“A digital isolated high voltage probe for measurements in power electronics”



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# A Digital Isolated High Voltage Probe for Measurements in Power Electronics

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***Abstract*—For the development and optimization of highly efficient power electronic systems, it is essential to precisely measure voltage signals of fast-switching high voltage semiconductors. Due to various reasons off-the shelf high voltage differential probes are not suitable for those measurements. In this paper a digital isolated high voltage probe, especially designed for measurements in power electronics, is presented. The analog to digital conversion of the input signal is already done at the probe, the galvanic isolation is done on the digital lines. In the paper a detailed explanation about the development is given as well as an extensive characterization of a built prototype. The prototype withstands a permanent isolation voltage of 1500 V. It continuously streams 18 bit ADC data at a sampling rate of 5 MS/s. Special care is taken to reach a flat frequency response and a superb linearity up to the maximum differential input voltage of 1500 V.**

***Index Terms*—Automotive electronics, power electronics, instruments–probes, power measurement, voltage measurement**

## I. Introduction

Power electronics are playing a dominant role in the 21st century, because they are the key to high efficient power converter systems [1]. One example for such a system is the electric drivetrain of an electric vehicle (EV), hybrid electric vehicle (HEV) or fuel cell electric vehicle (FCEV). Here an inverter is used to transform a dc voltage, delivered by a battery or a fuel cell, into a variable-frequency 3-phase ac voltage to power a motor (Fig. 1). A further example is a photovoltaic system; here an inverter is used to transform the dc voltage, delivered by the photovoltaic cells, into a constant-frequency 3-phase voltage system (Fig. 2). For the development and optimization of such systems, it is essential to precisely measure in- and output voltages of the inverter. Since power electronics use fast-switching semiconductor devices to approximate sinusoidal output voltages, the voltage signals not only contain the fundamental wave but also some high frequency harmonics. Especially for power and efficiency measurements of inverters it is very important to also measure those harmonics with an adequate accuracy [2], [3].

### *A. High Voltage Differential Probe*

The state of the art probe for measuring floating high voltage signals is the high voltage differential probe (Fig. 3). Nearly every manufacturer of oscilloscopes and electrical

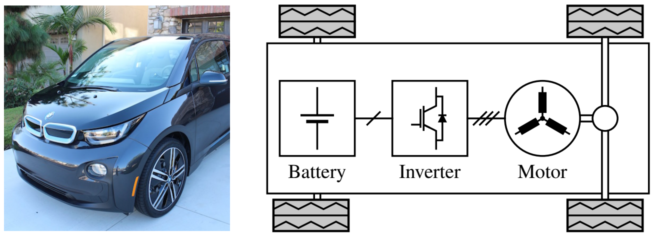



Fig. 1. Automotive electric drivetrain: A battery provides the energy; further an inverter generates a variable-frequency 3-phase voltage to power the motor.

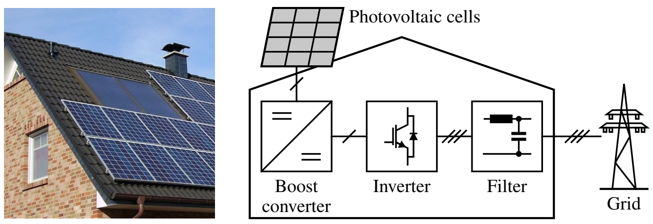



Fig. 2. Photovoltaic system: First the small dc voltage of the photovoltaic cells is increased by a boost converter; afterwords the inverter builds a constant-frequency 3-phase ac voltage to connect to the grid.

measurement equipment offers a few different types. It consists of two well matched input voltage dividers and a differential amplifier. The ground related output signal is the scaled down input differential voltage. High voltage differential probes, especially developed and characterized for measurements on power electronics, are shown in [4], [5].

