Ultra Low-Cost High-Voltage Isolated Differential Probe for Teaching and Training

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***Abstract*—Measurement of time-varying high-voltages is necessary in various teaching, training, and research scenarios, in domains ranging spanning multiple disciplines beyond just electric power engineering. While low voltage levels (<100V) can usually be measured directly by oscilloscopes with inexpensive passive probes, higher voltages (>400V) often require specialized probes and/or oscilloscopes which are expensive. Also, most oscilloscopes lack galvanically isolated channels, which adds further challenges to measurement of multiple floating (not grounded) high voltages. Although both problems can be solved by differential high-voltage probes, these are quite expensive and not cost-effective for teaching laboratories where large numbers of such probes may be needed. This paper presents a novel, inexpensive isolated high-voltage differential probe intended for use in undergraduate and graduate labs in Power Electronics, Electric Machines and Drives, Renewable Energy, etc. It is designed for input voltages up to 600V with a bandwidth of 350KHz. The design is self-contained with a removable lithium-ion battery and is designed to directly interface to a standard oscilloscope. The design also includes gain and offset correction for periodic calibration. Simulation results were validated using a preliminary hardware prototype, following which a compact version was created with optimized layout. This design is found to be excellent for cost-sensitive applications including universities, makerspaces, and startups and industries.**

***Index Terms*—High Voltage (HV) measurement, Differential probe, Isolation amplifier, Teaching and Training**

I. INTRODUCTION

High-voltage signals are common in diverse applications spanning power electronics, electric drives, renewable energy systems, and high-voltage equipment. High voltages are also common in many consumer electronics that contain large displays or motor drives. Advancements in power electronics and newer wide-band-gap semiconductors have spurred a move to higher system voltages. As an example, within two decades, electric vehicles have moved from 48V or 96V onto 400V and now even 800V systems [1]. Solar photovoltaic systems, which were once limited to 400V, are trending over 1500V [2]. Measuring such time-varying high voltages is essential not only for product development, research and testing, but also in teaching and training. The most common method for measuring such time-varying high-voltage signals is to use an oscilloscope with a dedicated high-voltage probe. In addition, since many of these high voltages are floating (i.e. not referenced to the common earth ground), it is necessary to use a differential probe. Additionally, if multiple voltages with different references are to be captured on a single oscilloscope, then the probes may need to be galvanically isolated as well [3]. To meet these stringent requirements, a number of specialized high-voltage probes have been developed. Most of these commercially available probes are quite expensive (well over USD 1000) [4]. Recently, optically isolated high-voltage high-bandwidth probes have been introduced [5], [6] with even better performance and prices to match (>USD 10,000). These are well out of reach for cost-sensitive buyers such as educational labs, maker-spaces, hobbyists, and early-stage hardware startups, hence there is a need for a lower bandwidth, lower voltage solution and cost-effective solution for this target market.

The dual differential probe presented in [7] has a 10MHz bandwidth and 7.3V/ns slew rate using high-performance analog amplifiers. The frontend uses carefully designed resistive dividers to attenuate the voltage appearing at the input of the op-amp. This design is not truly isolated and the dependence on very-high bandwidth op-amps drives up the BOM cost. Further, for lower voltages the attenuation cannot be lowered by bypassing resistors since the probe is not truly isolated. A similar approach, without galvanic isolation, is developed in [8], [9].

True galvanic isolation is desirable particularly for limiting common-mode noise, especially in high slew-rate applications like WBG measurements. Here, analog-to-digital conversion followed by optical transmission of the digital data yields the best performance [10]. However, the high sampling rate required, (along with the complexity of recovering the signal on the other end on a host device with GUI software) drives up the cost.

In [4] a high common-mode voltage active differential probe is presented that allows a standard oscilloscope to display and quantify waveforms in circuits . It supports bandwidths up to 100 MHz and can reliably measure differential voltages

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up to 1000 V AC and 1400 V AC/DC. In [11] a novel fiber-coupled sensor utilizing the Pockels effect in lithium niobate crystal enables direct, contactless, and high-bandwidth (GHz to DC) measurement of High Voltage (45kV) through light modulation, eliminating voltage dividers and physical connections, ideal for isolated and unobtrusive voltage sensing in various applications.

