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Design and Implementation of a Low-Cost 3-phase Voltage Data Logger with Cellular IOT

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Abstract: *This study presents the design, implementation and performance evaluation of a low-cost three-phase voltage data logger with cellular Internet of Things (IoT) capability for remote monitoring of electrical distribution systems. The system was developed using an Arduino Nano microcontroller (ATmega328P), three independent voltage-sensing channels, signal-conditioning circuits, a real-time clock, an SD-card storage unit and a SIM800L GSM module for wireless data transmission to the MathWorks ThingSpeak cloud platform. A rechargeable battery arrangement was incorporated to support system operation. The developed prototype was deployed on a 415 V three-phase distribution network to evaluate its voltage acquisition, local storage and remote communication capabilities. Experimental results showed that the system acquired between 5 and 12 readings per second, with an average sampling rate of approximately 8 readings per second. Analysis of the local measurements revealed channel mean values of 228.03, 227.07 and 227.90 on 8 October 2021, while measurements recorded on 11 October 2021 produced mean values of 235.50, 235.50 and 203.60, respectively, indicating a substantial difference in the third measurement channel. The cloud-based records also demonstrated successful transmission of three-channel voltage measurements, with 26 non-zero records from entries 130–159 producing mean values of 234.81, 233.50 and 234.15 across the three channels. During testing, transient current demand from the GSM module occasionally affected the power supply and SD-card recording. A 2200 µF capacitor was consequently connected across the 4 V supply and ground to improve transient current support. The results demonstrate that the developed system can provide affordable three-phase voltage-magnitude monitoring, timestamped local data storage and remote access to measurement records. The instrument offers a practical solution for preliminary distribution-network monitoring, although further calibration and power-supply improvements are required to enhance measurement reliability.*

Keywords: *Arduino Nano; cellular IoT; GSM; three-phase voltage monitoring; ThingSpeak; voltage data logger.*

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1.0 Introduction

Monitoring electrical supply voltage is essential for ensuring the reliability, safety and efficient operation of modern power systems, industrial installations, commercial facilities and residential electrical networks. In three-phase distribution systems, the magnitudes and phase relationships of the three phase voltages provide important information about the operating conditions and quality of electricity supply. However, distribution networks are frequently exposed to voltage variations arising from load switching, feeder impedance, unbalanced loading, electrical faults and the integration of distributed generation (Bollen & Hassan, 2011). These disturbances can adversely

affect electrical equipment, reduce operational efficiency and contribute to equipment failure. Consequently, continuous voltage monitoring and time-stamped data acquisition are important for identifying abnormal supply conditions, evaluating voltage stability and supporting appropriate maintenance decisions. Periodic manual measurements are often inadequate for identifying intermittent or short-duration voltage variations, making automated data-logging systems increasingly relevant to electrical distribution monitoring (Djokic *et al*., 2005).

Traditionally, electrical voltage and power-quality monitoring have relied on dedicated power-quality analysers and specialised measurement instruments. These instruments provide comprehensive measurement capabilities, including root mean square (RMS) voltage, frequency, voltage unbalance, sags, swells, interruptions, transients and harmonic distortion. However, their relatively high acquisition costs can limit their deployment in applications requiring continuous monitoring at multiple locations, particularly in educational institutions, small industries and resource-constrained environments (Christe *et al*., 2020; Gallo *et al*., 2010; Pardo-Zamora *et al*., 2021; Rasoulnia *et al*., 2026). The IEEE Recommended Practice for Monitoring Electric Power Quality provides guidance on identifying and characterising power-quality disturbances, while IEC 61000-4-30 specifies measurement methods for evaluating power-quality parameters in 50/60-Hz electrical systems (IEC, 2025; IEEE, 2019). These standards emphasise the importance of appropriate measurement procedures, sampling, time synchronisation, data processing and measurement accuracy. Nevertheless, the comprehensive capabilities of commercial analysers may exceed the requirements of applications primarily concerned with recording and monitoring voltage magnitudes over extended periods.

Advances in low-cost microcontrollers and embedded computing technologies have created opportunities for developing flexible and economically accessible electrical measurement and monitoring systems. Microcontroller-based data loggers can acquire measurement signals at predetermined intervals, process the acquired information and store the results for subsequent analysis. Their relatively low cost, compact design and ease of programming make them suitable for application-specific monitoring systems (Abdullahi *et al*., 2025; Aluma & Wilshurst, 2019; Burse *et al*., 2023; Macheso & Thotho, 2022). Mohrem *et al*. (2018) demonstrated the feasibility of microcontroller-based real-time measurement and monitoring with data-logging capabilities, while Bello *et al*. (2015) developed a standalone general-purpose data logger integrating sensing, analogue-to-digital conversion, processing, display and data storage. These studies establish the suitability of embedded platforms for affordable monitoring applications, although their measurement configurations and intended applications differ from those required for continuous three-phase voltage acquisition and remote data accessibility.

Three-phase voltage monitoring presents additional technical requirements because the three phase voltages must be measured independently while maintaining appropriate electrical isolation, signal scaling, measurement accuracy and consistency between channels. Inaccuracies arising from differences in the measurement channels can introduce errors in the assessment of phase-voltage variations and unbalance (Bogarra *et al*., 2022; Gosbell *et al*., 2002; Mohamed *et al*., 2026). Sarkar and Sengupta (2008) demonstrated the feasibility of implementing a low-cost microprocessor-based three-phase energy-metering system, while Juwito *et al*. (2023) developed a prototype monitoring and data-logging system for three-phase electrical installations. More recently, Prasetyo *et al*. (2024) investigated an IoT-enabled three-phase power-quality monitoring unit, demonstrating the application of embedded technologies to remote electrical-system monitoring. These developments indicate growing interest in affordable three-phase

measurement architectures. However, the practical implementation of such systems involves balancing measurement accuracy, hardware complexity, data acquisition requirements, storage capacity and communication reliability.

The choice of the microcontroller and analogue-to-digital converter (ADC) is particularly important in determining the measurement performance of an embedded voltage-monitoring instrument. ADC resolution, input range, conversion accuracy and sampling characteristics influence the quality of the acquired measurement data. Arduino-based platforms offer an accessible development environment, relatively low hardware costs and extensive support for interfacing with electronic components and communication modules (Kondaveeti *et al*., 2021; Nguyen *et al*., 2018). Although external high-resolution ADCs can improve measurement resolution and provide additional input channels, their inclusion may increase hardware cost and implementation complexity (Godo *et al*., 2024; Itterheimova *et al*., 2021). Consequently, the selection of an appropriate acquisition architecture should be based on the intended measurement parameters, required resolution, sampling frequency, signal-conditioning arrangement and acceptable measurement uncertainty (Attivissimo *et al*., 2007; Duran & Rueda, 2025; Itterheimova *et al*., 2021; Salvatore & Spataro, 2008). For applications primarily concerned with monitoring voltage magnitudes and identifying sustained deviations from nominal supply conditions, a suitably designed analogue measurement and conditioning circuit can provide a practical alternative to more computationally demanding waveform-acquisition systems.

Voltage transduction and signal conditioning are equally important because distribution-system voltages cannot be connected directly to the low-voltage analogue inputs of microcontrollers. An appropriate voltage-sensing arrangement is therefore required to reduce the monitored voltage to a safe and measurable level while maintaining a reliable relationship between the input voltage and the conditioned signal (Carlos *et al*., 2019; Hussein & Abojlala, 2026). Electrical isolation, signal scaling, rectification, filtering and input protection are essential considerations in developing such measurement circuits. The conditioned signal must also remain within the permissible input range of the ADC to prevent saturation and damage to the microcontroller. Errors arising from component tolerances, signal scaling, ADC quantisation and calibration can directly affect the accuracy of the calculated voltage measurements (Catunda *et al*., 2003; Fusiek & Niewczas, 2026; Marin *et al*., 2026; Novotny & Sedlacek, 2008; Serguisz *et al*., 2025). Therefore, the sensing and signal-conditioning stages constitute fundamental components of the measurement instrument and require appropriate calibration and experimental validation.