### *B. Isolated High Voltage Probe*

For some applications the use of a high voltage differential probe is not possible. One example is the measurement of the gate-emitter voltage in power electronics. The relatively small gate control voltages are superimposed by high voltage common mode jumps. Thus, the voltage probe requires a very high common-mode rejection ratio (CMRR). A further example is the measurement of the inverter output voltages where the inverter is already assembled in an EV. For that purpose an isolated measurement concept is necessary, because the earth connected measurement with a differential

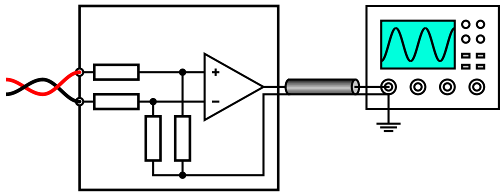
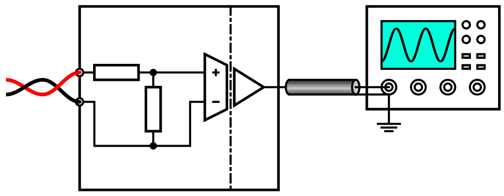
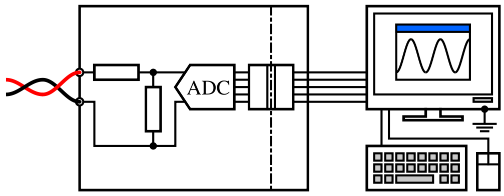


Fig. 3. High voltage differential probe: Two well matched input dividers scale down both input voltages; further a differential amplifier outputs the scaled down input differential voltage.



(a) Analog isolated high voltage probe




(b) Digital isolated high voltage probe

Fig. 4. Isolated high voltage probe; the signal isolation of such a probe may either be done at the analog signal or at the digital interface.

high voltage probe could cause an isolation error. Isolated oscilloscopes or battery powered oscilloscopes should not be used for floating measurements in power electronics [4]. The isolation in isolated oscilloscopes is not designed for continuous operation at several hundreds of volts; battery powered oscilloscopes, may introduce a large capacitance to earth. Thus, it is recommended to use isolated high voltage probes. The signal isolation of an isolated probe may either be done at the analog signal or at the digital interface.

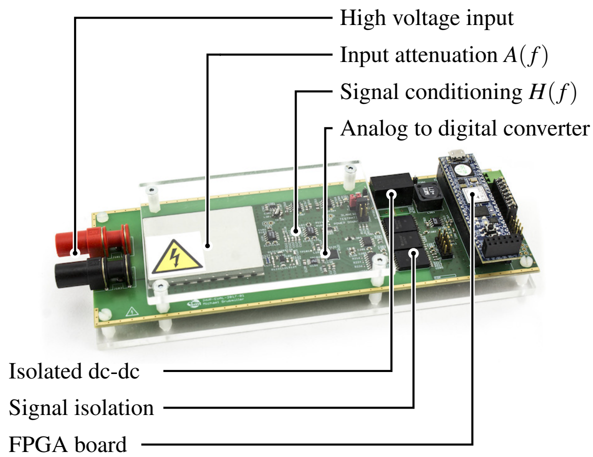
*1) Analog Isolated High Voltage Probe:* An analog isolated high voltage probe uses a high voltage divider to scale down the input voltage and an isolation amplifier to isolate the output from the input. The isolation amplifier could also be replaced by a fiber optic transmission system [6], [7]. The advantage of an analog fiber optic transmission is, that there is no limitation regarding the isolation voltage; drawbacks are the poor linearity and a strong aging effect.

*2) Digital Isolated High Voltage Probe:* In a digital isolated high voltage probe the analog to digital conversion is already done in the probe. The isolation is done by isolating the digital data lines. This may be realized by a digital isolation integrated circuit (IC), a digital fiber optic transmission or even wireless. In [8], [9], a Bluetooth probe is shown; with this approach the cabling can be reduced, especially when there are more measurement points at the same time, e.g. measuring all 3 inverter output voltages and the dc input. A drawback of this probe is, that the Bluetooth data transfer is too slow for continuous transmission of high-sampling-rate and high-resolution data. Thus only short time slots are measured and stored in a memory before they get transmitted.

