Characterization of an Oil-Insulated Capacitive Voltage Divider for Transient Overvoltage Measurement

J. A. Zamora, E. Aguilera, E. Soto, J. C. Chacón

***Abstract*-- A voltage divider is a device designed to reduce the amplitude of a high-voltage signal so that an instrument can safely measure it. The sensed signal is proportionally reduced, allowing the actual magnitude of the signal to be determined by the low-voltage output signal provided by the divider. This device is widely used in systems for measuring induced voltages in overhead electrical networks, making it crucial to understand its transformation ratio and the frequency spectrum it can capture. This article presents the characterization of an oil-insulated capacitive voltage divider, providing a comprehensive description of the device and its tests. Through visual inspection and a model built in CST Studio 2022, the parameters shaping the circuit scheme of the divider are identified, and their respective values are calculated or measured. In the same constructed model, applying an impulse equivalent to its maximum supported voltage is simulated to observe the behavior of the divider internally. Laboratory tests reveal a transformation ratio 5287:1 with a standard deviation of 58.8 V and an optimal operating frequency range between 30 Hz and 2.4 MHz. These experimental data can be a reference when using this divider to record and measure transient overvoltages.**

***Keywords*: capacitive voltage divider, voltage division ratio, frequency response, electromagnetic model, circuit parameters.**

I. Introduction

One of the most recurrent causes of failures in medium voltage overhead lines is overvoltages induced by cloud-to-ground lightning strokes occurring in their vicinity. In order to implement protection strategies against these induced overvoltages, it is pertinent to understand their characteristics thoroughly. Hence, measurement campaigns are conducted on overhead networks using equipment designed for such signals. Examples include measurements taken in Pretoria, South Africa [1], along the coastal area of Fukuy, Japan [2], in the state of Florida, USA [3], at the University of Sao Paulo, Brazil [4], in a rural test field in Guangzhou, China [5], in the Santo Angelo region in southern Brazil [6], and in the central region of Colombia [7] [8].

Voltage dividers, which function to proportionally reduce the magnitude of the overvoltage so that the waveform can be recorded by a measuring instrument, typically an oscilloscope, make the measurement of transient overvoltages in overhead lines possible. While manufacturers of these devices disclose their technical specifications, it is recommended to experimentally validate their characteristics in order to interpret the obtained data more accurately. During the preparations for a measurement campaign in Samana, Colombia [7], a voltage divider specially designed for transient overvoltages is tested, and its division ratio is determined to be 4975:1 without being able to validate the frequency range experimentally. Later, a divider with similar properties is tested in La Palma, Colombia [8] to determine its division ratio and frequency range. Other works reference the study of a resistive voltage divider used in electric vehicle applications [9], the design of a voltage divider with an electronic isolation interface for power measurements [10], the proposal of three error estimation techniques in resistive dividers for signals up to 200 kHz [11], the design and manufacturing of a divider with ceramic capacitors submerged in epoxy resin within an insulator [12], the characterization of an air-insulated capacitive voltage divider [13], the theoretical and experimental study of a transformerless diode-capacitor voltage divider for kinetic energy harvesters [14], a DC Voltage precision resistive divider performing decade ratios from 10:1 to 107:1 for the calibration of nanovoltmeters from 1 µV to 10 V [15], a calibration device and measuring method of power frequency high voltage divider by means of the difference comparison method [16], the analysis of a capacitive voltage divider desing for measuring µs and ns characteristic time voltage occurrence [17], and the development and verification of capacitive voltage divider for measuring fast transient phenomena in the ns range with frequencies up to 500 MHz [18].

During the year 2024, a measurement campaign of induced voltages is carried out on an overhead distribution network in Barrancabermeja, a municipality in the heart of the Magdalena River Valley, between the foothills of the eastern mountain range and the Magdalena River, in Colombia. The air currents rising from the mountain range collide with higher-altitude air currents, and in this interaction, electrical charges are