Data storage and communication are additional considerations in the development of automated voltage-monitoring systems. Unlike conventional voltmeters, which primarily provide instantaneous measurements, data loggers generate time-stamped records that allow voltage variations to be examined over extended periods. Arduino-based platforms equipped with secure digital (SD) card modules and real-time clocks provide relatively inexpensive means of storing measurement records for subsequent analysis (Beddows & Mallon, 2018; Wickert *et al*., 2019). Previous investigations have demonstrated the application of microcontroller-based data acquisition and logging systems in different monitoring environments (Camilo *et al*., 2020; Pachauri *et al*., 2021). The recorded data can be used to examine temporal voltage variations, compare the behaviour of individual phases and identify sustained deviations from predefined voltage limits. Furthermore, the integration of cellular communication and Internet of Things (IoT) technologies enables measurement information to be transmitted to remote servers for online access and visualisation. Cloud-based monitoring platforms such as ThingSpeak provide facilities for receiving,



storing and displaying remotely transmitted sensor measurements. The development of low-cost web-based voltage-monitoring systems has demonstrated the relevance of remote data accessibility to electrical supply monitoring (Tse & Chan, 2003). Similarly, open-source monitoring architectures and IoT-based smart-metering systems have demonstrated the potential of affordable embedded technologies for continuous energy and electrical-system monitoring (Oberloier & Pearce, 2018; Palacean, 2024; Viciana *et al*., 2018). The integration of local storage and remote communication is particularly useful because local records can be maintained when network connectivity is unavailable, while cloud transmission facilitates remote access to the acquired information.

The interpretation of recorded voltage measurements also requires an understanding of the characteristics and limitations of the acquisition system. Dugan *et al*. (2021) identify voltage variations, sags, swells, interruptions and harmonic distortion as important power-quality phenomena requiring appropriate measurement and analysis. Bollen (1999) provides a detailed treatment of voltage sags and interruptions, while Arrillaga *et al*. (2000) discuss techniques for assessing power-system quality. Bollen and Gu (2006) further demonstrate the importance of signal-processing techniques in extracting information from measured electrical waveforms. However, the ability to characterise these disturbances depends on the measurement architecture and sampling frequency. Systems based on analogue conversion of AC signals to representative DC voltage levels are primarily suitable for monitoring voltage magnitudes and relatively sustained variations. They do not provide the original waveform information required for comprehensive harmonic, frequency or transient analysis. Accordingly, the measurement capabilities of low-cost monitoring instruments must be evaluated in relation to their actual sensing and acquisition configurations.

Despite advances in microcontroller-based electrical monitoring, there remains a practical need for an affordable and readily reproducible three-phase voltage data logger that integrates independent phase-voltage measurement, local time-stamped storage, cellular communication and backup power within a single monitoring platform. Previous studies have demonstrated the feasibility of individual components and related monitoring architectures, including low-cost three-phase measurement, embedded data acquisition, cloud-based monitoring and IoT-enabled power-quality analysis (Juwito *et al*., 2023; Mallala *et al*., 2025; Prasetyo *et al*., 2024; Sarkar & Sengupta, 2008). Nevertheless, the integration and experimental evaluation of these functions within a compact system that combines analogue RMS voltage measurement, SD-card data storage, GSM-based cloud transmission and battery-supported operation remains an important practical development objective. In particular, the reliability of local data recording during communication interruptions, the continuity of operation during utility supply disturbances and the calibration of independent voltage-measurement channels are important considerations in developing an economically accessible monitoring instrument. Addressing these requirements can provide a useful alternative for applications where continuous voltage-magnitude monitoring is required but the cost and complexity of comprehensive commercial power-quality analysers are not justified.

In view of these considerations, this study aims to design, implement and experimentally evaluate a low-cost three-phase voltage data logger incorporating cellular IoT communication. The developed system employs an Arduino Nano based on the ATmega328P microcontroller, three independent voltage-sensing channels with analogue signal conditioning, an SD-card storage module, a real-time clock and a SIM800L GSM communication module for transmitting measurement records to the

MathWorks ThingSpeak cloud platform. A rechargeable lead-acid battery and an automatic phase-selection charging arrangement are incorporated to support continued system operation during interruptions in the utility supply. Specifically, the study involves the development of the voltage-sensing and signal-conditioning circuits, integration of the processing, storage and communication units, calibration of the measurement channels, and experimental evaluation of the system's voltage-recording and remote data-transmission capabilities.

The significance of this study lies in the development of an affordable, portable and accessible platform for continuous three-phase voltage-magnitude monitoring. By integrating local data storage with cellular communication and cloud-based visualisation, the system provides both historical measurement records and opportunities for remote observation of electrical supply conditions. Its relatively simple hardware architecture makes it potentially useful for electrical engineering laboratories, educational institutions, small-scale industrial installations, research activities and preliminary monitoring of distribution networks. Furthermore, the use of readily available electronic components provides opportunities for local fabrication, maintenance and adaptation to different monitoring requirements. Although the developed instrument is not intended to replace comprehensive power-quality analysers used for harmonic and transient measurements, it offers a practical and economical approach to monitoring phase-voltage variations and identifying sustained under-voltage and over-voltage conditions. The study therefore contributes to the development of accessible embedded monitoring technologies by demonstrating the integration and experimental application of three-phase voltage measurement, time-stamped data logging, cellular communication and battery-supported operation within a single low-cost system.

2.0 Materials and Methods

The data logger consists of the following units: power supply, signal conditioning, processing/storage and communication. The block diagram of the system is presented in Fig. 1.

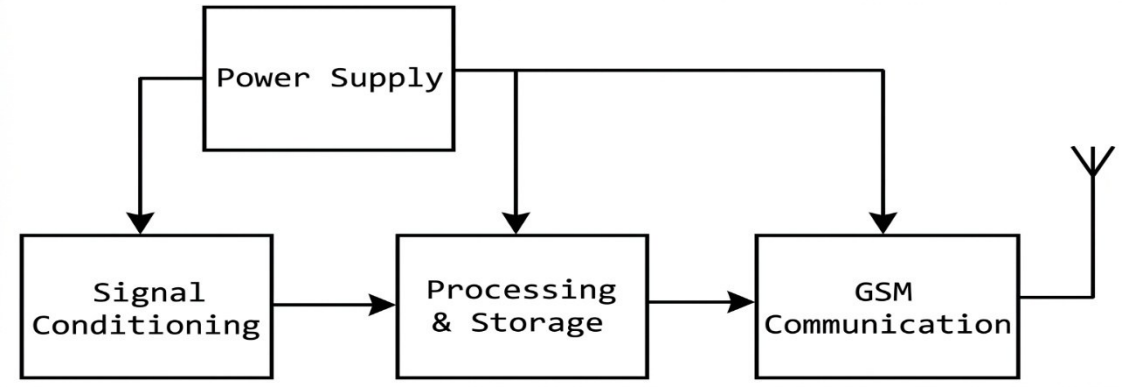


Fig. 1: Block diagram of data logger

2.1 Power Supply and Battery Management

The system power comes primarily from the battery which is always monitored by the software algorithm to ensure the battery is always charged. The power required to charge the battery comes from the mains through a 240/15V/3000mA step down transformer. A relay circuit for each phase is used to connect the power supply transformer to any of the phases available with the Red phase having the highest priority followed by the Yellow phase and then the Blue phase. This means that the algorithm monitors the battery voltage and the voltage from the three phases. If the battery voltage falls below

12.7V and the Red phase voltage is greater than 170V, the algorithm actuates the relay circuit connected to the Red phase in order to draw power from the Red phase to charge the battery until the battery voltage reaches 14.4V after which the relay circuit is turned off to cut power supplied to the battery. If the Red phase voltage is less than 170V, the Red phase relay is turned off and the Yellow phase relay is turned on to supply power for charging the battery. If the voltages of both the Red and Yellow phases are below 170V, the algorithm turns off both the Red and Yellow phase relay circuits and actuates the Blue phase relay circuit to draw power from the Blue phase to charge the battery. The circuit diagram for the relay circuit is shown in Fig. 2.