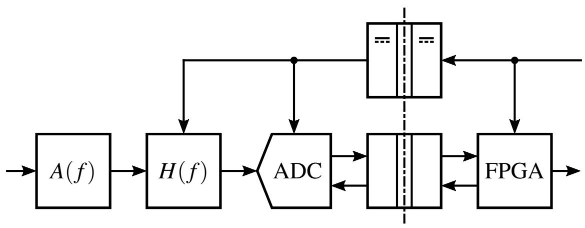
In this paper the authors present their work on a digital isolated high voltage probe with a continuous isolation voltage of 1500 V. The probe continuously streams the 18 bit ADC data at a sampling rate of 5 MS/s. Special care is taken to reach a flat frequency response and a superb linearity over the complete input voltage range of ±1500 V.

## II. Development of a Digital Isolated High Voltage Probe

The basic concept of a digital isolated high voltage probe is shown in Fig. 4b; a more detailed block diagram and a foto of the built prototype is given in Fig. 5. At first the high




(a) Prototype




(b) Block diagram

Fig. 5. Prototype and block diagram of the developed digital isolated high voltage probe.

input voltage gets attenuated by $A(f)$. Further some analog signal conditioning $H(f)$ is necessary, before the analog-to-digital conversion is done. Output lines and input control signals of the ADC are galvanically isolated with digital isolation components. The control of the the ADC and the data transmission from the ADC to a computer is implemented in an FPGA. To power the galvanic isolated part of the circuit an isolated dc-dc module is used. In the following sections, the particular stages are explained more in-depth.

### A. Input Attenuation

The input stage of the probe is a frequency-compensated resistive-capacitive voltage divider [10]–[12]. The divider has an input impedance of $4\,\mathrm{M}\Omega$ parallel with $5.5\,\mathrm{pF}$. To reach high linearity, resistors with very low temperature and voltage coefficient ($25\,\mathrm{ppm/K}$, $1\,\mathrm{ppm/V}$) and capacitors with C0G dielectric are chosen. The dividers' attenuation $A = 1/750$ leads to an output voltage of $\pm 2\,\mathrm{V}$ at the maximum input voltage of $\pm 1500\,\mathrm{V}$. In order to reach a defined stray capacitance, necessary for a well defined frequency response, a shield is put around the divider. A detailed circuit and an in-depth simulation framework including the parasitic behavior of the passive components and a stray capacitance approximation has already been presented by the authors [5], [13].

### B. Signal Conditioning

Some analog signal conditioning circuitry is applied to interface the input attenuator to the ADC. First, a programmable gain amplifier (PGA) is used to expand the dynamic range of the ADC. The PGA has a switchable gain of 1, 2, 5, 10 and 20, enabling additional input voltage ranges of $750\,\mathrm{V}$, $300\,\mathrm{V}$, $150\,\mathrm{V}$ and $75\,\mathrm{V}$. Second, a fully differential amplifier generates the differential input signal, necessary for the ADC. The fully differential amplifier is also used as an anti-alias filter, implemented with a multiple feedback (MFB) topology. The filter is a 3rd order Bessel type with a $-3\,\mathrm{dB}$ cutoff frequency at $1\,\mathrm{MHz}$ and a dc gain of 2.

### C. Analog-to-Digital Conversion

The used ADC is the LTC2385-18 from Linear Technology, an 18 bit successive approximation register (SAR) type with $5\,\mathrm{MS/s}$ sampling rate. The component is chosen for its excellent linearity (maximum $\pm 1.5$ LSB integral linearity error) and the very good signal-to-noise ratio (SNR) of $95.7\,\mathrm{dB}$.