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generated, which are responsible for the formation of lightning. As a result, this region experiences high lightning activity, which in turn exposes the electrical networks in the area to a significant number of induced voltages, putting their proper functioning at risk. Therefore, the overhead networks installed in this region can provide a considerable amount of induced voltages, facilitating the analysis of this phenomenon in tropical areas. The design and construction of the induced voltage measurement system implemented in this campaign it is considered to include a voltage divider capable of withstanding more than 50 kV of input, reducing the voltage signal to levels low enough for an oscilloscope to record it, and producing at its output a voltage waveform identical to the transient input voltage. Indeed, it is necessary to experimentally validate the properties of the voltage divider selected for this measurement campaign. This study aims to experimentally characterize an oil-insulated capacitive voltage divider, which includes proposing a circuit diagram representative of the device, simulating its behavior under maximum supported voltage, determining its transformation ratio, and validating its frequency range. This article is organized as follows: Section II provides a detailed description of the divider and presents the technical specifications given by the manufacturer. Section III concisely describes the simulations and laboratory tests to be performed. Section IV presents the results of each test, including the circuit diagram of the divider along with the values of its circuit parameters, the behavior of the divider under maximum supported voltage, its transformation ratio, and its frequency range. Section V presents the conclusions of this work.

II. Capacitive Voltage Divider Under Study

The voltage divider under study is cylindrical, with a height of 46 cm and a maximum diameter of 21 cm. Fig. 1 shows its internal device (left) and external cover (right).

Fig. 1. Capacitive voltage divider: internal components (left) and their outer cover (right).

The external cover consists of an outer solid base of laminated aluminum, 5 cm in height, with an external diameter of 21 cm and an internal diameter of 17 cm, onto which a hollow HDMW polymer cap is screwed. This cap is 39 cm in height, with a thickness of 15 cm and a depth of 32 cm. The top of the HDMW cap features a finish similar to high-voltage pin-type insulators. The purpose of the external cover is to house the internal device and keep it immersed in dielectric transformer oil to increase its dielectric strength compared to air, thereby extending the voltage range it can withstand. Fig. 2 shows a longitudinal view of the voltage divider's interior, detailing the internal device's components and those of the external cover. The high-voltage signal is transmitted by a solid aluminum rod with a diameter of 6 mm from the outside of the cover to a central electrode held by an acrylic lid. An inner base supports the acrylic lid and a middle cylinder with a height of 3.8 cm and an internal diameter of 9.4 cm. Just 1.2 mm below the middle cylinder, an electrically isolated pickup ring with a height of 6.4 mm and an internal diameter of 9.4 cm is found. This ring is connected to the central conductor of a 50 Ω BNC connector through a 50 Ω resistor.

In contrast, the ground of the BNC connector is connected to the pickup ring via four parallel polyester capacitors. The central electrode, the inner base, the middle cylinder, and the pickup ring are concentric. Their geometry and positioning allow for forming capacitances, which, together with the polyester capacitors, ensure that the output low voltage in the BNC connector is proportional to the input high voltage. The grounding of the divider is achieved through the external base. The inner base is attached to the outer base, and the middle cylinder is attached to the inner base, so these three parts have electrical continuity and are grounded. The ground of the BNC connector is connected to the inner base via a wire, ensuring that the connector's ground is the same as that of the voltage divider.

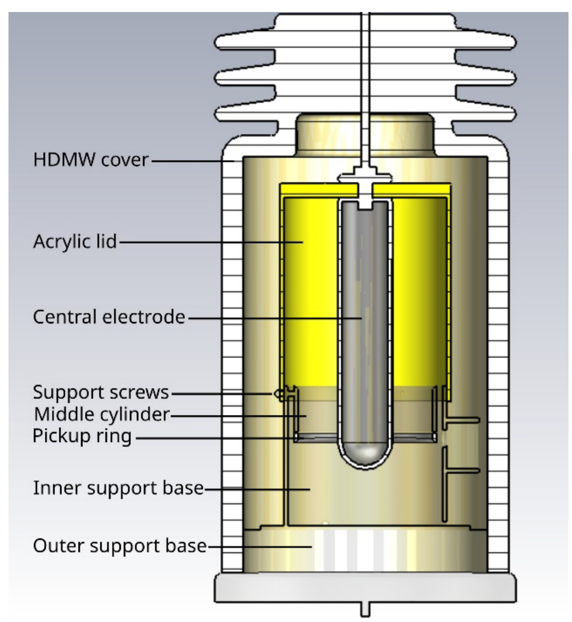

Fig. 2. Longitudinal section view of the capacitive voltage divider.

