring kit with a set of two parameters to monitor the electrical system. In this paper the researchers presented a single-phase voltage monitoring kit based on the “M5 Stack Core2 kit” processor. The variables included a combination of current and voltage acquired through “PZEM 004T V3.0” sensors and the data sent to the cloud database through a GSM network to the server.

In the voltage and current real time monitoring study, research was conducted through a web application and a mobile application, both designed to observe and record variables for subsequent analysis. The results demonstrated the relationship between mains power and current consumption. However, the primary concern remains the cost incurred by the customer, which does not significantly contribute to quality monitoring. The layout employed in this instance in is (Figure 2.5) similar to that presented in this study (Putra, 2025).

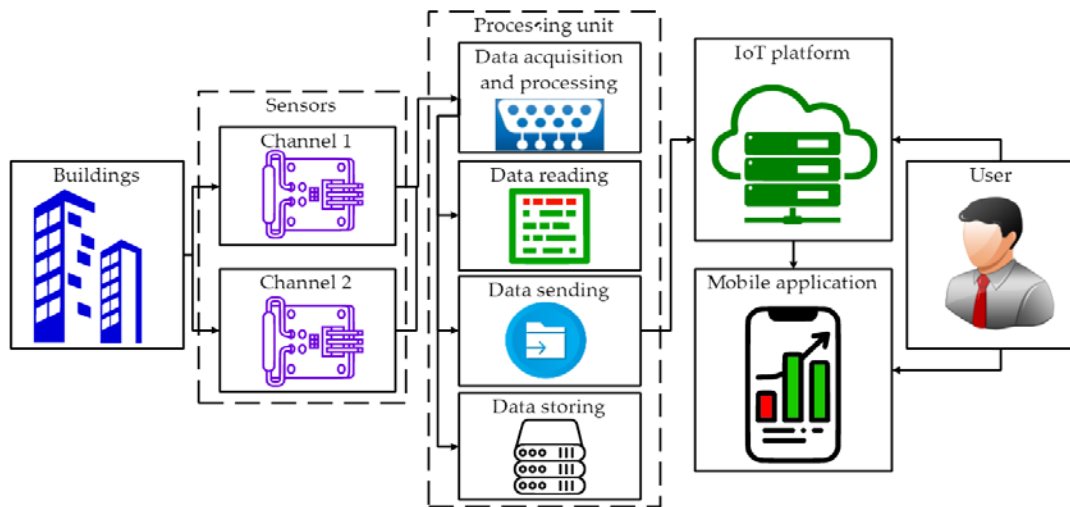


Figure 2.5: Voltage and Current sensor

Source (Varela-Aldás et al., 2022)

In accordance with the IEEE Standard 1668 workshop remarks, the researcher utilized this document as a reference to establish the voltage limits as a bench mark for assessing service quality (Varela–Aldás et al., 2022). Figure 2.7 shows the different standards around the world, Uganda uses 415/ 240 V at the domestic user end, and this study looked at type a which is the three phase four wire star wiring, using single phase against neutral to acquire the voltage reading as show in figure 2.6, line red or yellow or blue against black (Agbolade & Sunmola, 2021).

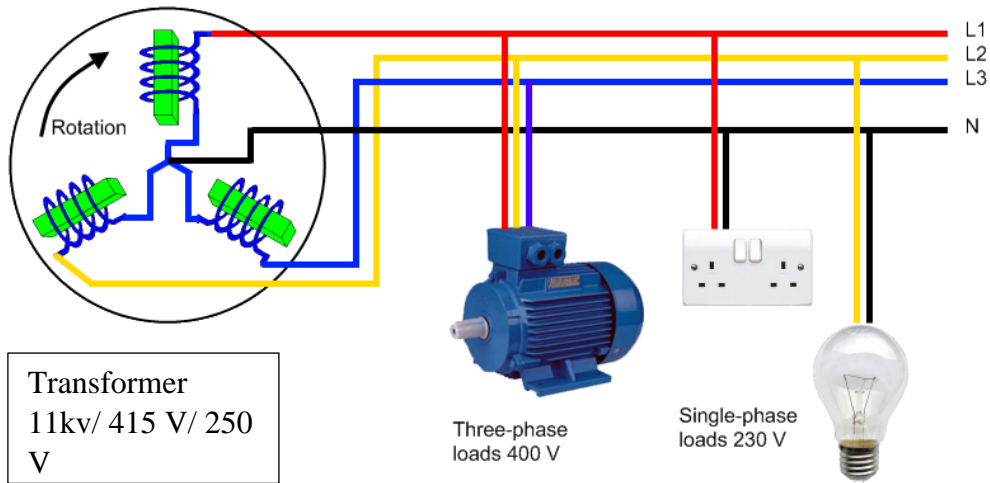


Figure 2.6: Single phase neutral illustration

Source (Jawaduddin et al., 2020)

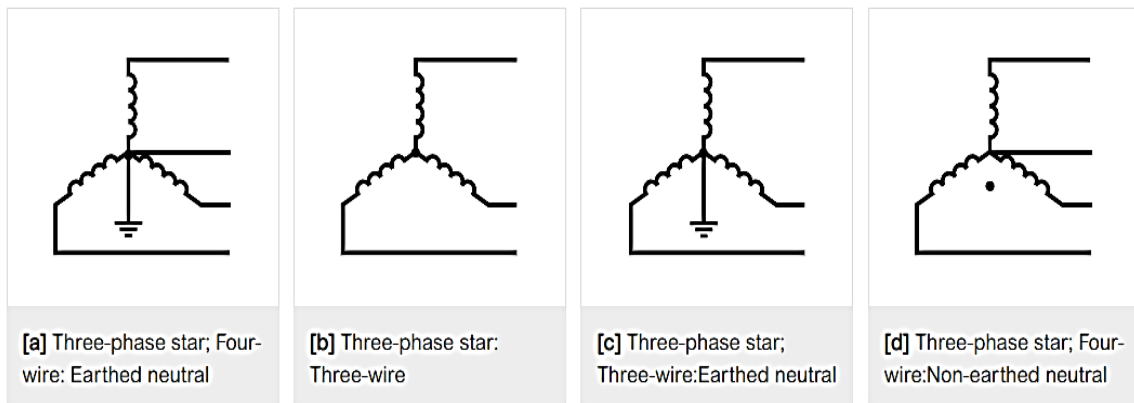


Figure 2.7: Three phase associated wiring diagram

## 2.4 Power Quality Indicators and Definitions

According to utility law, power quality is measured from its reliability. According to the load aspect, it is the power supplied for satisfactory performance of all equipment. According to the end user point of view, it is referred to as, “any power problem manifested in voltage, current, or frequency result into failure or miss operation of customer equipment” (Ishaya et al., 2023).

According to IEEE power quality is defined as “the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment”.

The International Electrotechnical Commission (IEC) defines power quality as a set of parameters that characterize the properties of the power supply delivered to the user under

normal operating conditions, specifically in terms of supply continuity and the characteristics of voltage magnitude, frequency, and waveform. The power supply system is capable of controlling only the quality of the voltage and does not influence the currents that loads may draw. Consequently, power quality standards are concerned with maintaining the supply voltage within specified limits. This aspect serves as the focal point for our project, which is designed to monitor these parameters effectively (Ravi & Kumar, 2022).

## **2.5 General Classes of Power Quality Problems**

The IEEE has led to the main effort in the United States to coordinate power quality standards. The IEC, IEEE classify electromagnetic phenomena into the groups as given below (Gade et al., 2021).

- i. low-frequency phenomena Harmonics
- ii. Inter harmonics Signal systems
- iii. Voltage flicker
- iv. Voltage dips (Sags) and interruptions
- v. Voltage imbalance, unbalance
- vi. Induced low frequency.
- vii. Voltage, Magnitude variations

Voltage fluctuations are changes in voltage levels. These changes can be random or happen continuously, usually between 0.9 and 1.1 per unit. When electrical devices use power in a way that changes quickly, it can cause these voltage changes, known as flicker. Flicker is named after the way it makes lights seem to flicker to our eyes. Voltage fluctuation is an electromagnetic issue, while flicker is a result of this issue that affects power quality. This study focuses on these electromagnetic changes (Kanchanapalli & Banka, 2024).

### **2.5.1 Voltage Imbalance**

Voltage or current unbalance happens when one of the three-phase voltages or currents is much different from the average of the three. This difference is shown as a percentage. It can also be explained as the ratio of the negative or zero-sequence component to the positive-sequence component. Voltage unbalance often occurs because of single-phase loads on a three-phase circuit. It can also happen if a fuse blows in one phase of a three-phase capacitor bank. If the voltage unbalance is more than 5 percent, it can cause big problems, especially in single-phasing situations. Therefore, the study focused on using voltage as the best way to check quality because of the problems that result from single-phase out of balance loads. The study

by Ciontea and Iov in a study of load balance influence referred to the same findings regarding load variations on single-phase networks (Ciontea & Iov, 2021).

### **2.5.2 Frequency Variations**

Frequency variations refer to the deviation of the power system's fundamental frequency from the designated nominal value, which is 50 Hz for Uganda. These variations can occur due to faults in the bulk power transmission system, the disconnection of a substantial load block, or the offline status of a significant generation source. In modern interconnected power systems, such frequency variations are infrequent within Uganda's electricity grid and, consequently, do not pose a significant concern (Biragbara, 2026).

### **2.5.3 Sags and Dips**

A sag is a drop-in voltage or current between 0.1 and 0.9 pu at the power frequency. This drop lasts from 0.5 cycle to 1 minute. Voltage sags happen because of system faults. They can also occur when heavy loads are turned on or when large motors start. In this study, I aimed to log this information by the change in events to reduce the frequency at which the monitoring system logs the voltage information. A swell is when the rms voltage or current at the power frequency goes up to between 1.1 and 1.8 pu for 0.5 cycle to 1 minute. Voltage swells happen when there is a temporary rise in voltage on the non-faulty phases during a single-line-to-ground (SLG) fault. They can also occur when a large load is turned off or when a large capacitor bank is energized (Sushma, 2023).

### **2.5.4 Interruption Momentary Electrical Power Systems**

An interruption of a duration limited to the period required to restore service by automatic or supervisory controlled switching operations or by manual switching at locations where an operator is immediately available. Such switching operations must be completed in a specified time not to exceed 5 min (Gurzyński et al., 2021).

### **2.5.5 Interruption Power Quality Monitoring**

A type of short-duration variation. The complete loss of voltage ( $<0.1$  per unit) on one or more phase conductors for a time between 30 cycles and 3s. Any interruption not classified as a momentary interruption. Interruption, sustained (power quality). A type of long-duration variation. The complete loss of voltage ( $<0.1$  pu) on one or more phase conductors for a time greater than 1 min. Interruption, temporary a type of short-duration variation. The complete loss of voltage ( $<0.1$  pu) on one or more phase conductors for a time between 3 s and 1 min.

Inverter, a power electronic device that converts direct current to alternating current of either frequency or a frequency required by an industrial process. Common inverters today employ pulse-width modulation to create the desired frequency with minimal harmonic distortion (Siregar et al., 2022).

### **2.5.6 Islanding**

Refers to a condition in which distributed generation is isolated on a portion of the load served by the utility power system. It is usually an undesirable situation, although there are situations where controlled islands can improve the system reliability. ITI curve, a set of curves published by the Information Technology Industry Council (ITI) representing the withstanding capabilities of computers connected to 120-V power systems in terms of the magnitude and duration of the voltage disturbance. The ITI curve replaces the curves originally developed by the ITI's predecessor organization, the Computer Business Equipment Manufacturers Association (CBEMA). Linear load, an electrical load device that in steady state of operation presents an essentially constant load impedance to the power source throughout the cycle of applied voltage (Tanoni et al., 2024).

### **2.5.7 Long-Duration Variation**

A variation of the rms value of the voltage from nominal voltage for a time greater than 1 min. Usually further described using a modifier indicating the magnitude of a voltage variation for example under voltage, overvoltage, or voltage interruption. The main parameters that the project considered for monitoring are defined below as per IEC std (Electrical power quality).

### **2.5.8 Over Voltage**

An overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for duration longer than 1 min. Overvoltage is usually the result of load switching (e.g., switching off a large load or energizing a capacitor bank). Incorrect tap settings on transformers can also result in system over voltages.

### **2.5.9 Under Voltage**

An under voltage is a decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 min. Sources of a surge are load switching on, or a capacitor bank switching off.

### 2.5.10 Sustained Interruptions

When the supply voltage becomes zero for a period more than 1 min, the long-duration voltage variation is considered a sustained interruption. Thresholds for calculating power variations.

### 2.6 Threshold Calculations

RMS (Root Mean Square), using the analytical method, in (Figure 2.8).

#### RMS Voltage Equivalent

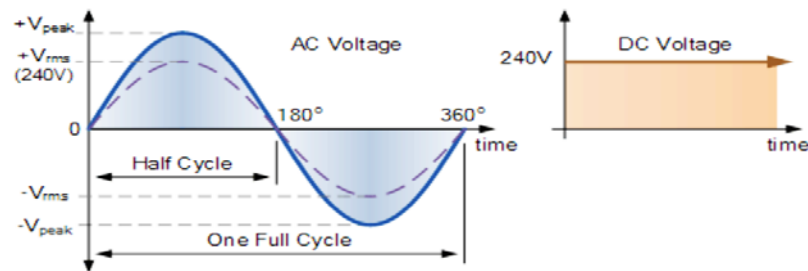


Figure 2.8: Wave forms for AC and DC

Source (Amiel et al., 2022)

Hence the calculation of the rms voltage of a sinusoidal waveform. The RMS voltage of a sinusoid or complex waveform can be determined by two basic methods. The graphical Method – which can be used to find the RMS value of any non-sinusoidal time-varying waveform by drawing several mid-ordinates onto the waveform (Amiel et al., 2022).

The positive half of the waveform is divided up into any number of “n” equal portions or mid-ordinates and the more mid-ordinates that are drawn along the waveform, the more accurate will be the result (figure 2.9).

Graphical Method:

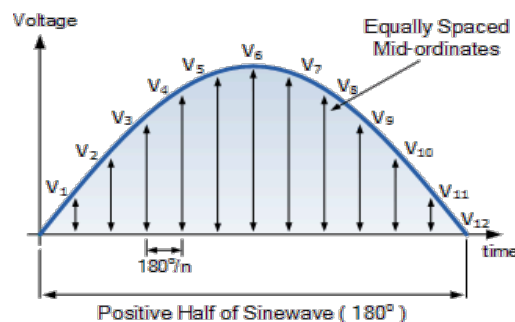


Figure 2.9: Half Wave form

Each mid-ordinate value of a waveform (the voltage waveform in this case) is multiplied by itself (squared) and added to the next. This method gives us the “square” or square part of the RMS voltage expression.

Next this squared value is divided by the number of mid-ordinates used to give us the mean part of the RMS voltage expression, and in our simple example above the number of mid-ordinates used was twelve. Finally, the square root of the previous result is found to give us the root part of the rms voltage equation (2.1 and 2.2).

The objective of this derivation was to demonstrate the root mean square ( $V_{rms}$ ) voltage in alternating current, as it constitutes a crucial parameter for the study.

$$V_{rms} = \sqrt{\frac{V_1^2 + V_2^2 + V_3^2 + \dots + V_n^2}{n}} \quad (2.1)$$

Where:

$V_1, V_2, \dots, V_n = \text{Sampled voltage Values (Mid – ordinates)}$

$n = \text{total number of samples (Amiel et al., 2022)}$

### 2.6.1 Analytical Method

Is a mathematical procedure for finding the effective or RMS value of any periodic voltage or current using calculus (Ahmed et al., 2022). The graphical method above is a very good way of finding the effective or RMS voltage, (or current) of an alternating waveform that is not symmetrical or sinusoidal in nature. In other words, the waveform shape resembles that of a complex waveform. A periodic sinusoidal voltage is constant and can be defined as  $V(t) = V_{max} \cdot \cos(\omega t)$  with a period of  $t$  (Jovel et al., 2024). Then we can calculate the root-mean-square (rms) value of a sinusoidal voltage ( $V(t)$ ) whereas,  $V_m$  is the peak or maximum value of the waveform. Dividing through further as  $\omega = 2\pi/T$ , the complex equation above eventually reduces down to:

$$V_{rms} = \frac{V_{pk}}{\sqrt{2}} = V_{pk} \times 0.7071 \quad (2.2)$$

Where:  $V_{pk}$  = the peak sinusoidal voltage

Then the RMS voltage ( $V_{RMS}$ ) (equation 2.1) of a sinusoidal waveform is determined by multiplying the peak voltage value by 0.7071, which is the same as one divided by the square root of two ( $\frac{1}{\sqrt{2}}$ ). The root mean square voltage, also known as the effective value, is determined by the magnitude of the waveform and is independent of both the waveform's frequency and its phase angle. In the context of this study and in accordance with IEEE standards, the recommended voltage is 240 volts  $V_{rms}$ . Voltage variation is calculated as a percentage per unit (PU).

The per-unit value of any quantity is defined as the ratio of actual value in any unit to the base or reference value in the same unit. Any quantity is converted into per unit quantity by dividing the numeral value by the chosen base value of the same dimension. The per-unit value is dimensionless(Hase et al., 2019). The voltage limits are defined in table 2.1. The thresholds in table 2.1 were used in the study to guide the in the operation of the system(Shahpouri & Kalantarian, 2024).

Table 2.1: Voltage limits

Variation	Lower limit $V_{PU}$	Upper limit $V_{PU}$	$V_{RMS}$	Duration
Voltage normal	0.9	1.0	216 - 240	< 1 minute
Voltage Swell	1.1	< 1.1	> 264	< 1 minute
Voltage Sag	0.9		< 216	< 1 minute
Voltage interruption	0.1		< 24	< 1 minute
Complete Voltage loss	0.1		< 24	>1 minute

## 2.7 System Development Literature

Various methodologies exist for system development, including rapid application development, joint application development, object-oriented development, extreme programming, and lean development. Among the most prevalent approaches for developing an information system are agile development, the prototyping model, and the system development life cycle which was the preferred method in this study ( Wiguna & Mahdiana, 2023).

