University of Zawia Journal of Engineering Sciences and Technology (UZJEST)
Volume 4, Issue 1, (2026), pp 13-23, ISSN 3006-2764

Design and Implementation of Arduino-Based Measurement Devices for Smart Grid Applications

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Received: 10-03-2026 | Accepted: 14-05-2026 | Available online: 18-05-2026 | DOI:10.26629/uzjest.2026.02

ABSTRACT

Smart grids require accurate measurement infrastructures to support real-time monitoring, load management, and efficient power system operation. Electrical parameters such as voltage, current, frequency, power factor, and active and reactive power must be continuously measured for effective grid monitoring. This paper presents the design and implementation of a low-cost Arduino-based measurement system for smart grid applications, emphasising measurement accuracy and practical deployment. Closed-loop Hall-effect voltage and current sensors are employed to improve measurement precision and provide galvanic isolation. Signal-conditioning circuits, including level shifting and voltage regulation, adapt sensor outputs to the Arduino input. A DC calibration method is applied to voltage and current sensors to enhance accuracy and reliability. The system is experimentally validated under laboratory conditions using inductive loads, and the results are compared with reference instruments. The experimental results demonstrate acceptable accuracy across the measured parameters, confirming the suitability of the proposed system for low-cost smart grid monitoring and load management applications.

Keywords: smart grid, Arduino controller, voltage sensor, current sensor, accuracy.

تصميم وتنفيذ أجهزة القياس المعتمدة على المتحكم أردوينو في تطبيقات الشبكات الكهربائية الذكية

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ملخص البحث

تتطلب الشبكات الذكية بنى قياس دقيقة لدعم المراقبة اللحظية، وإدارة الأحمال، والتشغيل الكفؤ لأنظمة القدرة الكهربائية. يستلزم ذلك القياس المستمر لمعاملات كهربائية أساسية تشمل الجهد، والتيار، والتردد، ومعامل القدرة، والقدرة الفعالة وغير الفعالة. تقدم هذه الورقة تصميم وتنفيذ نظام قياس منخفض التكلفة قائم على منصة أردوينو لتطبيقات الشبكات الذكية، مع التركيز على دقة القياس وقابلية التطبيق العملي. تم استخدام حساسات الجهد والتيار المعتمدة على تأثير هول ذات الحلقة المغلقة لتحسين دقة القياس وتوفير العزل الكهربائي. كما تم تصميم دوائر تكييف الإشارة، بما في ذلك إزاحة المستوى وتنظيم الجهد، لملاءمة مخرجات الحساسات مع مداخل المتحكم. تم تطبيق منهجية معايرة بالتيار المستمر على حساسات

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الجهد والتيار بهدف تحسين الدقة والموثوقية. جرى التحقق من أداء النظام تجريبياً في المعمل باستخدام أحمال حثية، مع مقارنة النتائج بأجهزة قياس مرجعية. أظهرت النتائج دقة مقبولة في المعاملات المقاسة، مما يؤكد ملاءمة النظام المقترح لتطبيقات المراقبة منخفضة التكلفة وإدارة الأحمال في الشبكات الذكية.

الكلمات الدالة: شبكة ذكية، متحكم دقيق، حساس جهد، حساس تيار، الدقة.

1. Introduction

A smart grid represents the modernisation of traditional electrical power systems by integrating advanced communication, sensing, and control technologies. One of the fundamental components of a smart grid is the measurement infrastructure, which enables real-time monitoring of electrical parameters and system conditions. The measurement devices can record real-time active power consumption, voltage, phase current, reactive power, maximum power consumption, energy, frequency, and power factor [1-4].

Traditional measurement devices such as Phasor Measurement Units (PMUs) and Digital Fault Recorders (DFRs) offer high accuracy [5]. However, their high installation and hardware costs often limit widespread deployment and large-scale adoption [6, 7]. As a result, low-cost and flexible alternatives have gained increasing attention. Arduino-based platforms provide an open-source, programmable, and affordable solution for developing distributed measurement devices suitable for smart grid applications [8-10]. These devices can be integrated into smart grid nodes to monitor grid health, enable demand response strategies, and detect abnormal conditions [9, 11].

