DISEÑO Y CONSTRUCCIÓN DE UNA SONDA DE MEDIDA PARA MEDIA TENSIÓN EN AC

DESIGN AND CONSTRUCTION OF A MEASUREMENT PROBE FOR AC MEDIUM VOLTAGE

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RESUMEN

Este trabajo presenta el diseño y construcción de una sonda de medida para media tensión hasta 12 kV, empleando un divisor de tensión capacitivo amortiguado. El prototipo sirve para realizar mediciones de tensión utilizando multímetros y osciloscopios convencionales en medidas de tensión en señales AC e impulsos, limitando al máximo las distorsiones de las ondas. Adicionalmente, se presentan los resultados de los cálculos matemáticos y simulaciones realizadas en Simulink - Matlab. Los componentes de diseño son elementos disponibles en el mercado para prácticas en baja tensión, esto garantiza el eficaz mantenimiento y reparación de la sonda.

PALABRAS CLAVE: Sonda de medida, Divisor de tensión, Medición de tensión, Media tensión, Impulsos de tensión.

ABSTRACT

This work presents the design and construction of a medium voltage probe up to 12 kV, using a damped capacitive voltage divider. The prototype can be used for voltage measurements using conventional multimeters and oscilloscopes in voltage measurements on AC and impulses, limiting to the maximum the waves distortion. In addition, the results of the mathematical calculations and simulations performed in Simulink - Matlab are presented. The design components are commercially available elements for low voltage practice, this ensures effective maintenance and repair of the probe.

KEYWORDS: Measurement probe, Voltage divider, Voltage measurement, Medium Voltage, Voltage Impulses.

1. INTRODUCCIÓN

Standard measuring instruments for A.C. are characterized by their design with probes or measuring points to work at industrial frequency and a maximum voltage of 1000 V, which makes necessary to use special devices for cases in which the voltages are higher. Commercially there are several designs that meet this need, however, the acquisition of these in relation to the applications does not justify the investment.

Therefore, in this work the design and construction of a capacitive damped probe is presented, which allows measurements of impulse and A.C. waves in medium voltage, according to the classification stipulated in [1], based on the proposals studied in [2] and as main feature allows measurements up to 15kV using conventional multimeters and oscilloscopes.

In order to measure impulse waves, voltage dividers have been implemented as in [3] and [4], where it is evident that the implementation of the divider allows a precise recording of the measured signal.

On the other hand, in academic and research applications, it has been worked the development of devices with specific applications, as in [5], where a device that allows measurements of medium voltage and up to 450 kHz was developed using the oscilloscope.

From the proposed design, it is necessary to obtain the resistance and capacitance values calculated in the equivalent circuit, in an artisan way with commercial elements for low voltage practices (electronic elements), a procedure that has also been performed in [3], [4] and [5], due to the difficulty in obtaining elements with the insulation necessary for the required voltage level.

In this regard, to achieve the designed voltage ratio and in order to obtain a reliable measurement, it is necessary to use the capacitive damped configuration, because, as mentioned in [6], the pure capacitive voltage divider configuration it's not suitable for measuring impulse-type signals, due to their high sensitivity at input voltages with short rise time.

Finally, the results of the mathematical calculations are presented, the simulations realized in Simulink - Matlab and the tests to the initial prototype are associated to the work developed by [7], resulting in a ratio of measurement of 1:93, which validates the data presented in the simulation.

2. METHODOLOGY

The type of divider was selected in order to measure A.C. current at industrial frequencies, as demonstrated in [7] and voltage impulse waves as in [8], [9], [10]. After studying the characteristics of the resistive dividers, pure capacitive and capacitive damped, the latter was chosen because it reduces the disturbance that affects the output signal according to what is exposed in [8] and there are disturbances in the measure when the pure capacitive divider is used [9], [10].

In order to theoretically determine the voltage ratio (a) equation (1) is used, which was employed in [2], and that allows to know the reading of signals that the probe can perform.

$$a = \frac{V_i}{V_o} = \frac{C_2 * (1 + R_1 * C_1)}{C_1} \tag{1}$$

Where:
V_i: Divider input voltage
V_o: Divider output voltage
C_1: Equivalent Capacitance 1.
C_2: Equivalent Capacitance 2.
R_1: Equivalent resistance 1.
a: Voltage ratio

The ideal ratio for the proposed design is 1: 100 (15kV / 150V), which is calculated between the input voltage (V_i) and the output voltage (V_o) of the divider. This data was compared with the obtained relation in the stress tests and the behavior of the divisor components was analyzed.