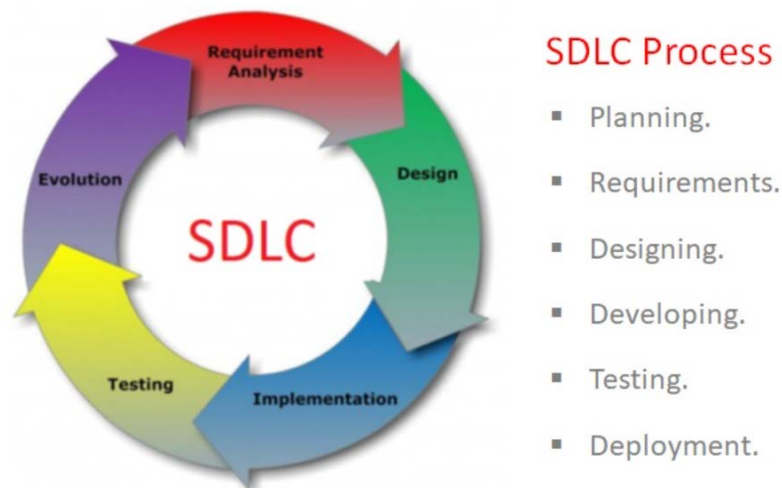


Figure 2.10: SDLC life cycle model

### 2.7.1 Study and Analysis Phase

This phase involves the gathering of the system requirements followed by analysis to study and validate the feasibility of these requirements for implementation into prototype system. The researcher, system developer and the system end users are the key persons in this phase. Hence, if possible, joint meeting sessions should be held to define, comprehend, gather, and record detailed requirements of the candidate system. The outcome of this phase is the system requirements specification document (SRSD). This phase was used in the methodology and literature review. System Design Phase the primary goal of the design phase is to build a technical blueprint/system design based on the inputs provided from the requirements gathering and analysis phase. The phase involves technical architecture, which is a comprehensive definition of the hardware, software and the telecommunications equipment needed to run the system. It also involves modelling, the activity in which IT specialists and system developers draw a graphical representation of the system design. The outcome of this phase is the system design document.

### **2.7.2 System Development Phase**

This is the longest phase of SDLC and is concerned with the physical construction of the system as set out in the design stage. At this stage, the system developers take the detailed system design documents developed at the design phase and transform them into the actual functional system. Secondly, the system developers write the necessary program codes as well as build the required system databases at the same time. The phase involves modules and codes and therefore prototype creation and development are at this stage. It is at this stage that documentation of the work that has been done to date takes place and hence system users are defined here.

### **2.7.3 System Testing Phase**

After system development at the previous phase, the system is handed over to the testing team. The primary goal of this phase is to evaluate and validate system functionality in accordance with its pre-defined requirements at the system analysis phase. During the testing phase, first, a quality assurance (QA) team develops comprehensive test conditions which are the conditions that the candidate system needs to satisfy before deployment to the end-users. Secondly, system testing can now be performed. Unit testing, integration testing, system testing, and acceptance testing are carried out at this phase. If all the tests run smoothly, documentation of all the work that has been done to date takes place followed by system release, operation, and maintenance of the study used this stage in the results phase.

### **2.7.4 Deployment Phase**

Once the application is fully developed and tested, it moves to the release phase. The system goes live and is released to the end user for actual use of the product. In other words, the system application is fully operational in a live environment where end users utilize it.

### **2.7.5 Operation and Maintenance Phase**

The aim of this phase is to ensure that the system remains fully operational and performs optimally until its end of life. Successful completion of the operations and maintenance phase should include the management of system changes to support end users, monitoring of system performance to identify errors, execution of necessary security activities such as backups, contingency planning, and audits, continuation of end-user support through training and documentation, and rectification of bugs and errors as requested by end users. Customer requests regarding system performance are considered feedback, which provides system

developers with insights into whether to modify the existing system for improvement or to terminate the system and develop a new one. The benefits of the waterfall model include;

Ease of comprehension due to its sequential development process with well-defined deliverables for each phase, facilitating project management. Enhanced learning opportunities at all phases for researchers seeking detailed insights, comprehensive documentation at every phase, aiding in-depth understanding of the project and future benchmarks.

Despite its advantages, the waterfall model has been criticized for its time-consuming nature, as each phase must be completed before the subsequent phase can begin. It is unsuitable for projects with uncertain requirements, as this model presupposes clarity during the requirement gathering and analysis phase. Any modifications in later stages can result in higher costs than initially anticipated. Furthermore, estimating costs is challenging, and user input and feedback are sometimes limited. In this study, the researcher employed this model during the software development stage.

### **2.7.6 Sample Size and Sampling Technique**

The general principle regarding sample size in this study was to recruit as large a sample as possible to enhance its representativeness without excessive effort. Since the research was experimental in nature, the calculation of sample size was contingent upon several factors, including the research design, sampling methods, the precision required, the variability of the factors under investigation, and the incidence of a particular variable within the population. The researcher compared various data collection techniques, including random sampling, stratified random sampling, and systematic sampling to determine which technique best represents the population behavior of power distribution. To represent the actual behavior of the voltage in the area, the systematic sampling technique was considered in this study because of its advantages(Khan et al., 2025).

The type of sampling is also used for homogenous population. The population is homogeneous in this case because it consumes electricity from the same power grid.

Advantages of systematic sampling technique:

- i. Operationally convenient - easier to draw a sample from a given sample size.
- ii. Distributes the sample more evenly over the population thus likely to be more efficient than particularly when the ordering of the units in the list is related to characteristics of the variable of interest.

- iii. The advantage of this sampling technique is its simplicity. Thus, the regularity and uniformity in selection makes the sampling systematic.

Disadvantages:

- i. Requires complete list of the population.
- ii. A bad arrangement of the units may produce a very inefficient sample.

This technique was appropriate because of the homogeneity of the population. Systematic sampling is known to reduce sample variation and errors by systematically choosing the  $n$ th sample in the sample size (Degiana 2019).

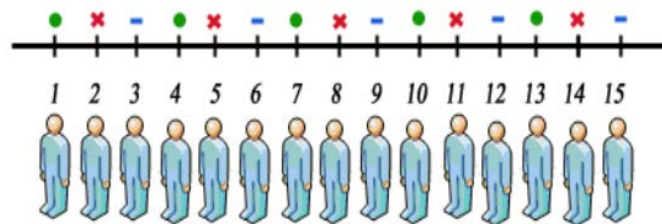


Figure 2.11: Systematic Sampling technique illustration

Systematic sampling is where every  $n$ th case after a random start is selected as an example of color-coding for example, if surveying a sample of consumers 1 to 15 in figure 2.13, every 3<sup>rd</sup> consumer may be selected from the sample. The advantage of this sampling technique is its simplicity. Thus, the regularity and uniformity in selection made the sampling systematic figure 2.14.

## 2.8 Sample Size Calculations

For systematic sampling,

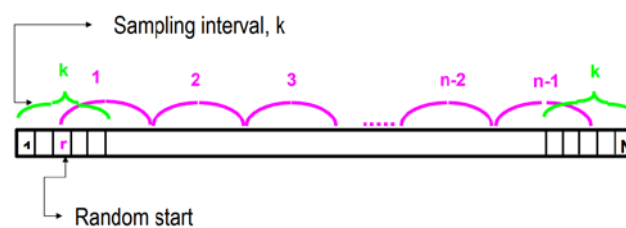


Figure 2.12: Interval uniform selection

Steps involved:

- i. Form a sequential list of population units and make notes.
- ii. Assign sampling numbers to each unit on the notes.
- iii. Decide on a sample size  $n$  and compute the skip (sampling interval),

$$K = \frac{N}{n} \quad (2.3)$$

Where; n sample size

N total population

K interval.

Choose a random number, r (random start) between 1 and k (inclusive) refer to figure 2.14

Select the unit with serial number r as the first unit in the sample.

Add “k” to selected random number to select the second unit and

Continue to add “K” derived from equation (2.3) repeatedly to the previously selected unit number to select the remainder of the sample, until n units are selected.

## **2.9 Identified Gaps**

Numerous studies have identified gaps analogous to those addressed in this research. In the domain of power distribution and system fault monitoring, researchers have highlighted that while efforts are made to ensure status monitoring and fault detection at the generation and transmission levels, such measures are lacking at the distribution level, particularly within domestic communities. This absence of fault monitoring and detection leaves the system vulnerable and significantly increases the risk of transformer damage due to overload (Nkinyam et al., 2025).

A study done in the distribution of low voltage circuits, the researchers presented a practical approach to estimating the secondary circuit topologies using historical voltage and power measurement data provided by smart meters and distributed energy resource sensors. In so doing, the low voltage distribution network would be modelled in size to avoid network overload

monitoring devices, the operating structure needed to be estimated indirectly. In this paper the researchers presented a new learning algorithm that used only voltage measurements to determine the operational radial structure. The algorithm was based on the key result stating that the correct operating structure was the optimal solution to the spanning tree problem that created a variance of nodal voltage difference at the electricity distribution network ends (El-Fergany, 2023).

Al- Jaafreh and Geev carried out a study on the impact on voltage and current imbalance in the low voltage networks, the study highlighted the need to plan and manage the operation of low voltage networks as a way to overcome voltage unbalance in low voltage networks. The study further highlighted the persistent need from other studies to develop traditional planning and operationalization of frameworks to cope with these new technologies that include increased use of renewable energy sources (RES) into the electricity grid. In addition, the different types of low carbon technologies (LCTs) such as electric vehicles (EVs) are becoming widely used. A significant portion of RES and LCTs is penetrated the LV distribution network and this would further increase the load on the already inefficient low voltage networks (Al-Ja' Afreh & Mokryani, 2019).

A study in power grids by Sarvani and Vineela identified a need to disconnect grids in cases where several power generation units were connected to the grid such as hydro, thermal, solar to supply power to the load. These generating units are needed to supply power according to the rules of the grid. If any feeder deviated from the acceptable limits of the grid, it would automatically get disconnected from the grid which in turn would prevent large scale brown out or black out of the grid power (Sarvani & Vineela, 2017). A study Carried out by Abro Jawaduddin sought proposed an automatic energy monitor to close the gap of real time feedback in energy distribution networks. The study further indicated that real time feedback solves the hustle of fault finding and makes it easy to monitor usage of energy by the consumer remotely and also made the information available (Jawaduddin et al., 2020).

## CHAPTER THREE: METHODOLOGY

### 3.1 Research Design

This study used sampling to gather qualitative and quantitative data, measurements were taken to evaluate the voltage behavior. Experiments were carried out on a test bench to support the methods used to address each of the objectives.

### 3.2 Sampling Frame

The total population in Kira Kimwanyi division Wakiso district according to the numbers supplied by the local chairperson from the resident's registry, at the time of data collection, there were 3848 residents. An average of 5 people per household was estimated for the sampling process purpose. This gave rise to a sample frame of (3848/5) resulting into a sample size of 770 single phase households and in these the shops were targeted because of ease of access.

#### 3.2.1 Sample Size

The systematic sampling technique was used because of its simplicity, speed in selection of samples, cost effectiveness, elimination of clustered bias, and easy execution with a master list. The elements were selected at a regular interval, where every  $n^{\text{th}}$  case after a random start was selected. The sample space was calculated using the sample space calculator equation 3.1.

$$n = \frac{Nz^2p(1-p)}{e^2(N-1) + z^2p(1-p)} \quad (3.1)$$

Where;

$n$  is the sample size,

$N$  is the population size,

$z$  is the confidence level (in percent, such as 90% = 0.9),

$p$  is the sample proportion (in percent, such as 50% = 0.5),

$e$  is the margin of error (in percent, such as 5% = 0.05).

$n = 31$

The equation (2.3) was used to calculate the systematic number of skips for every sample measurement taken.

Where;

- K is the systematic number of skips,
- N Single phase households,
- n Sample size.

Therefore

$$K = 25$$

### 3.3 Tools and Instruments

A digital multimeter fluke 115 was used to measure voltage from the sample population where the data was collected from the single-phase users. Voltage readings were recorded from every 26<sup>th</sup> sample of the population. Garmin Extrex 30 GPS was used to pick location coordinates as shown in (figure 3.1).



Figure 3.1: GPS and digital multimeter

The Fluke 435 power quality Analyzer figure 3.2 was used to measure a range of power quality parameters and the data stored on its memory. The device showed data in various graphs to display the behavior, trends, and activity of these power quality factors. The tool was set the tool to store measurements every 10 seconds.

A transformer was identified a transformer located in the Kira Kimwanyi zone, from which the output power lines were traced to the selected sample population. The type of supply and the

dwellings chosen were single-phase users, all situated within the same sample space as the identified transformer output line. Prioritization was given to health and safety, as well as ease of access to the premises for the data collection team, before entering the premises.

### 3.3.1 Control Data Capture

The readings were taken from the meter box of the selected sample. This involved a setup test point within the sample space area where voltage recordings were taken at different times of the day (figure 3.2) for over a period of 14 days using the Fluke 435 power quality analyzer, to capture the data for the time of day where the domestic premises were out of reach especially during the late hours of the night.



Figure 3.2: Fluke 435 power quality analyzer

### 3.4 Establishing the Design Specifications

In the first phase of the SDLC, requirements gathering and analysis was performed. This enabled the study to list and categorize the requirements for the system. Some of the requirements were gathered using techniques from literature reviews, expert knowledge, and discussions where the existing material in line with the proposed system was analyzed. A summary of the system requirements and specifications document was compiled.

This objective set out to determine four distinct requirements:

- i. Functional requirements
- ii. Operational requirements
- iii. Technical requirements
- iv. Establishment of the system external Interfaces

The study used the following steps to achieve the objective:

- i. The review of available related literature for each of the requirements to establish suitable components.
- ii. Study of manuals related to the hardware components of choice for the system.
- iii. Discussion sessions with personnel with specialty in electronics and software to further advise on best practice.
- iv. Definition of system components and the corresponding functions that they perform during system operation.
- v. Description of technical requirements for the candidate system.
- vi. Determination of System External Interfaces.

### **3.5 Designing a Functional Prototype**

- i. Designed the block diagram of the candidate system.
- ii. Using a personal computer with Eagle design software application, the circuit diagram of the candidate system was designed as for every stage of the block diagram.
- iii. Using pseudo code, the researcher wrote down several objects to guide the development of code one function at a time, component by component that was later developed using C++.
- iv. Tried out each designed stage with a sample software to observe functionality and output characteristics for every stage of the system developed.

### **3.6 System Assembly**

Used a Veroboard to assemble components together and coding of the individual stages of the prototype system. With the help of specialists in the programming field and electronics, I configured, programmed the microcontroller using the Arduino programming environment to establish communication for all attached components with the microcontroller. The above processes were repeated by adding components with minor changes in the design until a desired function was achieved at a particular stage. The working prototype was transferred on to a single sided stripboard using a soldering gun and solder wire to attach the components until the entire system was assembled. The resulting unit was placed in a plastic housing for protection from physical damage.

#### **3.6.1 Calibration**

The assembled prototype was connected to an active single-phase power source, following the procedure on the flowchart figure 3.3. using a Fluke multimeter model 115, the voltage sensor

calibration probe was adjusted until the prototype reading matched the fluke multimeter reading.

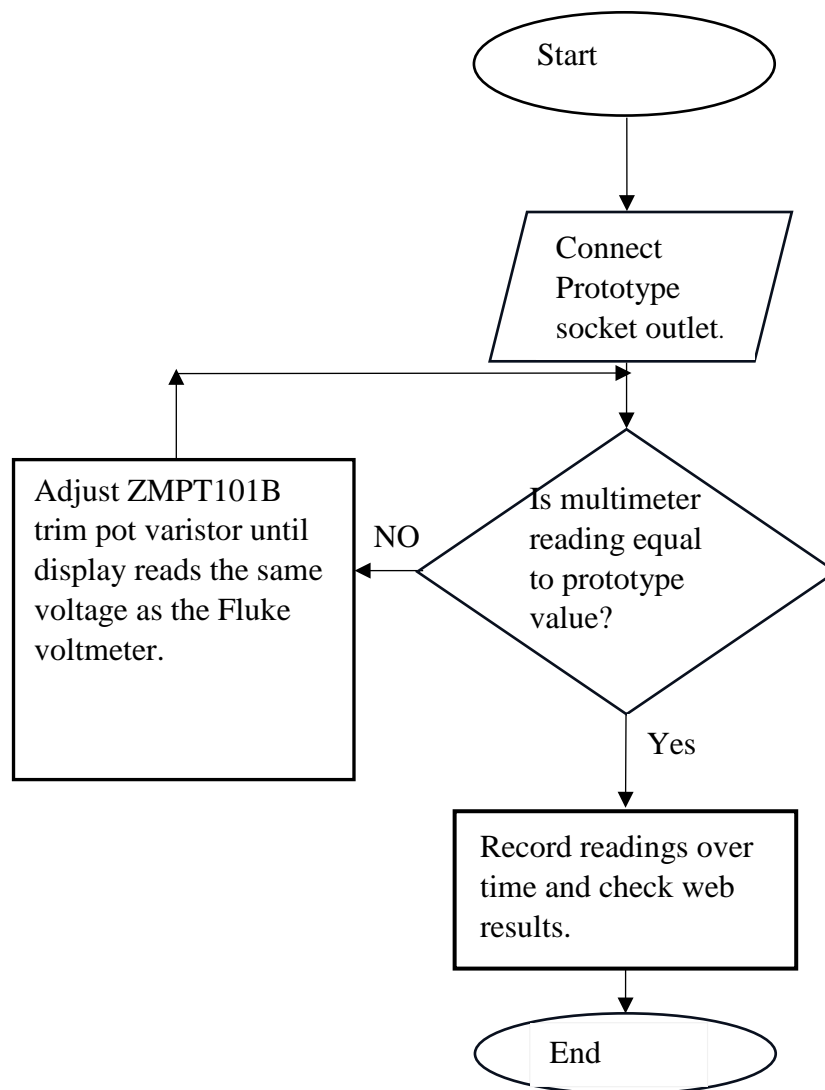


Figure 3.3: Voltage calibration

Following the initial software setup, additional software tests and adjustments of the pseudo code and corresponding code were done as per (Figure 3.3), as outlined in appendix IV, to verify that all system components were interacting as expected. With each modification, continuous improvements were observed, ultimately resulting in the system achieving the anticipated performance output.

