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A Low-cost Optocoupler-Based Isolator System for IoT-Based Voltage Measurement in Low and High voltage DC Applications

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Abstract

Internet of things (IoT) connected devices operate at extremely low voltages that are susceptible to common-mode noise and electromagnetic interference. As a result of this, integrating IoT devices with low or high-voltage direct current power sources requires galvanic isolation which is often expensive to attain. In this work, the use of a low-cost conventional optocoupler (4N35) in the galvanic isolation of an IoT voltmeter required to measure the potential difference of a low voltage direct current source with a maximum relative error of 1% was investigated and experimentally verified. The proposed isolator circuit was first simulated using NI Multism and then fabricated on a printed circuit board for experimental verification after satisfactory simulation results. Measurement results from the experimental verification process were used to fit quadratic and cubic regression equations that approximate the input signal voltage from the isolator's output voltage measured by the IoT voltmeter. Lastly, the isolator and IoT voltmeter were connected to a variable 100-1000 VDC source via a potential divider network for performance verification at a voltage step of 100 VDC. Here, the isolator successfully achieved its primary goal of providing galvanic isolation between the voltage source and the IoT voltmeter while maintaining a maximum relative error of 1%.

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1. Background

Direct current (DC) sources are voltage sources whose polarity does not reverse at any point in time. DC voltage sources are classified by the International Electrotechnical Commission (IEC) into three different categories which

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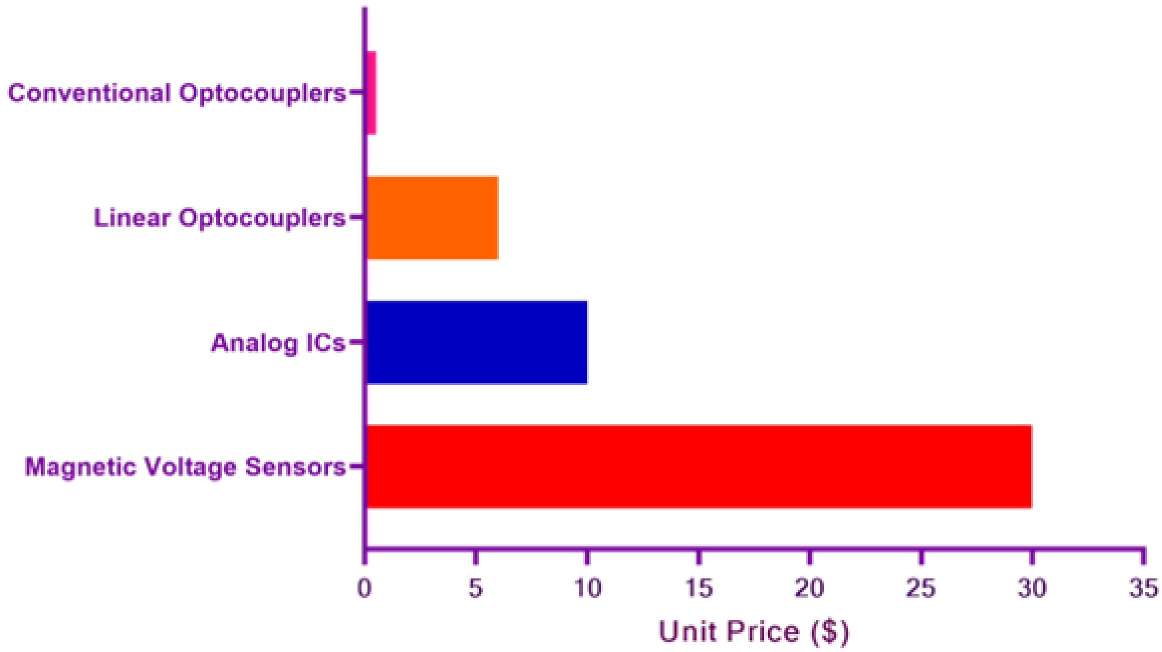