### D. Isolation

Before choosing any isolation component for power or signal isolation, one has to understand the terminology for isolation ratings. Definitions are given in different standards; a good summery is given in [14]. Datasheets of isolation ICs and dc-dc modules usually advertise a very high isolation voltage at their first page. It is very important to know that this is only a transient isolation voltage, tested for $60\,\mathrm{s}$ (qualification testing) or $1\,\mathrm{s}$ (production testing), but must not be applied continuously. For that reason some manufacturers also give a value for the maximum isolation working voltage or some kind of conversion between transient isolation voltage and maximum isolation working voltage.

*1) Supply isolation:* For isolating the power supply a Recom R05P05S/X2/R8 is used. It is a $1\,\mathrm{W}$ unregulated dc-dc converter with $5\,\mathrm{V}$ in- and output voltage. It has a reinforced isolation of $8\,\mathrm{kV}$ (tested for $1\,\mathrm{s}$) and may be used for a continuous isolation voltage of $4\,\mathrm{kV}$ [15]. The added isolation impedance due to the converter is $15\,\mathrm{G}\Omega$ parallel with $10\,\mathrm{pF}$.

*2) Signal Isolation:* For isolating the digital ADC in- and output lines, isolation ICs of the ISO7820x and ISO7830x series of Texas Instruments are used. These parts are the only parts available, combining a high data rate ($100\,\mathrm{Mb/s}$) with a very high maximum isolation working voltage ($2000\,\mathrm{V}$) and high common-mode transient immunity ($\pm 100\,\mathrm{kV}/\mu\mathrm{s}$). The added isolation impedance due to the isolation ICs is about $300\,\mathrm{G}\Omega$ parallel with $3\,\mathrm{pF}$.

To guarantee the high isolation not only on component level but also on system level, all creepage distances between the isolated circuit parts are chosen according to [16]. In addition the printed circuit board (PCB) is milled underneath the digital isolation ICs and the dc-dc module to prevent any deposition of conductive dirt or moisture.

### E. Control and Data Transmission

To control and readout the ADC, and transfer the ADC data to a computer, a field programmable gate array (FPGA) is used. The FPGA continuously outputs the ADC data via two $100\,\mathrm{Mb/s}$ UARTs. The UART signals are sampled by a logic analyzer and further streamed to a computer over USB.

## III. Experimental Characterization

In the following sections, the performance of the built prototype of the digital isolated high voltage probe is analyzed. Measurement procedures and results are presented.

### A. Noise and SNR

To measure the output noise, positive and negative input of the probe are shorted and $1 \cdot 10^6$ ADC samples $d_i$ are taken. The RMS output noise $E_{\mathrm{out}}$ is then calculated by

$$E_{\mathrm{out}} = \sigma(d_i)\,, \tag{1}$$

where $\sigma(d_i)$ is the standard deviation of the ADC samples $d_i$. For better interpretation the input referred noise $E_{\mathrm{rti}}$ is calculated by

$$E_{\mathrm{rti}} = E_{\mathrm{out}} \cdot V_{\mathrm{lsb}} \cdot \frac{A}{H}\,, \tag{2}$$

where $V_{lsb}$ is the voltage of the least significant bit of the ADC, $A$ is the attenuation of the input divider and $H$ is the gain of the programmable gain amplifier and the fully differential amplifier. Thus the SNR expressed in dB-full-scale (dBFS) results to

$$\mathrm{SNR} = 20 \cdot \log_{10}\left(\frac{\widehat{v}_{\mathrm{in,max}}/\sqrt{2}}{E_{\mathrm{rti}}}\right), \tag{3}$$

where $\widehat{v}_{\mathrm{in,max}}$ is the maximum allowable input voltage of the particular input range. Results of the measurements are shown in Tab. I.