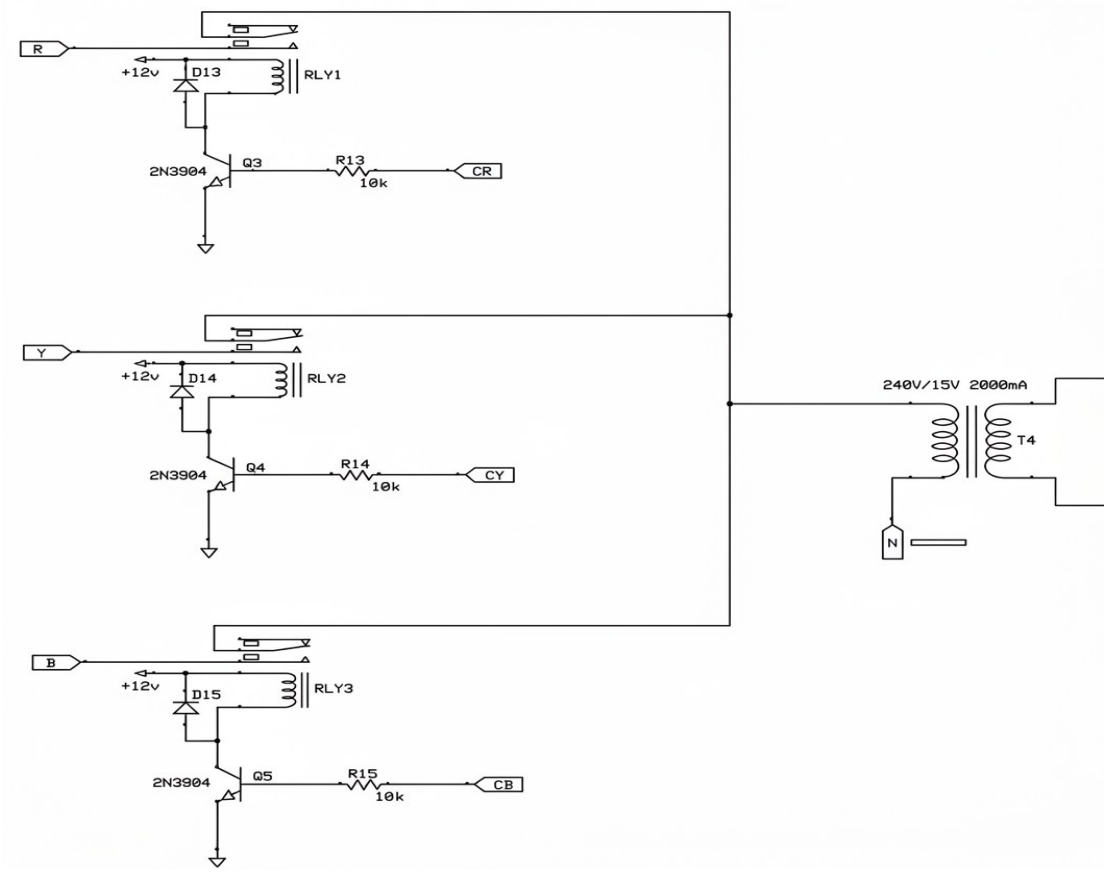


Fig. 2: Relay Circuit

Diodes D13, D14 and D15 are freewheeling diodes used to protect the transistors Q3, Q4 and Q5 from high transient voltages resulting from switching the relay coils.

Transistors Q3, Q4 and Q5 are general purpose switching transistors suitable for this application. In this case, resistors R13, R14 and R15 are 10k ohm base current limiting transistors selected to limit the base currents of the transistors Q3, Q4 and Q5. Values from 10k to 18k can be used for this application.

Transformer T4 is a 240/15V, 3000mA transformer for powering the battery charging circuit. Diodes D16, D17, D18 and D19 form a bridge rectifier to convert the AC voltage from the transformer to DC voltage.

C10 is a filter capacitor used for filtering the rectified DC to minimise ripples in the DC output. The value of C10 in µF is computed using equation 1.

$$C10 = \frac{2.4 \times I_{dc}}{V_{r(rms)}} \quad (1)$$

where I_{dc} is the DC current drawn in mA, $Vr_{(rms)}$ is the ripple voltage in volts and C10 is the filter capacitor value. Here we estimate $V_{r(rms))}$ to be 0.75V and I_{dc} to be 1.5A given that the battery charges at 10% of its rated capacity of 6Ah. Computing the value of C10 thus gives 4800µF.

LED4 is the power supply LED which indicates the presence of DC power to the system.

R17 limits the current passing through LED4. Given that the output of the transformer supplying the bridge rectifier is rated at 15V and the current required to pass through LED4 (I_{LED}) is 14mA, R17 is then calculated as shown in equation 2 and 3.

$$R_{17} = \frac{2V_m - V_{LED}}{\pi \times I_{LED}} \quad (2)$$

$$\frac{(2\times\sqrt{2}\times 15)-2}{\pi \times 15 \times 10^{-3}} = 919 \approx 1k\ ohm \quad (3)$$

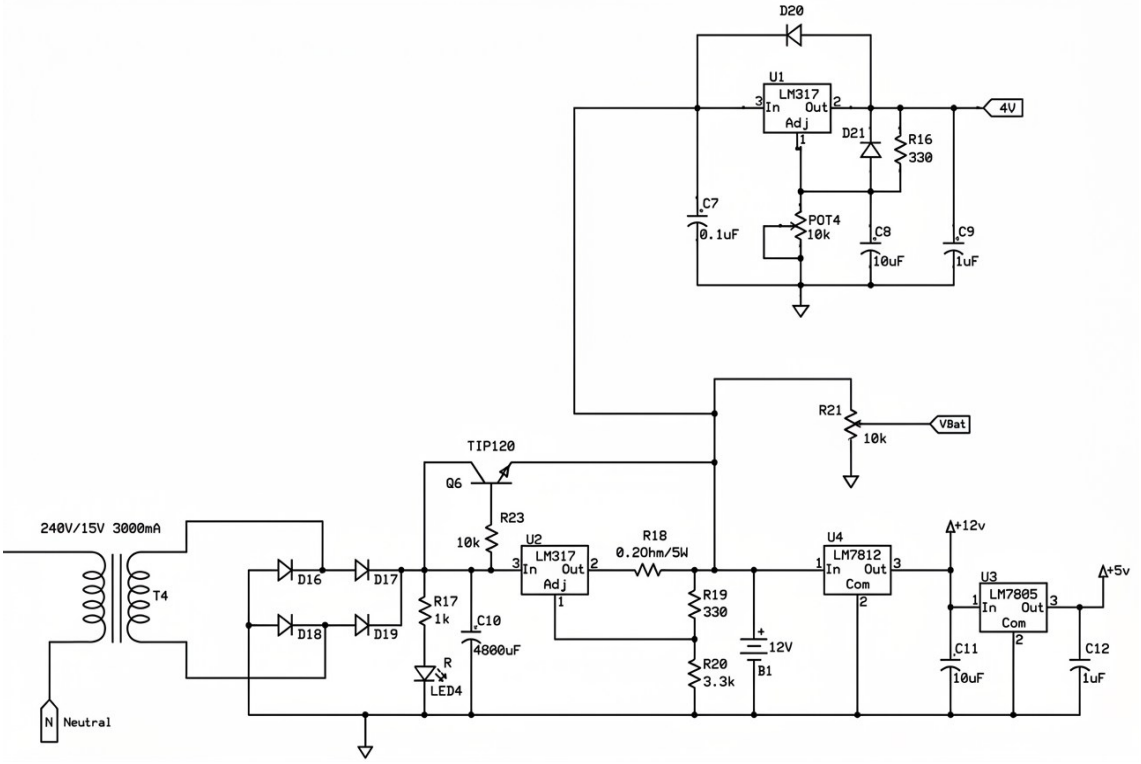


Fig. 3: Power Supply Circuit

U2 i.e. LM317 is a variable regulator and together with R18, R19 and R20 forms a battery charger in accordance with datasheet recommendations.