Figure 1. Price comparison between commonly used HVDC galvanic isolation systems and conventional optocouplers

are: Extra-low voltage DC represents DC voltage values below 120 volts, Low voltage DC (LVDC) represents DC voltage values between 120 volts and 1500 while High voltage DC (HVDC) represents DC voltage values greater than 1500 volts [1]. Voltage measurement and monitoring in Extra low voltage DC systems are cheap and relatively easy as the management of common-mode noise and ground loops are easily achieved. On the other hand, managing common mode noise resulting from ground loops in Low and High voltage DC source and measurement circuits is a tedious task, which is further complicated by the risk of electrocution and arcing [2]. To this end, safe and precise voltage measurement and monitoring in LVDC and HVDC systems require voltage division, which attenuates the high voltage, and galvanic isolation, which completely separates the high and extra-low voltage references. Figure 1 shows the cost comparison of galvanically isolating LVDC and HVDC systems from extra-low voltage measurement systems using existing isolation methods and the conventional optocoupler approach proposed in this study.

Precise and time-bound voltage measurements and monitoring LVDC and HVDC is often required in applications such as renewable energy power transmission, power supply monitoring for isolated water systems in rural areas, battery management systems, power usage metering, and data logging in controlled test and experiment setups [3-6]. As these applications are often remotely configured to facilitate risk management, they are expensive to monitor and maintain in real-time.

Although the Internet of Things (IoT) has brought about the cheap connectedness of physical systems and devices to the internet and each other in real-time and has enhanced remote monitoring and control owning to the robust communication protocols it employs [7], one of its greatest advantages, which is the capability to remotely detect and rectify anomalous operations in the automated control of physical devices [8] cannot be directly leveraged in LVDC and HVDC applications. This is because IoT devices are extra low-voltage devices that operate within strict voltage levels and exceeding these voltage levels even for a short time can damage them or interfere with the integrity of their data transmission process [7].

While this drawback can be remedied using isolation systems that can eliminate direct voltage referencing (galvanic isolation) between an IoT device and LVDC or HVDC sources, the associated cost of deploying existing galvanic isolation systems on a large scale quickly overshadows the cheap connectedness attainable with IoT devices. To this end, this study aims to investigate and experimentally verify the use of a low-cost conventional optocoupler in the galvanic isolation of an IoT voltmeter required to measure the potential difference of an LVDC voltage source with a maximum relative error of 1%.

The remainder of this paper is organized as follows; section 2 explores the existing methods of measuring LVDC and HVDC with galvanic isolation, section 3 defines the methodology and materials employed in the simulation and experimental verification processes, section 4 presents and discusses the simulated and experimental results and section 5 concludes the study.

2. Literature review

The major methods of measuring LVDC and HVDC voltage levels with galvanic isolation include the use of magnetic voltage sensors, analog isolation ICs (isolation operation amplifiers and isolated analog to digital converters), and optocouplers (both linear and conventional). Relevant literature on each of these isolation devices is reviewed in this section.

2.1. Magnetic voltage sensors

Hall effect sensors, fluxgate sensors, and giant magneto-resistive sensors which operate by intensifying the magnetic response of an induced current are the commonly used magnetic sensors for DC voltage measurements in literature [9-11]. In these sensors, the voltage signal to be measured is first converted to a current signal using a preresistor and then passed through a magnetic flux concentrator. The intensity of the magnetic induction is then measured and used to derive the voltage value using the Biot-Savart Law [12].

As magnetic voltage sensors are modified magnetic current sensors, the linearity of their measurement depends on current and requires a constant current to operate reliably. To this end, magnetic voltage sensors used in high-voltage DC measurements often require high-wattage preresistors and can consume as high as 20 watts [9]. Also, their current transfer ratio is susceptible to electromagnetic interference and they must be a shield to operate properly, further increasing deployment costs [10, 11].

2.2. Analog Isolator ICs

Solid-state isolator chips utilize solid-state semiconductor technologies in isolating high and low-voltage systems from extra low-voltage systems. These chips are often standard isolation amplifiers and analog to digital converters and are available as off-the-shelf products that can be purchased from chip manufacturers. Common examples are the AMC1001 fully differential isolation amplifier [13] and isolated sigma-delta ADCs such as AD7403-EP [14]. However, Wang et al. [15] in their study utilized an AD978 in isolating their voltage measurement system from the HVDC source. While the AD978 does not provide full galvanic isolation between the two systems, it utilizes different voltage sources for operating analog and digital signals and completely converts the analog input to its digital equivalent before transmitting it to the low-voltage measurement system, thus, offering some levels of common mode rejection.