This paper presents a much lower cost, galvanically isolated probe primarily for educational use. True galvanic isolation makes it possible to measure multiple floating voltages simultaneously on one oscilloscope - for example when measuring three phase voltages and one DC-link voltage in an inverter-fed drive; or primary and secondary voltages on a transformer, etc. Voltage levels in such applications are usually 400V (three-phase) or lower; hence the proposed design is targeted for 600V. Switching voltages are or the order of few tens of kilohertz, hence a system bandwidth of 300kHz is used. The 'high'-side of the probe is powered by a removable, rechargeable lithium ion battery, making it self contained. Finally, the probe incorporates gain and offset correction circuits to improve the accuracy of differential voltage measurements using potentiometers, again keeping cost low. The probe presents high input impedance and minimizing adverse loading effects on the measured circuit, ensuring the preservation of signal integrity during analysis.

II. Proposed High Voltage Probe with isolation

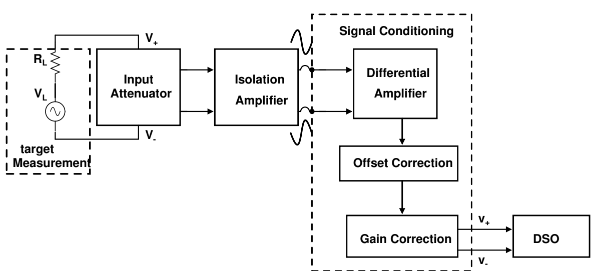

Fig. 1. Block diagram of the proposed high voltage probe

Fig 1 illustrates the block diagram of the proposed HV probe. The design consists of an attenuator stage, followed by an isolation stage and a differential amplifier. The attenuator stage is responsible for reducing the voltage level, while the isolation stage ensures capacitive isolation between the probe and the measurement circuit. The differential amplifier is used to achieve ground referencing and amplify the signal. Furthermore, the design includes an offset correcting circuit to enable DC level shift and a gain correcting circuit. The probe achieves a magnification factor of 250x by maintaining unity gain correction. The proposed probe can provide isolation up to a voltage rise of 2100V, as the isolation amplifier used in the design supports such high isolation levels.

A. Attenuator

The input range of the isolation amplifier is limited between +300mV and -300mV, and therefore the high input voltage needs to be attenuated to the desired range. As shown in Fig 2, the attenuator circuit consists of eight series-connected 250kΩ resistors and one 1kΩ resistor. The input voltage across the 1kΩ resistor is then fed to the isolation amplifier. The attenuation factor can be calculated using the following equation:

$$\text{Attenuation factor} = \frac{R_{\text{input}}}{R_{\text{total}} + R_{\text{input}}} \tag{1}$$

where R_{total} is the total resistance of the attenuator circuit (8 x 250kΩ) and R_{input} is the resistance across which the input voltage is applied (1kΩ). This yields an attenuation factor approximately equal to 2000. The input voltage range of the HV probe can be calculated as:

$$\text{Input range of HV Probe} = 2000 \times \text{(-300mV, +300mV)} \tag{2}$$

where (-300mV, +300mV) is the input voltage range of the isolation amplifier. The proposed HV probe can therefore measure input voltage signals in the range of -600V to +600V.

B. Isolation Amplifier

Isolation is provided by the AMC1301 isolation amplifier, from Texas Instruments. The AMC1301 requires a +5V power supply, which is generated using the LM7805 regulator. Fig 4 demonstrates the gain value of the isolation amplifier to be 18.6 dB, from LTspice simulation. The voltage gain is therefore 8, up to 100 KHz.

Fig 5 shows the LC low-pass filter employed in the power supply to eliminate undesired noise signals before they reach the isolation amplifier. To ensure that only DC signals are permitted, the cutoff frequency of the LC low-pass filter is set as low as possible. The specified cutoff frequency of the LC filter is as follows.

$$\begin{aligned} C &= C_1 + C_2 + C_3 \\ &= 470\mu\text{F} + 0.1\mu\text{F} + 0.01\mu\text{F} \\ &= 470.1\mu\text{F} \end{aligned} \tag{3}$$

Now, using the combined capacitance ($C = 470.1\mu$F) and the value of the inductor ($L = 1$mH), the cutoff frequency of the LC low-pass filter using is calculated using the formula:

$$\begin{aligned} f_c = \frac{1}{2\pi\sqrt{L \cdot C}} \qquad &= \frac{1}{2\pi\sqrt{1\text{mH} \cdot 470.1\mu\text{F}}} \\ \approx \frac{1}{2\pi \cdot 154.167\text{kHz}} \qquad &\approx 1.03\text{kHz} \end{aligned} \tag{4}$$

C. Differential Amplifier

The initial step in the signal conditioning process as shown in Fig 1 involves utilizing a differential amplifier to convert the differential input into a ground-referenced signal which allows the signal to be fed into an oscilloscope for further analysis. The construction of a differential circuit is demonstrated in Fig 2, which employs an LF356 integrated circuit operational amplifier (op-amp) for this purpose.