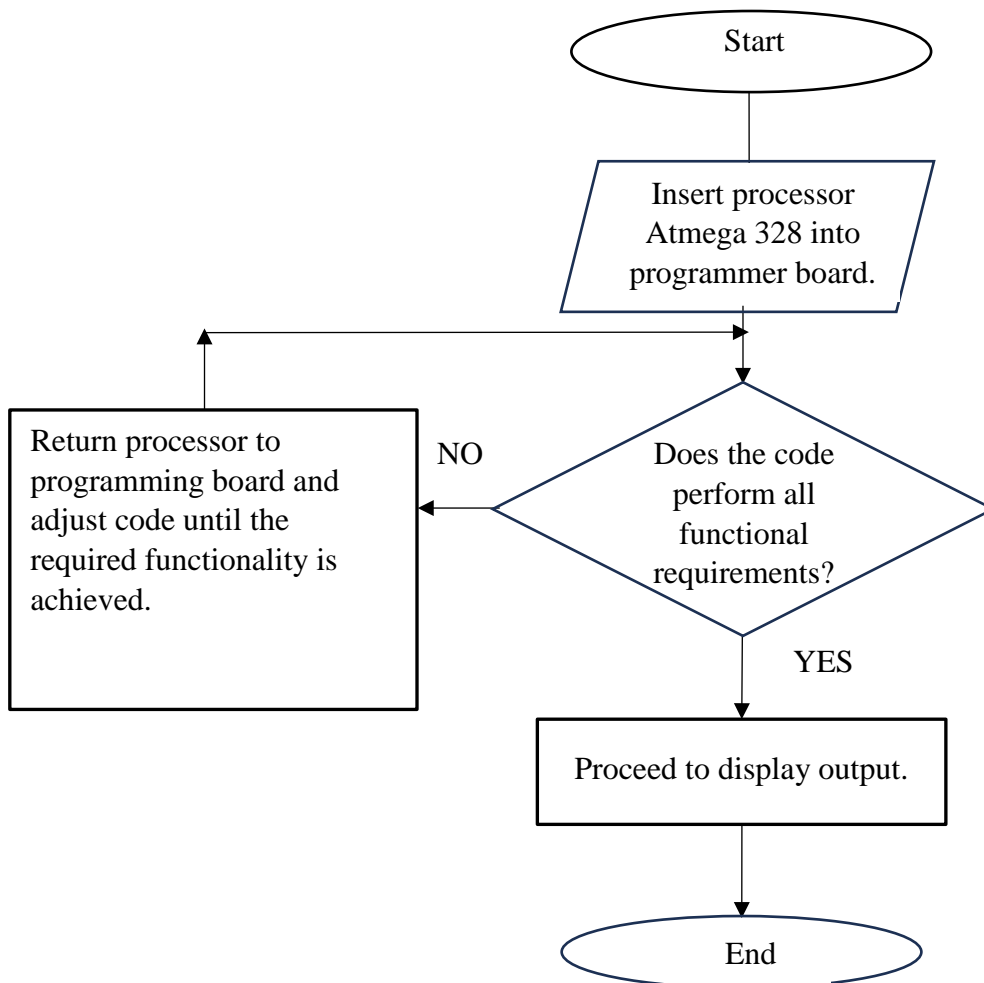


Figure 3.4: Software calibration

### 3.7 Evaluation and Testing of the Prototype

The goal of this phase was to test and validate system functionality in accordance with the defined requirements. A detailed system test plan using the evaluation phase of SDLC through discussions, review of related studies and expert knowledge to determine the system specifications, testing tools, and testing approaches for every stage. Carried out risk assessment to identify the would be risks in filed deployment and results recording. This section outlines the methodological framework utilized to fulfill the research objectives, and the following chapter details the findings derived from the implementation of these methods.

## CHAPTER FOUR: PRESENTATION AND DISCUSSION OF THE RESULTS

### 4.1 Introduction

This chapter presents the results and discussion derived from the employed methods and discusses them in comparison with similar studies. The findings encompass system requirements, system design, evaluation, result presentation, testing and adjustments.

### 4.2 Sample Population Results

The results collected from the sample population are found at appendix v, these included a GPS coordinate, the voltage reading, and the time the reading was taken. From appendix V, the voltages are within range with each other with a slight difference of 3 to 5 volts as the distance from the transformer increases. Using section 3.2.1 to generate parameters in (Table 4.1).

Table 4.1: Sampling Parameter Set

Number of house hold (3848/ 5)	Sample space (n)	Number of skips using (K)	Number field points measured
N = 770	770	25	31 < n < 68

The field results and the test bench results were found to have a similar behavior where voltages were seen to be dropping during the peak hours with a variance between 3 to 5 volts based on the distance from the transformer, specifically the occurrences of voltage dropping to 219 V, align with the technical definitions of voltage sags, which represent a decrease in RMS voltage between 0.1 and 0.9 per unit (Kanchanapalli & Banka, 2024; Sushma, 2023). When compared to the stable off-peak readings of 230 V shown in (Table 4.2), these drops highlight a critical vulnerability in the local distribution network.

Such sags, as visualized in (Figure 4.5), are often the direct consequence of inadequate wiring or the simultaneous activation of inductive loads (Afonso et al., 2021; Ravi & Kumar, 2022). Furthermore, while this study focuses on these voltage fluctuation events, it is essential to consider that any deviation from the 230 V – 250 V range—including voltage swells exceeding 1.1 P.U. can be equally detrimental to sensitive electronic infrastructure (Asoh & Chia, 2022). The observed data thus provided empirical evidence that supports the power quality monitoring system development as proposed earlier in this paper to ensure real time events visibility

### 4.2.1 Testbench Data Captured

The Fluke 435 power quality analyzer in figure 3.2, was used to work as a reference to compare voltage readings within the sample space. The instrument was used to capture to trend the behavior of the electricity during the late hours where the data could not be collected from the premises with in the sample space. Data was collected at different times of the day and some of the results are displayed in (figure 4.1).

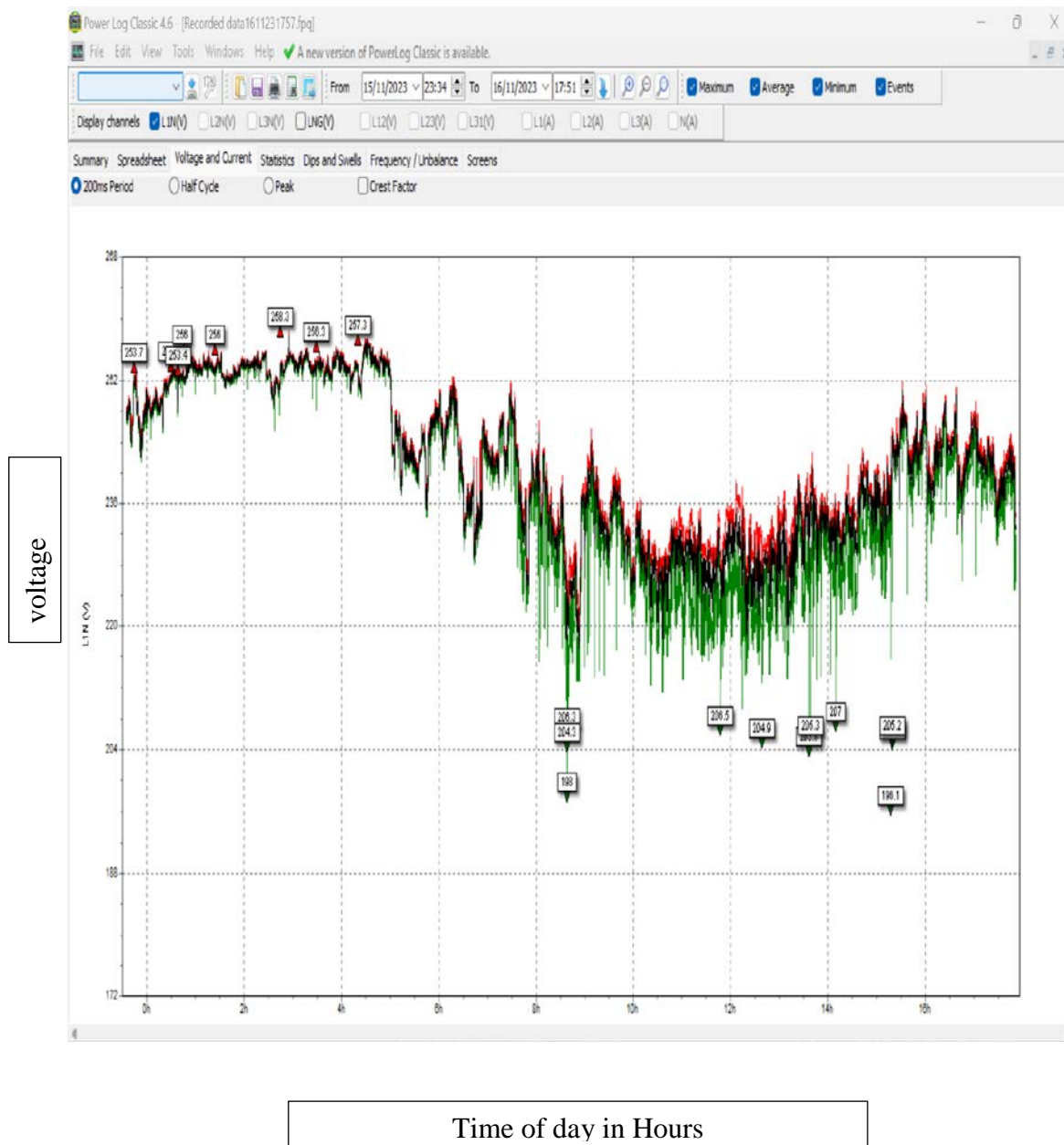


Figure 4.1: Voltage variation between 00:00hrs to 03:00pm

The (Figure 4.2), illustrates data captured during peak hours, the results were used in the bench marking of the system during the calibration stage.

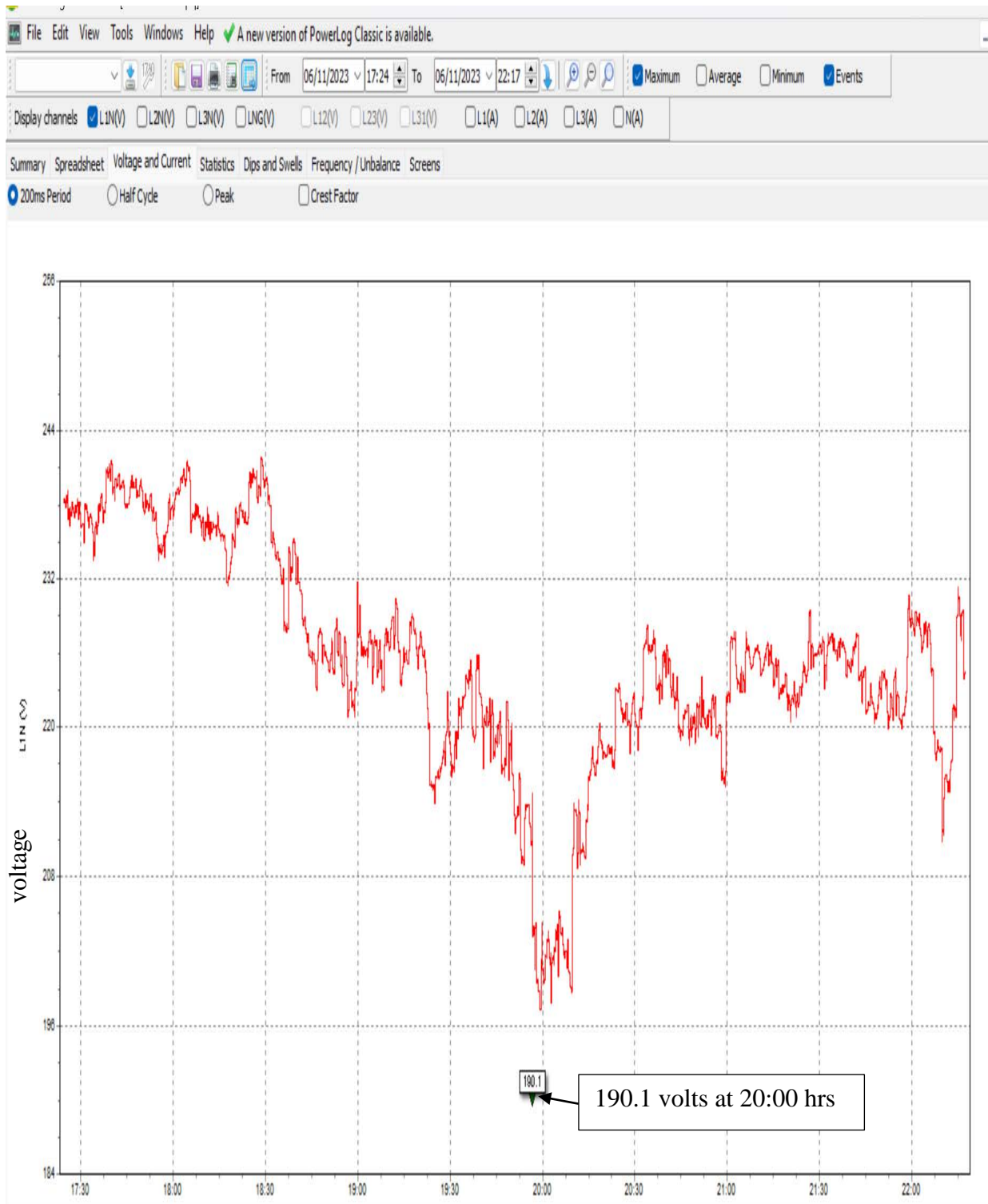


Figure 4.2: Voltage drop between 19:00 - 23:00 hours

Observations from (Figure 4.2), there was a voltage drop between 19:00 hours and 23:00 hours and this was caused due to the loading of the grid given that at this time, lights and household appliances are at peak use. From (Figure 4.3) the voltage started to rise at 23:00 hours.

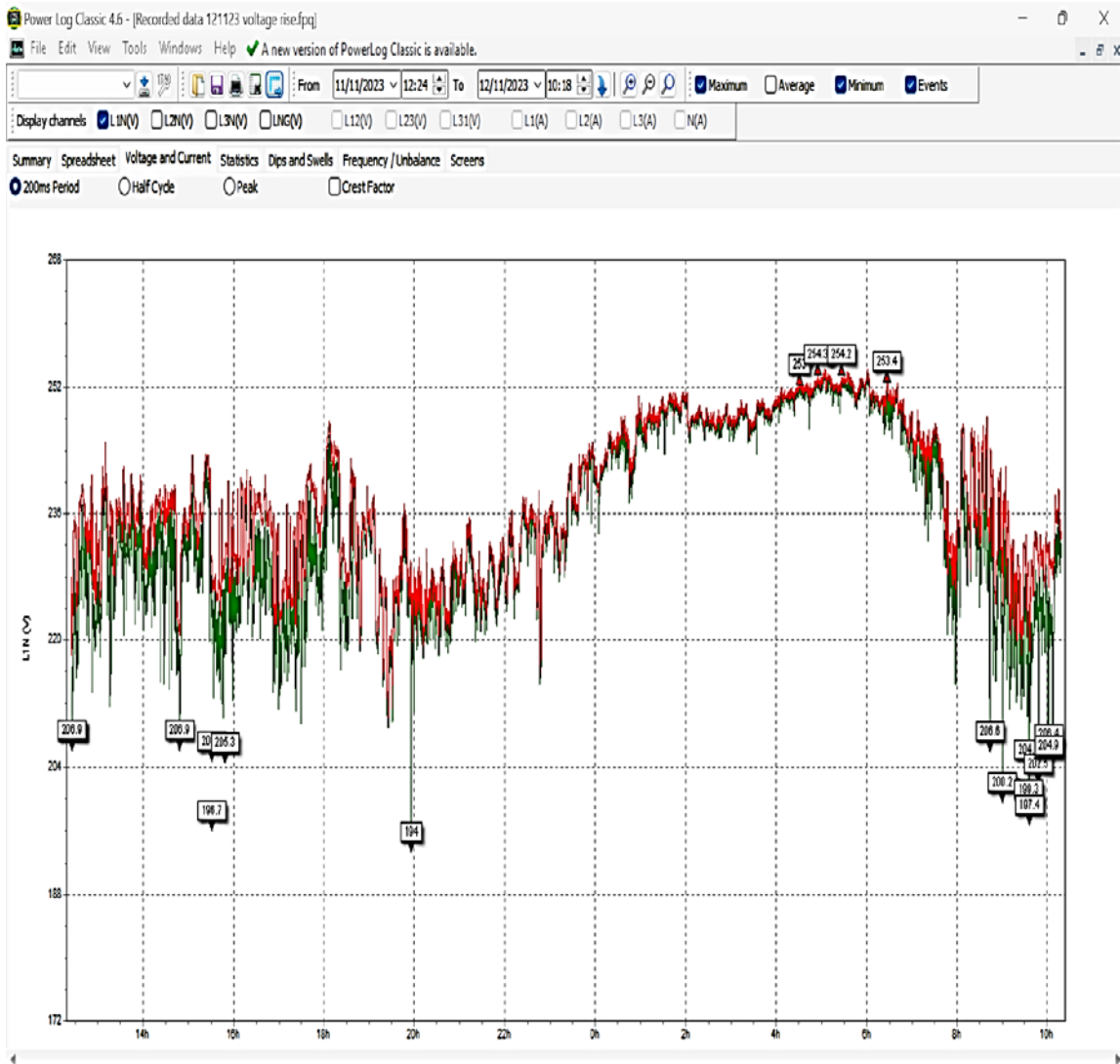


Figure 4.3: Voltage rise between 23:00 - 05:00 hours

From 22:00 hours through to the morning as per (Figure 4.3), there is a voltage rise. The summary in (Figure 4.4) categorizes the voltage behavior through the 24 hours of the day justifying the deviation from the standard requirements.