Apart from providing better immunity from common mode noise and electromagnetic interference, analog isolator ICs also consume less power when compared to magnetic voltage sensors and are therefore better alternatives in high voltage low current applications. Nevertheless, analog isolator ICs are expensive and typically cost between 10 – 80$ per unit. Thus, they are often used in applications where their consequent cost implications are justified.

2.3. Optocoupler-based isolators

Solid-state light emitting diodes are current-controlled semiconductor devices that emit light when electrical current flow across its junction [16]. The relative intensity of the emitted light can then be detected with a solid-state light detection device which develops a photocurrent proportional to the amount of irradiation [17]. This method of current transfer provides galvanic isolation between the LED and the light detection device. The current transfer ratio (CTR) is however not linear in all regions as the current/ power characteristic of LEDs does not progress linearly [18]. As a result, optocouplers used in practical applications in which CTR linearity is crucial are implemented in a closed-loop approach with a second photodetection device providing feedback control [19, 20]. Conventional optocouplers however consist of a single Infrared LED and IR detection device and do not integrate any form of feedback control and are therefore characterized with LED and photocurrent dependent on temperature and LED forward voltage stability.

Due to CTR linearity, linear optocouplers are the most used type of optocouplers for galvanic voltage measurement. Nevertheless, some researchers have also employed the use of conventional optocouplers for the galvanic voltage measurement process in their LV or HV DC applications. Zihui & Zhihao [21] in their study used two ordinary optocouplers to achieve a linear input/ output voltage response between two isolated voltage sources. In this application, one optocoupler served as the isolation device while the other provided current feedback typically replicating at a reduced cost the closed-loop approach used in linear optocouplers. Garcia-Orellana et al. [3] in their application used ordinary optocouplers to measure the voltage levels of a solar panel and a DC motor. In other to account for the non-linearity of the optocouplers, they used only the linear region of the optocoupler transfer curve and used a look-up table of values for voltage conversion. Singh et al. [22] first converted the high voltage values into a frequency-modulated signal using a voltage-to-frequency converter and then used ordinary optocouplers to perform frequency measurements of the voltage values.

Although they possess a reliable CTR response, the associated cost of implementing galvanic isolation using linear optocoupler is still disparate when compared to the cost implication of using conventional optocouplers. Likewise, existing methodologies that have implemented conventional optocouplers in galvanic voltage measurement make use of complicated methodologies that take up considerable circuit board space or are difficult to reproduce, thus justifying this study.

2.4. IoT in Low and High Voltage measurement

The application of the internet of things to remotely monitor voltage levels in LV and HV systems has mostly been carried out in the field of electrical power consumption metering. This application directly involves measuring AC voltages and mostly employ cheap AC voltage transformers modules such as ZMPT101B which convert the mains voltage to be monitored to extra-low DC voltage measurable using IoT devices [23]. In LV and HV DC measurements, however, the associated cost of galvanic isolation has prevented the widespread adoption of the cheap connectedness provided by IoT. Transmission of measurement information and control of the measuring device in IoT applications can occur via standardized communication methods such as Bluetooth [24], WIFI, and GSM transmission [3]. In recent times, Cloud-based transmission is being favored for long-range timely information transmission in IoT compared to the use of GSM and GPRS signals [7]. This can be attributed to the versatility of modern communication technologies such as LTE, 5G, and 6G.

This study aims to develop a low-cost and easily reproducible conventional optocoupler-based isolation system that galvanically isolates an LVDC IoT voltmeter with a maximum relative error of 1%. It achieves this by exploiting the fairly linear characteristic between the forward current (I_f) in the 1 to 10 mA range and the collector-emitter current (I_{CE}) of a conventional optocoupler to produce an output voltage linearly proportional to an applied input voltage within a defined range. This setup minimizes the number of circuit elements in the isolation system and conditions the input signal to output voltage values that completely utilize the operating range of the IoT device's analog-to-digital converter (ADC).

3. Material and methods

The 4N35 Optocoupler with Phototransistor Output was the conventional optocoupler of choice in this study. As this optocoupler is designed specifically for logic switching applications, suitable basic operating parameters of the optocoupler were first carried out using its datasheet. These operating parameters were used to develop a proposed circuit for simulation analysis. After a satisfactory simulation operating point, the proposed circuit was experimentally verified in a low-voltage DC operating environment.