Despite significant progress in Arduino-based measurement systems, several challenges still face these devices in fully replacing industrial standards. Ensuring measurement accuracy and maintaining calibration remain key concerns, particularly in applications requiring long-term stability, high precision, and robustness to environmental variations. These constraints drive the adoption of closed-loop sensing architectures and calibration approaches to improve measurement reliability. This paper focuses on the implementation of closed-loop current and voltage sensors that employ feedback systems to continuously adjust and correct their outputs, thereby improving measurement accuracy and stability. In addition, adopting a robust sensor calibration methodology directly supports the research objective of enhancing overall system performance.

2. Research System Design

The proposed system involves designing sensing and signal-conditioning units alongside programming Arduino-based controllers to accurately determine key electrical parameters, such as current and voltage RMS values, frequency, phase shift, and power factor for smart grid monitoring and load management.

2.1 Hardware Design

The hardware design of the proposed measurement system focuses on developing reliable sensing and signal-conditioning circuits for acquiring electrical parameters in smart grid applications. The hardware consists of voltage and current transducers, level-conditioning circuits, voltage regulation units, and phase-shift detection circuits. These components work together to ensure safe signal acquisition, electrical isolation, and compatibility with the Arduino microcontroller for accurate parameter measurement.

2.1.1 Current Transducer

The current transducer used is the LEM LA25-P Hall-effect sensor, connected as shown in Figure 1. The LA25-P provides galvanic isolation between the power circuit and the measurement platform, enhancing both noise immunity and operational safety. Furthermore, the LA25-P is a closed-loop (compensated) Hall-effect current sensor. In this type of sensor, a compensation current is generated by an internal amplifier to counteract the magnetic field produced by the primary current, resulting in improved measurement accuracy compared to open-loop sensors [12].

The current measured on the primary side generates a proportional secondary current in the current transducer with a conversion ratio of 1:1000. This secondary current flows through the measurement resistor R_M, producing a corresponding voltage. The maximum allowable voltage across R_M is ±5V; voltages exceeding this range will saturate the input of the Arduino's analogue-to-digital converter ADC.

Due to the fact that $i_p=1000\times i_M$, so the value of the measurement resistor R_M can be determined by Equation 1.

$$u_M = i_M \times R_M < 5V \tag{1}$$

$$R_M < \frac{5V}{i_{M(\max)}} = \frac{5V}{10mA} = 500\Omega \tag{2}$$

In this work, a 260Ω resistor is used for the measurement resistor R_M due to the hardware availability in the laboratory.

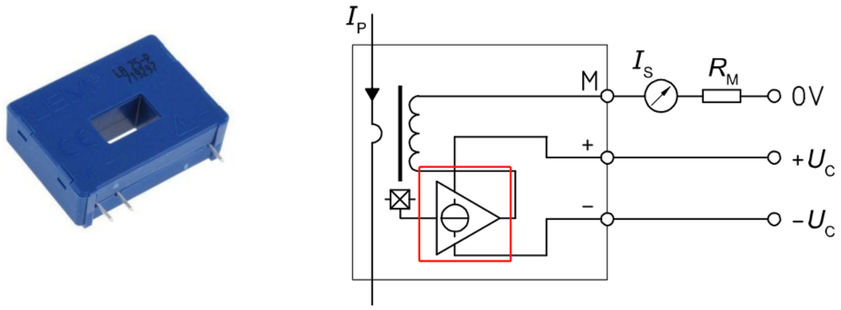

Figure 1. Current sensor measurement circuit [12].