The voltage rises from 23:00 hours to 05:00 hours is due to reduced load as the consumers go sleep. The (Figure 4.4) extracted from the fluke 435 tool shows a summary of voltage fluctuations and the bottom left side is a clear indicator of an overload to that phase during the peak hours.

The downloaded data from the data logger Fluke 435 and the field measurements, were used in benchmarking the power quality monitoring system.

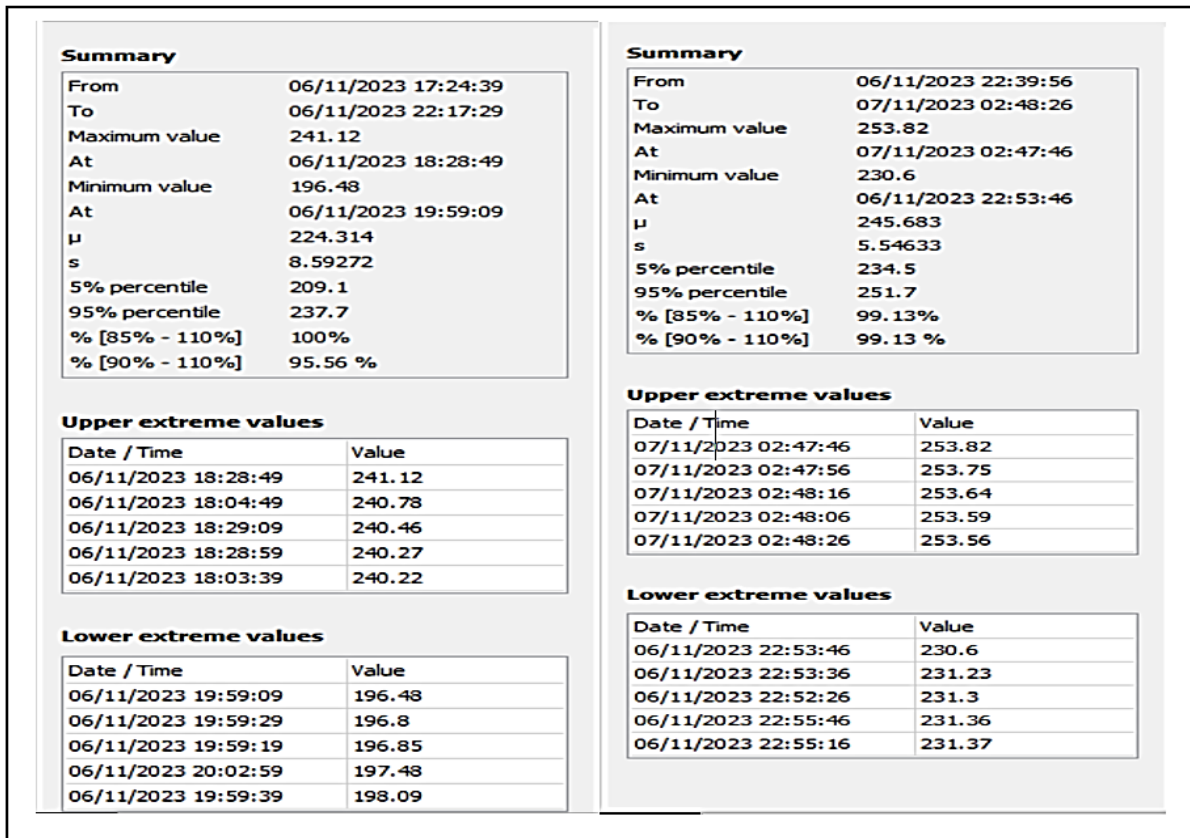


Figure 4.4: Summary of the voltage measurements

Based on the data presented in (Figure 4.4), which illustrates the statistical summaries of voltage monitoring over two distinct periods on November 6th and 7th, 2023, the following notes summarize the key findings and their technical significance within the context of the thesis. Temporal variation in power quality, (Figure 4.4) provides a comparative analysis between peak evening hours (17:24 to 22:17) and late-night/ early-morning off-peak hours (22:39 to 02:48). This distinction is critical for identifying the impact of consumer demand on grid stability (Kuwałek, 2024; Ravi & Kumar, 2022).

A peak period Instability, with a critical undervoltage event was recorded at 196.48 V (19:59:09). This represents a significant sag, falling well below the 0.9 p.u. threshold (approx. 207 V) required for safe equipment operation (Asoh & Chia, 2022; Sushma, 2023). The average voltage during this period was 224.31 V, which is below the nominal 230 V standard, indicating sustained "brownout" conditions during high-demand hours (Helonde, 2024; Tyagi, 2024). Compliance: Only 95.56% of the readings stayed within the 90%-110% range, confirming frequent disturbances that justify the need for the system development in this study (Asoh & Chia, 2022).

### 4.3 Sampling Experiments Observations

Table 4.2: Observations on the test bench

Time of day in hours	Voltage readings volts	Variation in volts	comments
00:00 - 09:00	250 - 280	+40	Overtoltage
09:00 - 12:00	220 - 248	-10 to +18	Normal
12:00 - 17:00	220 - 241	+ or - 10	Acceptable range
17:00 - 23:00	196 - 217	-44 to -23	Under voltage

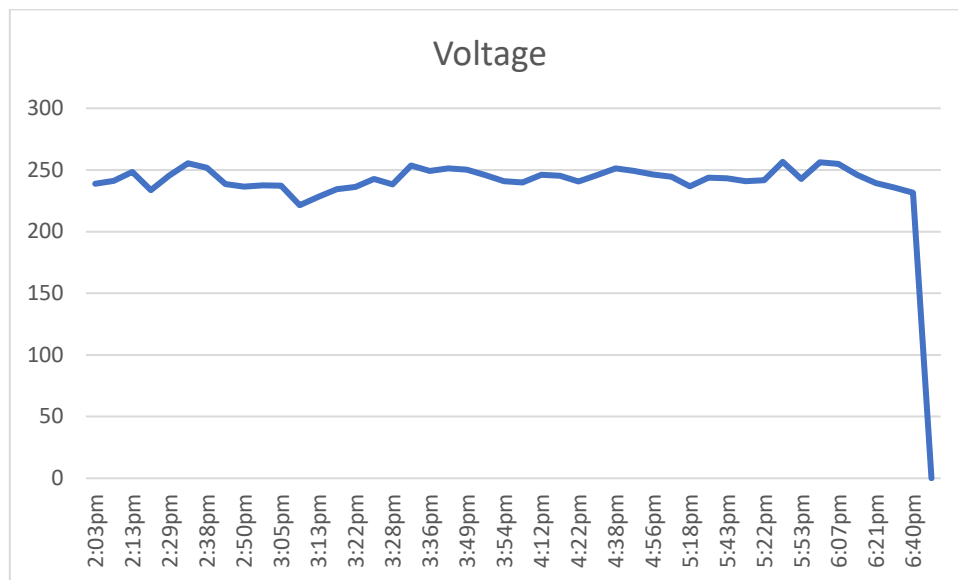


Figure 4.5: Field Measurements

### 4.4 Testbench and Field Measurements

Voltage measurements from the power logger at a fixed test point (Table 4.1) were similar to the sample space measurements with the fluke 110 meter (Figure 4.5) taken from the population, the sample space results can be found in appendix IV where by between 14:00 hours and 18:40 hours, the voltage readings were within acceptable range and of the same behavior. The data showed continuous voltage variations at different times of the day. The voltage was out of limits at different times of the day due to the line overload and a long-extended distribution line which is a challenge to the area transformer and therefore the

customer equipment requires fulltime voltage monitoring and protection. Appendix v and vi indicate the results from the measuring tools.

#### 4.5 The Design Specifications.

The design specifications include functional, operational, and technical requirements.

Table 4.3: Project tools and resources document

Item	Results
Software	Programming application C++ (Language)
	Document Production Windows Operating System And operations Microsoft Office
	Circuit design Eagle Open-source software
	Arduino Programming Arduino IDE
	Arduino Lib Extra Functionalities to the IDE
	Storage and database Thing Speak Internet of things open-web server server.
Hand tools	Soldering Iron, Phillips screw drivers
Hardware	Voltmeter, Fluke 115, Fluke 435. Data logger, Garmin Extrex 30 GPS GPS

The hardware resources listed in (Table 4.3) include the Fluke 115 and Fluke 435, which served as the voltmeter and data logger, respectively, alongside the Garmin Extrex 30 GPS for location tracking. The tools were used to represent the measurements infield for the Fluke 115 and fixed-point measurements for the fluke 435.

##### 4.5.1 Functional Requirements Description

Functional requirements refer to the system functions or tasks performed during system operation to meet the objective, and these are listed below. The system should measure voltage continuously and transmit it to the webserver for storage. The system should compare the voltage input with the required standards to trigger a required action.

The system should protect the load through automatic disconnection in cases where extreme voltage is detected as an added advantage, this protects consumer equipment that have no individual protection. The system should send out an alert to the test phone configured as a simulation in place of the power company Office as an alert indicating out-of-range voltages in real time via SMS. The system should compile and present voltage quality measurements and the trends to the server.

#### **4.5.2 Operational Requirements Document**

Operational requirements focused on the key conditions that the prototype must satisfy to perform its intended functions, and these were; The response time of the system should be real time. Coverage – The system is internet based and can be accessed anywhere via GSM network where coverage exists. Installation – The system was installed, upgraded, and maintained in a laboratory environment, also able to work overnight on different days of the week with safety controls in place. Power Source – The system uses AC/DC adaptor that connects to the premise source voltage 220/230 volts ideal input for the prototype.

Control – The system is controlled by an AtMega328p Microprocessor Unit that reads off signals from the voltage sensor, formats the output, controls the relays as per the conditions in comparison with the instruction set assigned to it, continuously populating the ThingSpeak server and sending text messages through the GSM module.

Portability – Being a Smart system for monitoring mains voltage at a consumer residence, the system is comprised of portable architecture capable of existing at a customer premises with minimal visibility.

User Interfaces – The system provides graphical user interfaces (GUIs) for all its operations, monitoring, reporting, escalation and technical operations like software upgrades and maintenance. User Support – The system reports to a web portal for purposes of storing all the information and present to its users. Maintenance and Monitoring – Through the user support interface, system performance is monitored to detect abrupt or gradual changes in performance, also to continuously improve the code.

Observing System Modes – The system has an LED for status monitoring and reporting. The red indicator reflects GSM connectivity. The blue LED light indicates load online.

Data Archive – The system records and displays data through ThingSpeak server, the data is then stored on the server over the cloud.

### 4.5.3 The Technical System Requirements

Technical requirements focused on how well the candidate system performs its predefined functions at a given time. The following key technical requirements were identified:

Response time: This is the elapsed time from when the power quality monitor sends an out-of-range SMS to the test mobile phone.

The time taken to switch off the load on over voltage or under voltage. The ideal response time taken is roughly 500 microseconds this can be found in the technical data for the AtMega328p.

System latency: This is the amount of time taken for data to travel from the server or test phone. The latency measured was 4 seconds is this could have been due to the network connectivity between the system and the remote server.

Other support components include the power supply that includes a set of voltage regulators to supply the circuitry with reliable safe stable voltage, table 4.3 states the hardware requirements.

### 4.5.4 System Hardware Requirements

Table 4.4: Voltage monitoring system components table

Requirements	Descriptions	details
Voltage sensor	Voltage variation detector	0 volts to 250 volts
Data acquisition processor	Data processor	Atmega 328P
Local display	LCD display	On-board display interface
Internet connectivity	Wireless	GPRS card
Storage	Local data base	Over 1024 megabytes
Neo GPS system	Live location insertion	GY-NEO-8M GPS module
DC buck converter	Regulate Sim 800 voltage	Dedicated power supply

#### **4.5.5 System Design**

The system design included the system architecture, hardware design, a functional block diagram, the software architecture, and the logical circuit drawings. After establishing the requirements of the system, the design phase of SDLC was used to achieve the second specific objective.

System Hardware Architecture refers to the identification of the system's physical components and their interoperability. It allowed the study to understand how the components would fit to create a working system architecture and provided the software component design important information that was needed in the software development and integration phase.

Figure 4.5 and figure 4.6, illustrates the functional flow between input and output, with functional blocks and lines delineating data flow and exchange. Figure 4.7, a functional wiring diagram, encompasses the primary components, interfaces with external systems, interfaces between subsystems, and identifies power sources, as well as data and structural interfaces. Expert knowledge, prior experiences, computing skills, literature reviews, and specific hardware requirements were utilized, with each selected for their respective functional descriptions.

#### **4.5.6 Support components**

The power supply, which incorporated a set of voltage regulators to provide the circuitry with a reliable, safe, and stable voltage, was examined in a study on fault monitoring systems where similar components were utilized (Ferreira et al. 2018).

A personal computer served as a circuit design tool using Eagle software and a central configuration device. Each of these components is illustrated in figure 4.9, which includes the electrical connections. The logical connectivity of the system's physical components is depicted in figure 4.10.

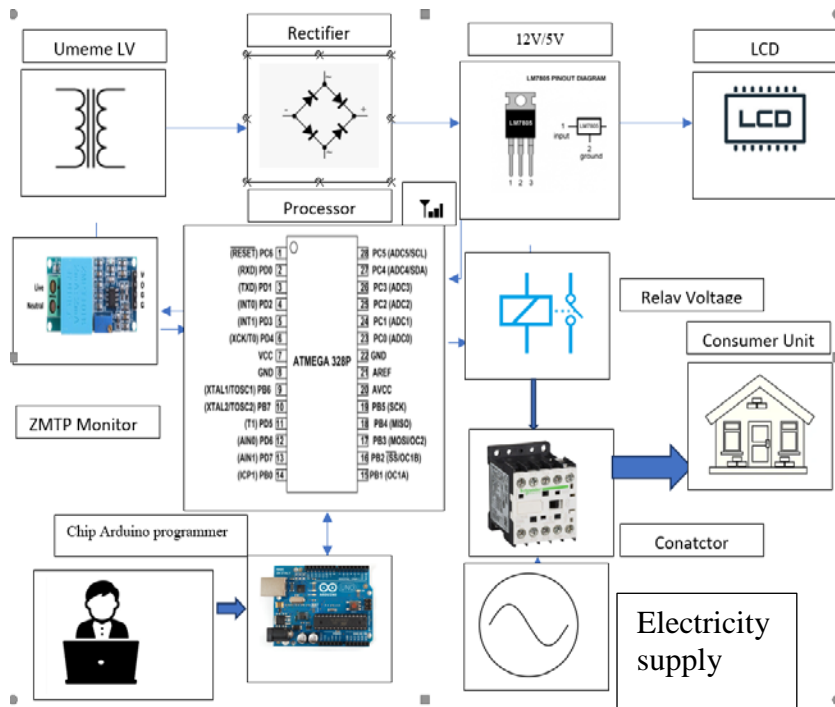


Figure 4.6: System hardware block diagram

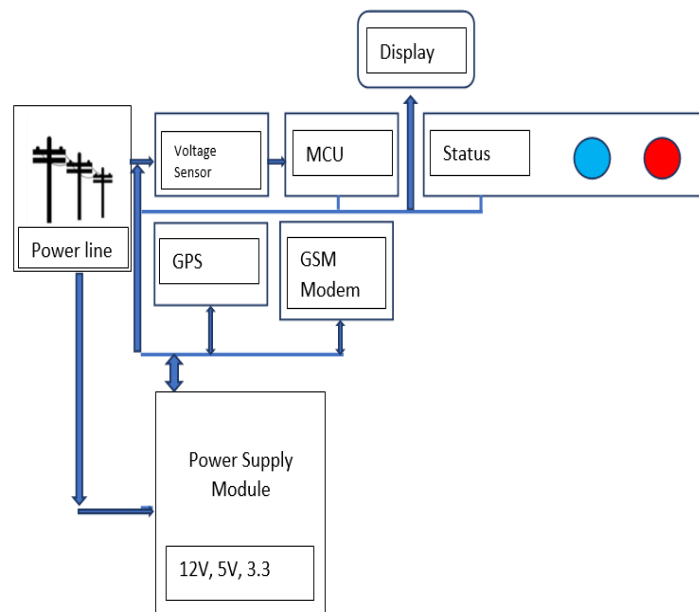


Figure 4.7: Associated block diagram

Logical flow diagram shown in figure 4.7 and figure 4.9 shows the signal and information flow of the system.

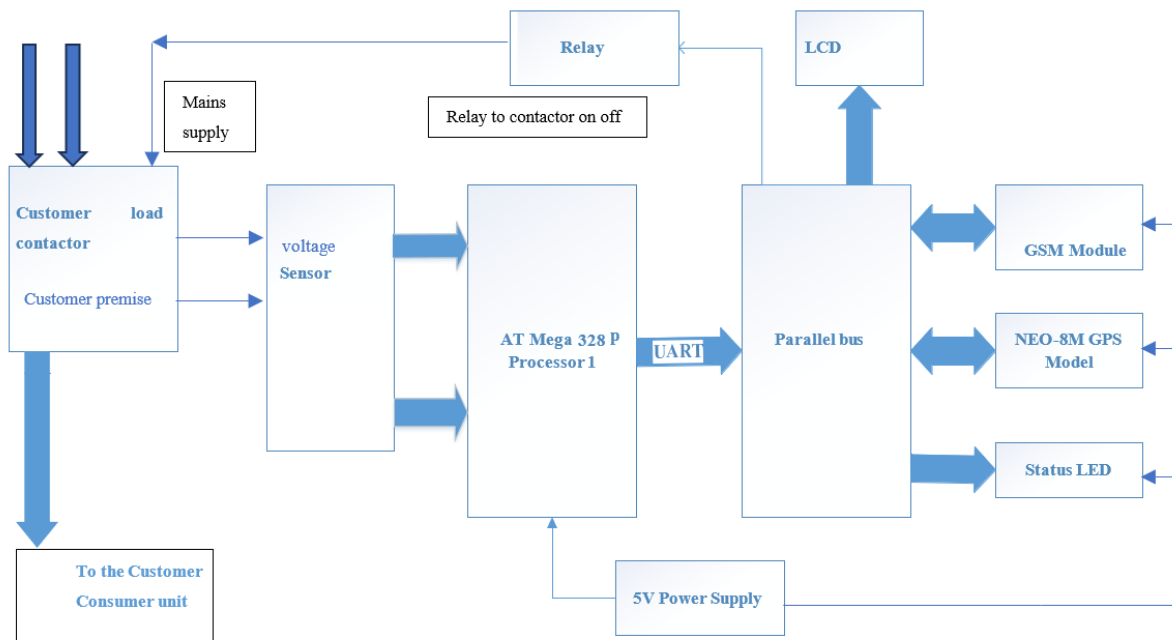


Figure 4.8: Logical flow block diagram of a designed system

#### 4.5.7 The Logical Circuit Designs

Using Eagle 9.6.2, a product of Autodesk in figure 4.10 software as the modelling application, logical components were identified and added to the logical circuit model shown in figure 4.11.