U4 (LM7812) is a positive 12V regulator.

U3 is a positive 5V regulator while C11 and C12 are filter capacitors for the 5V regulator.

Q6 is a power Darlington transistor used to boost the current supplied through U3 while R23 is the base limiting resistor for Q6.

The variable linear regulator U1 (LM317) together with POT4, D20, D21, R16, C7, C8 and C9 form a variable voltage regulator adjusted with POT4 to give 4V.

R21 is a 50kΩ potentiometer used to scale down the battery voltage to a value that the analogue pin of the microcontroller can handle for the purpose of measuring the battery voltage level. The transfer ratio is given as shown in equation 4. Where V_a is the microcontroller analogue pin full scale voltage and V_b is the battery voltage level.

$$transfer\ ratio = \frac{V_a}{V_b} \quad (4)$$

Since V_b is chosen to be 15V (the maximum obtainable), and V_a is 5V (full scale voltage), the transfer ratio is calculated as shown in equation 5. This ratio is used to multiply the measured battery voltage to determine the voltage at the potentiometer wiper that connects to the analogue input pin.

$$transfer\ ratio = \frac{5}{15} = \frac{1}{3} \quad (5)$$

2.2 Processing/Storage

The processing/storage circuit consists of the microcontroller (M1) as well as the real time clock (RTC) (M2) and the SD (secure digital) card module (M3). The SD card module stores a copy of the data logged while the RTC synchronises all measurements and transmissions. The microcontroller that runs the algorithm is an Arduino Nano which in turn uses an ATMEGA328p AVR microcontroller.

The SD card module connects to the microcontroller through the serial peripheral interface (SPI) port while the RTC on the other hand connects to the microcontroller via the inter-integrated circuit (I^2C) port. Fig. 4 shows the processing/Storage circuit.

V_R, V_Y and V_B are the analogue voltage inputs to the microcontroller.

R, Y and B are the signal outputs that turn on relay that connects the phase to the charging circuit. V_{batt} is the analogue signal indicating the voltage level of the battery RST is the reset input for the GSM module. This is used to reset the GSM module when necessary.

FNX is the signal output that turns on/off the green LED which indicates the logging functionality.

and the GSM module (M4).

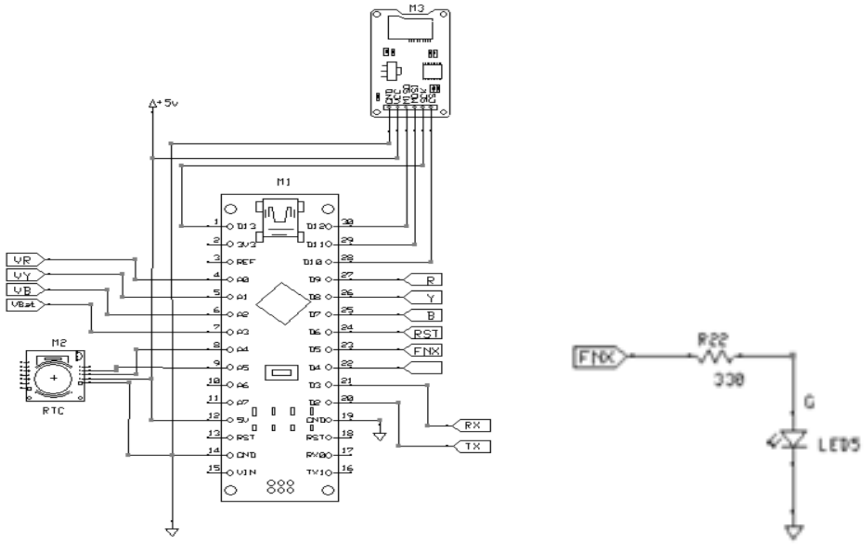


Fig. 4: Processing/Storage Circuit

2.3 GSM Communication

The GSM module is responsible for transmitting the measurement data via the GSM/GPRS network to the ThingSpeak server. Since the GSM module operates using a 2.8V logic, transistor-based logic level converters are used to connect the GSM module's 2.8V logic to the microcontroller 5V logic level. The GSM module connects to the microcontroller via the universal asynchronous receiver transmitter (UART) port as depicted in Fig. 5. The 4V terminal shown in Fig. 5 both connect to the 4V output of the power supply circuit. The 2.8V shown on the logic level converter is obtained by dropping the 4V of the power supply by 1.4V using two silicon diodes as shown in Fig. 5.

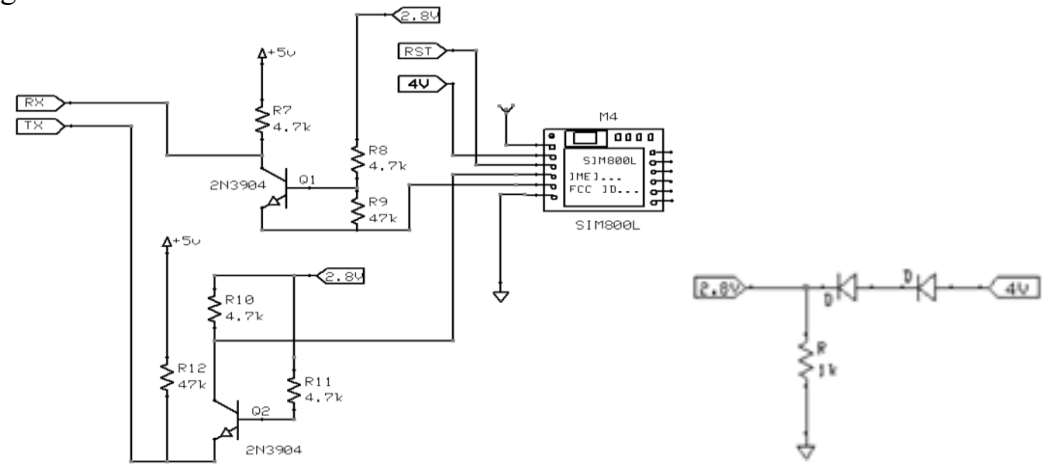


Fig. 5: GSM Communication Circuit

2.4 Signal Conditioning

The function of the signal conditioning circuit as shown in Fig. 6 is to convert the grid AC voltage to a DC voltage proportional to the rms value of the AC voltage. To achieve this, the AC phase voltage is first stepped down using 240/12V/300mA transformers T1, T2 and T3 for the three phases. D1 – D12 form bridge rectifiers for rectifying the mains voltages while capacitors C1 to C6 filter the AC signals to obtain a DC signals.

LED1, LED2 and LED3 are indicator lights for the each of the phases while resistors R1, R3 and R5 are 1kΩ current limiting resistors for the LEDs as derived from equation 3.

Zener diodes ZD1, ZD2 and ZD3 along with the resistors R2, R4 and R6 protect the analogue input pins of the microcontroller from transient or surge voltages. The zener diode prevents the voltage from rising beyond the absolute maximum of 6V.

POT1, POT2 and POT3 are 10kΩ potentiometers for scaling down the DC voltage signal to a range compatible with the microcontroller analogue pins. Given that transformers T1, T2 and T3 have a fixed transformation ratio, the transfer ratio for the signal conditioning circuit is calculated as shown in equations 6 and 7.

$$V_{in} = 240V,\ V_a = 5V \tag{6}$$

$$\therefore transfer\ ratio = \frac{5}{240} = \frac{1}{48} \tag{7}$$

Where V_a is the full scale voltage of the analogue to digital converter of the microcontroller and V_{in} is the input AC rms voltage. This ratio is used to multiply the measured voltage to determine the voltage at the potentiometer wiper.

The fuses F1, F2 and F3 are 1A fuses for protecting the system against short circuit while V1, V2 and V3 are 390V varistors which protect the system against transient over-voltage.