2.1.2 Voltage Transducer

The LV25-P voltage transducer, manufactured by LEM, is a Hall-effect–based sensor that provides galvanic isolation between the power circuit and the measurement platform. Although it is designed to measure voltage, the LV25-P operates internally according to the closed-loop (compensated) current transducer principle. The input voltage is first converted into a proportional primary current through an external resistor. This current generates magnetic flux in the core, which is detected by a Hall element. A compensation current is then driven through a secondary winding to cancel the magnetic flux (zero-flux operation). As a result, the output signal is proportional to the input voltage, with improved accuracy compared to open-loop sensors [13].

The LV25-P voltage transducer schematic circuit is shown in Figure 2, which operates by converting the input voltage into a primary current i_p , through an external resistor. The secondary current i_M is proportional to the primary current (i_M=2.5×i_p). Proper selection of the external resistor ensures that i_p remains within the recommended range of ±14 mA, guaranteeing accurate and safe operation.

Therefore, the external resistor R_1 can be determined by Equation 3, ensuring that the primary current i_p remains within the allowable range.

$$R_1 > \frac{1.2\times u_{p(\max)}}{14mA} = \frac{1.2\times 220\times\sqrt{2}}{14mA} = 26.7k\Omega \tag{3}$$

Where u_p(max) is the maximum possible value of u_p. A 20% safety margin is applied to the estimated maximum voltage of $220 \times \sqrt{2} = 311$V. In this work, a 25kΩ resistor is used for R_1, which is the available value of power resistors in the laboratory.

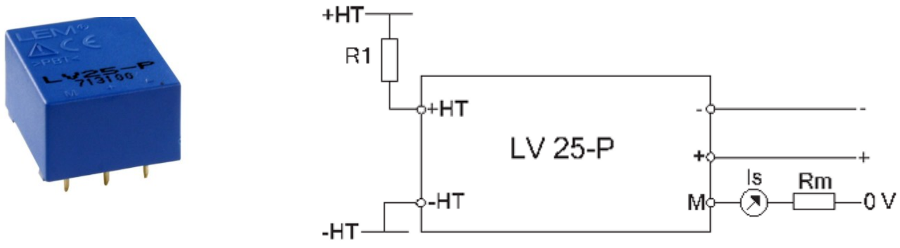

Figure 2. Voltage sensor measurement circuit [13].

The value of the measuring resistor R_M is selected based on the allowable range of u_M. The maximum voltage range that can be measured across the measuring resistor is ±5V; applying a voltage higher than this limit will saturate the Arduino's *ADC* input. Since $i_M = 2.5 \times i_p$, the value of the measuring resistor can be calculated using Equation 4.

$$i_{M((max)} \times R_1 = 2.5 \times \frac{1.2 \times u_{p(\max)}}{R_1} R_M < 5V \tag{4}$$

$$R_M < 334.9\Omega$$

In this work, a 100Ω resistor is used for R_M, as it is the available resistor in the laboratory and satisfies the measurement requirements.

2.1.3 Level Conditioning Circuit

The Arduino microcontroller can only handle positive voltages, so negative sinusoidal signals from voltage and current sensors must be conditioned using an op-amp–based voltage conditioning circuit, as shown in Figure 3. Voltage conditioning circuits shift sensor signals into the 0–5 V range of a microcontroller by adding a 2.5 V DC offset, allowing sinusoidal signals with negative values to be safely processed using an op-amp [14].

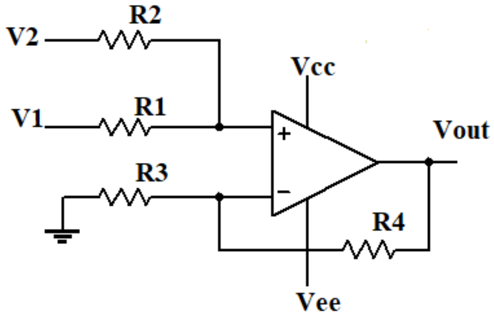

Figure 3. Voltage conditioning circuit [14]

To avoid signal amplification and maintain unity gain, all resistors must have equal values ($R_1=R_2=R_3=R_4=10k\Omega$). A voltage regulator is used to supply a 2.5 V offset required for proper signal conditioning.