According to the technical specifications provided by the manufacturer, this voltage divider can withstand impulses of up to 300 kV. It has a transformation ratio of 5050:1, measured in insulating oil at a temperature of 35 °C with an accuracy of 5%. For a load of 1 MΩ, it has a frequency range between 30 Hz and 4 MHz and a droop rate of 0.02 %/μs. The high-voltage insulating oil in the divider has a density of 0.88 g/cm3, a dielectric strength of 15.7 kV/mm, and a dielectric constant of 2.33.

III. Test to be Performed

A. Calculation of Circuit Parameters

A full-scale model of this fully assembled device is first created in CST Studio 2022 software to characterize the capacitive voltage divider under study. The full-scale model aims to thoroughly inspect the divider, determine its equivalent circuit, and calculate its respective parameters using E-Static Solver. The values of the four polyester capacitors and the resistor are also measured with an AMPROBE LCR55 A multimeter.

B. Maximum Voltage Simulation

In the voltage divider model constructed in CST Studio 2022 software, a 300 kV impulse is simulated at the high voltage input to observe the electric fields that arise inside the device when subjected to the maximum voltage it can theoretically withstand. Observing the electric fields is expected to determine whether there is no arcing inside the divider when subjected to its maximum voltage.

C. Transformation Radio Test

Fig. 3 shows the HAEFELY WO 533090 system used to generate the lightning-type impulses required for this test.

Fig. 3. The HAEFELY WO 533090 impulse generator used in the transformation ratio test.

The test consists of applying four lightning-type impulses with theoretical parameters of 1.2 μs front time and 50 μs tail time, with peaks between 37.5 kV and 203.2 kV in the high-voltage terminal of the divider. Through a HAEFELY CS1000 damped capacitive voltage divider with a calibrated transformation ratio of 720.5:1, an oscilloscope UNI-T UTD2102CEX measures each high-voltage pulse. Another oscilloscope of the same model captures the low-voltage signal from the divider under study to measure the output voltage peak for each applied impulse. The ratio V_{in}/V_{out} is calculated. V_{in} is the high-voltage input peak measured using the reference divider HAEFELY CS1000, and V_{out} is the low-voltage output peak obtained from the divider under study. The average of these ratios is then calculated to obtain the experimental transformation ratio. Additionally, each input voltage peak is divided by the theoretical transformation ratio of 5050:1, comparing the results obtained using the theoretical transformation ratio and the experimental results.

D. Frequency Sweep Test

This test involves injecting a sinusoidal signal of 15 $V_{pk\text{–}pk}$ into the high-voltage terminal and varying its frequency between 30 Hz and 5 MHz. A UNI-T UTD2102CEX oscilloscope measures the low-voltage signal to observe any potential variation in the output peak-to-peak voltage. This test aims to validate the frequency range within which the voltage divider can maintain a tolerable signal amplitude, meaning it is not considered attenuated.

IV. Results

A. Voltage Divider Modeling

In CST Studio 2022, a full-scale model of the capacitive voltage divider is constructed, as shown in Fig. 2. Meanwhile, Fig. 4 shows a closer view of the internal parts of the divider, illustrating the equivalent capacitances found and the formation of the circuit model representing the device.

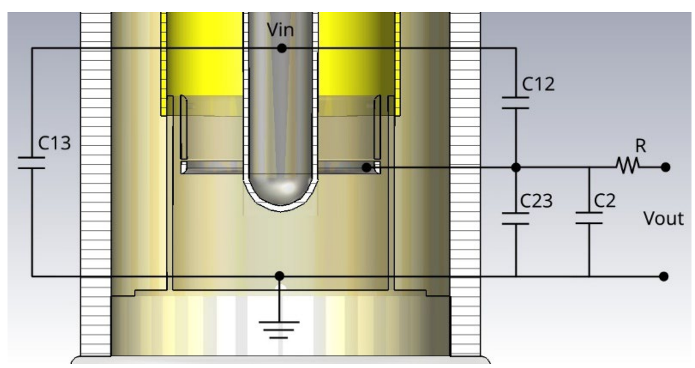

Fig. 4. Circuit diagram of the capacitive voltage divider; it shows the internal components that make up the capacitances in the circuit (see Fig. 2).

