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Cost-effective hardware solutions for experimental validation in renewable energy emulation and storage systems

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ABSTRACT

Experimental validation is essential in renewable energy emulators and energy storage systems to ensure reliability, accuracy, and practical implementation. However, the high cost of AC/DC converters, measurement circuits, and microcontroller-based control platforms limits access to experimental validation, particularly in developing regions. This paper proposes cost-effective hardware and software solutions for validating renewable energy systems and storage management. The proposed approach is based on affordable power converters, low-cost voltage and current measurement circuits, data acquisition tools, and open-source control platforms. The methodology includes the design, implementation, and experimental testing of these low-cost solutions under different operating conditions. The obtained results demonstrate satisfactory measurement accuracy, stable behavior, and acceptable error margins, confirming the feasibility of the proposed setup for experimental validation. These solutions provide a scalable and accessible alternative to expensive laboratory platforms, enabling researchers and institutions with limited resources to perform reliable experimental studies and contribute to the advancement of sustainable energy technologies.

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1. INTRODUCTION

Experimental validation is a cornerstone of scientific research, as it ensures that theoretical and simulation-based results can be effectively transferred to real-world applications. In the fields of electrical energy and electrotechnics, this step is particularly important because it directly affects the reliability of power systems, the performance of control strategies, and the efficiency of energy conversion systems. As noted by [1], [2], validation not only confirms the accuracy of simulations but also demonstrates the practical feasibility of engineering solutions. However, financial and logistical constraints often prevent researchers, especially in developing regions, from carrying out this essential validation stage [3], [4].

Several experimental tools required for renewable energy emulators and energy storage systems, such as isolated voltage and current measurement boards, signal conditioning circuits, AC/DC converters, DC/DC converters, and compatible control platforms, remain costly and difficult to access [5], [6]. In addition, integrating these tools with microcontroller-based control systems and software environments such as MATLAB/Simulink or LabVIEW can increase the complexity and total cost of the experimental setup [7], [8]. As a result, many research works remain limited to simulation studies, which reduces their practical applicability and makes it difficult to evaluate their behavior under real operating conditions [9].

To address these limitations, recent advances in open-source hardware and software have encouraged the development of affordable experimental platforms [10], [11]. Solutions based on Arduino, Raspberry Pi, low-cost data acquisition systems, and custom-designed electronic boards can provide flexible and functional alternatives to expensive commercial equipment [12]. Moreover, collaborative resource sharing within laboratories can help optimize available infrastructure and reduce financial constraints [13], [14].

The novelty of this study lies in proposing an integrated and cost-effective experimental validation framework for renewable energy emulators and energy storage systems. Unlike many existing works that focus mainly on simulation or depend on expensive commercial validation platforms [15]-[17], this paper combines low-cost power converter boards, isolated voltage and current measurement circuits, signal conditioning stages, microcontroller-based control modules, and accessible data acquisition tools within a practical and reproducible methodology [18], [19]. The proposed approach aims to bridge the gap between theoretical modeling, simulation, and real laboratory implementation, particularly for researchers and institutions with limited financial resources.

This article presents cost-effective strategies for experimental validation in electrical energy and electrotechnics research. It proposes accessible tools and methodologies for resource-limited environments while ensuring acceptable accuracy, reliability, and scalability. The proposed solutions target applications in power systems, renewable energy emulators, energy storage management, and control engineering, contributing to more credible and practical experimental research.

The remainder of this paper is organized as follows: Section 2 presents the proposed experimental platform, including the power converter box, voltage and current measurement boards, and isolated MOSFET/IGBT gate-driver module. Section 3 presents and discusses the experimental validation results. Finally, Section 4 summarizes the main conclusions and future research directions.

2. METHOD

This chapter summarizes the development of an experimental platform for power converter emulation, starting with a variable DC-DC power supply as the main energy source. A modular didactic box was created to test various converter topologies (buck and boost). Measurement boards were designed to condition and isolate analog signals for acquisition systems (DSP, dSPACE, MCU) [20], [21]. A gate driver board with galvanic isolation was also developed to control MOSFETs and IGBTs. The resulting platform is robust, flexible, and well-suited for research, prototyping, and educational use [22], [23].