2.1.4 Voltage Regulator

Voltage regulators are crucial for maintaining stable voltage levels in sensor and microcontroller systems. The LM317T, shown in Figure 4, provides an adjustable positive voltage controlled by a resistor ratio and used to ensure reliable and safe operation of the level conditioning circuit [15].

The output voltage is controlled by the ratio of resistors R_1 and R_2, which is:

$$V_{out} = 1.25(1 + \frac{R_2}{R_1}) \tag{5}$$

By considering $R_1=R_2=10k\Omega$, the voltage regulator can handle 2.5V to the level conditioning circuit.

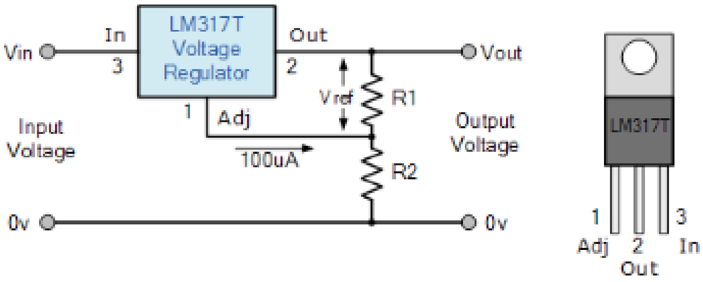

Figure 4. LM317T Voltage regulator circuit [15]

2.1.5 Phase Shift Measurement Circuit

The circuit shown in Figure 5 measures the phase difference between voltage and current, typically caused by inductive loads. Sinusoidal signals are converted into square waves using an op-amp comparator, and the phase difference is obtained through a subtraction circuit, enabling power factor calculation. The resistor values are equal ($R_1=R_2=R_3=R_4=1$ $k\Omega$) to ensure that the signal is not amplified [14].

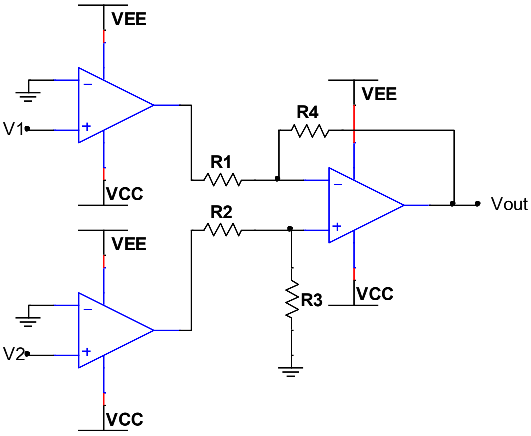

Figure 5. Phase Shift Measurement Circuit [14]

2.2 Software Design

The software design complements the hardware implementation by processing the acquired signals and calculating the required electrical parameters. The Arduino microcontroller is programmed to perform signal sampling, parameter extraction, and real-time computation of RMS voltage, RMS current, frequency, phase shift, and power factor. This software framework ensures efficient integration between sensing hardware and measurement algorithms.

2.2.1 Determination of Electrical Parameters

The determination of electrical parameters is essential for monitoring and evaluating the operating conditions of smart grid systems. In this work, the measured sensor signals are processed using mathematical relationships implemented in the Arduino program to derive voltage, current, frequency, phase shift, and power factor. These parameters provide the basis for calculating active and reactive power and assessing load behaviour.

RMS Voltage and Current Measurement

Analogue voltage and current signals are supplied to Arduino input pins A0 and A1. These signals are converted into digital samples using the Arduino's built-in ADC. The ADC operates with a 10-bit resolution, allowing it to represent 1,024 (2^{10}) discrete analogue levels, corresponding to a maximum input voltage of 5V [16].
The ADC reading value:

$$ADC_{reading} = \frac{1023}{5} \times measured\ analog\ voltage \tag{6}$$

A calibration process was conducted to achieve accurate measurements by establishing the relationship between the actual voltage and current waveforms and the readings from the Arduino's ADC.