Since the outer base is connected to the inner base and the outer is connected to the middle cylinder, these three parts are modeled together as a single piece known henceforth as the base, which is grounded. A capacitance is observed between the central electrode and the base, from now on referred to as

C_{13}. A capacitance between the central electrode and the pickup ring, referred to as C_{12}, and another between the pickup ring and the base, referred to as C_{23}, are also observed. The circuit diagram includes a capacitor C_2 representing the four polyester capacitors arranged in parallel, referred to as the low voltage capacitor, and the resistor R. The CST Studio 2022 electrostatic solver allows the calculation of the circuit parameters by simulating a 300 kV impulse applied to the high-voltage contact of the divider. Table I summarizes the results obtained in this study phase. The capacitance C_{12} has a value of 1.49 pF, the capacitance C_{23} has a value of 47.36 pF, and the capacitance C_{13} has a value of 15.34 pF. The low-voltage capacitor and the resistor were also measured, recording 6 nF and 50 ohms, respectively. C_{13} does not influence the transformation ratio, but its magnitude is 10.3 times greater than C_{12}, which can reduce the impact of stray fields [13].

TABLE I
CIRCUIT MODEL PARAMETERS OF THE VOLTAGE DIVIDER UNDER STUDY

	Values	Method
C_{12}	1.49 pF	Simulated
C_{23}	47.36 pF	
C_{13}	15.34 pF	
C_2	6 nF	Measured by multimeter
R	50 Ω	

B. Maximum Voltage Simulation Results

Fig. 5 shows a longitudinal section of the electric field distribution inside and outside the voltage divider model under a simulated 300 kV impulse using the CST Studio electrostatic solver. The maximum value on the electric field scale is set at 15.7 kV/mm, equivalent to the dielectric strength of the oil in the device.

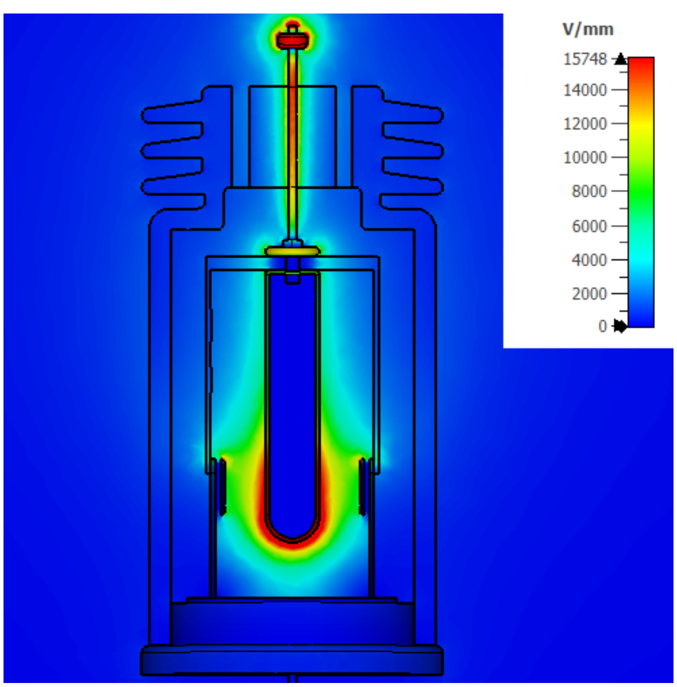

Fig. 5. Distribution of the electric field inside the voltage divider, longitudinal section view.

Considering the distances between the internal parts of the divider, the simulated electric fields do not exceed the dielectric strength imposed by the oil, meaning that under the maximum theoretical voltage, no electrical breakdown occurs in the oil. Therefore, no arcing occurs between the internal parts. The smallest distance between the internal parts of the divider is 1.2 mm between the middle cylinder and the pickup ring. In this small space, the electric field reaches a maximum value of 4.4 kV/mm, which is much lower than the value needed to cause a breakdown in the dielectric oil of the divider. These results support the claim that the capacitive divider can withstand the maximum theoretical impulse voltage. Since arcing cannot occur inside the voltage divider under a 300 kV impulse, it is evident that the calculated capacitive parameters remain stable even at the maximum supported voltage and can proportionally reduce the input signal.

C. Transformation Ratio Results

A series of lightning-type voltage pulses are applied to the capacitive divider using an impulse generator. Fig. 6 shows the results obtained from the transformation ratio test, comparing the voltages measured in the laboratory with those obtained by applying the theoretical division ratio to the input signals. On average, the transformation ratio is 5287:1 with a standard deviation of 58.8 V. A percentage error of 4.7% is observed concerning the theoretical ratio. The experimental transformation ratio allows for a more precise estimation of the input signal magnitude of the voltage divider, that is, the induced overvoltage in an overhead line.