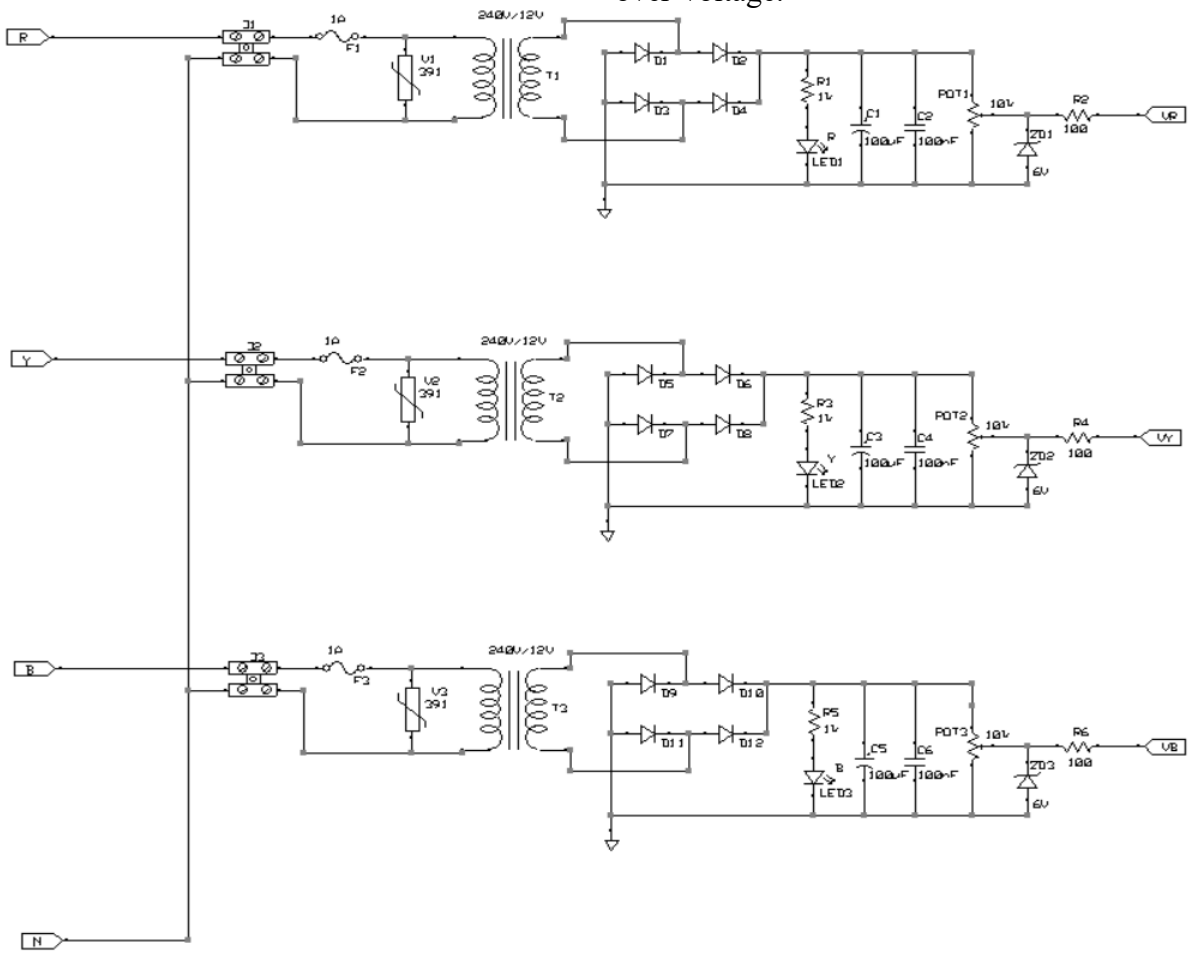


Fig. 6: Signal Conditioning Circuit

2.5 Calibration Procedure/Flow Chart

The following procedure was followed to calibrate the data logger and the flow chart of the data logger algorithm is presented in Fig. 7.

1. The three phases inputs were connected to one phase
2. The incoming mains voltage was measured with a digital voltmeter
3. The incoming mains voltage was divided by 48 (refer to equation 1)
4. The three signal potentiometers were adjusted to give a voltage equal to the incoming mains voltage divided by 48. This is a rough calibration estimate and may not be exactly what is being measured from the mains using the multi-meter. It is intended to put the voltage at the analogue pins in the measuring range.
5. The Arduino is connected to the USB port and the serial monitor was turned on. The serial monitor displayed the measured AC voltage as the logger generated a log of the phase voltage.
6. The value displayed was carefully fine-tuned by adjusting the 10kΩ signal potentiometers and observing the values displayed on the serial monitor and on the multi-meter. This was done until all the values were the same and equal to the incoming mains value displayed on the multi-meter.
7. The Arduino was disconnected from the USB port after the logger had been calibrated.

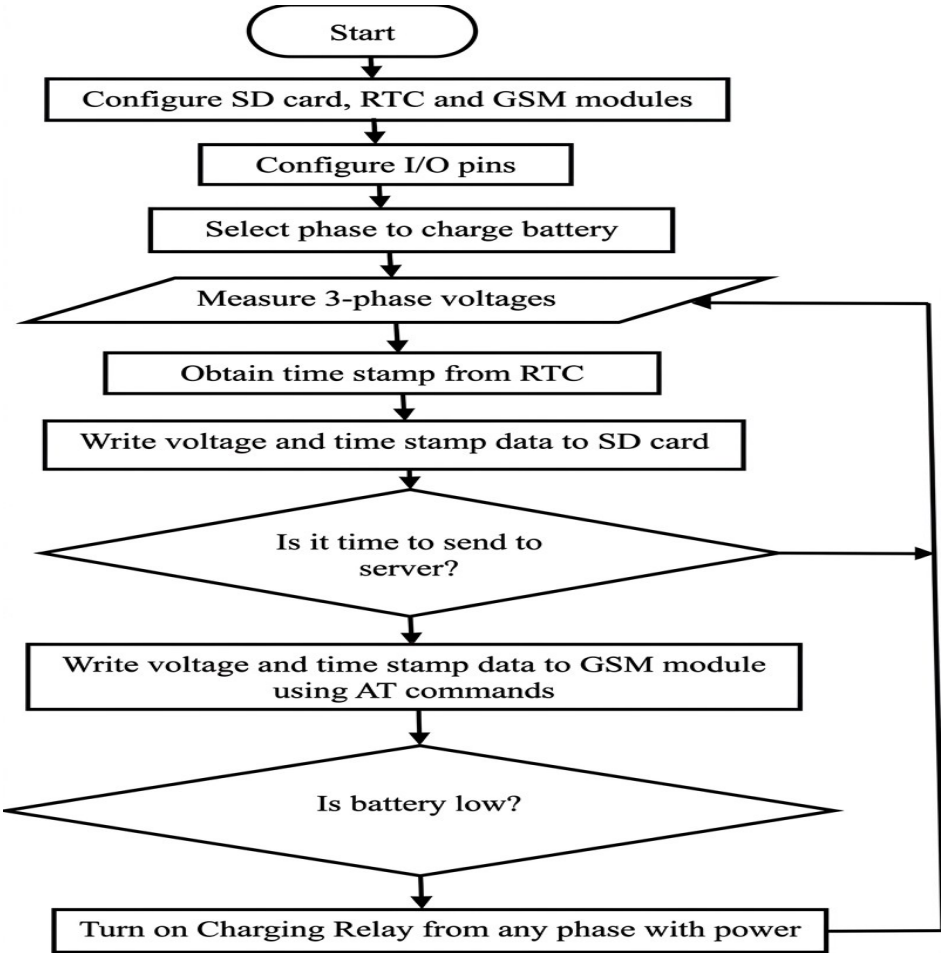


Fig. 7: Flow Chart of the data logger algorithm

2.6 Hardware Implementation

Fig. 8 shows some of the circuit boards implemented. The pictures displayed in Fig. 9 show the stages in the mounting and assembling of the data logger from left to right and from top to bottom. The first picture

shows only the three (3) signal transformers and the power supply transformer. The sixth picture of Fig. 9 (i.e. second row, second picture) shows the complete data logger with all the modules and boards assembled. The last picture (i.e. second row, third picture) shows the cover of the unit.