To determine the minimum number of capacitors that make up C_1, equation (2), is used, an approach proposed in [2].

$$n_{min} = \frac{V_{max}}{V_{nco}} \tag{2}$$

Where:
V_{max}: Maximum divider voltage
V_{nco}: Rated voltage of each capacitor
n_{min}: Minimum number of capacitors that make up the high voltage capacitance.

In order to obtain the specific value of C_1, the relation in [2] is used, which corresponds to equation (3).

$$C_1 = \frac{C_{1-i}}{n} \tag{3}$$

Where:
C_{1-i}: Capacitance of each C_1 capacitor C_1
n: Number of capacitors C_1, (min $n \geq n$)

On the other hand, for the calculation of C_2, equation (4) was used.

$$C_2 = \frac{C_1}{a} \tag{4}$$

However, for C_2 only the commercial options of capacitance shown in Table 1 were available, and it is important to emphasize that in the configuration of the divider, it's C_2 the capacitance that makes it possible to connect to the probe the multimeters for voltages above 1kV without causing them any damage.

Table 1. Equivalent capacitors designed based on commercial values.

Commercial values	Option 1	Option 2	Option 3	Option 4
Equivalent capacitor 1	47 µF	10 µF	58 nF	96 pF
Equivalent capacitor 2	0.82 µF	1.3 µF	4,7 µF	9,16 nF
Measure ratio	38.46	38.9	39.65	93.5

Source. Own elaboration.

From the previous data the option 4 was chosen, because with these values the measurement ratio was adjusted to the initial design.

With the selected values for the equivalent capacitances the array of series capacitors is built, taking into account the specific data that listed in Table 2.

Table 2. Characteristics of used capacitors and resistors

Characteristics	**C_1**	**C_2**	**R_1**	**R_2**
Magnitude per unit	1 nF	0,22 μF	390 k **Ω**	39 k **Ω**
Design voltage per unit	2 kV	630 **V**	2 kV	2 kV
Number of units	9 unds	24 unds	13 unds	3 unds
Total magnitude of the array	90 pF	9,16 nF	5 M**Ω**	130 k**Ω**
Total voltage of the array	15 kV	15 kV	15 kV	15 kV

Source. Own elaboration

The equivalent circuit of the capacitive damped divider consists of two capacitors and two resistors connected in series as shown in Figure 1.

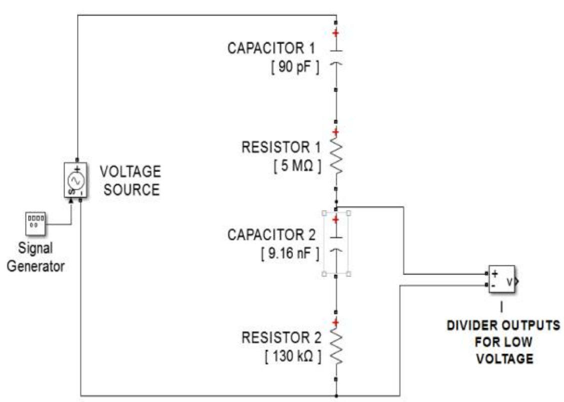

Figure 1. Equivalent circuit. **Source.** Own elaboration

In the previous circuit the actual values of each component with which the divisor was built are established, and the measurement points are shown.
The comparison of the behavior of the signal at the output of the probe with the components of theoretical values and design values was performed by simulation, as observed in Figure 2

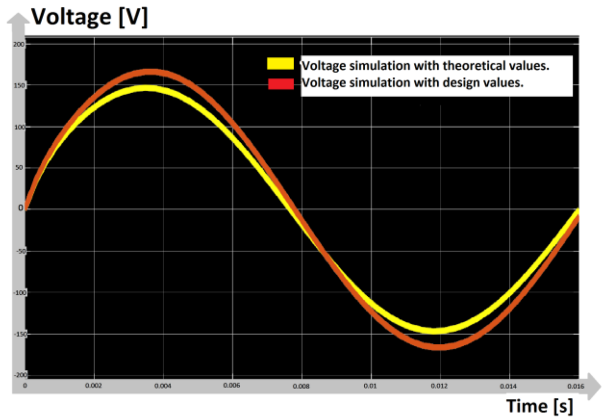

Figure 2. Comparative simulation of voltage signals. **Source.** Own elaboration.

In the previous figure it is observed that in spite of having a design ratio of 1: 100 (15kV / 150kV) and obtaining by simulation a theoretical ratio of 1: 93.5 (15kV / 160.3V), it is evident that the two signals are within the industrial frequency.