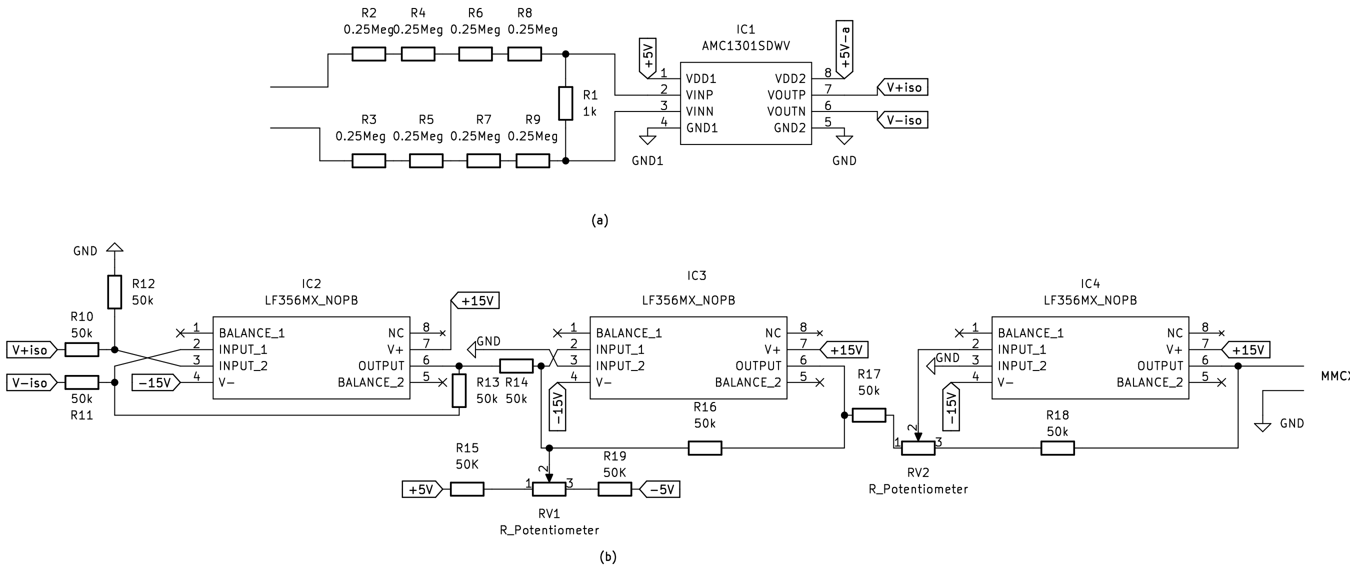

Fig. 2. (a) Circuit diagram of attenuator and isolation amplifier stage. (b) Circuit diagram of differential, offset correction, and gain correction stage.

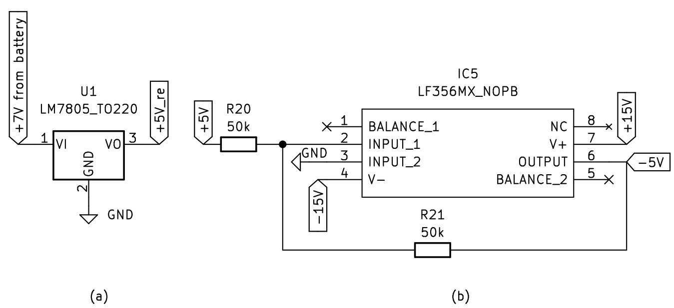

Fig. 3. (a) 5V Regulator. (b) Representation of -5V generation.