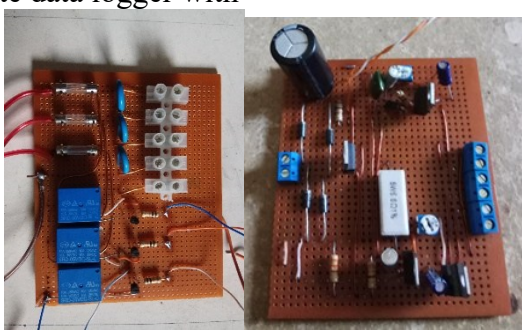


Fig. 8: Circuit Boards

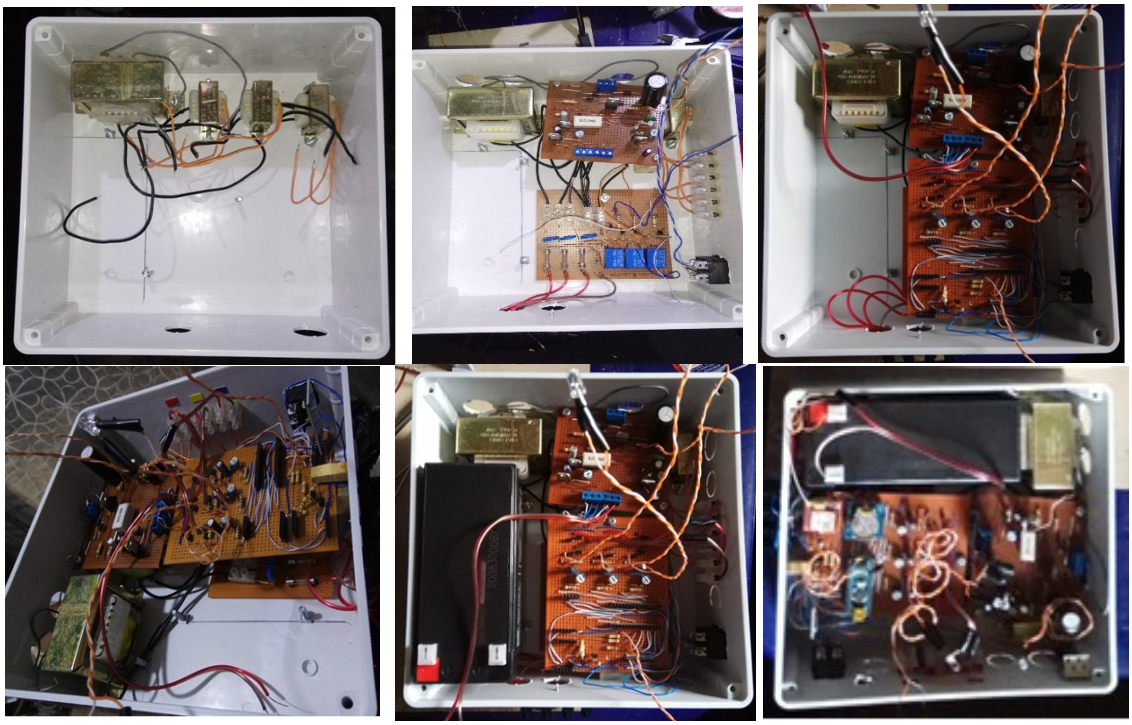


Fig. 9: Data logger implementation stages

3.0 Results and Discussion

3.2 Analysis of Three-Phase Voltage Measurements

The voltage measurements obtained during deployment provide an indication of the logger's ability to capture variations in the three phase voltages under actual distribution-network operating conditions. Tables 1–4 present representative measurements recorded on 8 October, 24 September, 11 October and 12 October 2021, respectively. The three measurement channels are identified as Reading 1, Reading 2 and Reading 3. Their numerical values provide a basis for examining the consistency of the recorded measurements, short-term voltage variations and differences between the monitored phases.

Table 1 presents 29 voltage observations recorded on 8 October 2021. The first measurement channel ranged from 227 to 229, while the second channel remained predominantly at 227, with an overall range of 227–228. The third channel varied between 227 and 229. The corresponding

mean readings were approximately 228.03, 227.07 and 227.90 for the three channels, respectively. The relatively narrow variation in the recorded values indicates that the supply voltage remained fairly stable during the observation period. The maximum difference between the three channel means was less than one measurement unit, suggesting a high degree of consistency in the recorded phase-voltage magnitudes during this interval.

Table 1: Data recorded on 8 October 2021

Date	Day	Time	Reading 1	Reading 2	Reading 3
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	227	227	227
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	228	227	227
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	227	227	227
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:29	228	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	229	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	229	228	229
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	229	227	228
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:30	229	228	229
10/8/2021	Friday	0:41:30	228	227	228
10/8/2021	Friday	0:41:31	228	227	228
10/8/2021	Friday	0:41:31	228	227	228
10/8/2021	Friday	0:41:31	227	227	227
10/8/2021	Friday	0:41:31	228	227	227
10/8/2021	Friday	0:41:31	228	227	228
10/8/2021	Friday	0:41:31	228	227	228

The limited variation observed in Table 1 also demonstrates the ability of the developed logger to capture relatively small changes in supply voltage. Although the measurements were recorded within a short observation period, the consistency of the three channels provides preliminary evidence of the stability of the sensing and acquisition arrangement under the prevailing operating conditions. This is important because reliable voltage monitoring requires the measurement channels to reproduce actual supply variations without introducing substantial channel-dependent differences. The result is

consistent with the measurement considerations discussed by Bogarra *et al*. (2022) and Gosbell *et al*. (2002), who emphasised the importance of measurement accuracy and channel consistency in assessing three-phase voltage conditions.

Table 2 presents measurements obtained on 24 September 2021. The first and second measurement channels recorded identical values throughout most of the observation period, with mean values of approximately 239.03 for both channels. The third channel recorded a slightly higher mean value of approximately 241.83. The respective measurement ranges were 239–240 for the first and second channels and 240–242 for the third channel. The overall mean of the three channels was approximately 239.97. Compared with the observations in Table 1, the measurements indicate a higher voltage level during this recording period, demonstrating the ability of the developed instrument to capture changes in supply-voltage magnitude across different monitoring sessions.

Table 2: Data recorded on 24 September 2021

Date	Day	Time	Reading 1	Reading 2	Reading 3
9/24/2021	Friday	1:56:48	239	239	242
9/24/2021	Friday	1:56:48	239	239	242
9/24/2021	Friday	1:56:48	239	239	242
9/24/2021	Friday	1:56:48	239	239	242
9/24/2021	Friday	1:56:48	239	239	242
9/24/2021	Friday	1:56:49	239	239	242
9/24/2021	Friday	1:56:49	239	239	242
9/24/2021	Friday	1:56:49	239	239	242
9/24/2021	Friday	1:56:49	239	239	242
9/24/2021	Friday	1:56:49	239	239	242
9/24/2021	Friday	1:56:49	240	240	240
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:50	239	239	242
9/24/2021	Friday	1:56:51	239	239	242
9/24/2021	Friday	1:56:51	239	239	242
9/24/2021	Friday	1:56:51	239	239	241
9/24/2021	Friday	1:56:51	239	239	241
9/24/2021	Friday	1:56:51	239	239	242
9/24/2021	Friday	1:56:51	239	239	241
9/24/2021	Friday	1:56:51	239	239	242
9/24/2021	Friday	1:56:52	239	239	242
9/24/2021	Friday	1:56:52	239	239	242
9/24/2021	Friday	1:56:52	239	239	242
9/24/2021	Friday	1:56:52	239	239	242

Table 3 presents the measurements recorded on 11 October 2021. The first and second channels recorded mean values of approximately 235.50 each, with individual observations ranging between 235 and 236. In contrast, the third channel recorded

substantially lower values, ranging from 201 to 205, with a mean of approximately 203.60. The difference between the mean readings of the first and third channels was approximately 31.90 measurement units. This represents a noticeable departure from the relatively consistent phase-voltage patterns observed in Tables 1 and 2.