3.1. Isolator operating parameters

The operating parameters of the isolator system were selected using the information obtained from the 4N35 primary optocoupler datasheet [25]. From the datasheet graph of Collector-Emitter Current vs. Temperature and forward current, it is observed that the collect-emitter current produced a fairly linear response to the forward current in the 0 – 5 mA region at almost all temperature values [25]. To leverage this electrical characteristic, an operational amplifier-based LED driver was integrated into the isolator system to maintain the quiescent operating points and prevent the forward current from overshooting the 5 mA stability point. This fixed the maximum input signal voltage into the amplifier at 2.5 V. The quiescent forward LED voltage and current were set to 1.3 V and >1 mA respectively to remove errors associated with zero-based measurement, a. As the circuit is intended to be used directly with the inbuilt ADC of an IoT device, the isolator system was configured to produce output voltages in the 0.1 – 4.9 V range which utilizes the full ADC operating range. The input side of the isolator was powered by 12 volts while the output side is powered by the IoT device.

3.2. Isolator circuit design

The isolator system is composed of two major circuits which are, the IR LED driver circuit and the output amplifier. The operation and design process of each circuit system is explained in this section.

3.2.1. IR LED driver circuit

The driver circuit was designed to ensure that the quiescent operating current of the isolator remained at a current value > 1 mA at its minimum input signal voltage level. This was achieved by biasing the ground reference of the input signal to a constant value of 1.3 volts using a potential divider before feeding it to a non-inverting amplifier serving as the LED driver. A current setting resistor of 1 kΩ provided a LED forward current I_f given as

$$I_f = V_{in}/1000 \tag{1}$$

where V_{in} is the input signal voltage and it varies between 1.3 and 4 volts.

During simulation, the driver circuit pegged the quiescent current of the IR LED at 1.3 mA and ensured that the maximum I_f of the LED did not exceed the 5-mA operating point. A low-cost LM358 operational amplifier was used as the driving amplifier in this circuit.

3.2.2. Output Amplifier Circuit

The primary function of the amplifier circuit is to condition the collector-emitter current I_{CE} of the optocoupler and the emitter voltage V_E to output voltage values that fully utilize the input range of the IoT device ADC. To prevent the optocoupler from saturating at the chosen V_{CC} of 5 V, the maximum emitter output voltage of the phototransistor V_{Emax} was chosen as 4 V. During simulation, the maximum I_{CE} observed was 8 mA. Thus, the emitter resistor was calculated Using an emitter resistor of

$$Re = \frac{V_{Emax}}{I_C} = 500\ \Omega \tag{2}$$

The isolator system's output voltage was conditioned using a non-inverting amplifier with a linear transfer function. The relationship between the amplifier input, gain, and feedback resistors were computed from the slope (m) and intercept (b) of the linear transfer function [26]. By selecting a gain setting resistor R7 much larger than the parallel equivalent of the input resistors R4 and R9 and setting V_{CC} as the reference voltage, the resistor-transfer function equation is reduced to;

$$R7 = (m-1)\ R6 \tag{3}$$

$$R4 = \left((5 \times \frac{m-1}{b}) - 1\right) R9 \tag{4}$$

During simulation, the isolator output voltage was between 0.7 and 3.6 V. With respect to the desired final output range of 0.1 to 4.9 V, the slope and intercept of the linear amplifier were m = 1.75 and b = 1.23. Choosing R6 = 40 kΩ and R4 = 1 kΩ, R7 was given as 30 kΩ while R9 was calculated to be 485.4 Ω and was achieved using a 1 kΩ potentiometer. To allow the output voltage of the non-inverting amplifier to swing between the final output range of the isolator circuit without saturation, a single supply rail-to-rail operational amplifier (TLV2461) was used. The circuit diagram of the proposed circuit is shown in Figure 2.