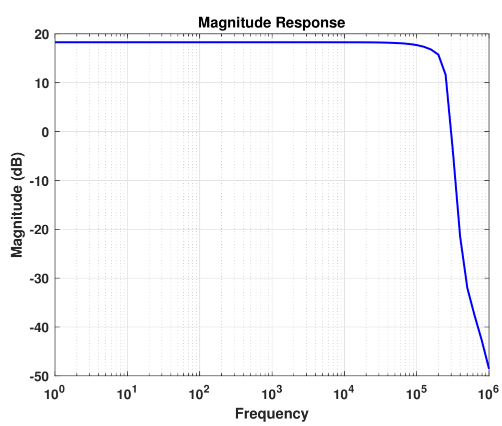

Fig. 4. Gain VS Frequency plot of isolation Amplifier from LTspice simulation.

D. Offset Correction

The expected output will have a DC offset at higher values of input voltage as shown in Fig 6. To address this issue, a correction is required by adjusting the DC level. This adjustment is achieved using a simple summing amplifier, where the DC level can be finely tuned using a trimmer. The actual circuit for the summing amplifier is depicted in Fig 2 as part of the combined circuit design. Additionally, the DC level shift can be adjusted both positively and negatively. The generation of +5V and -5V DC voltages required for this purpose is illustrated in parts (a) and (b) of Fig 3, respectively. These voltage sources play a crucial role in achieving the desired DC level adjustment in the signal conditioning circuit.

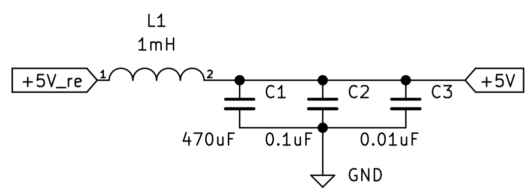

Fig. 5. LC low pass filter

E. Gain Correction

In the context of signal conditioning for high-frequency applications, it is observed that as the gain of the isolation amplifier decreases, above the 100 kHz range. To address this issue and enable proper gain correction above 100 kHz, a gain correction circuit is required. As a solution, an inverting amplifier was incorporated as a crucial component of the signal conditioning circuit. This circuit, illustrated in Fig 2, includes a trimmer that allows for manual adjustment of the gain. Implementing the gain correction stage ensures that the signal conditioning system can effectively compensate for attenuations and ensure accurate signal amplification at higher frequencies.

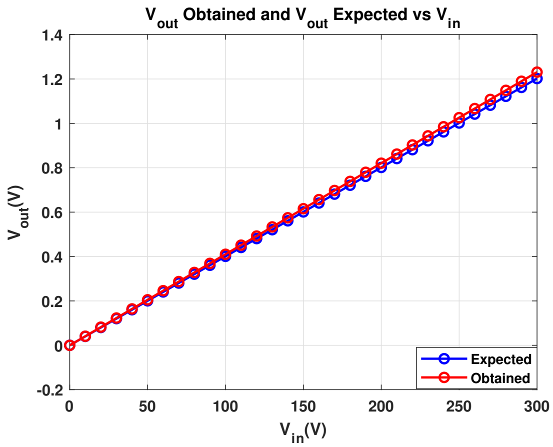

Fig. 6. Gain Error

III. Simulation Results

A simulation has been done using LTspice software to validate the proposed high voltage probe design. The simulation outputs of each stage when subjected to a 300V peak sinusoidal input signal of frequency 50Hz is shown in Fig 7. The initial signal is attenuated 2000 times through the attenuator, resulting in a corresponding plot as shown in the graph. Subsequently, the attenuated signal is amplified 8 times by the isolation amplifier. Further, the differential plot showcases the ground-referenced version of the amplified signal.

Moving forward, the offset correction stage demonstrates the inverted signal with appropriate offset correction, while the gain remains unchanged. Following this stage, the final output plot depicts a phase difference of 0 compared to the input, due to the re-inversion of the signal. Consequently, the final output signal is 250 times attenuated when compared to the initial input signal.

The simulation results presented in Fig 7 highlight the effective signal processing stages involved, including attenuation, amplification, inversion, and offset correction, which leads to the final desired output.