The substantial difference in the third-channel readings suggests a possible phase-voltage abnormality during the observation period. If the readings represent volts, the third channel was approximately 13.5% lower than the mean of the first two channels. Such a difference could indicate an actual voltage reduction in the corresponding supply phase, an abnormal distribution-system operating condition or a measurement-channel problem arising from signal conditioning, calibration or electrical connection. The available measurements alone cannot establish which of these possibilities caused the observed difference. Nevertheless, the ability of the developed logger to record and distinguish such differences demonstrates the practical importance of independent three-phase voltage monitoring. In particular, a single-channel monitoring arrangement might not adequately reveal the condition observed in the third channel.

The observed difference also reinforces the importance of appropriate calibration and validation of the individual sensing channels. As explained by Attivissimo *et al*. (2007) and Novotny and Sedlacek (2008), measurement uncertainty and errors introduced during signal acquisition can affect the reliability of electrical measurements. Therefore, although the third-channel readings suggest a possible abnormal voltage condition, further comparison with an independently calibrated reference instrument would be required to determine whether the difference originated from the electrical network or the measurement subsystem.

Table 3: Data recorded on 11 October 2021

Date	Day	Time	Reading 1	Reading 2	Reading 3
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	204
10/11/2021	Monday	10:32:51	235	235	203
10/11/2021	Monday	10:32:52	235	235	204
10/11/2021	Monday	10:32:52	236	236	204
10/11/2021	Monday	10:32:52	236	236	204
10/11/2021	Monday	10:32:52	236	236	204
10/11/2021	Monday	10:32:52	236	236	203
10/11/2021	Monday	10:32:52	236	236	201
10/11/2021	Monday	10:32:52	236	236	202
10/11/2021	Monday	10:32:52	236	236	203
10/11/2021	Monday	10:32:52	236	236	204

10/11/2021	Monday	10:32:53	236	236	204
10/11/2021	Monday	10:32:53	235	235	204
10/11/2021	Monday	10:32:53	235	235	203
10/11/2021	Monday	10:32:53	235	235	203
10/11/2021	Monday	10:32:53	235	235	204
10/11/2021	Monday	10:32:53	235	235	203
10/11/2021	Monday	10:32:53	235	235	203
10/11/2021	Monday	10:32:53	236	236	203
10/11/2021	Monday	10:32:54	235	235	204
10/11/2021	Monday	10:32:54	236	236	204
10/11/2021	Monday	10:32:54	236	236	204
10/11/2021	Monday	10:32:54	236	236	204
10/11/2021	Monday	10:32:54	236	236	205
10/11/2021	Monday	10:32:54	236	236	204

Table 4 presents measurements obtained on 12 October 2021. The first channel recorded values between 237 and 239, with a mean of approximately 238.00. The second channel recorded values between 237 and 239, with a mean of approximately 237.97, while the third channel ranged from 230 to 231, with a mean of approximately 230.10. The overall mean of the three measurement channels was approximately 235.36. The first and second channels therefore exhibited very similar voltage magnitudes, whereas the third channel remained approximately 7.86 measurement units below the first-channel mean.

Although the difference observed in Table 4 was smaller than that recorded in Table 3, it still indicates a measurable variation between the three phase-voltage channels. If the recorded values are expressed in volts, the third-channel mean was approximately 3.3% lower than the mean of the first two channels. This suggests that the voltage differences observed in the distribution network were not necessarily restricted to a single monitoring session. However, because the observations were collected on different dates and at different times, they should not be interpreted as evidence of a continuous or persistent fault affecting the same phase. Rather, they demonstrate the usefulness of repeated measurements for examining changes in phase-voltage conditions over time.

Taken together, the results in Tables 1–4 demonstrate that the developed data logger was capable of recording variations in the three monitored voltage channels under actual distribution-network conditions. While the observations in Tables 1 and 2 show relatively close agreement between the channels, Tables 3 and 4 reveal more pronounced differences in their recorded magnitudes. These differences demonstrate the relevance of independent phase-voltage acquisition for identifying potential abnormalities that may not be apparent from measurements of only one phase. The findings are consistent with the importance of three-phase voltage monitoring highlighted by Sarkar and Sengupta (2008), Juwito *et al*. (2023) and Prasetyo *et al*. (2024).

Table 5 presents the initial cloud records, covering entries 1–29 between 3 and 5 September 2021. Entries 1–16 contain timestamps and entry identification numbers but no recorded measurement values. Subsequent entries show the appearance of individual channel values, with 240 recorded

in field 1 at entry 17, field 2 at entry 18 and field 3 at entry 19. Entries 20 and 21 contain zero values across all three fields. Similarly, entries 26 and 27 contain zero values in the three measurement fields.

The presence of blank and zero-valued entries indicates that the cloud dataset did not contain valid voltage measurements in every recorded entry. Blank fields may indicate incomplete data transmission, initialisation records or the absence of measurement values at the time of entry creation. Likewise, the zero-valued records may represent communication interruptions, unavailable measurements or actual zero readings. The available records do not establish the precise cause of these entries; therefore, they should not automatically be interpreted as actual voltage interruptions. Nevertheless, their occurrence identifies an important consideration in remote monitoring systems, namely the need to distinguish valid measurements from missing or potentially invalid records. This is particularly relevant when cloud-based measurements are subsequently used for statistical analysis or electrical-system performance assessment.

Table 4: Data recorded on 12 October 2021

Date	Day	Time	Readin	Readin	Readin
10/12/202	Tuesda	3:49:5	238	237	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	231
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	231
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	237	237	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	231
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	239	239	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230
10/12/202	Tuesda	3:49:5	238	238	230

Table 5: Data records (Entries 1–29)

Created_at (CET)	entry_id	field1	field2	field3
2021-09-03 00:35:34	1			
2021-09-03 00:55:49	2			
2021-09-03 01:01:52	3			
2021-09-03 01:07:55	4			
2021-09-03 01:13:58	5			
2021-09-03 01:29:40	6			
2021-09-03 01:35:43	7			
2021-09-03 01:41:45	8			
2021-09-03 01:47:49	9			
2021-09-03 01:53:52	10			
2021-09-03 01:59:55	11			
2021-09-03 02:05:58	12			
2021-09-03 02:12:01	13			
2021-09-04 03:39:04	14			
2021-09-04 10:07:18	15			
2021-09-04 10:15:02	16			
2021-09-04 10:15:20	17	240		
2021-09-04 10:36:51	18		240	
2021-09-04 10:37:56	19			240
2021-09-04 10:40:51	20	0	0	0
2021-09-04 10:45:19	21	0	0	0
2021-09-04 13:20:11	22			
2021-09-04 14:04:21	23			
2021-09-04 14:43:26	24			
2021-09-04 14:52:25	25			
2021-09-04 22:13:33	26	0	0	0
2021-09-04 22:17:54	27	0	0	0
2021-09-05 02:12:57	28			
2021-09-05 02:16:00	29			

Table 6 provides further evidence of the remote data-recording capability of the system through entries 130–159, covering measurements recorded on 8 and 9 September 2021. For entries 130–142, the three measurement fields contain voltage readings ranging from 214 to 235. The corresponding measurements show variations between the three channels, with values of 218, 217 and 219 recorded at entry 130, and 235, 233 and 233 recorded at entry 135. These observations demonstrate that the cloud platform received and retained measurements from the three channels rather than a single aggregated voltage value.

Entries 143–146 contain zero readings across all three fields. These records occur consecutively between 6:29:10 and 6:38:08 on 8 September 2021. Their occurrence suggests a period during which valid voltage values were not available in the transmitted records. Possible explanations include interruption of the monitored supply, temporary acquisition failure or communication-related problems. However, without corresponding local SD-card records and independent measurements, it is not

possible to determine the actual cause. The distinction between missing measurements and genuine zero-voltage conditions is important because treating invalid records as actual measurements could lead to misleading conclusions about supply reliability.