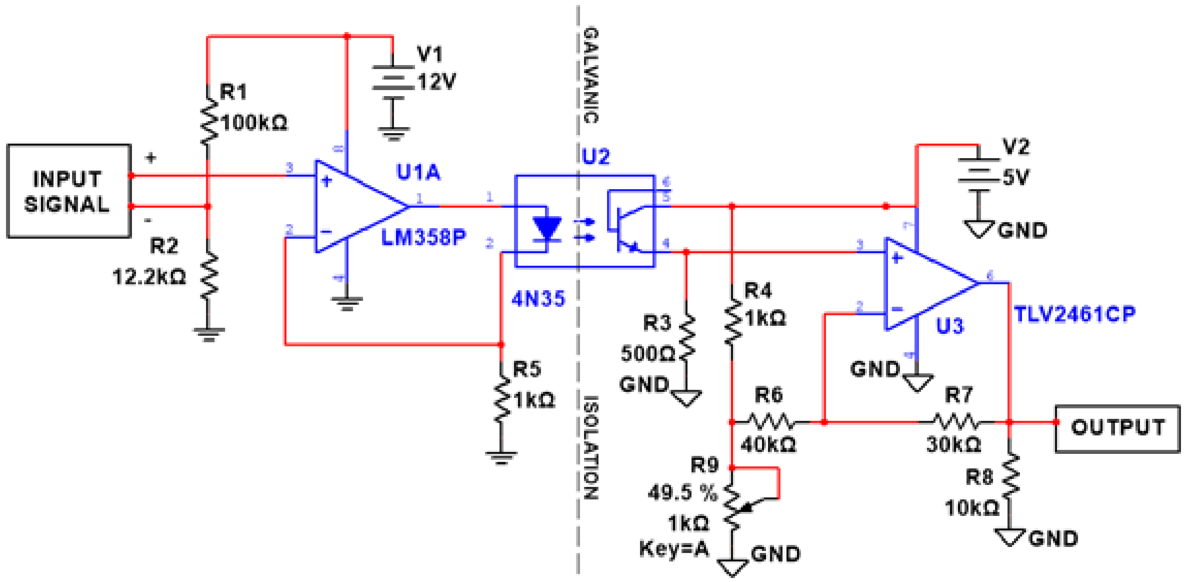

Figure 2. Circuit diagram of the isolator circuit

3.3. *Experimental verification*

The simulation analysis of the proposed isolator circuit produced a linear and highly correlated trendline between input signal voltage values in the 0 – 2.5 V range and output voltage values in the 0.1 – 4.9 V range. To this end, the proposed circuit was fabricated on a printed circuit board and tested with a DC voltage between 0 and 2.5 V at a step of 0.25 V. The output voltage values corresponding to the step inputs were measured using a UNIT UT890C digital multimeter and were used to experimentally verify the simulation results. While the measured output values obtained during experimental verification were within the 90% confidence band of the simulated output voltage, the quadratic and cubic regression equations generated using the simulated values were insufficiently accurate to precisely estimate the input signal within acceptable relative error bands. As a result, the experimental data was used to generate new quadratic and cubic regression equations that could be used to estimate the input signal voltage from the measured output voltage. Equations 5 and 6 represent these equations, with y representing the input signal voltage and x representing the measured output voltage.

$$y = -0.0143x^2 + 0.5937x - 0.0434 \tag{5}$$

$$y = 0.0056x^3 - 0.0555x^2 + 0.6728x - 0.0723 \tag{6}$$

The isolator circuit was connected to an adjustable 100–1000 VDC power source via a 1000–2.5-volt potential divider network for performance verification in the desired operating environment. The output voltage from the isolator circuit was fed directly to the ADC input of an ESP32WROOM IoT device configured as a simple voltmeter, and the voltage increment from the source was done in 100-volt steps. The IoT device uses the quadratic and cubic regression equations to estimate the signal voltage at the input of the isolator circuit, then multiplies it by the voltage division factor to estimate the value of the HV source voltage. Snapshots of the isolator circuit, complete experimental setup, and a window in the measurement dialog are shown in Figure 3.