The values of the resistors that were used in the damped capacitive voltage divider were obtained from the simulations performed with each of the commercial options. An analysis of the signals delivered by each arrangement was made and it was verified that the R1 = 5MΩ together with R2 = 130kΩ keep the signal at an industrial type frequency, as seen in option 4 of Figure 3.

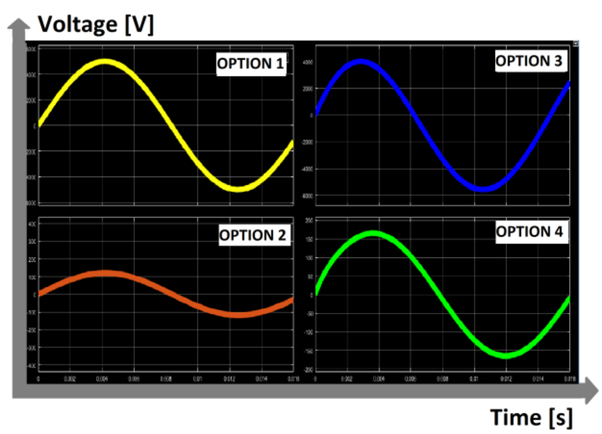

Figure 3. Comparison of the divisor signals employing different resistive and capacitive values. **Source.** Own elaboration

It is observed that the capacitance is directly proportional to the amplitude of the wave and the resistance is directly proportional to the frequency [2].

Moreover, in order to ensure a good insulation of the circuit, preventing disruptions produced by electric arc, a test of the consistency of the polyurethane foam inside a PVC was made, as presented in Figure 4.

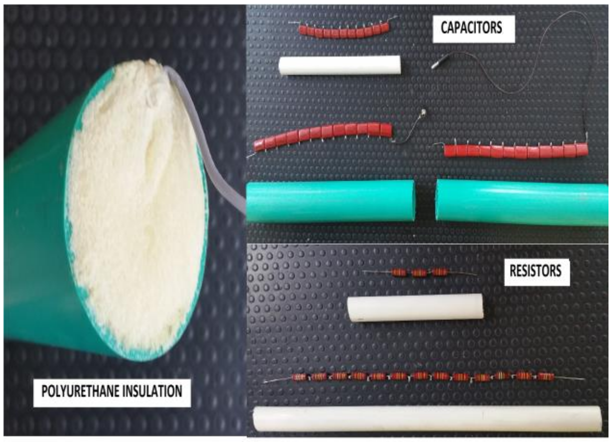

Figure 4. Probe components and polyurethane insulation. **Source.** Own elaboration

In the quest to obtain an insulating material that supports the circuit voltages, polyurethane foam was the most successful and affordable option. To ensure that each component of the probe was completely covered with the foam, resistance 1 and 2 were introduced into ½ "tubes, capacitor 1 into a ½" tube and the capacitor 2 was divided into two tube sections of 1 ½ ", which are connected in series by a cable.

3. RESULTS

With the prototype built, three tests are performed, from which data can be obtained to make a comparative analysis with the design and simulation of the device.

In order to carry out the validations, connections are made to each component in the circuit, so that the connection and layout for the tests are proposed. As shown in Figure 5, multimeter A is connected directly to the high voltage side of the transformer (input voltage) and through the medium voltage probe, multimeter B is connected between resistor 1 and capacitor 2.

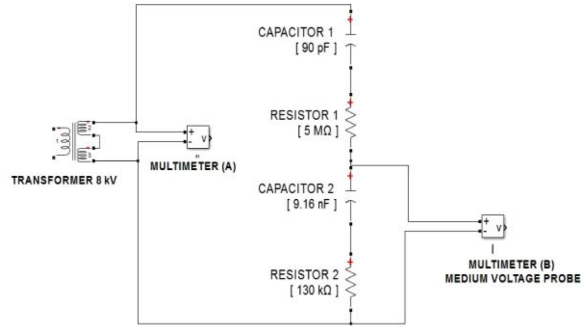

Figure 5. Equivalent circuit with measuring elements. **Source.** Own elaboration

In the initial test the probe is connected to a transformer in vacuum, gradually increasing the voltage as seen in Table 3.

Table 3. AC voltage measure to a transformer in vacuum.