2.1. Power converter box

In experimental power electronics research, a versatile converter box with MOSFETs or IGBTs offers a modular platform for testing various topologies. Figure 1 presents the didactic converter box developed and used in our laboratory for the experimental implementation and validation of different power converter configurations. The platform provides flexible access to the power semiconductor switches and their connections, allowing different converter topologies to be assembled and tested according to the experimental requirements. In our lab, we used 20N60 N-channel MOSFETs, known for their high switching speed, 600 V drain-source voltage, 20 A current capacity, and low RDS(on), ensuring efficient, high-frequency operation and reduced losses ideal for validating theoretical models and hands-on experimentation [24].

Figure 1. Didactic box converter

By integrating six 20N60 MOSFETs, this versatile converter box enables the implementation of multiple power electronics topologies such as DC-DC converters (buck, boost, buck-boost), DC-AC inverters (single and three-phase), AC-DC rectifiers for PFC, multilevel NPC inverters, and matrix converters for direct AC-AC conversion. Its reconfigurable and modular design makes it ideal for academic and research use, allowing flexible experimentation with minimal cost estimated around $20 using the lowest-priced components.

2.2. Measurement boards for voltage and current analysis

The voltage measurement process begins with a voltage divider formed by two resistors: $R2 = 8\,M\Omega$ and $R1 = 260\,k\Omega$. When an input voltage VE is applied, the voltage drop across the smaller resistor R1, denoted as $VE1$, is expressed in (1).

$$VE1 = VE \times \frac{R1}{R1+R2} = VE \times \frac{260\,k\Omega}{260\,k\Omega + 8\,M\Omega} \approx VE \times 0.0313 \quad (1)$$

This significantly attenuated voltage is then buffered using an operational amplifier (TL084, U2A) in a voltage follower configuration, which ensures high input impedance preventing loading of the voltage divider low output impedance for stable signal propagation, and unity gain to preserve the signal amplitude for accurate processing. The buffered signal $VS1$ is then amplified by a second op-amp stage (U2B), configured as a non-inverting amplifier. The gain of this stage is adjustable using a multiturn potentiometer $RV1 = 100\,k\Omega$, in combination with a fixed resistor R4 = 10 kΩ. The amplification gain is calculated by the standard formula for a non-inverting amplifier as (2).

$$Gain = 1 + \frac{RV1}{R4} = 1 + \frac{100\,k\Omega}{10\,k\Omega} = 11 \quad (2)$$

The resulting output $VS2$ is expressed in (3).

$$VS2 = G \cdot VS1 \quad (3)$$

To adapt the signal to the dynamic range of the data acquisition system, an adjustable DC offset is introduced using a third op-amp stage (U2C). A potentiometer RV2 = 10 kΩ is connected between symmetric supply rails $+V1$ and $-V1$, with a wiper feeding the non-inverting input of U2C. Assuming $+V1 = +15\,V$ and $-V1 = -15\,V$, the output offset Voffset injected can vary between (4) and (5).

$$Voffset\ min = -15\,V (RV2\ at\ ground\ side) \quad (4)$$

$$Voffset\ max = +15\,V (RV2\ at\ positive\ rail) \quad (5)$$

The offset voltage is combined with the amplified signal through the subsequent operational-amplifier stage using R5 = R6 = 47 kΩ and R7 = R8 = 10 kΩ.

The resulting signal $VS3$, now both amplified and shifted, is then fed into an ISO124 isolation amplifier. The ISO124 is a high-performance precision isolation amplifier that provides galvanic isolation between input and output up to 1500 V, high linearity, low offset drift, and effective rejection of common-mode noise and ground loops. Such isolation is essential in industrial environments where measurement systems often interface with sensors referenced to different ground potentials, preventing signal corruption and protecting sensitive circuitry.

The power architecture incorporates a 12 V DC adapter that feeds two IA1215S isolated DC-DC converters. The first converter delivers power to all analog stages, including the operational amplifiers and signal conditioning circuits, while the second converter exclusively supplies the isolated output side of the ISO124, thereby maintaining galvanic isolation and preventing any cross-interference. By integrating voltage attenuation, impedance buffering, adjustable gain, programmable offset, and galvanic isolation, the designed voltage measurement board ensures a robust, flexible, and accurate interface between high-voltage analog inputs and low-voltage data acquisition systems such as those based on LabVIEW or Simulink [25], [26].