RMS values of voltage and current are calculated using Equation 7 [16].

$$f(n) = \sqrt{\frac{1}{n}\left(\sum_{i=0}^{n} x_i^2\right)} \tag{7}$$

where n is the number of samples.

Frequency Measurement

An Arduino-based digital frequency counter is designed to measure the frequency of an input signal via the digital pin D_2. The **pulseIn** function is used to determine the duration of the high and low pulses of the input signal, and their sum is used to calculate the signal's period. The frequency is then calculated by Equation 8.

$$F(Hz) = \frac{1{,}000{,}000}{pulseHigh\ duration + pulseLow\ duration} \tag{8}$$

Phase Shift and Power Factor Measurement

The pulse width generated by the designed phase-shift circuit is measured via the digital pin D_2 using the **pulseIn** function. The pulse duration is then converted into a phase using Equation 9:

$$Phase\ Angle(\varphi(Degree)) = \frac{Pulse\ Duration\ (seconds)}{Period} \times 360 \tag{9}$$

The power factor is calculated by taking the value of cos φ.

2.2.2 Measurement Program Flowchart

The Arduino microcontroller was programmed to determine the RMS values of current and voltage, as well as the frequency, phase shift, and power factor, and to retrieve these parameters through pins A0, A1, and D2. The program flowchart used in this work for electrical parameters measurement is shown in Figure 6.

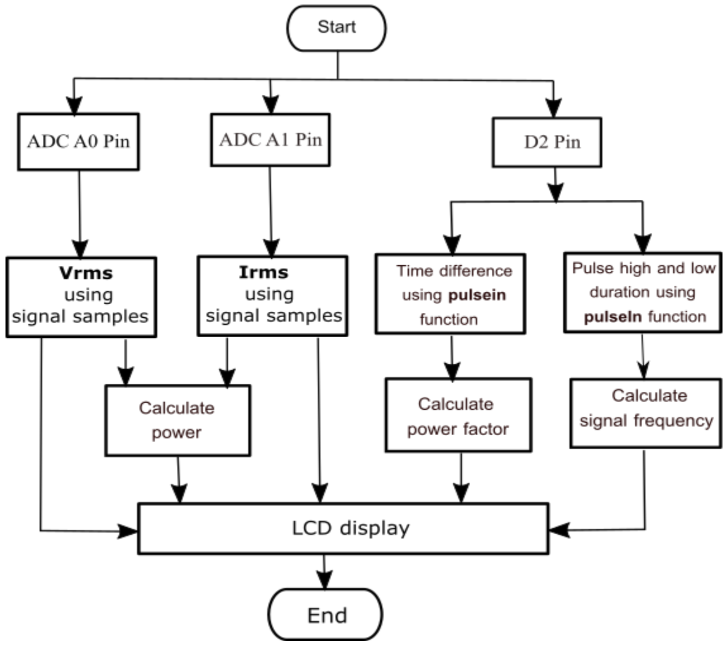

Figure 6. Measurement program flowchart

3. Experimental Setup

The experimental setup was developed to validate the performance of the proposed Arduino-based measurement system under practical laboratory conditions. It includes the implementation of sensing circuits, signal-conditioning stages, and the Arduino controller connected to inductive loads. The setup enables the evaluation of measurement accuracy by comparing the obtained results with standard reference instruments.

3.1 Hardware and System Implementation

The proposed measurement system was designed and implemented to measure the electrical quantities required for monitoring and managing loads in smart electrical grids. These quantities include voltage, current, frequency, power factor, as well as active and reactive power. The system was designed based on a supply voltage 220V,50Hz AC connected to a load of (Z=387.16+j399.4 Ω), which reflects the inductive nature of electrical grid loads. The voltage and current sensor circuits, Arduino microcontroller, and conditioning circuits were tested and successfully implemented in the laboratory. The Arduino is loaded and configured with the measurement code, which was tested and verified in IDE 1.8.1 version. The experimental setup used in this work is shown in Figure 7.