Table 6: Data records (Entries 130–159)

Created_at (CET)	Entry_id	Feld 1	Field 2	Field 3
2021-09-08 05:50:04	130	218	217	219
2021-09-08 05:53:06	131	231	229	229
2021-09-08 05:56:04	132	222	220	222
2021-09-08 05:59:04	133	216	214	216
2021-09-08 06:02:04	134	231	229	229
2021-09-08 06:05:04	135	235	233	233
2021-09-08 06:08:06	136	230	228	230
2021-09-08 06:11:10	137	226	224	226
2021-09-08 06:14:07	138	217	216	218
2021-09-08 06:17:12	139	223	221	221
2021-09-08 06:20:04	140	230	228	229
2021-09-08 06:23:05	141	228	226	226
2021-09-08 06:26:04	142	231	229	230
2021-09-08 06:29:10	143	0	0	0
2021-09-08 06:32:07	144	0	0	0
2021-09-08 06:35:04	145	0	0	0
2021-09-08 06:38:08	146	0	0	0
2021-09-09 01:02:03	147	251	250	249
2021-09-09 01:05:02	148	248	248	248
2021-09-09 01:08:02	149	246	246	244
2021-09-09 01:59:02	150	244	244	244
2021-09-09 02:02:02	151	240	239	240
2021-09-09 02:05:02	152	235	234	235
2021-09-09 02:08:04	153	235	235	234
2021-09-09 02:11:02	154	249	248	249
2021-09-09 02:29:03	155	242	241	242
2021-09-09 02:32:02	156	236	236	236
2021-09-09 02:35:02	157	251	249	249
2021-09-09 02:38:02	158	251	249	251
2021-09-09 02:41:02	159	239	238	239

The subsequent records, particularly entries 147–159, show the resumption of non-zero measurements on 9 September 2021. The recorded values ranged from 234 to 251 across the three channels. At entry 147, the channels recorded 251, 250 and 249, respectively, while entry 158 recorded 251, 249 and 251. The measurements demonstrate that the system continued to acquire and transmit varying voltage values following the sequence of zero-valued entries. The observed changes also illustrate the usefulness of cloud-based records for examining voltage behaviour at different monitoring times.

Considering the 26 non-zero records in Table 6, the calculated mean values of the three measurement fields were approximately

234.81, 233.50 and 234.15, respectively. The overall mean across the three channels was approximately 234.15. These values provide an indication of the voltage magnitudes represented in the remotely stored dataset. The relatively close agreement between the channel means suggests that the three measurement fields generally retained comparable voltage information, although individual differences were evident. The findings demonstrate the ability of the GSM-based communication subsystem to transfer multi-channel measurement records to the cloud platform for subsequent access and interpretation.

The successful availability of the records on ThingSpeak supports the practical usefulness of the selected cellular communication architecture. Unlike systems that depend exclusively on local displays or physical retrieval of stored data, the developed arrangement provides remote access to the measurement records. This feature is particularly relevant to monitoring installations located away from the operator or in facilities where continuous physical supervision may be inconvenient. The results are consistent with the objectives of IoT-based electrical monitoring systems reported by Mallala *et al*. (2025), Palacean (2024), Tse and Chan (2003) and Viciana *et al*. (2018), which demonstrate the relevance of web-based data accessibility to modern electrical monitoring applications.

3.5 Measurement Consistency and Practical Monitoring Capability

The combined observations from the local and cloud-based records provide an indication of the practical measurement and data-management capabilities of the developed instrument. The local records in Tables 1–4 demonstrate the acquisition of three-channel voltage measurements at different dates and times, while Tables 5 and 6 demonstrate the availability of measurement records through the remote ThingSpeak platform. The integration of these functions establishes the logger as a distributed measurement and recording system rather than merely a conventional voltage indicator.

The differences observed between the three measurement channels are particularly relevant to the intended application. Tables 1 and 2 show relatively consistent phase-voltage magnitudes, whereas Tables 3 and 4 reveal more pronounced differences between the channels. These observations demonstrate how independent voltage monitoring can provide information about possible phase-voltage deviations and support the identification of conditions requiring further investigation. Nevertheless, a formal assessment of voltage unbalance would require the appropriate calculation using validated phase-voltage or sequence-component measurements. The differences in the recorded channel averages should therefore be regarded as preliminary indicators rather than definitive voltage-unbalance indices.

The system's average acquisition rate of approximately eight readings per second also defines its measurement capability. This rate is suitable for recording voltage magnitudes and examining relatively sustained changes in supply conditions. However, because the developed signal-conditioning arrangement converts the AC input into a representative DC signal, the system does not retain the original voltage waveform for detailed frequency-domain or transient analysis. Consequently, the recorded measurements should not be interpreted as sufficient for comprehensive harmonic assessment or the characterisation of very short-duration power-quality disturbances. Dugan *et al*. (2021), Bollen (1999) and Bollen and Gu (2006) emphasise that such analyses require appropriate waveform acquisition and signal-processing techniques. The developed instrument is therefore more appropriately

considered a low-cost three-phase voltage-magnitude monitoring and data-logging system.

An additional observation concerns the interaction between the GSM communication module and the data-storage subsystem. The occasional interference associated with the relatively high current demand of the SIM800L module demonstrates that the performance of an integrated monitoring instrument depends not only on the accuracy of its voltage-sensing circuits but also on the stability of its supporting power supply. The addition of the 2200 μF capacitor represents a practical modification to improve the transient current support available to the GSM module. However, the observed interruptions in SD-card writing indicate that further improvements, including a dedicated GSM power supply, appropriate decoupling and improved separation of sensitive measurement and communication circuits, would be beneficial.

Overall, the experimental findings demonstrate that the developed instrument achieved its principal design objectives of acquiring three-phase voltage measurements, recording the measurements locally with time information and transmitting measurement records through cellular communication to a cloud-based platform. The combination of an Arduino Nano microcontroller, independent voltage-sensing channels, SD-card storage, a real-time clock, GSM communication and battery-supported operation provides a relatively accessible architecture for continuous voltage-magnitude monitoring. The results therefore support the practical relevance of the developed system for electrical engineering laboratories, educational institutions, small-scale industrial installations and preliminary monitoring of distribution networks where affordability, remote accessibility and historical voltage records are important considerations.

4.0 Conclusion

This study successfully designed, implemented and evaluated a low-cost three-phase voltage data logger with cellular IoT capability. The Arduino Nano-based system integrated three independent voltage-sensing channels, an SD-card storage unit, a real-time clock and a SIM800L GSM module for remote data transmission to the ThingSpeak cloud platform. Field deployment on a 415 V three-phase distribution network demonstrated its ability to acquire, timestamp and store voltage measurements locally while providing remote access to recorded data. The system achieved an average acquisition rate of approximately eight readings per second.

The recorded measurements demonstrated the logger's ability to capture variations in voltage magnitude across the three phases and identify differences that may indicate abnormal supply conditions or measurement-channel inconsistencies. The integration of local and cloud-based storage also provided complementary means of accessing and preserving measurement records. Furthermore, the addition of a 2200 μF capacitor helped address power-supply disturbances associated with the GSM module's transient current demand, highlighting the importance of adequate power management in IoT-based monitoring systems.

Overall, the developed instrument provides an affordable and practical approach to three-phase voltage-magnitude monitoring, particularly in locations where remote supervision and historical data access are desirable. Although it is not intended for detailed waveform, harmonic or transient analysis, its performance establishes a useful foundation for low-cost electrical monitoring. Future improvements should include calibration against a standard reference instrument, enhanced power-supply isolation, improved handling of

missing or invalid data and increased ampling capability to support more comprehensive power-quality assessment.

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Declarations

Ethical Approval and Consent to Participate

Not applicable

Availability of Data and Materials

Data shall be made available upon request

Competing Interests

The authors declare that they have no competing interests.

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Author Contributions

Samuel Tsaku Aluma conceptualised the study, designed and developed the voltage data logger, performed the experiments, analysed the results and prepared the initial manuscript. Kassam H. Danjuma contributed to the system design, technical implementation, testing and evaluation of the developed prototype. Wutokkwatda Bayura contributed to technical review, interpretation of the experimental results and manuscript revision. All authors read and approved the final manuscript.