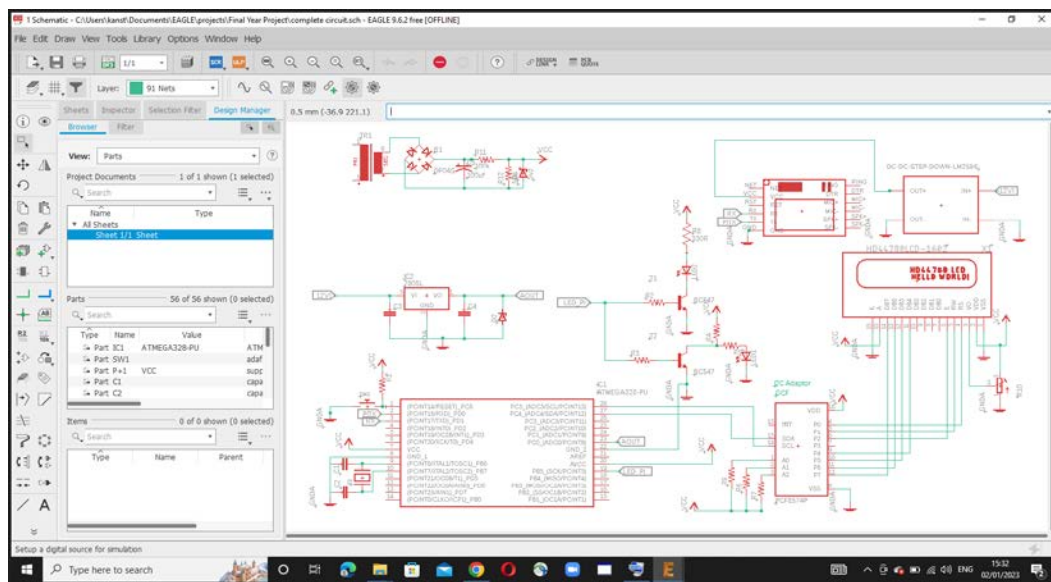


Figure 4.9: Eagle software circuit design environment

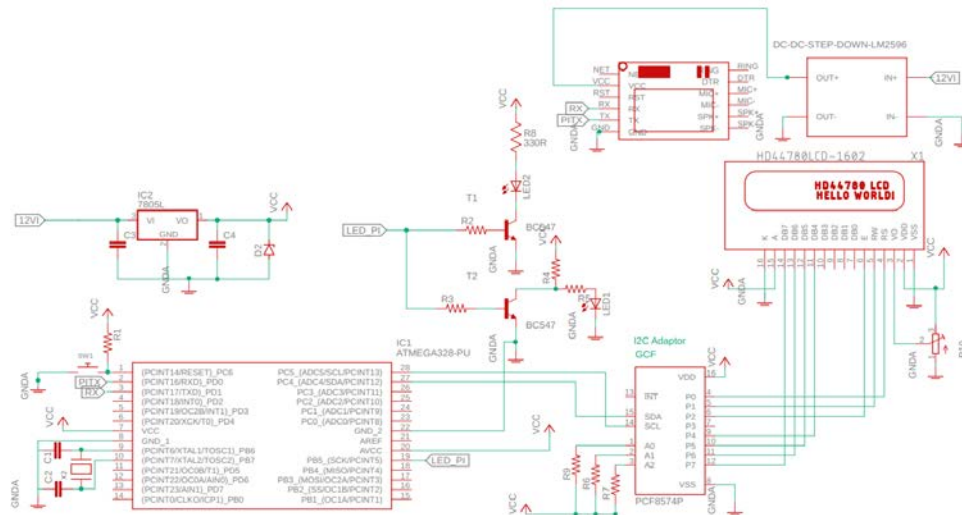


Figure 4.10: The overall system schematic layout diagram

#### 4.5.8 Presentation and Data Storage

The ThingSpeak server serves as a database platform for the Internet of Things (IoT), specifically designed to support research endeavors. It is accessible via the internet as an open-source portal (Figure 4.13). This platform enables users to aggregate, visualize, and analyze live data streams within a cloud-based environment. Among the primary functionalities of the ThingSpeak server are the ability to;

- i. Easily configure interfaces to send data to ThingSpeak using popular IoT protocols.
- ii. Visualize your sensor data in real-time,
- iii. Aggregate data on demand from third-party sources.
- iv. Use the power of Matlab to make sense of your IoT data.
- v. Run your IoT analytics automatically based on schedules or events.
- vi. Prototype and build IoT systems without setting up servers or developing web software.
- vii. Automatically act on your data and communicate using third-party services.

The open-source website was the appropriate choice because it fulfilled our database requirements, facilitated the presentation of results, and included an existing database that supports study projects without incurring additional costs. (Figure 4.12) illustrates the information flow design, while the interface login is depicted in (Figure 4.13). A similar configuration is observed in the literature on automatic energy metering (Jawaduddin et al., 2020).

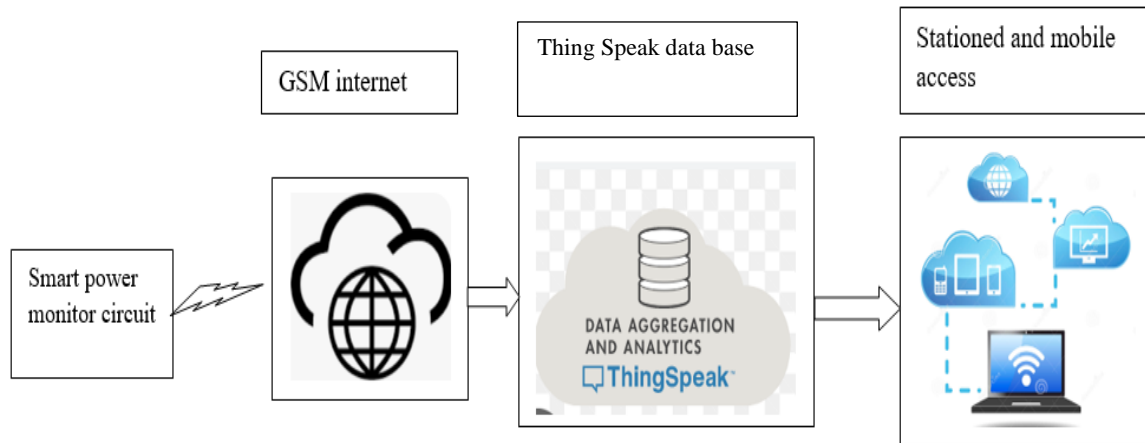


Figure 4.11: Data Flow Architecture

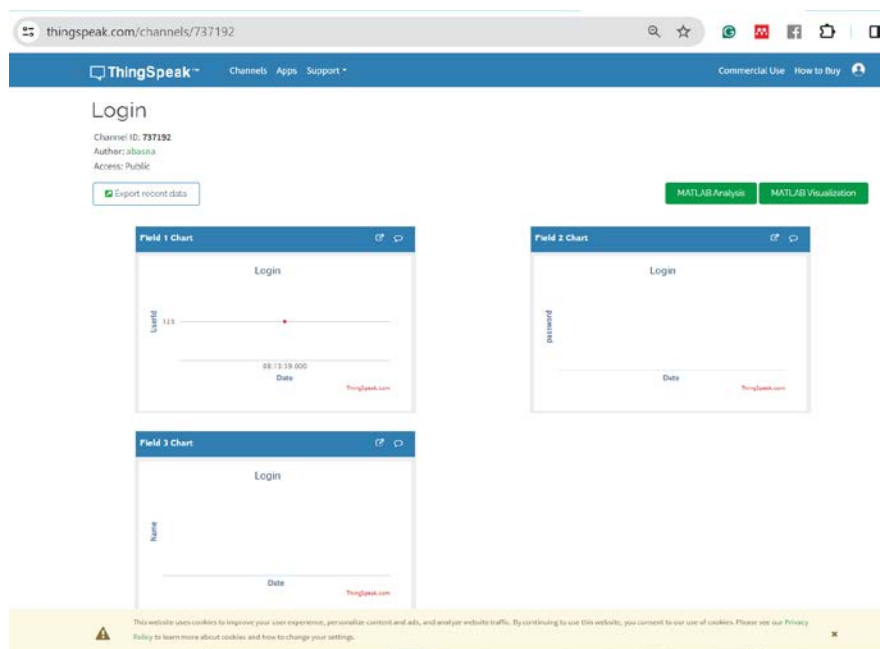


Figure 4.12: ThingSpeak Server Login Interface

#### 4.6 Prototype Development

In this section, the components developed during the design stage were integrated to construct a functional prototype. Following the completion of the design phase of the Systems Development Life Cycle (SDLC), which fulfilled the second specific objective of building a prototype, the subsequent task in the third stage of the SDLC involved assembling the system prototype. This stage was divided into work packages, each with its respective deliverables, as informed by relevant literature (Azeez et al., 2019). Utilizing expert knowledge, past experiences, computing skills, and literature reviews, the researcher, with the assistance of

experts, assembled the identified system components. A detailed account of these components, including the electrical connections, is provided in Section 4.6.1.

#### 4.6.1 The voltage Sensor

ZMPT101B transformer module (Figure 4.14). This is an Arduino based unit tested in several projects that measure AC input voltage from 0 to 1000 volts with an operating voltage of 5volts to 30volts. An analogue output signal from 0 to 5 that is feed into the microcontroller.

VCC: Module power supply input of 5 V, GND: Ground, OUT: Module output which is analogue.

The ZMPT101B module is a compact single-phase AC voltage sensor module based on the minuscule 2mA/ 2mA precision voltage transformer ZMPT101B made by qingxian zeming langxi electronic with the associated wiring diagram figure 4.15.

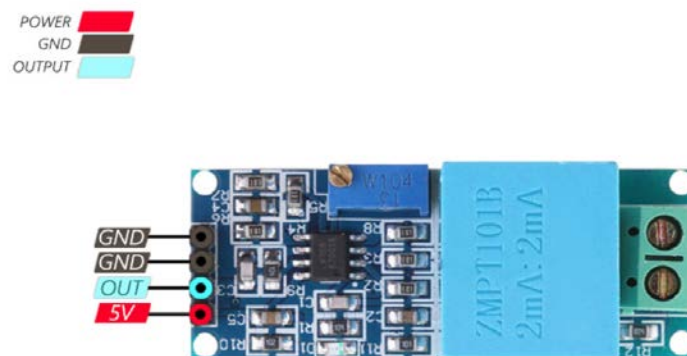


Figure 4.13: ZMPT107 voltage reading module

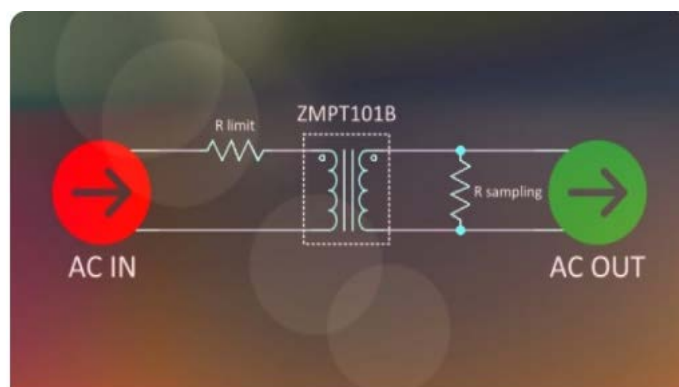


Figure 4.14: Voltage sensor circuit diagram

The connection to the microcontroller programming module of the ZMPT107 is depicted in (Figure 4.16). During assembly, and to ensure interoperability, each component was connected individually, followed by testing of communication.

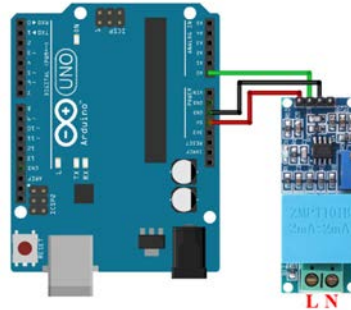


Figure 4.15: PMTZ-101 module programming

#### 4.6.2 Data Acquisition

For data acquisition, the ZMPT101 Voltage Sensor Communication Module was utilized. This module operates as a transducer, converting input voltage into a digital signal transmitted via asynchronous serial communication. Figure 4.17 presents its components and functional layout. One end contains terminal blocks for power supply and voltage input, while the opposite end features a 5 V communication interface for data transmission. The module simultaneously receives power and input signals, processes the measurements, and transmits the voltage data to the measurement system.

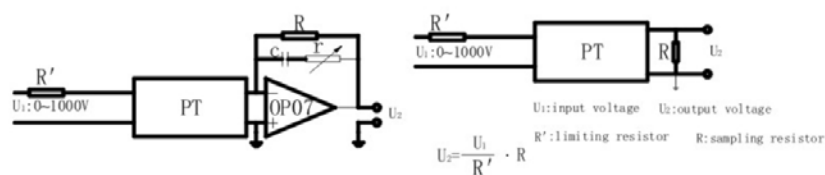


Figure 4.16: Input voltage and output interface to Processor

#### 4.6.3 The Microprocessor

The ATmega328P, shown in Figure 4.17, is a low-power CMOS 8-bit microcontroller based on the enhanced AVR RISC architecture. It executes most instructions in a single clock cycle, achieving performance close to 1 MIPS per MHz. The AVR core integrates a comprehensive instruction set with 32 general-purpose registers, all directly connected to the Arithmetic Logic Unit (ALU). This configuration enables simultaneous access to two registers within a single

instruction cycle, enhancing processing efficiency. As a result, the architecture delivers improved code efficiency and significantly higher performance compared to conventional CISC microcontrollers.

The ATmega328P features 32 KB of in-system programmable Flash memory with read-while-write capability, 1 KB EEPROM, and 2 KB SRAM. It includes 23 general-purpose I/O lines, 32 working registers, and three flexible timer/counters with compare modes. Additional features comprise internal and external interrupts, a programmable USART, a 2-wire serial interface, and an SPI port. The device also integrates a 6-channel 10-bit ADC (8 channels in TQFP and QFN/MLF packages), a programmable watchdog timer with an internal oscillator, and five selectable power-saving modes. In idle mode, the CPU is halted while peripherals such as SRAM, timers, USART, serial interfaces, SPI, and the interrupt system remain operational. Detailed specifications are provided in (Table 4.5), with comparable implementations reported in (Jasim et al. 2021).

Table 4.5: AVR ATMEGA Parameter Set

Parameter	Value
CPU	8-bit AVR
Performance	20 MIPS at 20MHz
Flash memory	32 kB
SRAM	2kB
EEPROM	1kB
Pin count	28-pin PDIP, MLF, 32-pin TQFP, MLF
Maximum operating frequency	20 MHz
Number of touch channels	16
Maximum I/O pins	26
External interrupts	2

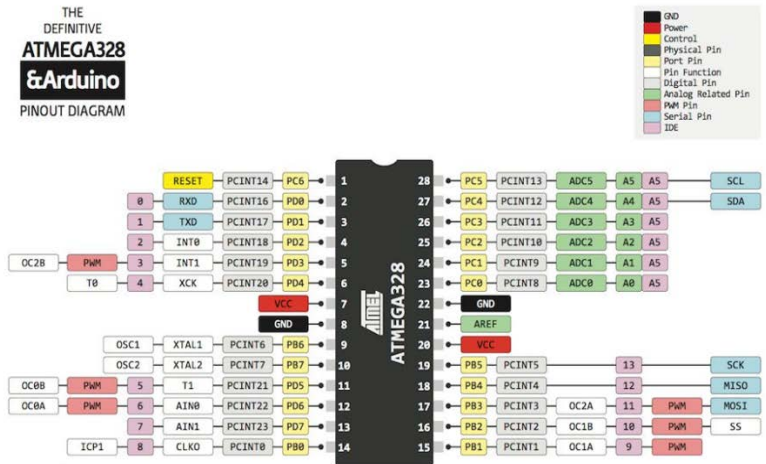


Figure 4.17: ATMEGA328 Processor

The ZMPT101B voltage sensor module is interfaced with the ATmega328P microcontroller (Figure 4.18), a single-board processor widely used in intelligent systems and prototyping applications. The microcontroller performs sensing, control, logical processing, and computation tasks. Programming is conducted using the Arduino environment, which employs a simplified version of C++, making it accessible for design and development. The platform is cost-effective, extensible in both hardware and software, and well-suited for rapid prototyping. Figure 4.17 illustrates the signal interfacing between the voltage module and the microcontroller, while (Table 4.6) outlines the programming modes.