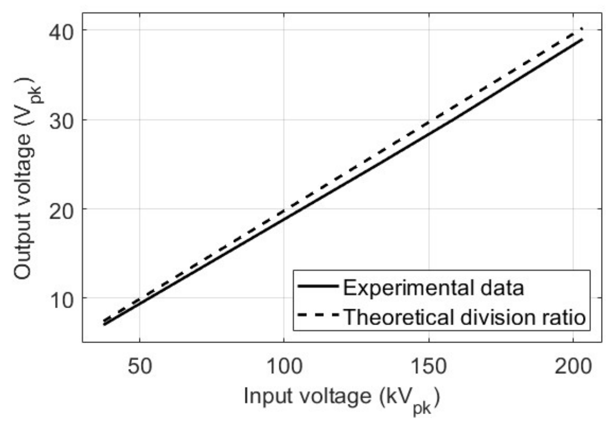

Fig. 6. Comparison between the experimental output voltage peaks and the voltages obtained through the theoretical division ratio.

Fig. 7 compares an input voltage pulse and its corresponding output signal from the divider under study. Both recordings exhibit signals similar to the standard lightning impulse. The high-voltage pulse measured with the reference divider has a tail time of 50.42 µs and a front time of 1.59 µs. Meanwhile, the output signal of the divider under study has a tail time of 49.7 µs and a front time of 1.59 µs. Fig. 8 provides a detailed view of the rise of a voltage pulse at both the input and output of the divider under study. Indeed, the voltage divider can capture even the noise in the signal input from the impulse generator. The recorded waveforms indicate that the voltage divider under study accurately reproduces transient signals similar to lightning-induced overvoltages. In fact, the device is designed for that purpose.

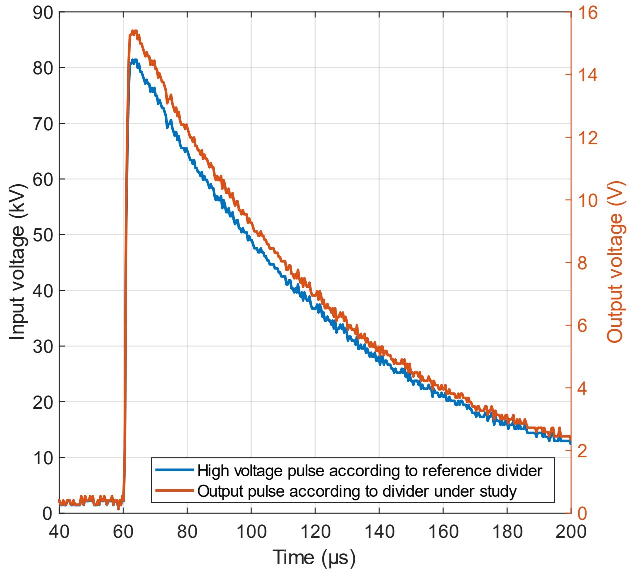

Fig. 7. Comparison between high voltage 81 kV input and low voltage output signals.

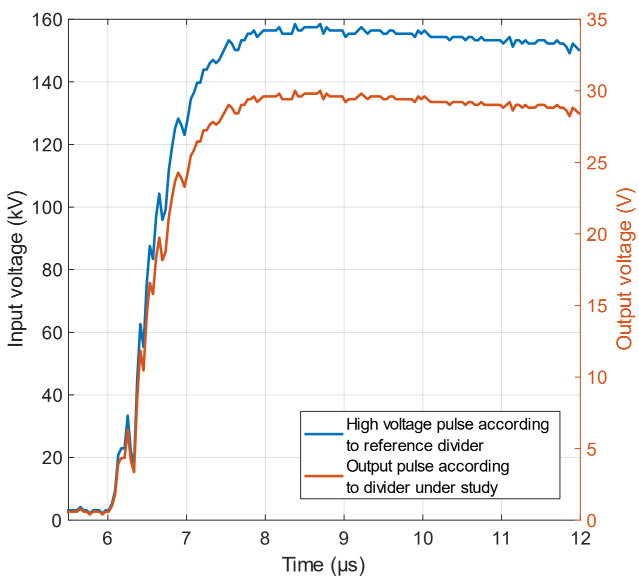

Fig. 8. Comparison between high voltage 158 kV input and low voltage output signals.