2.2.1. Voltage measurement using voltage divider

In this circuit, a voltage divider is used to scale down an input voltage of 160 V to a measurable 5 V for further signal processing. As shown in Figure 2, the developed voltage measurement board is based on a resistive voltage-divider network designed to provide a proportional low-voltage representation of the measured high-voltage signal. This configuration enables the voltage signal to be safely adapted to the input range of the data acquisition and control system while maintaining a simple and cost-effective measurement approach.

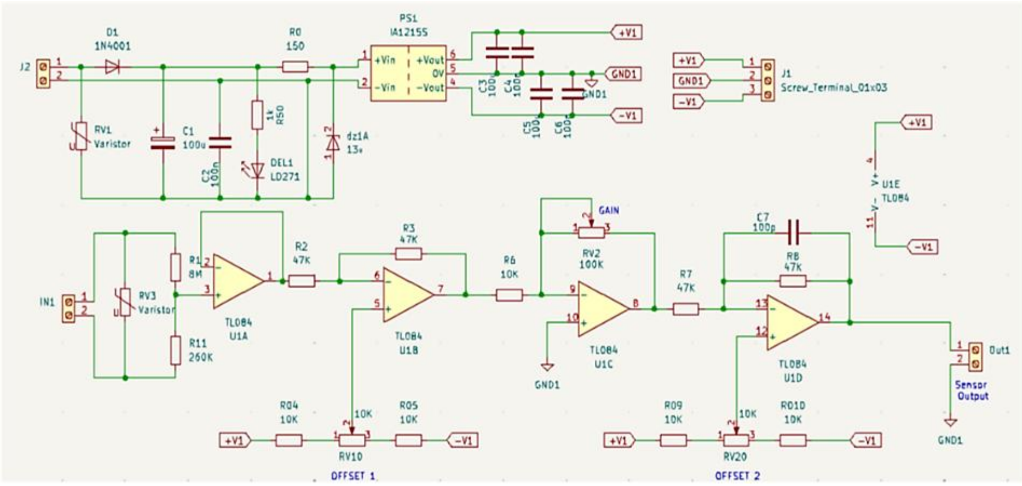

Figure 2. Measurement voltage board based on resistive divider

The voltage divider consists of two resistors, R_1 and R_2, where the output voltage V_{out} is determined by (6).

$$V_{out} = V_{in} \times \frac{R_1}{R_1+R_2} \tag{6}$$

To achieve a reduction from 160 V to 5 V, appropriate resistor values must be chosen while considering power dissipation and accuracy. For instance, if R_1 = 260 kΩ and R_2 = 8 MΩ, the ratio will be (7).

$$V_{out} = 160 \frac{260 \text{ k}\Omega}{260 \text{ k}\Omega + 8 \, M\Omega} \approx 5 \, V \tag{7}$$

A buffer amplifier (TL081), configured as a unity-gain voltage follower, is used after the voltage divider to provide impedance matching. This prevents loading effects from the following stages and ensures that the measured voltage remains stable. Next, adjustable gain and offset amplifiers allow fine-tuning of the signal, adapting it to the input requirements of the data acquisition system (DAQ) or microcontroller (MCU) being used. The gain control (via a potentiometer RV1) ensures that the scaled voltage fits within the dynamic range of the acquisition system, while the offset adjustment shifts the signal to accommodate systems that cannot read negative voltages. The estimated cost of this circuit remains highly affordable based on AliExpress prices bringing the total estimated cost to around 4.35$. However, the voltage divider has limitations, such as limited accuracy due to resistor tolerance and susceptibility to noise without proper shielding [27], [28].

2.2.2. Voltage measurement using voltage transducer LV25P

The LV25-P voltage transducer uses a Hall effect closed-loop design to measure high voltages with electrical isolation. The practical implementation of the proposed LV25-P-based voltage measurement circuit is illustrated in Figure 3. For optimal accuracy, the primary resistor $R2$ should produce a 10 mA nominal current. Using higher $R2$ (e.g., 50 kΩ) reduces power loss but also accuracy. To ensure stability and minimize thermal drift, $R2$ should remain low relative to the primary winding resistance, making the system suitable for voltages from 10 V to 500 V.