Table 4.6: Program modes

Programming signal	Pin Name	In/Out	Function
RDY/BSY	PD1	O	High means ready for a new command/ otherwise busy
OE	PD2	I	Output Enabled (Active low)
WR	PD3	I	Write pulse (Active low)
BS1	PD4	I	Byte select (“0” = Low byte, “1” High byte)
XA0	PD5	I	XTAL action bit 0
XA1	PD6	I	XTAL action bit 1

PAGEL	PD7	I	Programme memory and EEPROM Data page load
BS2	PC2	I	Byte select 2 (“0” = Low byte, “1” = 2nd High byte)
DATA	PC [1:0]: [5:0]	PB I/O	Bidirectional data bus (out when OE is low)

The Fluke 115 meter is used to measure the input voltage which varies from 0 to 250V AC. The ADC output of the sensor at 0 input voltage is 512 divisions hence if 512 to 1024 is allowed to reflect 0 to 1000 V range then 512 to 640 divisions will be suitable to scale 250 V range. In this regard with 250 V connected to the sensor the maximum ADC is adjusted to be 640 using the sensor trim pot, this serves as the reference.

An AC voltage source, measured using a Fluke 115 multimeter, is applied to the sensor. The Arduino program samples the signal 1000 times, recording the minimum and maximum ADC values for each input voltage. The corresponding peak-to-peak input voltage and ADC output are then tabulated for analysis. Processed data is transmitted via USB and captured using Excel data streaming, where it is stored temporarily for visualization and graph generation.

#### 4.6.4 Interfacing the GPS Module

The GY-NEO-8M module (Figure 4.19) is an advanced GPS receiver based on the u-blox M8N chipset, supporting UART communication and equipped with an active antenna. It is interfaced with the microcontroller development board as illustrated in (Figure 4.20). The module includes a rechargeable battery and can also connect directly to a computer via a USB-to-TTL converter.

The NEO-8M provides high-speed and high-accuracy positioning by processing signals from multiple satellite systems, including GPS, GLONASS, Galileo, BeiDou, and QZSS. It features onboard memory for storing configuration settings and is fully compatible with Arduino, making it suitable for a wide range of applications.

POWER  
GND  
USART

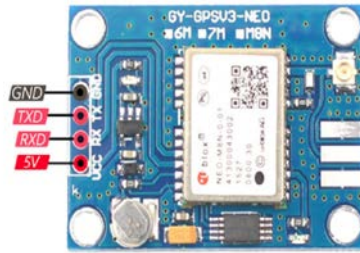


Figure 4.18: GPS Module

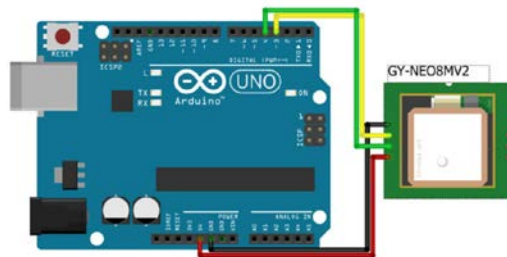


Figure 4.19: Programming Board to GPS module

#### 4.6.5 SIM800L GPRS Module

SIM800L GPRS module in (Figure 4.21) is a miniature GPRS modem which can be integrated into a great number of IoT projects. This module is used to accomplish almost anything a normal cell phone can do, like SMS text messages, make or receive phone calls, connecting to internet through GPRS, TCP/IP, and more. This module was chosen because it supports quad-band GSM/GPRS network, meaning it works anywhere in the world for connectivity purposes.



Figure 4.20: SIM900 GPRS modem

At the core of the module is a SIM800L GSM cellular chip from SIMcom. The operating voltage of the chip is from 3.4 V to 4.4 V, which makes it an ideal candidate for direct battery supply voltage. This makes it a good choice for embedding into projects without using a lot of space. All the necessary data pins of SIM800L GSM chip are broken out to 0.1" pitch headers. This includes pins needed for communication with the microcontroller over UART.

The module supports baud rate from 1200 bps to 115200 bps with auto-baud detection making it ideal for transmission of multiple data sets.

The module needs an external antenna to connect to a network. The module comes with a helical antenna soldered directly to NET pin on PCB. The board also has a U.F.L connector facility in case you want to keep the antenna away from the board. There's a SIM socket on the back, and any activated 2G micro-SIM card works perfectly. Correct direction for inserting SIM card is engraved on the surface of the SIM socket to reduce user error.

#### 4.6.6 LCD Display

JHD162A is a 16×2 LCD module based on the HD44780 driver from Hitachi (Figure 4.22). The JHD162A LCD module has 16 pins and can be operated in 4-bit mode or 8-bit mode. Here we are using the LCD module in 4-bit mode. Before going into the details of the project, let's have a look at the JHD162A LCD module. The schematic of a JHD162A LCD pin diagram is given in figure 4.21 LCD pin map.

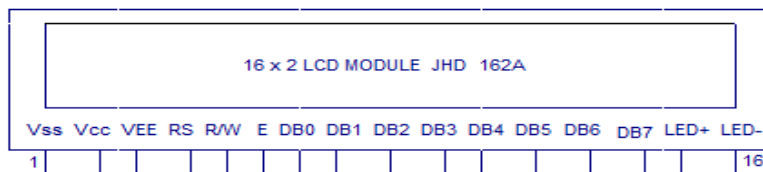


Figure 4.21: LCD Pin Map

The name and functions of each pin of the 16×2 LCD module is given below. Pin1 (Vss) ground pin of the LCD module. Pin2 (Vcc) power to LCD module (+5 V supply is given to this pin) Pin3 (VEE) contrast adjustment pin. This is done by connecting the ends of a 10K potentiometer to +5 V and ground and then connecting the slider pin to the VEE pin. The voltage at the VEE pin defines the contrast. The normal setting is between 0.4 V and 0.9 V. Pin4 (RS) register select pin. The JHD162A has two registers namely command register and data register. Logic HIGH at RS pin selects data register and logic LOW at RS pin selects command register.

If we make the RS pin high and feed an input to the data lines (DB0 to DB7), this input will be treated as data to display on LCD screen. If we make the RS pin low and feed an input to the data lines, then this will be treated as a command (a command to be written to LCD controller – like positioning cursor or clear screen or scroll). Pin5 (R/W) read/write modes. This pin is used for selecting between read and write modes. Logic high at this pin activates read mode

and logic low at this pin activates write mode. Pin6 (E) this pin is meant for enabling the LCD module.

A HIGH to LOW signal at this pin will enable the module. Pin7 (DB0) to pin14 (DB7) these are data pins. The commands and data are fed to the LCD module through these pins. Pin15 (LED+) anode of the back-light LED. When operated on 5 V, a 560-ohm resistor should be connected in series to this pin. Pin16 (LED) cathode of the back-light LED. RS pin of the LCD module is connected to PB1. R/W pin of the LCD is grounded. Enable pin of the LCD module is connected to PB2.

In this project, the LCD module and AVR controller are interfaced in the 4-bit mode as depicted on the system circuit. This means only four of the digital input lines (DB4 to DB7) of the LCD are used to meet the requirements for this project. This method is very simple, requires less connections and you can almost utilize the full potential of the LCD module. Digital lines DB4, DB5, DB6 and DB7 are interfaced to digital pins PD5, PD6, PD7, and PB0. The 10K potentiometer is used for adjusting the contrast of the display.

#### 4.6.7 Calibrating the System.

Figure 4.23 shows the assembled system ready for the calibration stage.

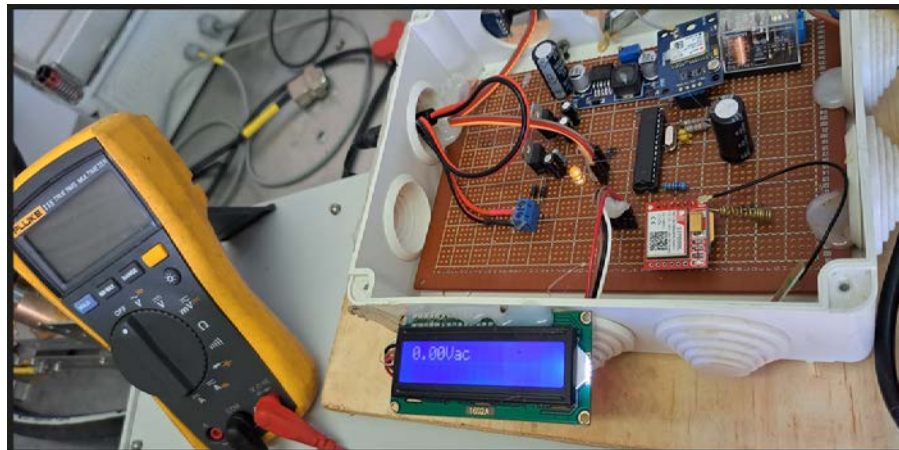


Figure 4.22: Assembled prototype

Using flow charts in section 3.7, the procedure was repeated until a desired result was achieved with reference to the readings on the LCD and the Fluke 115 Multimeter.

#### 4.6.8 Validity and Reliability

Using the Fluke multimeter 115, the system outputs voltage was measured and compared with the results on the prototype display as well as the ThingSpeak server display, continuous readings were taken in comparison with the multimeter readings over time and they were found to be matching. The voltage readings were exactly the same on the measuring instruments, the prototype and the remote view. However, there was a delay of 3 to 5 seconds when there was a change between the device on site and the remote view on the mobile devices.

#### 4.6.9 System Results

Figure 4.24 illustrates the display from the Thingspeak server during the system testing phase, while figure 4.24 depicts the presentation on the mobile device.

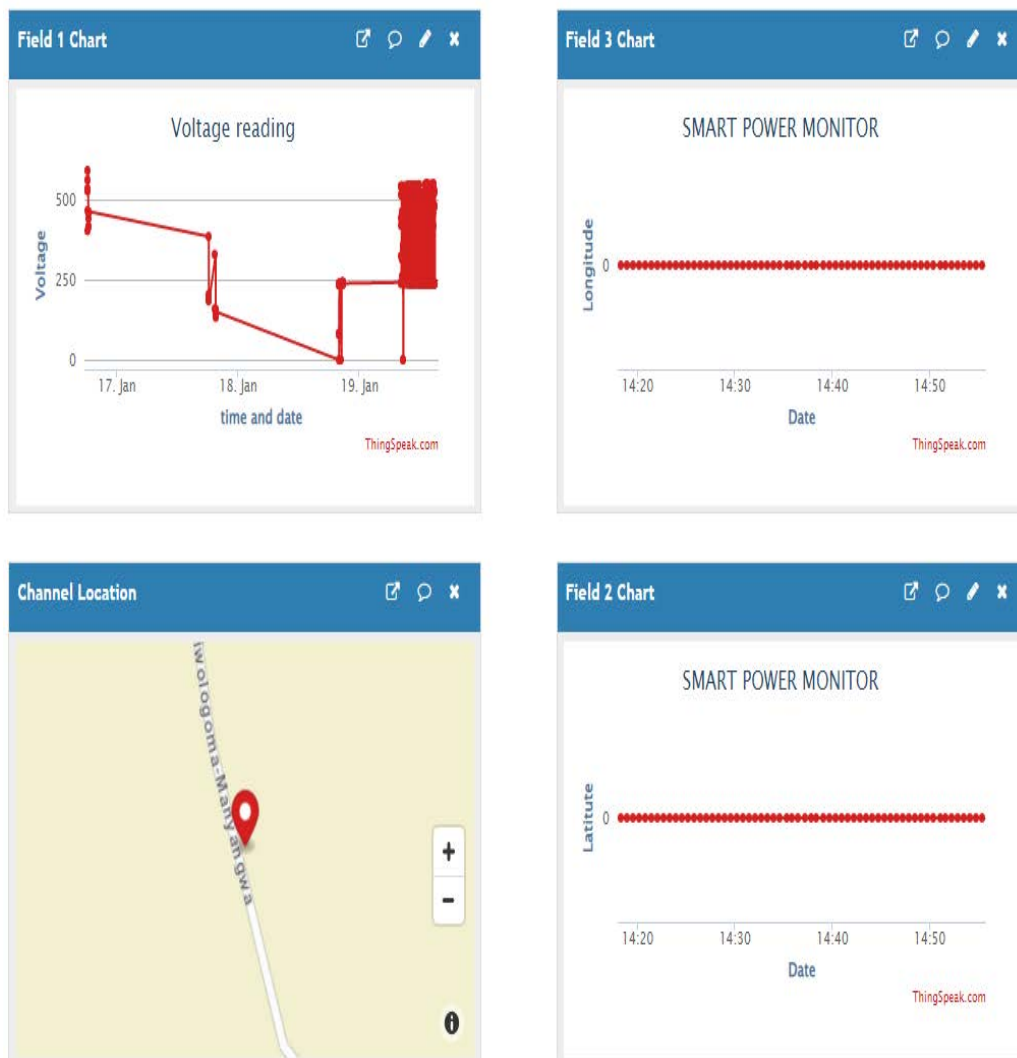


Figure 4.23: ThingSpeak Presentation

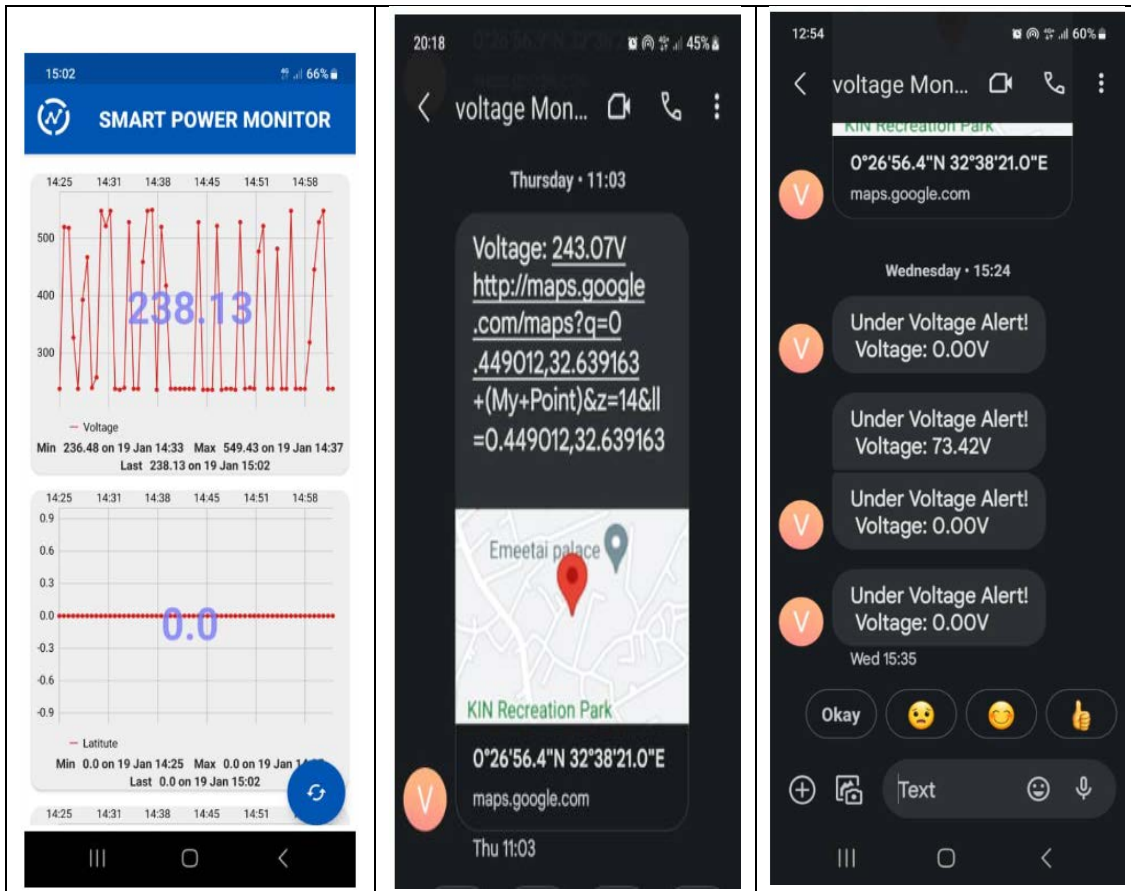


Figure 4.24: Application and Text Message Display

Figure 4.25, is a combination of mobile device logins left screen the voltage behavior to the right is the SMS alerts detailing the condition of the single-phase network as per that time of day when the system was under testing time, date, and location were displayed.

#### 4.7 Testing and Evaluation

Supply voltage (R.M.S) was observed online and the system was able to report the voltage variations. The data was stored by the ThingSpeak server, and the display was able to show graphs plotting the voltage trends. The data was extracted in a one-day cycle, downloaded from the ThingSpeak server into Microsoft excel. The (Figure 4.25) shows the high points and low points as the fluctuations, over voltage, under voltage, power failures at different times of the day. (Figure 4.27) shows a calibrated prototype.

