Characterization of a Capacitive Voltage Divider

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

***Abstract*—Voltage dividers are devices designed to reduce high voltages according to a transformation ratio to facilitate their measurement for different purposes. Among them is the detection of transient overvoltages in medium voltage lines. It is convenient to know the transformation ratio of the sensor and its working frequency range for the correct measurement of overvoltages. This article shows the characterization process of an air-insulated capacitive voltage divider used to measure induced voltages in distribution networks. A detailed description of the device is shown, such as how it works and the tests carried out for its characterization. The parameters of its equivalent circuit are obtained by modeling the voltage divider in the CST Studio 2021 software; through laboratory tests, its experimental transformation ratio is obtained; and through a frequency sweep applied to the divider, its frequency response is determined. Indeed, the experimental transformation ratio is 10667.46:1, and the frequency range obtained experimentally is between 60 Hz and 4 MHz, different data from those given by the manufacturer. These experimental data can be used as a reference for the capacitive voltage divider.**

***Keywords*—characterization, division ratio, frequency range, simulation, transient surges, voltage divider.**

I. Introduction

MUCH of the damage to medium voltage networks and their associated equipment, such as insulators and distribution transformers, are caused by flashovers that, in turn, are the consequence of transient induced overvoltages caused by indirect cloud-to-ground lightning that surpass the insulation of such elements. In order to design and implement more effective actions for the protection of medium voltage lines against these overvoltages, it is necessary to develop research to better understand the characteristics of these transient voltages. Many investigations have focused on obtaining transient voltage measurements experimentally to achieve this goal. It is the case of the measurements made by Eriksson *et al.* on a 10 km long line in Pretoria, South Africa [1]; by Yokoyama *et al.* in Fukui, Japan [2]; by Master and Uman *et al.* in Florida, USA [3]; on an experimental distribution network within the University of Sao Paulo between 2002 and 2009, in Brazil [4]; on a 220 V energized distribution network in a test field in Guangzhou, China [5]; and on a L-shaped 819 m long line in Santo Angelo, Brazil [6], among others.

Transient surges usually far exceed the working voltages of distribution networks, the reason why using voltage dividers is required. In order to understand more precisely the characteristics of the measured transient surges, it is accurate to know the transformation ratio of the voltage divider and its frequency response with certainty. During an induced voltage measurement campaign carried out in the year 2000 in Samana [7] (central region of Colombia) a voltage divider insulated in oil is tested. The results determined that its experimental transformation ratio is 4975:1, but the researchers assume the frequency range given by the manufacturer. Subsequently, in 2009, an oil-insulated voltage divider of the same reference was tested in La Palma, Colombia [8]. Its transformation ratio was 4930:1 and a frequency range between 60 Hz and 2 MHz was determined. None of the previous articles presented tests of the air-insulated voltage divider; they also did not show calculations of the equivalent circuit parameters. Design and characterization of a resistive voltage divider with a maximum voltage of 1 kV and a frequency range up to 10 MHz applied to electric vehicles have been carried in [9]. The design and characterization of a resistive-capacitive voltage divider with an electronic insulation interface applied to a PQ power measurement have been presented [10]. In a study done by the National Measurement Laboratory, Australia, proposed three techniques for estimating the error in phase and quadrature of resistive voltage dividers at frequencies up to 200 kHz [11]. Researchers from the University of Chongqing, China, designed and constructed a voltage divider with ceramic capacitors immersed in epoxy resin inside a medium voltage insulator [12].

This paper aims to present the experimental characterization of an air-insulated capacitive voltage divider, the purpose is to determine its circuit parameters, transformation ratio, and frequency response experimentally. This paper is organized as follows: Section II describes the voltage divider under study according to the technical specifications given by the manufacturer and by manual inspection of parts and electronic components. Section III briefly describes the tests to be performed on the device. Section IV shows the experimental data obtained through the tests and simulations: the equivalent circuit parameters, the transformation ratio, and the frequency response of the voltage divider. In section V the conclusions of the paper are presented.

II. Capacitive Voltage Divider Under Study

A. Physical Description

Fig. 1 shows the device under study. This voltage divider is cylindrical, with just 24.77 cm of height and 15.7 cm of maximum diameter. Due to its dimensions and low weight, it is easy to transport and install in facilities.