D. *Frequency Sweep Test Results*

Fig. 9 shows the output voltage of the capacitive divider when applying a constant magnitude voltage of 15 $V_{pk\text{-}pk}$ and a variable frequency between 30 Hz and 5 MHz. The results exhibit behavior similar to a low-pass filter, starting with a maximum output voltage of 5.2 V and reaching its cutoff frequency at 2.4 MHz, which indicates that the experimental frequency range of the divider is between 30 Hz and 2.4 MHz, equivalent to 60% of the theoretical frequency range but sufficiently broad to faithfully record transient signals such as overvoltages induced by indirect lightning strokes on overhead lines.

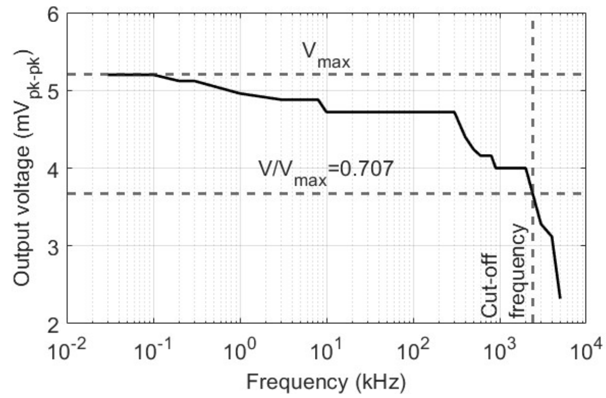

Fig. 9. Frequency response of capacitive voltage divider to a sinusoidal signal ranging from 30 Hz to 5 MHz.

The results exhibit behavior similar to a low-pass filter, starting with a maximum output voltage of 5.2 V and reaching its cutoff frequency at 2.4 MHz. This indicates that the divider's experimental frequency range is between 30 Hz and 2.4 MHz, equivalent to 60% of the theoretical frequency range but sufficiently broad to faithfully record transient signals such as overvoltages induced by indirect lightning strokes on overhead lines.

V. Conclusions

The voltage divider is crucial in measuring overvoltages induced in medium voltage overhead lines. This device functions to proportionally reduce the voltage signal to a magnitude appropriate for capture by a measuring instrument while preserving the original waveform. Therefore, it is essential to experimentally verify its technical specifications before installation in an overhead network to gain a more accurate understanding of the signals recorded by the measurement system. This work presents the characterization of an oil-insulated capacitive voltage divider, and its results are summarized below:

- The full-scale model of the divider built in CST Studio 2022 reveals the formation of a capacitance C_{12} of 1.49 pF, a capacitance C_{13} of 15.34 pF, and a capacitance C_{23} of 47.36 pF. With these calculated parameters, along with the low voltage capacitance of 6 nF and the resistance of 50 **Ω**, the circuit model of the capacitive divider is constructed.
- When simulating a 300 kV impulse applied to the divider's high-voltage terminal, the electric fields calculated within it do not cause flashovers between the internal parts, which indicates that this design can withstand this maximum theoretical voltage and

proportionally reduce the voltage through the action of the capacitances.

- The transformation ratio test shows an experimental division ratio of 5287:1, with a standard deviation of 58.8 V and a percentage error of 4.7% compared to the theoretical one.
- The frequency sweep test shows an experimental frequency range between 30 Hz and 2.4 MHz, equivalent to 60% of the theoretical range between 30 Hz and 4 MHz.

These experimentally validated technical specifications determine the frequency spectrum in which a signal can be reliably captured and the actual magnitude of the waveform obtained at the low-voltage terminal. Although this device can be used in laboratory tests, its compact design and relatively low weight make it easy to transport to remote areas and install in overhead distribution networks. Its outer casing provides resistance to various weather conditions encountered in the field. At the same time, its oil insulation allows it to withstand transient overvoltages commonly found in medium-voltage networks without difficulty. Additionally, its capacitive design enables high-fidelity reproduction of the transient signal waveform. Future work is expected to validate the maximum voltage the outer HDMW polymer cover can withstand and include this capacitive divider in an induced voltage measurement system installed in an overhead distribution network.

VI. References

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