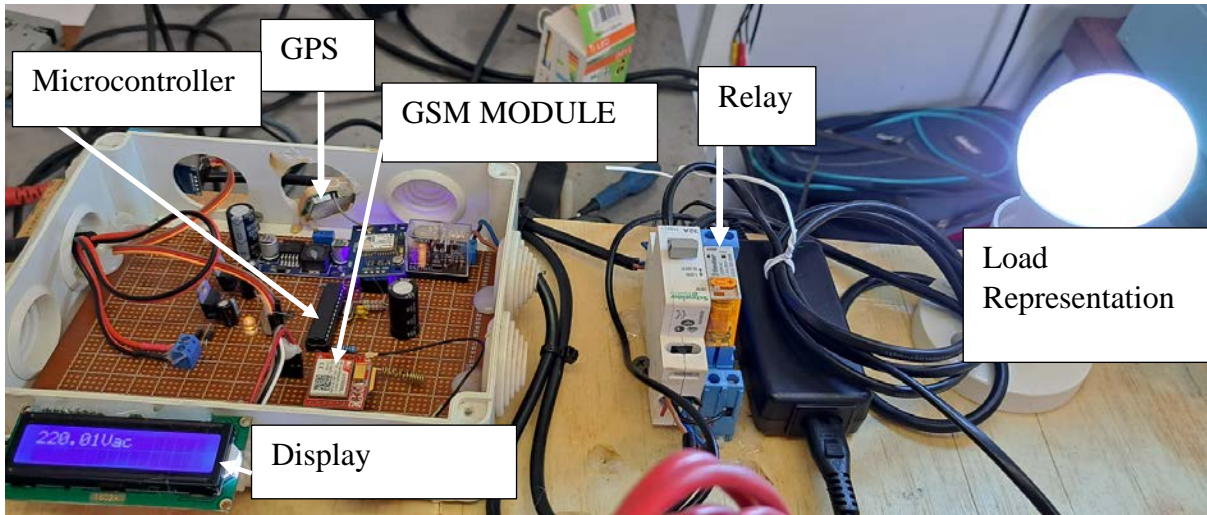


Figure 4.25: Prototype with load switched

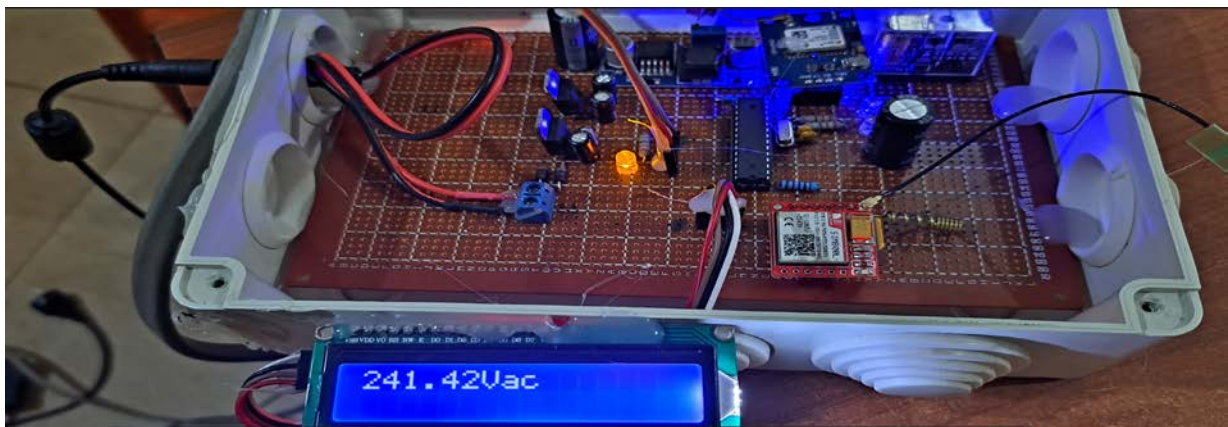


Figure 4.26: Calibrated prototype

On the test bench, the ZMTP101 voltage transducer measures the power line and converts the AC voltage reading into a 0 to 5 V DC output. The signal is transmitted serially to the ATmega328 microcontroller. The microcontroller processes the data (ranging from 0 to 1023 units) and calculates the RMS voltage alongside the GPS coordinates. This information is sent to the GSM 800 module, which converts the data into a GPRS signal for transmission over the internet to the ThingSpeak IoT server.

The IoT server provides a database for storing and displaying the information in a desired format. When the voltage exceeds 250 V, the microcontroller signals the relay to switch off the mains contactor to protect the domestic installation equipment. Figures 55 through 60 illustrate the displayed results; the calibration process is consistent with established literature regarding the ZMPT101B. Furthermore, the integration of these components enables real-time

monitoring and automated protection by providing immediate notifications through virtual terminals or SMS when readings deviate from the preset thresholds (Reddy & Naresh, 2022).

Table 4.7: Functional Requirements Testing

Parameter	Tools reference	Corrective action	Test 1	Test 2	Result
Voltage read	Fluke 110	Calibration	Fail	Pass	Pass
On load	Blue LED ON	none	Pass	Pass	Pass
Over Voltage Switch off	Blue Led Off	none	Pass	Pass	Pass
Location insertion	GPS LED SMS, WEB	Wait 40 minutes	pass	pass	40 minutes Before lock
Graphical Display	WEB ThingSpeak	none	pass	pass	Pass
Data Polling	WEB, Display	none	Pass	Pass	Pass
Data Download	WEB	none	Pass	Pass	Pass
Mains off Data reading	Fluke 110	Rechargeable Battery to be incorporated.	Fail	Fail	Fail

After testing as per (Table 4.7) most parameters were in conformity with the standards hence the system passed the required tests of the researcher which meets the main objective of the research. Further monitoring and evaluation were carried out to for further continuous improvements.

#### 4.7.1 Limitations

The system could not continue functioning while the mains were fully off or disconnected. The future functional system must have a battery charger circuit and a rechargeable 12 volts battery, in the current state the system must boot down on power loss, this affects the GPS acquired coordinates, data loss due to time taken without mains presence, keeps the web polling nothing during time without mains voltage.

#### 4.8 Risk

As a project management practice, risks were identified that could impact or deviate our project outcomes. The main objectives of this project risk management were to Identify, analyze, and respond to the risks that the study could face, determined tools, processes, and procedures that would be used to manage and control risks in case any occurred. The (Table 4.8) lists the would be risks and how they would be mitigated in case of occurrence.

Table 4.8: Risk Register

Risk ID	Risk	impact	Strategy	Assigned
1.	Incorrect software	Component incompatibility	Consulted experts	Study owner
2.	Component Failure	System failure	Component selection with reviews and support	Study owner and Expert consultation
3.	Electrical shocks	injury	Safety standard	Study owner
4.	Incorrect results	Study failure	Comparison with collected data	Study Owner
5.	Acceptance of Project By stakeholders	Lack of funding	Reserved for innovation purpose	Supervisor
6.	Equipment failure	Project Fail	Expert Advice	Study owner
7.	Web data loss	Loss of data	Local Backup	Study owner
8.	Improper documentation	No compliance	Continuous Objectives review	Supervisor
9.	Budget limitations	No completion	Keep it simple	Study owner

The study’s risk management approach was aligned with established literature on risk management and ISO 9001 standards. Several risks were identified and categorized in Table 4.7. The first risk involved the use of inappropriate or costly licensed software; this was mitigated through expert consultation and a review of similar studies. The second risk concerned component failure, addressed by selecting widely used components with reliable support and availability (Chashin et al., 2021).

Electrical hazards, particularly the risk of electric shock, were also identified. This was mitigated through cautious handling of equipment, especially in areas with uncertain voltage levels, and by enforcing the use of appropriate personal protective equipment (PPE). Stakeholder acceptance was another critical risk factor, as the success of the study depended on the cooperation of participating households, observers, intended end users, and power providers. Lack of support could have resulted in delays or cancellation. To address this, the local area chairman was engaged during initial field visits and later assisted with data

collection, ensuring community cooperation through effective communication and stakeholder engagement.

To minimize equipment-related risks, components with available technical support and accessible spare parts were selected. Data loss was mitigated by regularly downloading and storing data locally to ensure availability in case of system or network failure. Documentation risks, including inaccurate or incomplete records, were addressed through immediate data entry, supplementary photographic records, and training of local personnel involved in data collection.

Budget constraints were also considered a potential risk, as limited resources could affect the study's scope, quality, or timeline. This was managed through careful resource allocation, the use of open-source software, and negotiation with suppliers for cost-effective equipment. The project prioritized core functionalities, with additional features implemented incrementally as resources allowed. Regular budget reviews and proactive financial management ensured that the study remained within its financial limits while maintaining overall quality. The evaluation of the prototype reveals a high degree of technical functionality in residential monitoring, characterized by successful data acquisition (Addow et al., 2025). However, the system encounters significant reliability obstacles in resource-constrained environments where frequent power grid instability and intermittent internet connectivity hamper continuous monitoring performance

## CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusion

The primary goal of this research was to develop and evaluate a robust voltage monitoring system capable of identifying power quality disturbances in low-voltage distribution networks. Based on the systematic execution of the research methodology, the following conclusions are drawn regarding the specific objectives.

### 5.2 Establishing Design Specifications

The first objective sought to establish technical and functional requirements for a monitoring system. Through a rigorous analysis of power quality indicators, it was determined in (section 4) that the system must operate within a nominal RMS range of 230 V to 250 V. The research identified that deviations below 0.9 per unit (p.u.) constitute undervoltage events that necessitate real-time logging. These specifications provided the foundational parameters for the hardware selection and the logic programmed into the microprocessor similar to work done in power quality disturbances (Helonde, 2024).

### 5.3 Design and Assembly of a Functional Prototype

The second objective involved the physical realization of the monitoring tool. By integrating a high-precision voltage sensor with a microprocessor and a SIM800L GPRS module, the study successfully developed a prototype capable of both local display and remote data transmission. Consistent with the approach described by Ravi and Kumar, the hardware design ensured that the system could accurately capture the "inrush currents" and voltage depressions typically associated with heavy inductive loads in residential settings (Ravi & Kumar, 2022).

#### 5.3.1 Calibration and Testing

Calibration was critical to ensure the reliability of the captured data. The results from the testbench experiments confirmed that the prototype's readings were consistent with standard industrial meters. Consistent with the work of Sushma (Sushma, 2023), this phase validated the system's ability to detect sags—defined as a decrease in RMS voltage between 0.1 and 0.9 p.u.—with high sensitivity.

### 5.4 Evaluation and Data Analysis

The final objective was to evaluate system performance in a real-world environment. The graphical data presented in (Figure 4.25) provides conclusive evidence of the system's functionality and performance trends. The field results showed that while off-peak voltages remained stable at 230 V, peak-hour consumption patterns led to significant fluctuations.

Critical findings as depicted in (Figure 4.25), the system successfully recorded voltage drops as low as 219 V. These findings align with the theoretical definitions of voltage sags caused by simultaneous household load activation and system overloads (Ravi & Kumar, 2022).

## **5.5 Summary of Findings**

In summary, this research has demonstrated that frequent voltage fluctuations are a significant challenge in the local distribution network, often pushing levels below the acceptable **230 V** threshold during peak periods. The development of this monitoring system provides a viable solution for the continuous assessment of power quality, offering a data-driven approach to mitigating the risks of equipment failure and system inefficiency (Manoj et al., 2022). By successfully meeting all specific objectives, this study contributes a functional tool and valuable field data to the field of electrical engineering.

This research successfully created a single-phase power quality monitoring system whose field measurements aligned closely with those obtained from test bench evaluations. The results verified the occurrence of voltage fluctuations across various times of the day, encompassing instances of both overvoltage and undervoltage. Furthermore, it was noted that individual phases displayed unique characteristics based on the load applied, even though they originated from the same three-phase transformer. Essential functional requirements, as outlined in Section 4.4.1, encompassing voltage, temporal aspects, and spatial location, were all proficiently recorded by the system.

The presence of similar works and expert guidance facilitated the creation of a straightforward, reproducible design subject to subsequent improvements. The implemented IoT-based monitoring system demonstrated significant data access flexibility, allowing remote user interaction and highlighting substantial potential for further refinement and expansion, including the integration of a decision-making and reporting system for enhanced insights and remote control capabilities (Ismail et al., 2025).

The successful implementation of such a system could contribute significantly to energy efficiency and optimization efforts, particularly in residential settings with increasing nonlinear loads. Future enhancements could involve expanding parameter monitoring beyond active power and power factors to include harmonic distortion, current waveforms, and transient response data, which would improve tool differentiation and reliability

Furthermore, exploring the efficacy of multilevel model extensions and refined algorithms could significantly enhance the accuracy and predictive capabilities of power quality assessments (Zjavka, 2022). Such advancements would not only refine the understanding of complex electrical phenomena but also enable the proactive identification and mitigation of potential power quality issues, moving towards more resilient and efficient energy grids. The integration of such a system with cloud-based platforms could further enable real-time monitoring and control, fostering more dynamic and responsive power management strategies in homes and offices (Sundaramoorthi & S., 2023).

Additionally, the developed system could be combined with advanced machine learning algorithms to predict power quality anomalies, thereby enabling preventative maintenance and optimizing energy distribution (Talbi et al., 2023).

## **5.6 Recommendations**

From the data collected, the study observed that every transformer phase had a unique behavior, with this finding, every supply phase of the transformer must have its own monitor unit to fully capture the essential parameters especially when it comes to load redistribution.

The study further proposes the following measures:

1. Incorporate software algorithms designed to monitor and enhance service quality, measurement accuracy, and surveillance of single-phase electricity distribution lines.
2. Develop a single integrated circuit capable of managing all parameters of the existing customer meters, thereby reducing overall system dimensions, production costs, and installation complexity.
3. Design a circuitry for embedding within existing energy meters to facilitate display functions and interoperability with SCADA systems.
4. Scale and adapt the software and hardware components for single-phase meters to support real-time data sharing within advanced metering infrastructures

## **5.7 Future work**

- i. Future investigations should focus on electricity distribution quality assurance, with particular emphasis on advanced energy meters that integrate voltage monitoring capabilities and employ GPRS communication channels for continuous data transmission and SCADA system updates. Such meters may be configured to generate

alerts upon voltage deviations from established thresholds, thereby enabling timely responses to power quality concerns. Furthermore, select smart meters can transmit voltage data in real time to utility providers via advanced metering infrastructure networks, supporting proactive grid management and accelerated fault detection at the household level. The incorporation of voltage monitoring functionalities into energy meters would augment device capabilities while contributing to enhanced power system reliability and improved customer satisfaction.

- ii. Subsequent research should explore the development of single-phase supply lines incorporating integrated physical-layer communication capabilities as a transport protocol. This approach offers considerable potential for advancing power distribution systems by enabling the concurrent transmission of electrical power and data signals over existing infrastructure. Such integration could facilitate smart grid technologies and home automation systems, thereby minimizing the requirement for separate communication networks and yielding cost efficiencies alongside improved grid data acquisition for end users. Research efforts in this domain should prioritize the optimization of modulation techniques to ensure reliable data transmission over power lines while mitigating interference with primary power distribution functions. Further exploration of advanced application-layer protocols such as for seamless real-time data exchange could ensure adaptability to dynamic demands in diverse smart grid environments (Šikić et al., 2020; Srivastava et al., 2022; Undersmoothing & S., 2023; Tightiz & Yang, 2020).
- iii. Additionally, investigating the application of machine learning algorithms for predictive analysis of voltage stability and anomaly detection within these integrated systems could further enhance grid resilience and operational efficiency (Hamdan, 2022).

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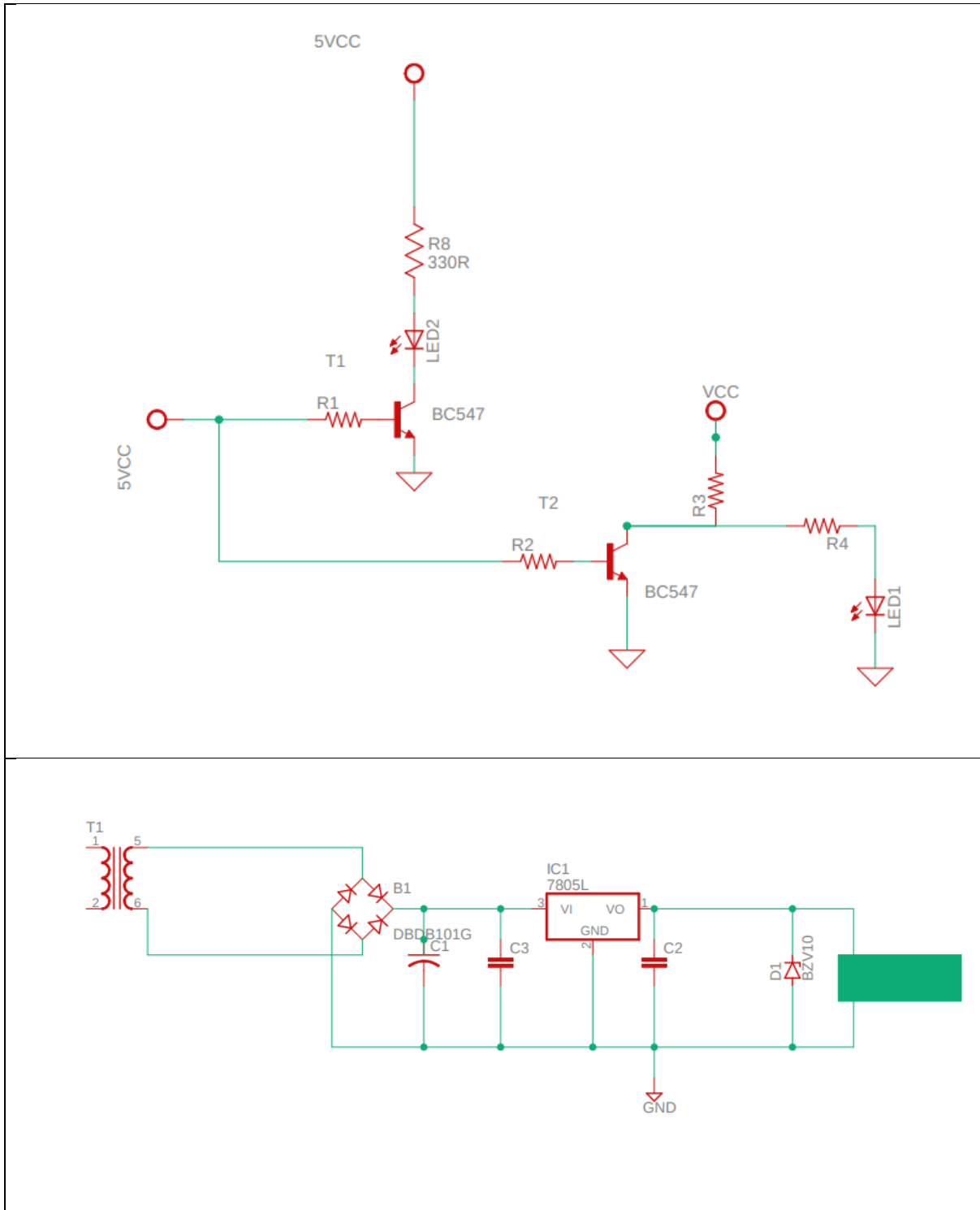
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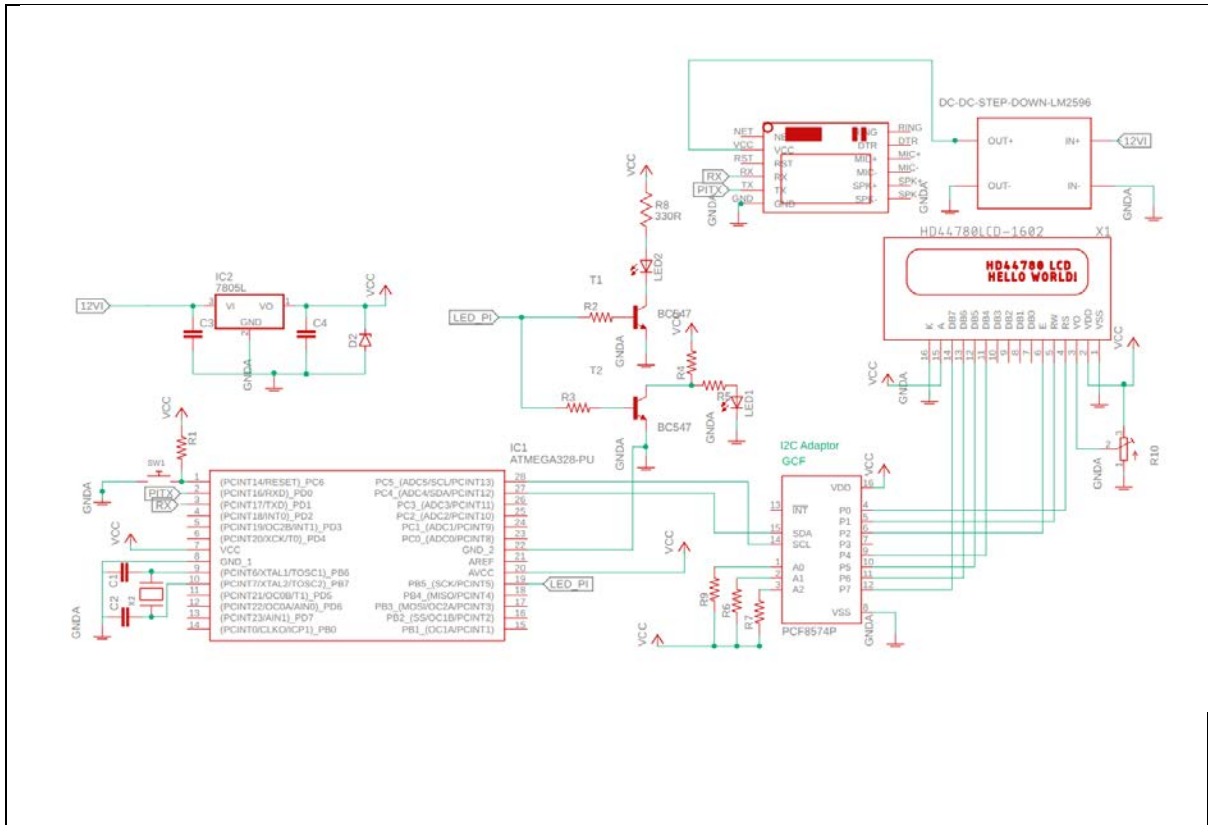
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## APPENDICES