IV. Hardware Results

This section describes the results obtained after implementation of the proposed HV probe design. The attenuator output is shown in Fig 8 when a 200 V peak-to-peak square wave input signal is applied which results in a 100 mV peak-to-peak output.

$$V_{\text{out,attenuator}} = \frac{200}{2000} = 100\ \text{mV}. \tag{5}$$

Fig 9 shows the output voltage after the isolation amplifier stage, which matches with the expected value.

$$V_{\text{out,isolation}} = 8 \times 100\,\text{mV} = 800\,\text{mV}. \tag{6}$$

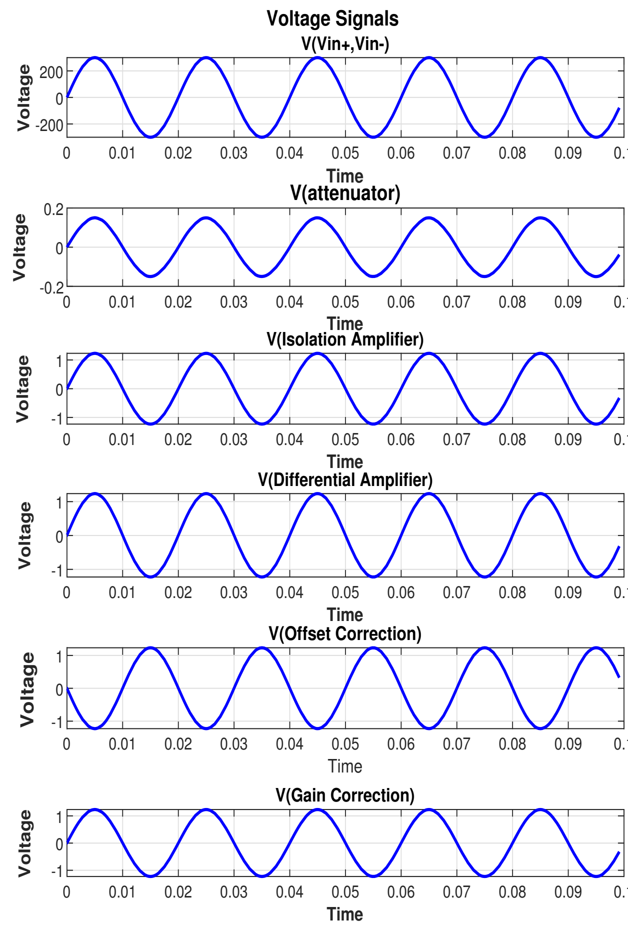

Fig. 7. LTSpice simulation results of each stage

Fig 10 shows the output voltage referenced to ground of the differential amplifier stage with unity gain. The expected output voltage of the differential amplifier stage should be 800 mV, whereas the obtained voltage obtained is 824 mV.

$$V_{\text{out,differential}} = 800\,\text{mV} \times 1 = 800\,\text{mV}. \tag{7}$$

Fig 12 shows the output voltage of the offset correction stage by providing 300 mV offset. Fig 11 shows the output voltage after the gain correction stage by providing an amplification factor of 2 .

$$V_{\text{out, gain}} = 2 \times 800\,\text{mV} = 1.6\,\text{V}. \tag{8}$$

In Fig 13, an experimental evaluation of the proposed HV probe design is presented alongside the industry standard Tektronix (P5200A) high voltage isolated differential probe. The results obtained for a square wave input signal of 200V peak-peak, 50 Hz demonstrate the results obtained from the Tektronix voltage probe and the proposed HV probe design closely match other, which serves as a compelling validation of the effectiveness and performance of the proposed HV probe design.