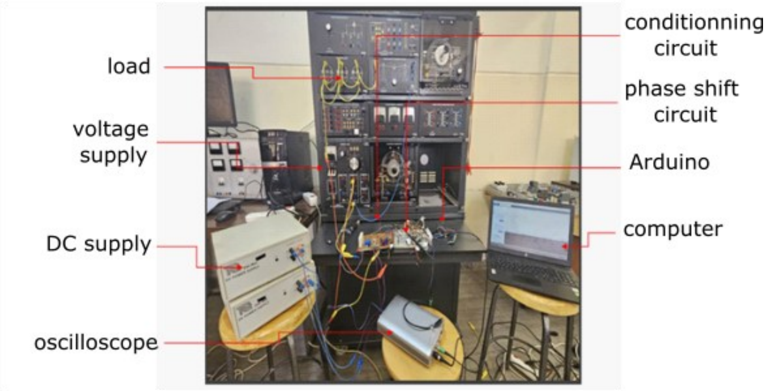

Figure 7. Experimental setup of the proposed Arduino-based measurement system

Figure 8 illustrates the implemented circuit designs for the current and voltage sensors, level-shifting, and voltage regulation, whereas Figure 9 presents the laboratory implementation of the phase shift and power factor circuit.

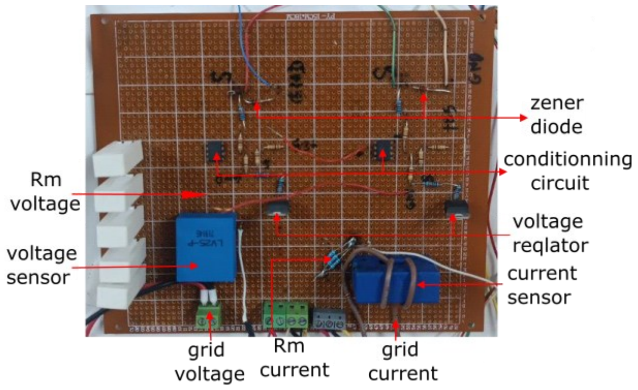

Figure 8. Implementation of sensor and conditioning circuits

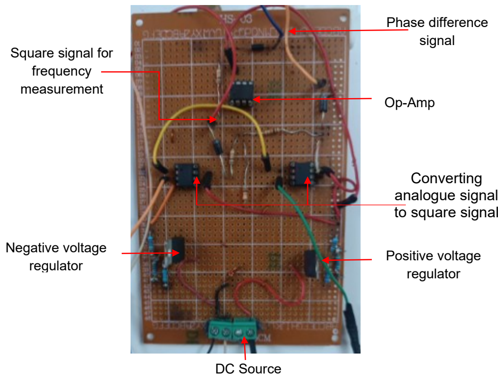

Figure 9. Implementation of the phase shift and power factor circuit

3.2 Results and Discussion

Figure 10 shows the output voltage waveform of the conditioning circuit, which was designed to offset the sensors' output signals by 2.5V, so that they fall within the suitable voltage range of the microcontroller inputs. These signals are fed to Arduino analogue input pins A0 and A1 to calculate the RMS value of voltage and current waveforms.