J. A. Zamora is with the School of Electrical, Electronic and Telecommunications Engineering, Universidad Industrial de Santander 680002, Bucaramanga, Colombia (e-mail: jorge2228117@correo.uis.edu.co).
E. Aguilera is with the School of Electrical, Electronic and Telecommunications Engineering, Universidad Industrial de Santander 680002, Bucaramanga, Colombia (e-mail: eaguiler@uis.edu.co).
E. Soto is with the School of Electrical, Electronic and Telecommunications Engineering, Universidad Industrial de Santander 680002, Bucaramanga, Colombia (e-mail: easotor@uis.edu.co).

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Fig. 1. Capacitive voltage divider.

Fig. 2 shows the circuit model of the voltage divider according to the datasheet provided by the manufacturer. The device comprises two capacitors connected in series. A high voltage capacitor C_1 is formed by a central electrode of 3.8 cm diameter and a pickup ring of 9.4 cm internal diameter and 0.64 cm height; a group of four polyester capacitors connected in parallel makes the low voltage capacitor C_2. A guard capacitor C_3 is formed by the central electrode and a middle cylinder of 9.4 cm internal diameter and 3.8 cm height connected to the device base. An acrylic cap supports the central electrode, so there is no electrical contact between the central electrode and the rings inside the base. The pickup ring is connected to the central conductor of a 50 Ω female BNC right angle connector through a 50 Ω resistor; meanwhile, the ground of the BNC connector is connected to the pickup ring through de low voltage capacitor. In this way, the output voltage of the divider is a known fraction of the input voltage. It is important to note that the base of the device must be grounded. As manufactured, the ground of the BNC connector is not connected to the base of the device, as shown in Fig. 2. However, the manufacturer clarifies that the BNC connector requires a ground connection and allows the user to choose how the said connection is made. Having the floating reference point could be beneficial by having different reference points between the capacitor divider and the voltage measurement device on the output connector. However, this study's circuit calculations have the same reference at both points.

B. Technical Specifications

According to the manufacturer, the oil-insulated device has a transformation ratio of 5000:1 and withstands a maximum pulse voltage of 300 kV. Air-insulated, the device exhibits a transformation ratio of approximately 11500:1 and withstands a maximum pulse voltage of 50 kV. By default, de voltage divider is manufactured insulated in air, so if the user wants to insulate the device in oil, he must acquire the dielectric oil and a suitable container to immerse it. For a 1 MΩ load, a frequency range from 30 Hz to 4 MHz and a drop rate of 0.02 $\%/\mu$s is expected.

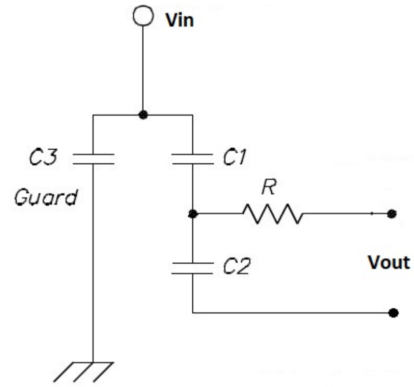

Fig. 2. Circuit diagram of the voltage divider provided by the manufacturer.

III. Tests to be Performed

A. Calculation of Circuit Parameters

The purpose is to characterize the capacitive voltage divider isolated in air, more precisely, to determine its transformation relationship and its frequency response experimentally. At first, a full-scale voltage divider model is built in the CST Studio 2021 software to calculate the parameters of the equivalent circuit C_1 and C_3. Meanwhile, a digital multimeter AMPROBE LCR55A quickly displays the equivalent capacitance of C_2. Thus, the parameters of the circuit diagram provided by the manufacturer are obtained.

B. Division Ratio Test

The transformation ratio test consists of injecting into the high-voltage terminal of the divider an AC voltage signal on a range from 10 V_{rms} to 420 V_{rms} on 10 V steps. An oscilloscope PicoScope 5242D is connected to the low-voltage terminal to measure the peak value of the output signal. The V_{in}/V_{out} ratio is calculated for each sample of the output signal V_{out} and its peak input value V_{in}. Finally, the average of all transformation ratios is calculated to obtain an experimental transformation ratio and compare it with the manufacturer. The circuit diagram of the voltage divider is constructed in Simulink, assigning to capacitances C_1 and C_3 the values calculated by CST Studio 2021 and the measured value directly to capacitance C_2. This same test is simulated in Simulink to find a theoretical transformation ratio and compare it with the experimental ratio.