### B. Frequency Response

For the measurement of fast-switching signals, the probe's frequency response is a very important parameter. Since the

TABLE I
NOISE, SNR AND BANDWIDTH OF THE PROTOTYPE

| **Input Range** $\widehat{v}_{\text{in,max}}$ (V) | **Noise** $E_{\text{rti}}$ (mV) | **Signal-to-noise** SNR (dBFS) | **Bandwidth** $f_{-3\,\text{dB}}$ (MHz) |
|---|---|---|---|
| 1500 | 30.5 | 90.8 | 1 |
| 750 | 20.6 | 88.2 | 1 |
| 300 | 15.4 | 82.8 | 0.9 |
| 150 | 13.3 | 78.0 | 0.8 |
| 75 | 11.3 | 73.4 | 0.6 |

absolute value can easily be calibrated, the relative frequency response $G/G_0$ is more significant.

$$G/G_0 = \frac{G(f)}{G(f = 10\,\text{Hz})} \tag{4}$$

$$= \frac{\widehat{d}(f)/\widehat{v}_{\text{in}}(f)}{\widehat{d}(f = 10\,\text{Hz})/\widehat{v}_{\text{in}}(f = 10\,\text{Hz})} \tag{5}$$

The measurement is done with a 0.1 % full-scale range (FSR) small signal input amplitude of $\widehat{v}_{\text{in}} = 1.5\,\text{V}$. Fig. 6 shows the Bode plot of the prototype's frequency response compared to the simulated curve of an ideal 3rd order Bessel filter. Fig. 7 shows the Bode plot in linear scale. It also shows the comparison of the prototype with a simulation of an ideal 3rd order Bessel filter as well the result of a detailed circuit simulation, including parasitic behavior of the passive components and models of the used op-amps. It can be seen that the prototype has a frequency response flatness better than $\pm 1\,\%$ up to 100 kHz.

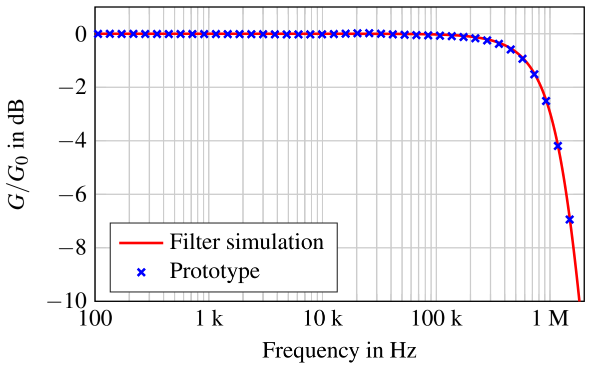



Fig. 6. Relative frequency response of the prototype. The simulated curve shows the frequency response of an ideal 3rd order Bessel filter.

## C. Common-Mode Rejection Ratio

For measurements on power electronics a probe with a high CMRR is necessary. The CMRR evaluation of the developed probe is done by first applying a sinusoidal voltage with an amplitude of $\widehat{v}_{\text{in,d}}$ at the probes' inputs and measuring the output amplitude $\widehat{d}_{\text{d}}$. In a second step the inputs are shorted and a sinusoidal voltage with the amplitude $\widehat{v}_{\text{in,cm}}$ is applied

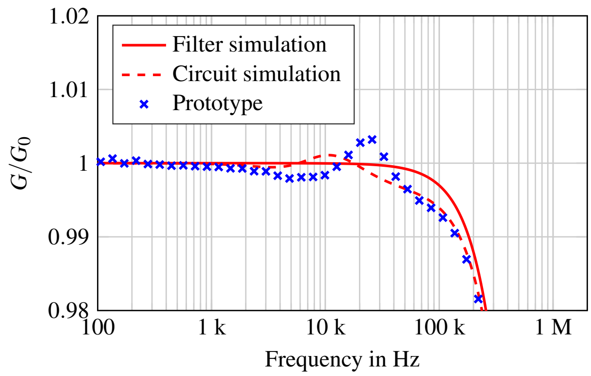



Fig. 7. Relative frequency response of the prototype in linear scale. The simulated curves show the frequency response of an ideal 3rd order Bessel filter and a circuit simulation of the whole analog input circuit.