A measurement board based on the LV25-P is relatively expensive, costing around 50$, compared to other solutions. However, its high reliability and precision make it an excellent choice for applications requiring accurate voltage measurements with galvanic isolation.

2.2.3. Current measurement using shunt resistor

A shunt resistor generates a voltage proportional to the current passing through it. Impedance matching and isolation amplifiers are used to ensure compatibility and safety. The major advantages of this approach include its simplicity, cost-effectiveness, and high accuracy for low-current applications [29]. However, it has limitations such as heat dissipation at high currents and the need for careful design to minimize power losses. The practical implementation of the current measurement board based on a resistive shunt is illustrated in Figure 4. The estimated cost of this shunt resistor-based measurement board is around 15$ to 25$.

2.2.4. Current measurement using a LA55P

The LA55-P is a high-precision closed-loop Hall-effect current sensor designed for AC and DC current measurement in industrial and power electronics applications [30]. The measurement circuit based on the LA55-P current sensor is shown in Figure 5. This isolation enhances safety and noise immunity, making it ideal for applications in power inverters, motor control, and renewable energy systems.

The used Hall-effect current sensor offers high accuracy, fast response, and low power consumption, making it ideal for dynamic current sensing in high-speed power supplies. A single versatile measurement board was designed to measure both voltage and current, differing only by input resistor values. It supports AC/DC signals, provides adjustable gain and offset for unipolar systems, and ensures galvanic isolation. However, the LA55-P solution remains relatively expensive (≈ $50) compared to other alternatives.