### Appendix I: Circuit diagrams 5volts supply





## Appendix II: Research Instruments

KIMWANYI LC1  
KIRA DIVISION WAKISO DISTRICT

November 26 2022

RE: To whom it may concern.

Dear sir/Madam:

This is to introduce Mr. Kalema Ansty Ezra on MSC. (TIID) student in the Department of Mechanical Engineering.

The student is in his research year of study and doing research entitle "Development of a single phase power monitoring system". He chose your premises as a case study and this is to request for permission to collect data and any other information related to the research.

The mode of information gathering will be through taking measurements of your electricity from domestic single phase socket at particular times of the day using a fluke digital voltmeter and a Garmin GPS device at a domestic single phase socket at particular times of the day for the purposes of the research he is undertaking.

This is therefore to request for access for the M.Sc. student into your premises.

Thanking you for your continued cooperation.

Yours in service,

Musoke Francis Mukiibi

Chairman - 07022776808



### Appendix III: Working code

---

```
/*t's actually a formula to calculate the input voltage RMS
* by using the maximum value of the sensor output voltage.
* And here's how it's derived: The graph of the sensor output
* Voltage when it has the supply Grid electricity as its input is given
* As the result of the first code. You can see that the maximum.
* Voltage is somewhere around 600. And we already know that the
* Input voltage RMS is 220V. First, the peak value of the sensor
* output voltage is divided by sqrt(2). -Since it is needed for
* Calculating the RMS- Then the rest is just a linear transformation
* To get an output around 220 from the sensor output voltage.
*/
#include <TinyGPS++.h>
#include <SoftwareSerial.h>
// The TinyGPS++ object
TinyGPSPlus gps;
// The serial connection to the GPS device
SoftwareSerial ss(8,7);
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
// Set the LCD address to 0x27 for a 16 chars and 2 line display
LiquidCrystal_I2C lcd(0x27, 16, 2);
```

---

---

```
const int relay=9;

double sensorValue1 = 0;

double sensorValue2 = 0;

int crosscount = 0;

int climb_flag = 0;

int val[100];

int max_v = 0;

double VmaxD = 0;

double VeffD = 0;

double Veff = 0;

void setup() {

  lcd.begin();

  lcd.clear();

  lcd.print("Voltmeter");

  delay(5000);

  Serial.begin(9600);          // the GPRS baud rate

  lcd.clear();

  lcd.print("Checking network");

  lcd.setCursor(0,1);

  lcd.print("Please wait....");

  delay(15000);

  delay(15000);

  Serial.begin(4800);

  delay(1000);
```

---

```
Serial.println("AT");

delay(1000);

Serial.println("AT+CMGF=1"); // set SMS mode to text

delay(100);

Serial.println("AT+CNMI=2,2,0,0,0");

delay(500);

Serial.println("AT+CREG?");

delay(500);

while (!(Serial.available()))
{

  lcd.clear();

  lcd.print("Check GSM Modem");

  lcd.setCursor(0,1);

  lcd.print("and retry....");

  delay(200);

}

String response=Serial.readString();

while(!(response.indexOf("+CREG: 0,1")>-1))

{

  Serial.println("AT+CREG?");

  response=Serial.readString();

  lcd.clear();

  lcd.print("Network ");

  lcd.setCursor(0,1);
```

---

```
lcd.print("Connecting.....");

delay(3000);

}

if(response.indexOf("+CREG: 0,1")>-1)

{

Serial.println("AT+CREG?");

response=Serial.readString();

lcd.clear();

lcd.print(" NETWORK");

lcd.setCursor(0,1);

lcd.print(" CONNECTED");

}

pinMode(relay,OUTPUT);

digitalWrite(relay,1);

Serial.println("AT");

delay(1000);

Serial.println("AT+CMGF=1"); // set SMS mode to text

delay(100);

Serial.println("AT+CNMI=2,2,0,0,0");

delay(2000);

ss.begin(9600);

/*Serial.println("AT+CMGF=1"); // set the SMS mode to text

delay(2500);

Serial.write("AT+CMGS=");
```

---

---

```
Serial.write(34); //ASCII of “

Serial.write("+256788131479");

Serial.write(34);

Serial.write(13);

Serial.write(10);

delay(2500);

Serial.println("Connection OK");

delay(2500);

Serial.write(26);

Serial.write(13);

Serial.write(10); //Ascii code of ctrl+z to send the message

    delay(3000);*/

}

void loop() {

    for ( int i = 0; i < 100; i++ ) {

        sensorValue1 = analogRead(A2);

        if (analogRead(A2) > 511) {

            val[i] = sensorValue1;

        }

        else {

            val[i] = 0;

        }

        delay(1);

    }

}
```

---

```
max_v = 0;

for ( int i = 0; i < 100; i++ )
{
  if ( val[i] > max_v )
  {
    max_v = val[i];
  }
  val[i] = 0;
}

if (max_v != 0) {
  VmaxD = max_v;
  VeffD = VmaxD / sqrt(2);
  Veff = (((VeffD - 420.76) / -90.24) * -210.2) + 210.2;
}

else {
  Veff = 0;
}

if(Veff>250)
{
  digitalWrite(relay,LOW);

  Serial.println("AT+CMGF=1");// set the SMS mode to text

  delay(2500);

  Serial.write("AT+CMGS=");
```

---

```
Serial.write(34); //ASCII of “
Serial.write("+256788131479");
Serial.write(34);
Serial.write(13);
Serial.write(10);
delay(2500);
Serial.print("\nOver Voltage Alert!\n Voltage: ");
Serial.print(Veff);
Serial.print("V");
delay(2500);
Serial.write(26);
Serial.write(13);
Serial.write(10); //Ascii code of ctrl+z to send the message
delay(5000);
}
else if(Veff<200)
{
digitalWrite(relay,LOW);
Serial.println("AT+CMGF=1"); // set the SMS mode to text
delay(2500);
Serial.write("AT+CMGS=");
Serial.write(34); //ASCII of “
Serial.write("+256788131479");
Serial.write(34);
```

---

```
Serial.write(13);

Serial.write(10);

delay(2500);

Serial.print("\nUnder Voltage Alert!\n Voltage: ");

Serial.print(Veff);

Serial.print("V");

delay(2500);

Serial.write(26);

Serial.write(13);

Serial.write(10);//Ascii code of ctrl+z to send the message

delay(5000);

}

else

{

digitalWrite(relay,HIGH);

}

delay(100);

lcd.clear();

lcd.print(Veff);

lcd.print("Vac");

VmaxD=0;

ss.begin(9600);

// This sketch displays information every time a new sentence is correctly
encoded.
```

---

---

```
while (ss.available() > 0){  
  
    gps.encode(ss.read());  
  
    if (gps.location.isUpdated()){  
  
        Serial.println("AT+CMGF=1"); // set the SMS mode to text  
  
        delay(2500);  
  
        Serial.write("AT+CMGS=");  
  
        Serial.write(34); //ASCII of “  
  
        Serial.write("+256788131479");  
  
        Serial.write(34);  
  
        Serial.write(13);  
  
        Serial.write(10);  
  
        delay(2500);  
  
        Serial.print("\nVoltage: ");  
  
        Serial.print(Veff);  
  
        Serial.print("V");  
  
        Serial.print("\nhttp://maps.google.com/maps?q=");  
  
        Serial.print(gps.location.lat(), 6);  
  
        Serial.print(",");  
  
        Serial.println(gps.location.lng(), 6);  
  
        Serial.print("(My+Point)&z=14&ll=");  
  
        Serial.print(gps.location.lat(), 6);  
  
        Serial.print(",");  
  
        Serial.println(gps.location.lng(), 6);  
  
        delay(2500);  
  
    }  
  
}
```

---

```
Serial.write(26);

Serial.write(13);

Serial.write(10);//Ascii code of ctrl+z to send the message

delay(5000);

}

}

if (Serial.available())

Serial.write(Serial.read());

Serial.println("AT");

delay(1000);

Serial.println("AT+CPIN?");

delay(1000);

Serial.println("AT+CREG?");

delay(1000);

Serial.println("AT+CGATT?");

delay(1000);

Serial.println("AT+CIPSHUT");

delay(1000);

Serial.println("AT+CIPSTATUS");

delay(2000);

Serial.println("AT+CIPMUX=0");

delay(2000);

ShowSerialData();

Serial.println("AT+CSTT=\"internet\\");//start task and setting the APN,
```

---

---

```
delay(1000);

ShowSerialData();

Serial.println("AT+CIICR");//bring up wireless connection

delay(3000);

ShowSerialData();

Serial.println("AT+CIFSR");//get local IP adress

delay(2000);

ShowSerialData();

Serial.println("AT+CIPSPRT=0");

delay(3000);

ShowSerialData();

Serial.println("AT+CIPSTART=\"TCP\", \"api.thingspeak.com\", \"80\");//start
up the connection

delay(6000);

ShowSerialData();

Serial.println("AT+CIPSEND");//begin send data to remote server

delay(4000);

ShowSerialData();

String str="GET
https://api.thingspeak.com/update?api_key=MODKP7S8SPA2E0R9&field1="
+ String(Veff) + "&field2="+String(gps.location.lat(),
6)+"&field3="+String(gps.location.lng(), 6);

Serial.println(str);

Serial.println(str);//begin send data to remote server

delay(4000);
```

---

---

```
ShowSerialData();

Serial.println((char)26);//sending

delay(5000);//waitting for reply, important! the time is base on the condition
of internet

Serial.println();

ShowSerialData();

Serial.println("AT+CIPSHUT");//close the connection

delay(100);

ShowSerialData();

}

void ShowSerialData()

{

//while(Serial.available()!=0)

//Serial.write(Serial.read());

// delay(5000);

}
```

---

#### Appendix IV: Voltage measured in the sample population

Point	Location	Time of day	Voltage reading (v)	Distance from transformer	from direct line
1.	X: 0.45333, Y: 32.673	8:00 am	253.0	150m	
2.	X: 0.45, Y: 32.67775	8:05 am	248.8	220m	
3.	X: 0.6941667, Y: 32.6878	8:14 am	257.4	050m	
4.	X: 0.668611, Y: 32.73861	8:28 am	235.0	490m	
5.	X: 0.6863889, Y: 32.769445	8:42 am	242.0	520m	
6.	X: 0.6819444, Y: 32.794722	8:50 am	242.0	620m	
7.	X:0.6955556, Y: 32.8113889	9:00 am	252.0	650m	
8.	X: 0.698889, Y: 32.7316667	9:41 am	231.0	290m	

No	Time	Voltage	Coordinates	
UMEA transformer				
1	2:03pm	238.8	N	00.269436
			E	032.38226
2	2:06pm	241.2	N	00.26904

			E	032.38231
3	2:13pm	248.5	N	00.26808
			E	032.38.210
4	2:25pm	233.6	N	00.26.771
			E	032.38260
5	2:29pm	245.5	N	00.26746
			E	032.38.274
6	2:34pm	255.3	N	00.26745
			E	032.38.229
7	2:38pm	251.9	N	00.26735
			E	032.38.265
8	2:46pm	238.6	N	00.26.680
			E	032.38.241
9	2:50pm	236.5	N	00.26.681
			E	032.38.254
10	2:58pm	237.5	N	00.28633
			E	032.38.254
11	3:05pm	237.2	N	00.26.709
			E	032.38.383
12	3:11pm	221.5	N	00.26.809
			E	032.38.446
13	3:13pm	228.3	N	00.26.828
			E	032.38.448

14	3:19pm	234.5	N	00.26.846
			E	032.38.443
15	3:22pm	236.3	N	00.26.865
			E	032.38.458
16	3:28pm	242.8	N	00.26.854
			E	032.38.425
17	3:28pm	238.4	N	00.25.856
			E	032.38.403
18	3:32pm	253.6	N	00.26.889
			E	032.38.426
19	3:36pm	249.3	N	00.26.912
			E	032.38.477
20	3:41pm	251.4	N	00.26.864
			E	032.38.491
21	3:49pm	250.3	N	00.26.895
			E	032.38.493
22	3:52pm	245.9	N	00.26.914
			E	032.38.487
23	3:54pm	240.9	N	00.26.920
			E	032.38.496
24	4:09pm	239.8	N	00.26.851
			E	032.38.380

25	4:12pm	246.1	N	00.26.861
			E	032.38.380
26	4:17pm	245.3	N	00.26.882
			E	032.38.380
27	4:22pm	240.6	N	00.26.882
			E	032.38.292
28	4:36pm	245.9	N	00.26.927
			E	032.38.212
29	4:38pm	251.2	N	00.26.925
			E	032.38.210
30	4:41pm	249.1	N	00.26.944
			E	032.38.206
31	4:56pm	246.3	N	00.26.929
			E	032.38.187
32	5:00pm	244.6	N	00.26.903
			E	032.38.112
33	5:18pm	236.7	N	00.26.928
			E	032.38.060
34	5:30pm	243.7	N	0026.975
			E	032.38.143
35	5:43pm	243.1	N	00.26.951
			E	032.38.221

36	5:30pm	240.8	N	00.27.014
			E	032.38.249

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KITYO'S TRANSFORMER

1	18:04pm – 6:04pm	244.5	N	0027.167
			E	032.37.962

2	6:09pm	248.7	N	0027.166
			E	032.37.971

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Umea Transformer

3	5:22pm	241.6	N	00.27.054
			E	032.381.232

4	5:50pm	256.6	N	00.27.010
			E	032.38.146

5	5:53pm	242.7	N	00.27.018
			E	032.38.127

6	5:57pm	256.2	N	00.27.030
			E	032.38.120

7	6:07pm	254.9	N	00.27.038
			E	032.38.103

8	6:13pm	246.2	N	00.27.035
			E	032.38.086

9	6:21pm	239.4	N	00.27.060
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			E	032.38.047
10	6:31pm	235.6	N	00.27.056
			E	032.38.064
11	6:40pm	231.6	N	00.27.056
			E	032.38.064
12	6:59pm	102.3	N	00.27.045
			E	032.38.045
22/11/2023				
1	4:28pm	237.4	N	00.27.117
			E	032.38.044
2	4:42pm	236.9	N	00.27.216
			E	032.38.079
3	4:45pm	239.2	N	00.27.226
			E	032.38.079
4	4:49pm	237.8	N	00.27.226
			E	00.27.226
5	4:53pm	241.9	N	00.27.226
			E	032.38.046
6	4:59pm	243.2	N	00.27.308
			E	032.38.078
7	5:01pm	252.6	N	00.27.308
			E	032.38.087
8	5:05pm	246.8	N	00.27.315

			E	032.38.114
9	5:09pm	240.8	N	00.27.273
			E	032.38.072
10	5:15pm	247.5	N	00.26.963
			E	032.38.204
11	5:19pm	244.3	N	00.26.938
			E	032.38.227
12	4:38pm	252.7	N	00.26.804
			E	032.38.212
13	5:40pm	251.6	N	00.36.805
			E	032.38.215
14	5:54pm	249.5	N	00.26.815
			E	032.38.245
15	5:58pm	242.3	N	00.26.904
			E	032.38.232
16	6:09pm	235.1	N	00.26.771
			E	032.38.262

**Appendix V. Peak hour voltage readings using developed prototype**