4. Result and Discussion

Figure 4 shows a graph of the simulated and measured output voltage values produced by the isolator system in response to input signal voltage values between 0 – 2.5 V at a step of 0.25 V. It can be seen from this graph that there is only a slight variation between the slopes both measurement trendlines. This is expected and can be attributed to

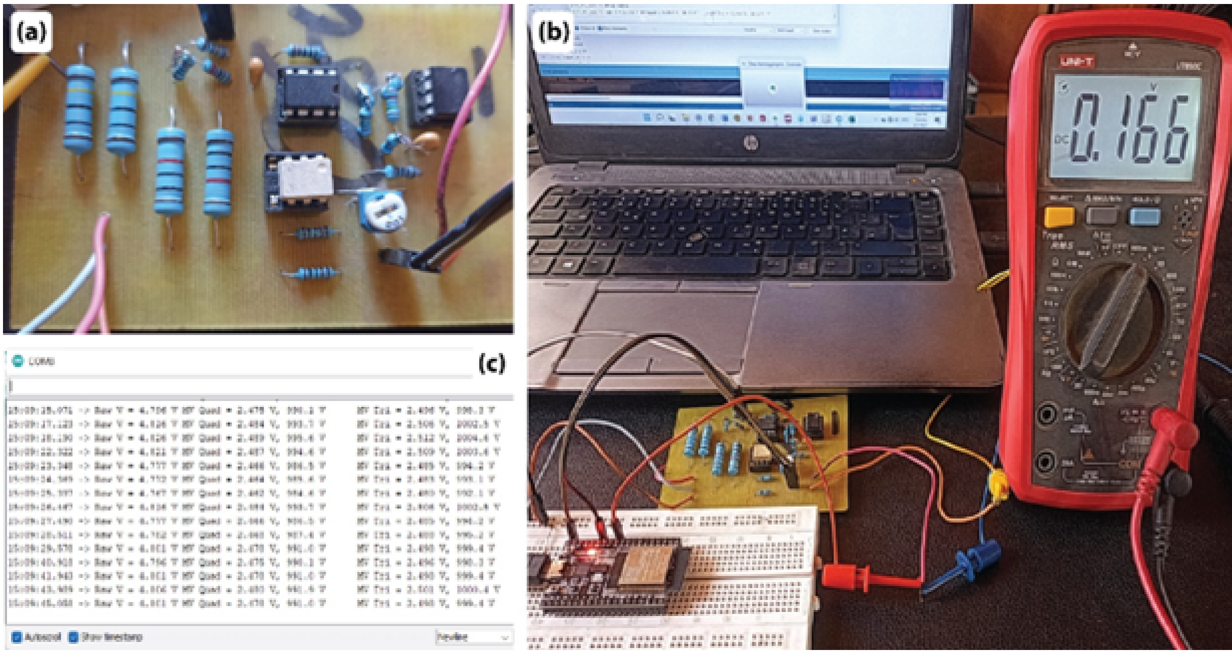

Figure 3. Snapshots of (a) the isolator circuit, (b) the experimental verification setup, and, (c) the measurement results dialog window.

the attenuation factors introduced by the real circuit elements used in the experimental verification process as opposed to the ideal components in the simulation analysis.

Table 1 shows the estimated voltage values and relative errors provided by the IoT device for high voltage DC values between 100 and 1000 VDC obtained using the quadratic and cubic regression equations. From the table, it can be seen that estimation with the cubic regression equation produced relative errors less than or equal to 1% throughout the full range of the HVDC input and a relative error less than or equal to 0.5% at HVDC voltages greater than or equal to 200 VDC while estimation with the quadratic regression equation only managed to produce relative errors lower than 1 % at HV input voltages greater than or equal to 400 VDC. This shows that the cubic transfer function provided a better estimation of the LVDC source voltage than the quadratic regression equations. It should be noted that recent levels of optimization in embedded systems programming have allowed the quick computation of floating-point numbers and the difference in the computation time of both equations is negligible. The non-inverting amplifier was also observed to preserve the linearity of the optocoupler transfer function and thus eliminate the need for using a higher-resolution ADC module. Overall, the developed isolator system is reliable and can also be effectively used in high-precision voltage measurement applications.

5. Conclusion

In this study, a low-cost and easily reproducible conventional optocoupler-based isolation system that galvanically isolates an LVDC IoT voltmeter with a maximum relative error of 1% has been developed and experimentally verified. This was achieved by exploiting a fairly linear relationship between the forward current of the LED and the collector-emitter current of the phototransistor of a conventional optocoupler in the mA range. After interpolation with a cubic regression equation, the isolator circuit demonstrated robust performance in measuring LVDC voltage values between 100 and 1000 VDC at a step of 100 V with a relative error not greater than 1% throughout the measurement range. The circuit directly leveraged the built-in ADC of the IoT device in the measurement process as its output lies between its ADC range. This provides an opportunity to integrate an IoT device directly into an LVDC or HVDC system for high-voltage monitoring or measurement.