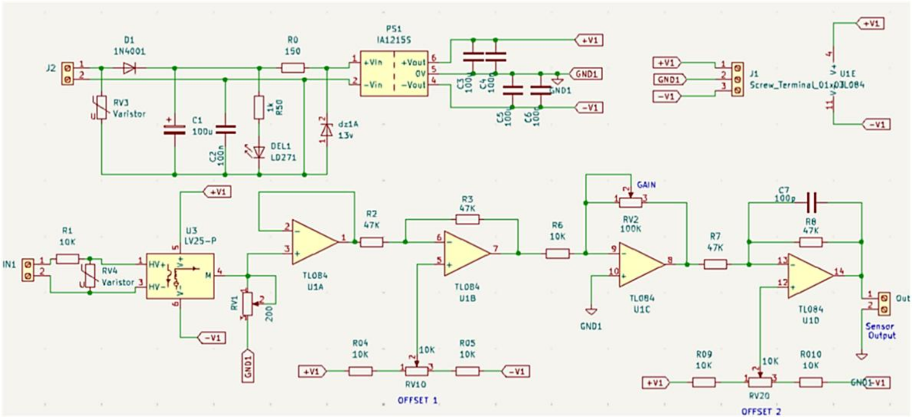

Figure 3. Measurement voltage board based on LV25P

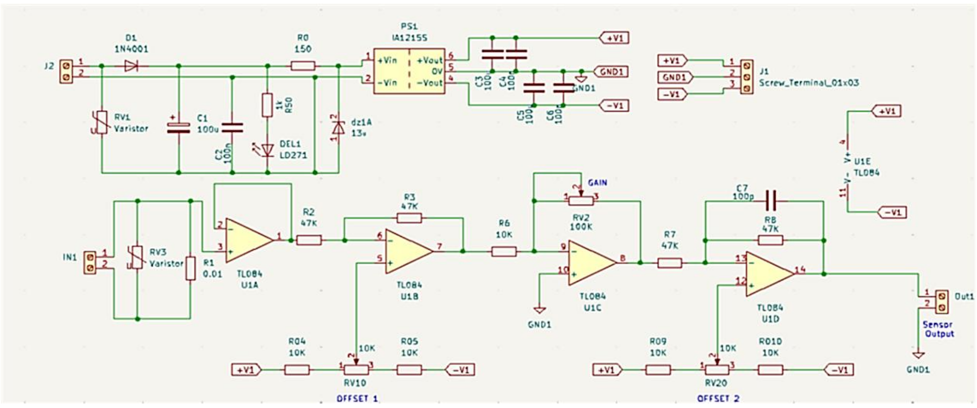

Figure 4. Measurement current board based on resistive shunt

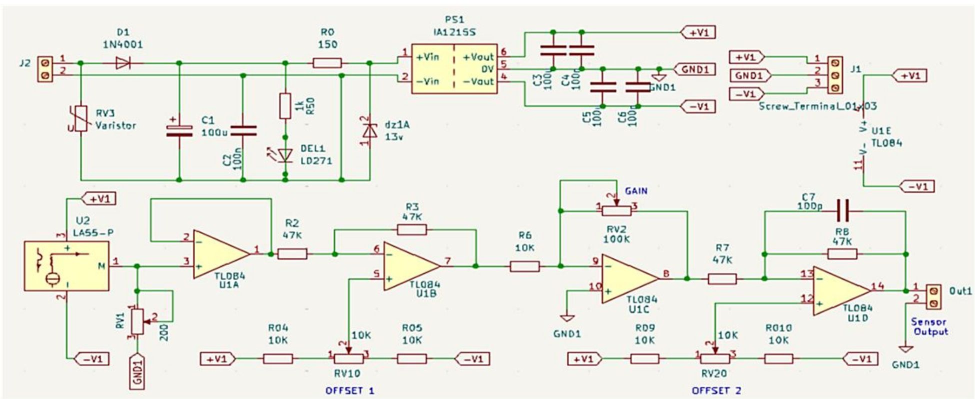

Figure 5. Measurement current board based on LA55P

2.3. Isolated control module for IGBT and MOSFET drivers

Driving MOSFETs and IGBTs with PWM signals through an optocoupler-based driver, such as the TLP351 series, is essential for ensuring reliable and efficient switching in power electronics applications. The schematic diagram of the TLP351-based isolated gate driver circuit used for MOSFET and IGBT switching is shown in Figure 6. From the datasheet, the TLP351 offers advantages such as a built-in LED and photodetector, ensuring fast response times and minimal propagation delay. It also features a wide operating temperature range (-40 °C to 85 °C) and a high isolation voltage of up to 3750 Vrms [31], [32].

To maximize versatility, we have developed a custom driver board with multiple outputs, fully compatible with various control platforms such as Arduino, ESP32, TI C2000 microcontrollers, and FPGAs. This multi-output driver board simplifies integration into diverse systems, providing a reliable and cost-effective solution for controlling high-power electronic switches in a wide range of applications. The estimated cost of this driver gate board is around 20$.