as a common-mode signal, resulting in an output amplitude of $\widehat{d}_{\text{cm}}$. Further the CMRR can be calculated by

$$\text{CMRR} = 20 \cdot \log\left(\frac{G_{\text{d}}}{G_{\text{cm}}}\right) = 20 \cdot \log\left(\frac{\widehat{d}_{\text{d}}/\widehat{v}_{\text{in,d}}}{\widehat{d}_{\text{cm}}/\widehat{v}_{\text{in,cm}}}\right). \tag{6}$$

As the amplitude of the input differential signal is equal to the amplitude of the input common mode signal, $\widehat{v}_{\text{in,d}} = \widehat{v}_{\text{in,cm}}$, the calculation can be simplified to

$$\text{CMRR} = 20 \cdot \log\left(\frac{\widehat{d}_{\text{d}}}{\widehat{d}_{\text{cm}}}\right)\Bigg|_{\widehat{v}_{\text{in,d}} = \widehat{v}_{\text{in,cm}}}. \tag{7}$$

Fig. 8 shows the resulting CMRR of the prototype. It displays a very high CMRR for low frequencies; for higher frequencies the CMRR decreases but still remains over 60 dB up to 2 MHz. The good CMRR values can only be reached by putting a shield around the divider, the analog circuitry and the ADC.

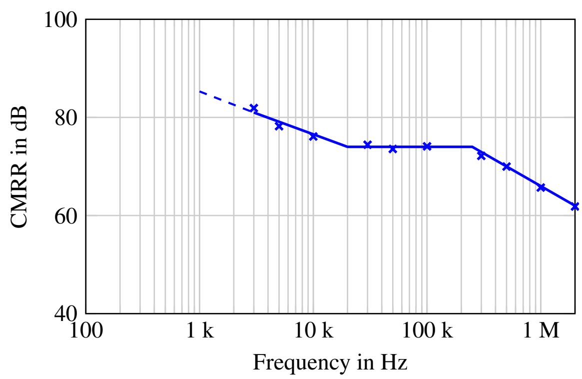



Fig. 8. Measured common-mode rejection ratio of the prototype.

## D. Rise/Fall Time and Propagation Delay

To measure rise/fall time and propagation delay of the probe, a square wave with 10 V amplitude is applied at the probe's input. Rise and fall time of the input signal is 2 ns. Fig. 9 shows the resulting output signal. It displays a

TABLE II
COMPARISON OF DIFFERENT HIGH VOLTAGE PROBES FOR MEASUREMENTS IN POWER ELECTRONICS

| | | **Tektronix P5202A [18]**<br>Differential probe | **Grubmüller et al. [5]**<br>Differential probe | **Lobsiger et al. [9]**<br>Isolated probe | **Presented probe**<br>Isolated probe |
|---|---|---|---|---|---|
| Input voltage | | | | | |
| - Differential | V | ±1300 | ±1000 | - (a) | ±1500 |
| - Common mode | V | ±1300 | ±1500 | > 1 M | ±1500 |
| Input impedance | | | | | |
| - Differential | MΩ ∣∣ pF | 10 ∣∣ 2 | 8 ∣∣ 2.8 | - (a) | 4 ∣∣ 5.5 |
| - To ground | MΩ ∣∣ pF | 5 ∣∣ 4 | 4 ∣∣ 5.5 | - | - |
| Isolation | | | | | |
| - Technique | | - | - | Bluetooth | Isolation IC |
| - Impedance | GΩ ∣∣ pF | - | - | >> | > 1 ∣∣ 13 |
| Bandwidth | MHz | 50 | 20 | 100 | 1 |
| CMRR | | | | | |
| - DC | dB | > 80 | 60 | - | > 80 |
| - Medium frequency | dB @ Hz | > 60 @ 100 k | 66 @ 100 k | > 80 @ 200 k (b) | 74 @ 100 k |
| - High frequency | dB @ Hz | > 30 @ 3.2 M | 62 @ 1 M | - | 66 @ 1 M |
| Analog-to-digital | | | | | |
| - Sample rate | MS/s | - | - | 400 | 5 |
| - Memory length | Samples | - | - | 200 k | - (c) |
| - Resolution | bit | - | - | 8 | 18 |

[a] The probe does not have a high voltage input - it has to be combined with a passive oscilloscope probe.
[b] Result in combination with a 10:1 passive oscilloscope probe.
[c] No memory on the device - continous streaming to a computer.