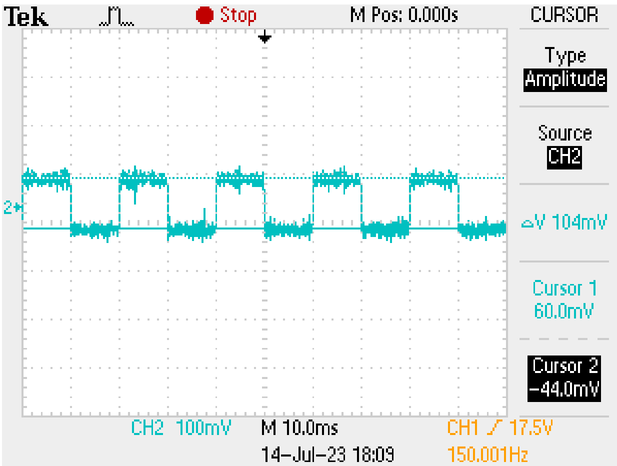

Fig. 8. Attenuator output

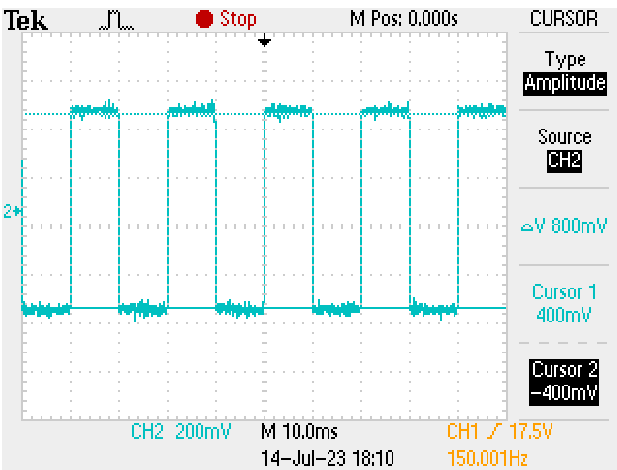

Fig. 9. Isolation amplifier output

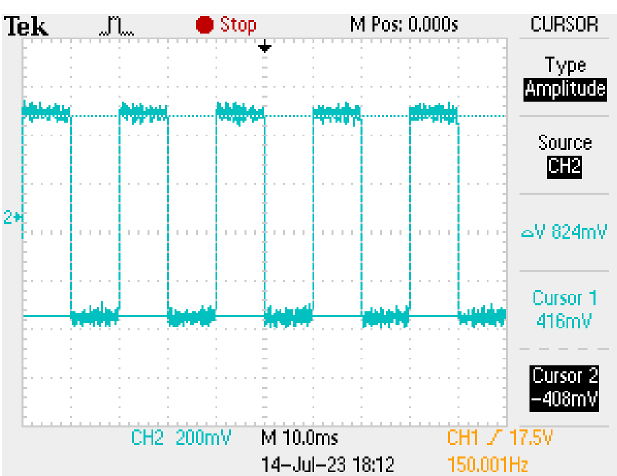

Fig. 10. Differential amplifier output

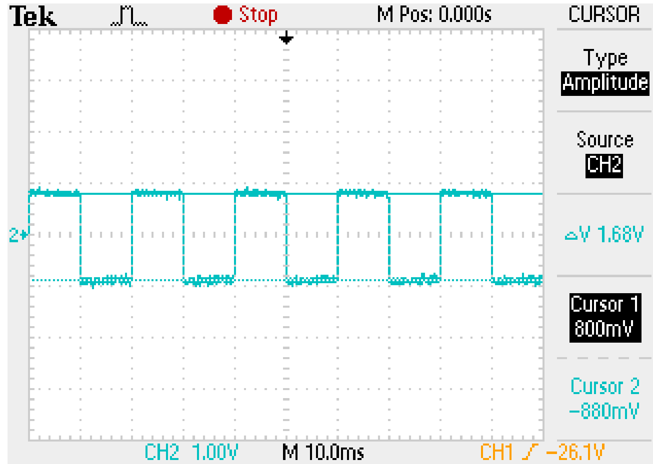

Fig. 11. Gain corrected output

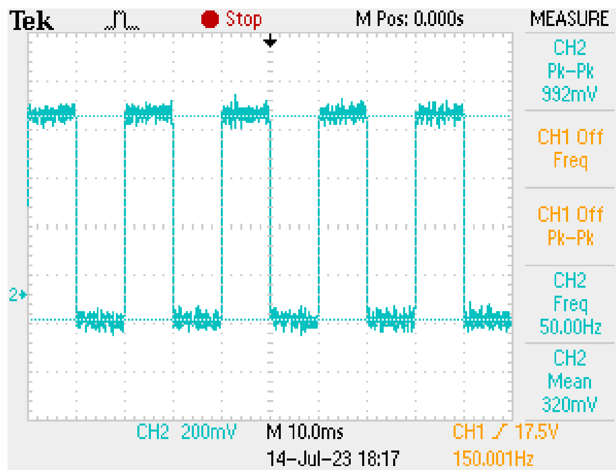

Fig. 12. Offset corrected output

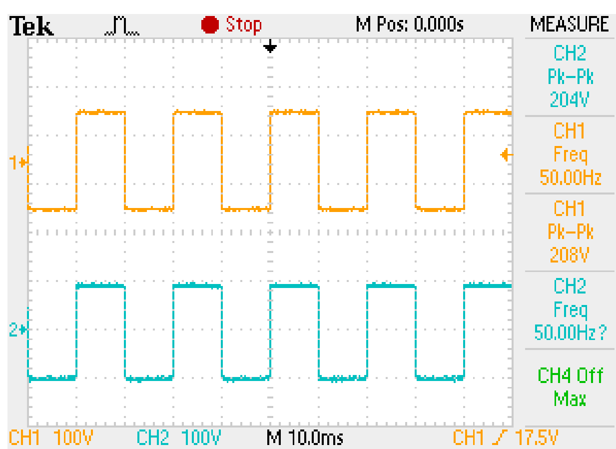

Fig. 13. Comparison plots of proposed HV probe with Tektronix probe

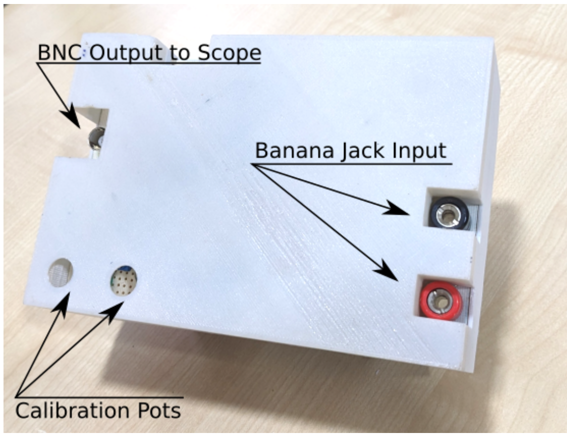

Fig. 14. First prototype with 3D printed enclosure showing banana-jack inputs and single BNC output. Potentiometers for calibration are accessible on the front panel

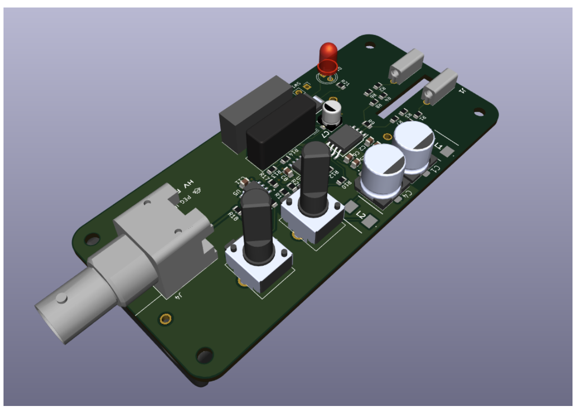

Fig. 15. Optimized layout with all-SMD components, clearance distances and compact design

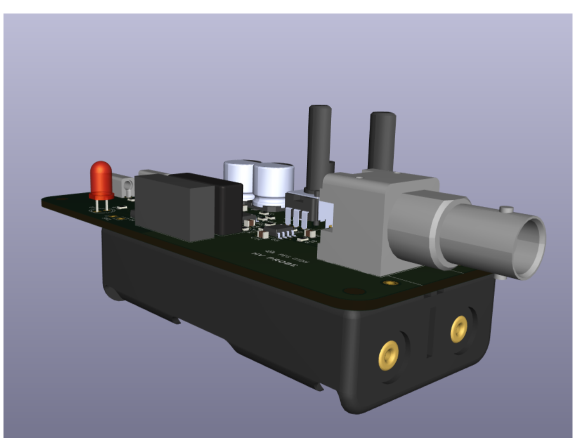

Fig. 16. 3D render of optimized layout sized to fit on the back of a 2S - 18650 battery holder.

TABLE I
COMPARISON OF DIFFERENT HIGH VOLTAGE PROBES FOR MEASUREMENTS

Probe Type	**Bandwidth**	**Voltage Rating [V]**	**Cost [$]**
Isolated Probe [8]	1 MHz	±1500	-
Differential Probe	20 MHz	±1000	-
Testec (SI-9001)	25 MHz	70,700	350
Proposed HV Probe	300 KHz	±600	50

V. Conclusion

A high-voltage isolated differential probe with a unique, low-cost design that can accurately measure differential voltage signals up to 600V has been proposed. The design of the proposed probe has been validated through simulation and hardware prototype. The results obtained show that the proposed probe can provide accurate voltage measurements of high voltage differential signals with good linearity and minimal distortion, thus making it a viable cost-effective and reliable alternative for high voltage measurements in laboratory applications.

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