The isolator system developed in this study employed a phototransistor-based optocoupler device. It is therefore recommended that the usability of photodiode-based conventional optocouplers for this application be investigated

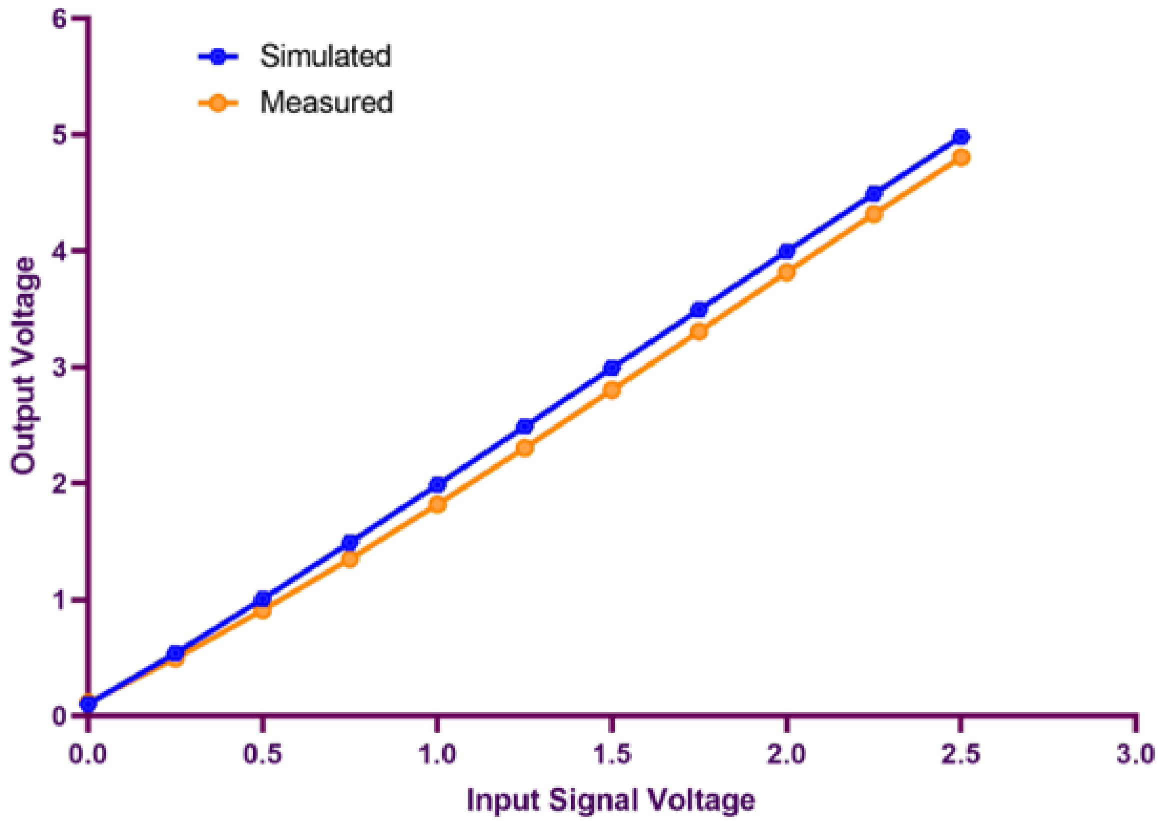

Figure 4. Graph of Input signal voltage against simulated and measured output voltage

Table 1. Table of approximated high voltage DC values and relative errors for LVDC voltage between 100 and 1000 volts

S/N	Measured DC Voltage	Quadratic Regression Equation		Cubic Regression Equation	
		Estimated Voltage Value (VDC)	Relative Error (%)	Estimated Voltage Value (VDC)	Relative Error (%)
1.	100	95	5	99	1
2.	200	192	4	199	0.4
3.	300	291	3	299	0.3
4.	400	396	1	401	0.2
5.	500	500	0	502	0.3
6.	600	600	0	597	0.5
7.	700	706	0.9	700	0
8.	800	806	0.8	801	0.1
9.	900	903	0.4	902	0.2
10.	1000	994	0.6	1000	0

and compared with results obtained in this study.

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