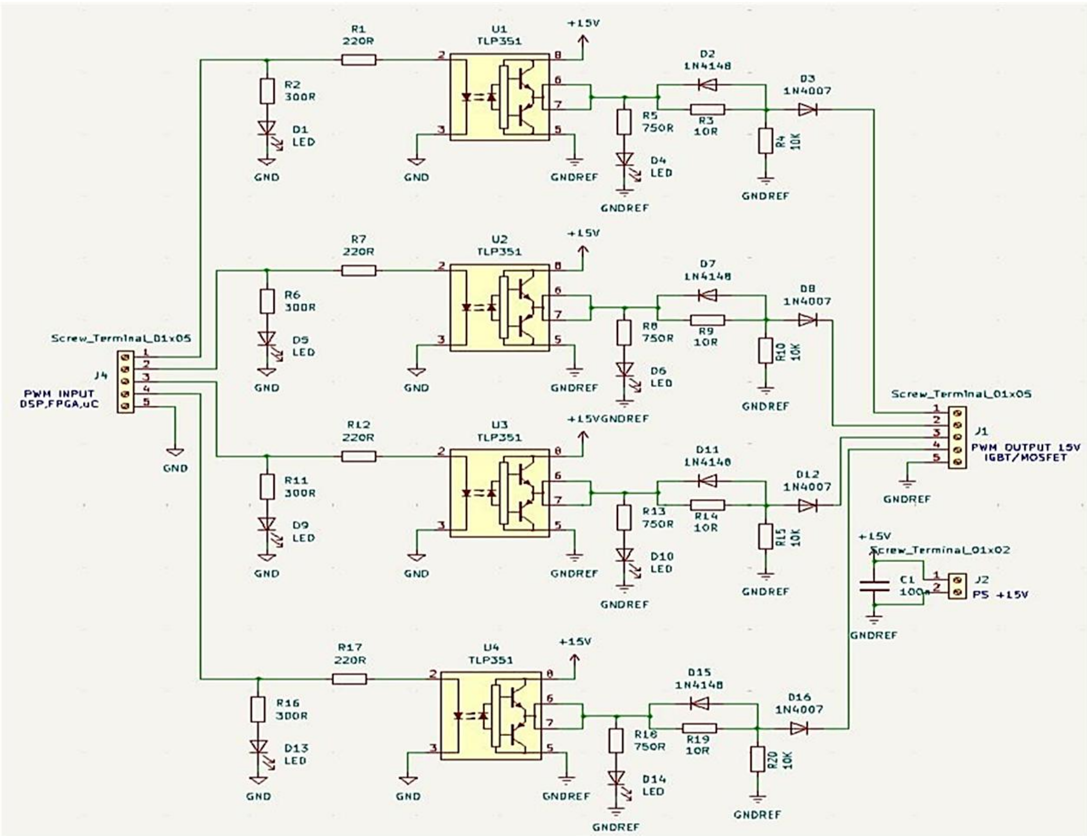

Figure 6. Schematic diagram of MOSFET/IGBT gate driver

3. RESULTS AND DISCUSSION

The proposed measurement and control boards were experimentally validated through a series of tests designed to assess their accuracy and reliability under real operating conditions. Figure 7 illustrates the developed Mosfet/IGBT gate driver board. This circuit was designed to provide isolated and reliable control signals to power semiconductor switches. It includes optocouplers for galvanic isolation and discrete components to ensure signal integrity and drive strength.

Figure 8 shows the experimental setup used to validate the measurement board. The test bench includes signal generators, multimeters, and an oscilloscope to verify the accuracy and dynamic response of the circuit under various input conditions. The results confirm that the proposed hardware meets the expected performance criteria in terms of linearity, impedance matching, galvanic isolation, and noise filtering. This demonstrates the feasibility and robustness of the low-cost solution developed in the laboratory.

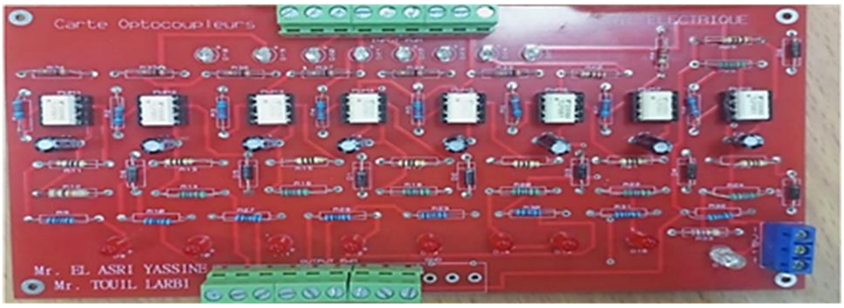

Figure 7. MOSFET/IGBT gate driver board

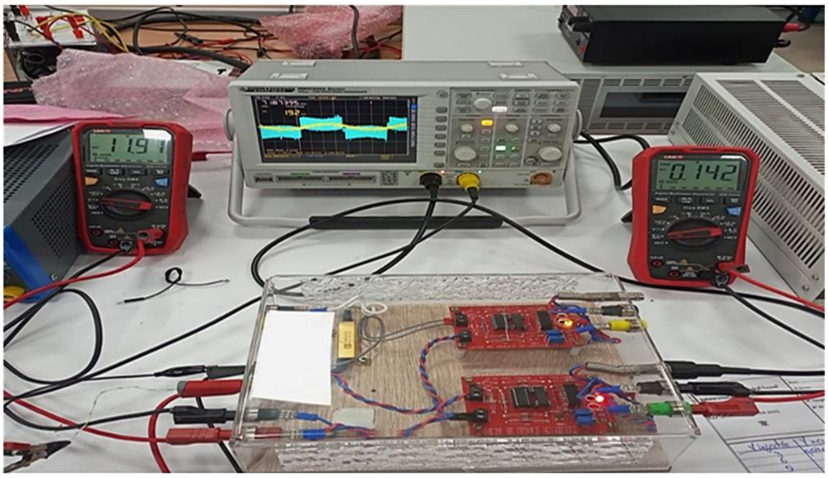

Figure 8. Test of measurement board

3.1. Voltage divider based board results

The measurement results obtained using the voltage divider circuit are presented in Table 1. This table shows the relationship between the input voltage and the corresponding output voltage across the divider. Table 1 presents the analog voltage measurements for AC and DC signals, respectively, using a voltage divider. In both cases, the measured values show good linearity with nearly constant ratios around 0.02 for AC and 0.011 for DC confirming the proper operation of the divider. Measurement errors are generally low, though slightly higher for very small or high voltage levels due to resolution limits or minor non-linearity.