C. Frequency Sweep Test

This test consists of injecting an 18 $V_{peak-peak}$ sine signal into the high voltage terminal of the divider and varying its frequency between 5 Hz and 10 MHz. An oscilloscope UNI-T UTD2102CEX connected to the low-voltage terminal of the divider allows for measuring the peak-to-peak output voltage. This test aims to validate the frequency range over which the voltage divider can keep a constant amplitude signal and compare this range with that given by the manufacturer.

IV. Results

A. Capacitive Voltage Divider Modeling

Fig. 3 shows the 3D model of the voltage divider built in CST Studio 2021, based on an insulator template. In this model, the device is air-insulated, its metal parts are aluminum, and the lid is acrylic. The software allows the simulation of all parts according to the dimensions of the actual parts.

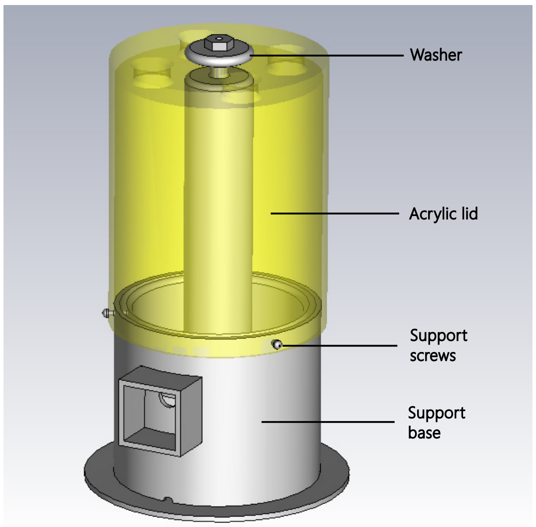

Fig. 3. 3D Model of capacitive voltage divider created in CST Studio 2021. The support base is connected to ground.

Fig. 4 shows the internal parts of the voltage divider and the circuit diagram that represents it. This schematic includes resistor R and low voltage capacitance C_2, which are electronic elements. How the internal metal parts make up the capacitances C_1 and C_3 are observed. The formation of an additional capacitance is also observed, which the authors identify as C_{23}.

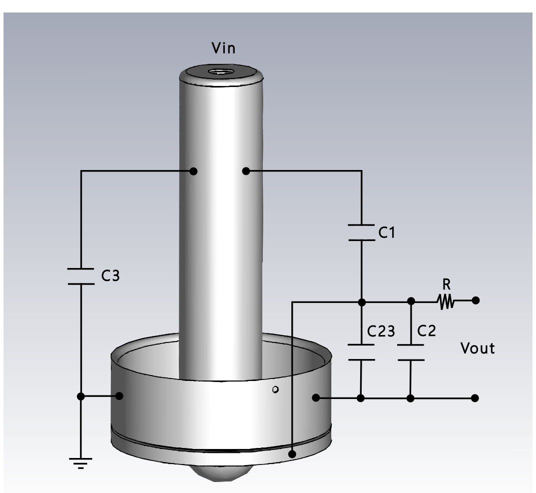

Fig. 4. Inner view of 3D model of capacitive voltage divider created in CST Studio 2021. The complete circuit diagram of the divider is included. The Middle cylinder is connected to the support base; in that way, it is connected to the ground.

CST Studio 2021 executes the Electrostatic solver to calculate the circuit parameters simulating a 50 kV pulse applied to the central electrode, which is the maximum voltage withstood for the divider according to the datasheet provided by the manufacturer. Table I summarizes the results obtained in this phase of the study. For C_1, it presents an approximate value of 0.64 pF. Similarly, for C_3, it presents an approximate value of 6.05 pF. The simulator also detects a capacitance C_{23} between the pickup ring and the middle cylinder (see Fig. 4) of approximately 20.35 pF. Moreover, the low voltage capacitance C_2 formed by the four polyester capacitors in parallel is measured with two different multimeters, and both measuring devices give a record of 6 nF. With these parameters, a new circuit diagram of the capacitive voltage divider was built as shown in Fig. 5. Capacitor C_3 does not impact the divider transformation ratio but is relevant to the phenomenon of stray fields. Since C_3 is approximately ten times greater than C_1, the impact on the stray field is reduced.

TABLE I
Parameters of the circuit diagram of the capacitive voltage divider.