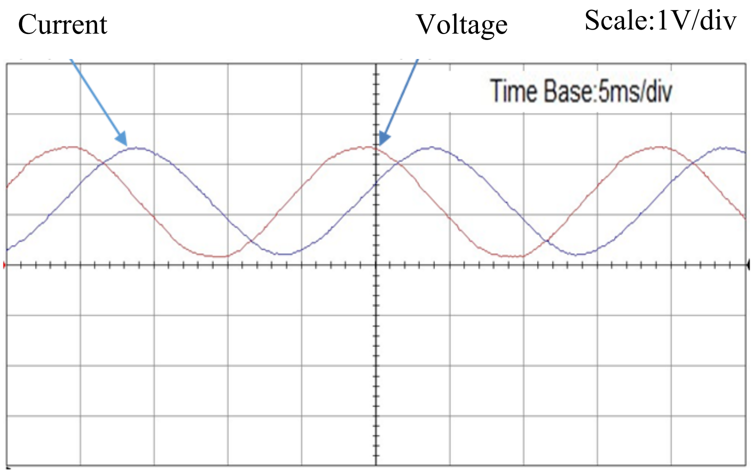

Figure 10. Waveforms of current and voltage sensor circuits after the conditioning circuit

The output signal of the phase shift circuit shown in Figure 11 is fed into a digital pin of the Arduino. This digital pin detects the time duration between zero crossing points of voltage and current signal waveforms using the **pulseIn** function, which is then used for the power factor measurements. The measured time difference between the two signals is 2.66ms, corresponding to a power factor of 0.79.

The DC calibration method is adapted in this paper by applying a set of DC voltages to the voltage sensor and determining the coefficients of the polynomials of the first order. The same technique is also applied to the current sensor, where the DC is applied to the current sensor.

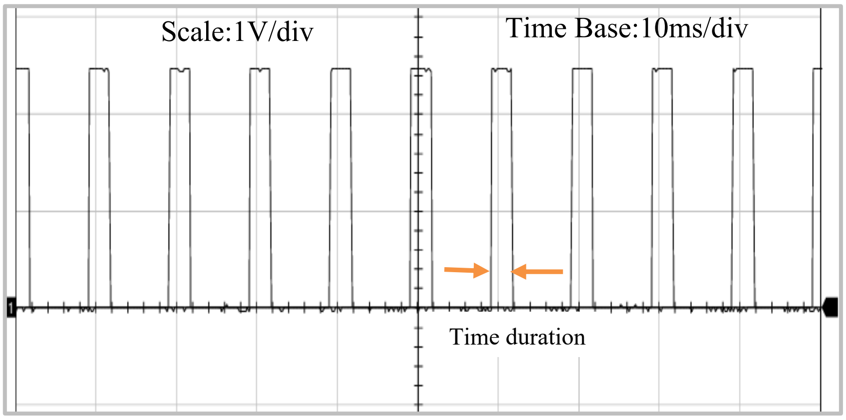

Figure 11. Output of the phase-shift measurement circuit

For the voltage sensor circuit, voltages between –320 V and +320V were applied with the voltage supply for a total of 33 different test voltages as shown in Figure 12. This process was also performed for the current sensor circuit within the -0.602A to +0.602A range, which accounts for 13 different test currents as shown in Figure 13.