3.2. LV25P based board results

The following measurement tables correspond to a voltage sensing system based on the LV25P Hall-effect transducer. This board is designed to measure both DC and AC analog voltages using a voltage divider configuration and signal conditioning circuitry. Table 2 presents the performance of the system for DC and AC voltage inputs, respectively.

The results demonstrate a consistent and nearly linear response of the LV25P-based board. For DC voltages, the ratio remains around 0.01 with low error percentages, except at low voltages (e.g., 5 V and -5 V) where accuracy decreases due to resolution limitations. Similarly, for AC voltages, the system shows stable behavior with a constant ratio of approximately 0.011.

3.3. Current shunt resistor based board results

Table 3 presents the experimental results obtained using the shunt-resistor-based current measurement board for both DC and AC current measurements. The results are used to evaluate the accuracy and linearity of the proposed current sensing circuit over the tested operating range. The results show a stable conversion ratio of approximately 0.105 for DC and 0.2 for AC, confirming the linear behavior of the measurement setup. The absolute error remains below approximately 7.3% over the tested range, with the largest deviations observed for some AC operating points.

Table 1. Divider board under DC voltage vs. AC voltage

DC injected value	Measured value	Ratio	Measured value* ratio	Error %	AC injected value	Measured value	Ratio	Measured value* ratio	Error %
9	0.175	0.0194	8.75	2.777	6	0.062	0.0103	5.63	6.06
60	1.197	0.0199	59.85	0.25	9	0.1	0.0111	9.05	1.01
180	3.6	0.02	180	0	30	0.336	0.0112	30.5	1.818
360	7.28	0.0202	364	1.111	60	0.666	0.0111	60.5	0.909
-360	-7.3	0.0202	-365	1.3888	90	0.992	0.011	90.1	0.202
-100	-2.008	0.02	-100.4	0.4	180	2.017	0.0112	183.3	1.868
-20	-0.405	0.0202	-20.25	1.25	220	2.485	0.0112	225.9	2.685
-5	-0.105	0.021	-5.25	5	240	2.735	0.0113	248.6	3.598

Table 2. LV25P board under DC voltage vs. AC voltage

DC injected value	Measured value	Ratio	Measured value* ratio	Error %	AC injected value	Measured value	Ratio	Measured value* ratio	Error %
5	0.0442	0.009	4.42	11.6	3	0.032	0.011	3.2	6.667
10	0.0957	0.01	9.57	4.3	5	0.052	0.01	5.2	4
70	0.713	0.01	71.3	1.86	10	0.1044	0.01	10.44	4.4
360	3.67	0.01	367	1.94	30	0.295	0.01	29.5	1.667
-360	-3.75	0.01	-375	4.17	70	0.669	0.01	66.9	4.429
-90	-0.955	0.011	-95.5	6.11	150	1.422	0.009	142.2	5.2
-10	-0.109	0.011	-10.9	9	200	1.91	0.01	191	4.5
-5	-0.056	0.011	-5.6	12	240	2.383	0.01	238.3	0.708

Table 3. Shunt-resistor board under DC current vs. AC current

DC injected value	Measured value	Ratio	Measured value* ratio	Error %	AC injected value	Measured value	Ratio	Measured value* ratio	Error %
0.951	0.0995	0.105	0.995	4.63	0.25	0.047	0.188	0.235	6
2.02	0.213	0.105	2.13	5.45	0.5	0.097	0.194	0.485	3
4.065	0.43	0.106	4.3	5.78	1	0.213	0.213	1.065	-6.5
10.02	1.0573	0.106	10.573	5.52	1.5	0.295	0.1967	1.475	1.66667
-10.1	-1.0649	0.105	-10.649	5.44	2.5	0.51	0.204	2.55	-2
-5.03	-0.529	0.105	-5.29	5.17	3.5	0.649	0.1854	3.245	7.28571
-0.95	-0.0999	0.105	-0.999	5.16	4	0.791	0.1978	3.955	1.125
-0.159	-0.016	0.101	-0.16	0.63	5	1.025	0.205	5.125	-2.5