	Capacitance	Method
C_1	0.64 [pF]	Simulated
C_{23}	20.35 [pF]	Simulated
C_2	6 [nF]	Measured by multimeter
C_3	6.05 [pF]	Simulated

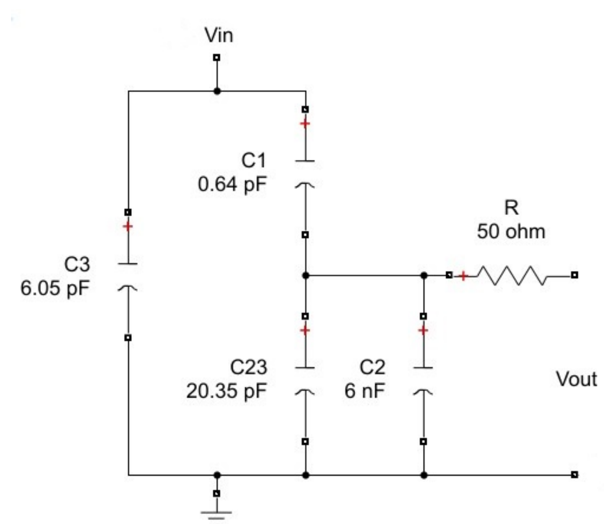

Fig. 5. Alternative circuit diagram of the capacitive voltage divider (compare with Fig. 4).

B. Division Ratio Test Results

Fig. 6 compares the values obtained in the transformation ratio test with those obtained by simulation in the circuit diagram built from the parameters calculated in the previous subsection. It shows a linear behavior in both data groups, corresponding to a device that proportionally reduces the voltage signal.

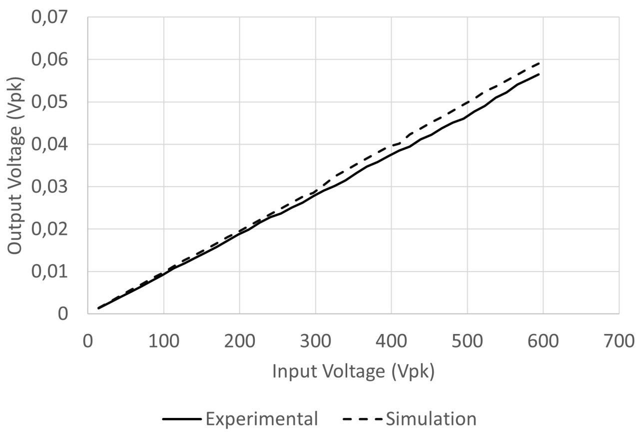

Fig. 6. Comparison between the peak values of output voltage obtained experimentally and the peak values obtained by simulation of the voltage divider in Simulink. Solid line: experimental data. Dotted line: Simulation data.

Table II summarizes the results obtained in this phase of the study. The average transformation ratio obtained from measurements made in the laboratory is 10667.46:1, and it presents an percentage error of 7.24 % for this value concerning the theoretical division ratio. On the other hand, the average of the transformation ratio obtained according to the simulation results is 10108.04:1, with an error of 12.1 % concerning the manufacturer's promised value. Although the transformation ratio obtained from laboratory measurements is closer to the value given by the manufacturer, it presents a more significant standard deviation of 103.31 concerning the standard deviation of the data obtained by simulation, which is 98.98. The division ratio test uses an autotransformer as a source. The increase in the voltage magnitude implies an increase in the number of turns in its internal winding, which leads to an increase in the internal resistance of the source. This is why the output voltage of the measured behaviour is lower than the simulated curve at higher input voltages.

The experimental transformation ratio allows estimating, with greater accuracy, the input value of the voltage divider, that is, the value of a transient voltage that a distribution network eventually experiences.

TABLE II

COMPARISON OF TRANSFORMATION RATIO ACCORDING TO THE DIVISION RATIO TEST RESULTS. INCLUDE THE DIVISION RATIO GIVEN BY THE MANUFACTURER AND THE PERCENTAGE ERROR CONCERNING IT.

	Division Ratio	Standard Deviation	Error (%)
Manufacturer	11500:1	—	—
Experimental Data	10667.46:1	103.31	7.24
Simulation Data	10108.04:1	98.98	12.1

C. Frequency Sweep Test Results

Fig. 7 shows the output peak-to-peak voltage of the voltage divider when a signal generator supplies a sinusoidal voltage at the divider input with a constant peak-to-peak magnitude of 18 V and varies its frequency between 5 Hz and 10 MHz. From 4 MHz, the divider delivers a distorted sine waveform. This distortion is maintained up to 10 MHz, which is the maximum frequency of the sweep test.