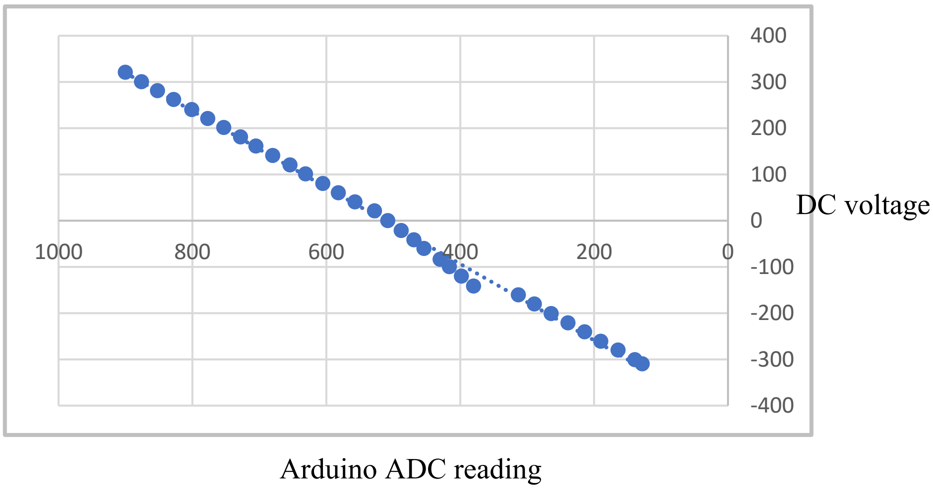

Figure 12. Calibration of the voltage sensor

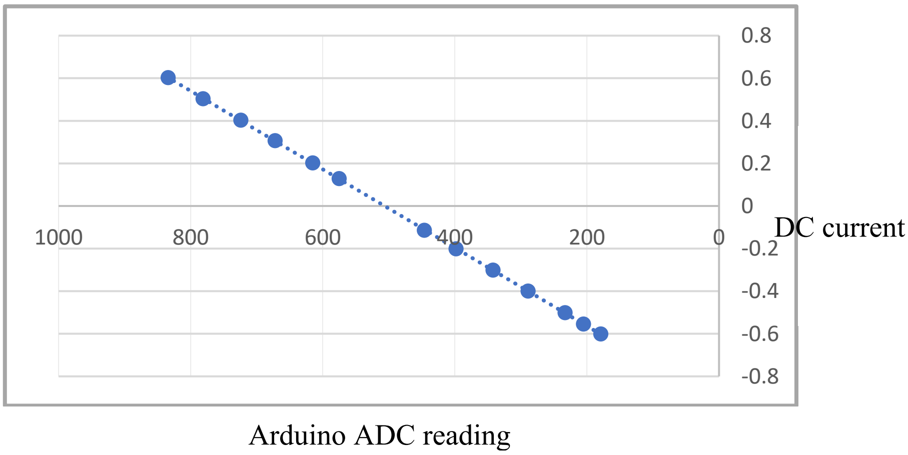

Figure 13. Calibration of the current sensor

The calibration equations 10 and 11 were integrated into the Arduino code to improve measurement accuracy.

$$V_{DC} = 0.8265 \times ADC_{reading} - 424.13 \quad (10)$$

$$I_{DC} = 0.0018 \times ADC_{reading} - 0.932 \quad (11)$$

The measured values obtained using the designed system were compared with the reference values acquired from the laboratory's available equipment, specifically the LVDAC computer-based data acquisition and measurement system from LabVolt/Festo. The results presented in Table1 include the reference values, the measured values, and the corresponding deviations, demonstrating that the designed system provides accurate measurements of voltage, current, power factor, and frequency. However, the average power measurement exhibits a higher error due to the cumulative errors in voltage, current and power factor measurements.

Table 1. Accuracy of the measured electrical parameters

Electrical quantity	**Measured value**	**Reference value**	**Error %**
Voltage (V)	227.15	229.2	0.9
Current (A)	0.4	0.4	0.0
Power factor	0.67	0.69	2.9
Active power (W)	60.8	64.6	5.86
Reactive power (VAR)	67.4	67.8	0.59
Frequency (Hz)	50.45	50.06	0.78

4. Conclusions

This paper presented the design and experimental validation of a low-cost Arduino-based measurement system intended for smart grid monitoring and load management applications. The proposed system integrates closed-loop Hall-effect voltage and current sensors with dedicated signal-conditioning circuits to ensure accurate and reliable acquisition of electrical parameters. Level-shifting and voltage regulation circuits were implemented to adapt sensor outputs to the input range of the Arduino.

A DC calibration methodology was applied to both voltage and current sensing stages to enhance measurement accuracy and reliability. The system was evaluated under laboratory conditions using inductive loads, and the measured parameters were compared with reference measurement instruments. The experimental results demonstrated acceptable accuracy across all evaluated parameters, validating the effectiveness of the proposed design.

Although the developed system does not aim to replace industrial-grade measurement equipment, it offers a cost-effective and flexible solution suitable for research, educational purposes, and small-scale smart grid deployments. Future work will focus on integrating the system into smart grid monitoring and control platforms and extending it with communication interfaces for real-time data transmission.

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