3.4. Current LA55P based board results

Table 4 shows the measurement results obtained using a current sensing board based on the LA55P Hall-effect sensor. This circuit was designed to measure DC current by converting it into a proportional voltage, which is then processed and scaled for analysis. The ratio between the injected and measured current values remains nearly constant around 0.05, indicating a linear and consistent response. For DC measurements, the error remains approximately 1.2–1.5%. For AC measurements, larger deviations are observed, with the maximum absolute error reaching approximately 6.7%. The experimental results obtained from all the developed measurement boards, including voltage and current sensing using LV25P and LA55P transducers demonstrate consistent linearity, acceptable error margins, and reliable performance across a wide range of input values. Both AC and DC measurements yielded stable ratios, validating the accuracy and stability of the circuits designed.

Table 4. LA55P board under DC current vs. AC current

DC injected value	Measured value	Ratio	Measured value* ratio	Error %	AC injected value	Measured value	Ratio	Measured value* ratio	Error %
3	0.152	0.051	3.04	1.33	0.25	0.2385	0.954	0.2385	4.6
15	0.739	0.049	14.78	1.47	0.5	0.4885	0.977	0.4885	2.3
40	1.972	0.049	39.44	1.4	1	1.067	1.067	1.067	-6.7
56	2.762	0.049	55.24	1.36	1.5	1.4775	0.985	1.4775	1.5
70	3.454	0.049	69.08	1.31	2.5	2.58	1.032	2.58	-3.2
76	3.753	0.049	75.06	1.24	3.5	3.35	0.9571	3.35	4.3
78	3.851	0.049	77.02	1.26	4	3.9575	0.9894	3.9575	1.1
81	3.999	0.049	79.98	1.26	5	5.127	1.0254	5.127	-2.5

4. CONCLUSION

This study presented an integrated and cost-effective framework for the experimental validation of renewable energy emulators, energy storage systems, and power electronic applications. The proposed approach addresses one of the main limitations encountered in experimental electrical engineering research: the high cost and limited accessibility of commercial power conversion, measurement, data acquisition, and control equipment. Rather than focusing on a single component, the developed framework combines affordable DC/DC power converter boards, isolated voltage and current measurement circuits, signal conditioning stages, gate-driver modules for MOSFETs and IGBTs, and accessible control and acquisition solutions within a modular experimental architecture.

The experimental investigations demonstrated that the developed hardware can provide stable operation and satisfactory measurement accuracy with acceptable error margins compared with commercial equipment. These results confirm that reducing implementation cost does not necessarily prevent the achievement of reliable experimental performance for research, prototyping, and educational applications. The modular structure of the proposed platform also facilitates its adaptation to different power levels, converter topologies, renewable energy emulators, and energy storage configurations. Consequently, the proposed solutions provide a practical approach for bridging the gap between numerical simulation and laboratory implementation, particularly for universities and research laboratories operating with limited experimental resources.

Future work will extend this platform toward a more integrated, intelligent, and autonomous experimental environment. Dedicated low-cost data acquisition boards will be developed with improved resolution, noise immunity, bandwidth, and electrical isolation, together with customized drivers for MATLAB/Simulink and LabVIEW. Particular attention will also be devoted to real-time operation, hardware-in-the-loop and power-hardware-in-the-loop implementation, long-term reliability assessment, and validation under dynamic operating conditions representative of photovoltaic, battery, supercapacitor, and hybrid energy systems.

A further research direction will investigate the integration of artificial intelligence techniques for adaptive control, anomaly detection, fault diagnosis, parameter estimation, and predictive maintenance. In parallel, the experimental platform will be coupled with physics-based and data-driven models to establish digital twins of renewable energy emulators, power converters, and storage systems. Real-time synchronization between the physical prototype and its virtual counterpart could enable continuous condition monitoring, online model updating, performance prediction, and intelligent control optimization. Such developments would transform the proposed low-cost validation framework into a scalable cyber-physical research platform supporting advanced experimentation, intelligent energy management, and next-generation sustainable energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Mohammed Chiheb	✓					✓				✓			✓	
Mohamed Koundi	✓	✓			✓				✓					

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available within the article. Additional experimental data can be obtained from the corresponding author upon reasonable request.

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