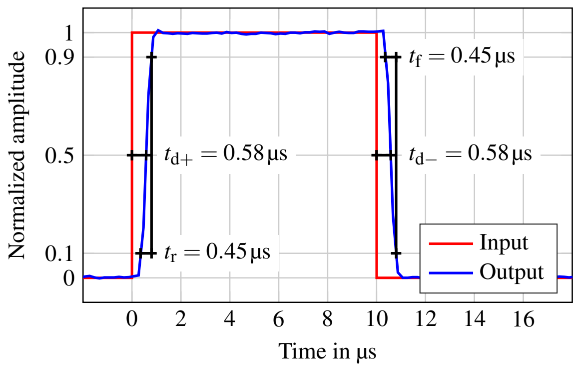



Fig. 9. Timing values of the prototype. The measurement is done with a 10 V amplitude square wave at the probes' input.

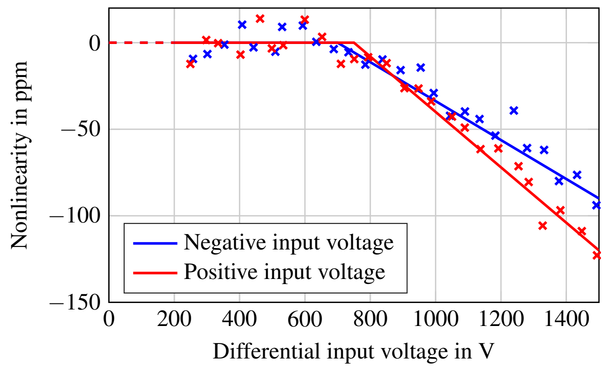



Fig. 10. Nonlinearity of the prototype for high voltage dc input voltages up to the full-scale range of ±1500 V.

symmetric behavior for falling and rising edges; propagation delay is 0.58 $\mu$s for both edges, rise and fall time is 0.45 $\mu$s.

### *E. Nonlinearity*

The measurement of the nonlinearity is done by applying a high voltage dc differential signal at the probes' input. The signal is provided by a high voltage dc source. It delivers a symmetrical high voltage around earth potential; the voltage is measured with two Keithley 2100 6 1/2 digit desk multimeters. Further the nonlinearity is calculated according to [17]. First the nominal gain of the probe is defined by a linear least square fit of the gain for input voltages from 0 to 50 % of the full-scale range. Second, the nonlinearity is then expressed by the deviation of the measured gain from the nominal gain of the previous step. Fig. 10 shows the resulting nonlinearity for negative and positive input voltages ranging up to the full-scale of ±1500 V. The resulting nonlinearity is better than 150 ppm.

### *F. Comparison*

Table II shows a comparison of a high-end differential high voltage probe from Tektronix [18], a differential high voltage probe previously presented by the authors [5], a Bluetooth isolated probe [9] and the presented probe. It can be seen that isolated probes have a better CMRR than differential probes. By comparing the Bluetooth probe with the presented probe, it is clear that both probes are designed for different use cases. The Bluetooth probe was designed for fast, very wide bandwidth short term measurements, like the measurement of the gate-emitter voltage of power converters. The presented probe is built for high precision continuos high voltage measurements, like necessary for power and efficiency measurements of automotive and solar inverters.

## IV. Summary

In this paper the authors present a digital isolated high voltage probe for measurements on power electronics. The experimental evaluation of a prototype shows, that the probe is suitable for measurements of fast-switching high voltage signals. Low noise, flat frequency response and very good linearity confirms that the probe can be used for high accuracy measurements.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