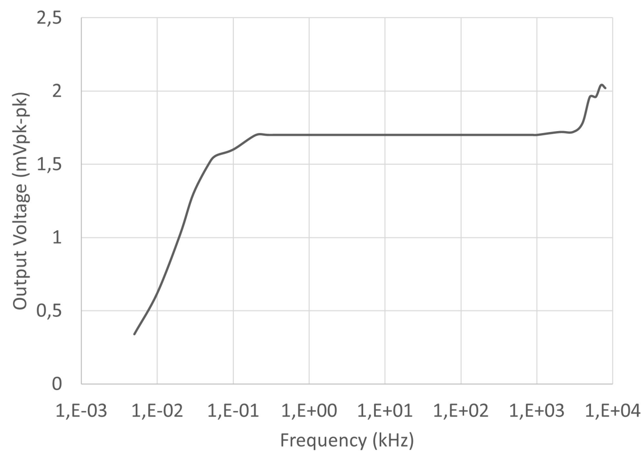

Fig. 7. Frequency response of capacitive voltage divider to a sinusoidal signal ranging from 5 Hz to 10 MHz.

Fig. 8 shows the experiment's results up to 4 MHz, where the voltage divider outputs a more stable sine wave between 60 Hz and 4 MHz. The difference between the magnitudes obtained at 60 Hz and 200 kHz is 8.2 %. The difference between the magnitudes obtained at 200 kHz and 4 MHz is also 4.7 %.

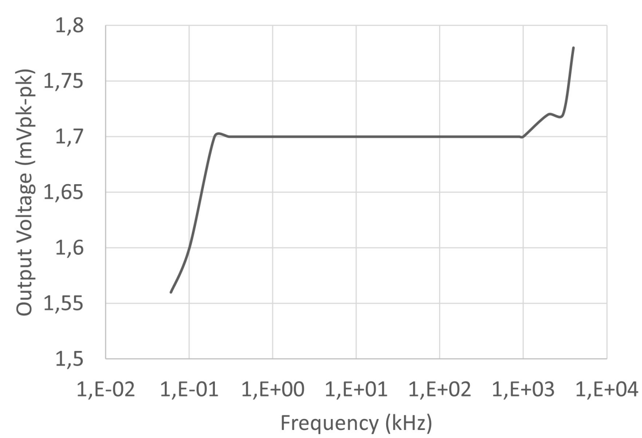

Fig. 8. Frequency response of capacitive voltage divider to a sinusoidal signal ranging from 60 Hz to 4 MHz. This graph allows more detailed observation of a uniform response without significant variations between 60 Hz and 4 MHz.

The frequency sweep test reveals a range of 60 Hz to 4 MHz. This range is less than that suggested by the manufacturer but is considered wide enough to detect transient surges properly, as like lightning-induced voltages.

V. CONCLUSIONS

The voltage divider plays a critical role when studying transient surges in medium voltage lines so that they can be detected by a measuring instrument such as an oscilloscope. For this reason, it is necessary to validate the characteristics of this sensor in order to measure the surges that affect the lines more accurately. This paper presents the characterization of the air-insulated capacitive voltage divider, which includes calculating the parameters of its equivalent circuit, the experimental estimation of its transformation ratio, and its operating frequency range. The main results may be summarized as follows:

- According to the results of CST Studio 2021, the high voltage capacitor C_1 is 0.64 pF, the guard capacitor C_3 is 6.05 pF, and the capacitance added to the circuit C_{23} is 20.35 pF. On the other hand, direct measurement shows that the low voltage capacitor C_2 is 6 nF (See Fig. 5).
- The device under study has an experimental transformation ratio of 10667.46:1 with a standard deviation of 103.31 and a difference of 7.24 % concerning the theoretical transformation ratio.
- The frequency sweep shows stable behavior between 60 Hz and 4 MHz, a lower range than that given by the manufacturer, which is between 30 Hz and 4 MHz.

These results allow for identifying with greater certainty a voltage wave amplitudes detected by induced voltage measurement systems and identifying the frequency spectrum of a signal that the equipment can reliably record. However, it is necessary to carry out more tests to gather data to validate the behavior of this voltage divider isolated in oil and against high-voltage signals.

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