Transformer low voltage side (multimeter A) [V]	Voltage measured at the transformer output (probe MV) [V]	Transformer high voltage side according to MV probe ratio [1:93,5]	Transformer ratio
10	6,62	619,0	61,9
20	13,91	1300,6	65,0
30,35	20,64	1929,8	63,6
40,27	27,38	2560,0	63,6
50,04	33,95	3174,3	63,4
60,12	41,09	3841,9	63,9
70,3	47,9	4478,7	63,7
80	54,2	5067,7	63,3
90,1	60,7	5675,5	63,0
100	67,2	6283,2	62,8
110,6	73,3	6853,6	62,0
120	78,7	7358,5	61,3

Source. Own elaboration

From the above table it can be seen that the operation of the medium voltage probe was correct, since it was measuring voltages above 1000 volts.

In the second test the values measured on the high voltage side of the source elaborated in [7], are compared with a calibrated multimeter and the medium voltage probe as shown in Table 4.

Table 4. Comparison with calibrated voltage measurement equipment

Source low voltage side [V]	Source output voltage measured with MV probe [V]	Source output voltage according to MV probe ratio [93,5] [V]	Voltage measured directly at source output with calibrated multimeter [V]
1,024	0,609	58,18	56,8
2,02	1,26	120,38	116,7
3,06	1,956	186,88	181,8
4,09	2,621	250,41	244,3
5,09	3,298	315,09	307,7
6,05	3,58	342,03	369,5
7,05	4,68	447,13	432
8,04	5,36	512,09	495
9,03	6,05	578,02	559
10,03	6,74	643,94	625
11,07	7,45	711,77	690
12,06	8,15	778,65	756
13,02	8,82	842,66	817
14,06	9,58	915,27	889
15,02	10,21	975,46	949

MV: Medium Voltage
Source. Own elaboration

For the last test data were taken every 5 volts at the transformer input, obtaining in the multimeter B a maximum voltage of measurement of 84V, observed in Table 5.

Table 5. Tensión medida con la sonda y su relación a la salida de la fuente

Source low voltage side [V]	Source output voltage measured with MV probe [V]	Source output voltage according to MV probe ratio [93,5] [V]
20,36	13,78	1288,43
25,12	17,05	1594,175
30,02	20,4	1907,4
35,02	23,83	2228,105
40,01	27,22	2545,07
45,18	30,71	2871,385
50,1	34,02	3180,87
55,08	37,31	3488,485
60,25	41,1	3842,85
65,3	44,1	4123,35
70,1	47,6	4450,6
75	50,8	4749,8
80	54	5049
85,3	57,6	5385,6
90,1	60,7	5675,45
95,1	63,7	5955,95
100	66,8	6245,8
105,1	70	6545
110	73	6825,5
115	75,8	7087,3
120	78,7	7358,45
130,3	84	7854

MV: Medium Voltage
Source. Own elaboration

According to the data shown in the above table, the medium voltage probe measures without problems voltages higher than 1kV and conserves the design ratio.

3. CONCLUSIONS

This work presents an alternative of handcrafted construction of a damped capacitive divider, which allows to measure impulse and A.C. waves in medium voltage up to 12kV.

The design of the device allows connection accessibility in the terminals and measurement points, providing security to users to the voltages that can occur in the components thanks to its elongated shape. In particular, the use of commercial components for low voltage in this probe, allows to make measurements up to 12kV with a noticeable reduction of costs in the construction.

In this damped capacitive voltage divider, the capacitance is responsible for providing the potential difference with reference to the ground of the impulse signal (amplitude of the wave), and the resistance is responsible for decreasing the oscillations of the frequency, which are produced by the divisor capacitances and inductances.

In order to obtain construction results adjusted to the design data, it is proposed to use specific components that are not handcrafted, that allow to achieve the rated voltage and the ratio designed.

4. RECOMENDATIONS

It is recommended to do tests to determine the durability of the probe with respect to the time of use and also to know how long it takes to the probe to lose its measurement accuracy.

It is proposed that for a complete analysis of the signals to be measured, the comparison of design simulations, tests with a hand-held probe and tests with a commercial probe should be carried out.

6. REFERENCES

[1] M. Minas y Energía de Colombia, *REGLAMENTO TÉCNICO DE INSTALACIONES ELÉCTRICAS (RETIE)*. COLOMBIA, 2013, p. 127.

[2] D. F. García Gomez, E. Marlés Saens, T. A. Prado, and M. Martínez, “Metodology for lightning impulse voltage divisors design,” *IEEE Lat. Am. Trans.*, vol. 7, no. 1, pp. 71–77, 2009.

[3] S. G. Arango, “Diseño y Construcción de un Generador de Impulsos de Alta Tensión , Portátil y Didáctico .,” 2013.

[4] D. F. García and D. F. Rincón, “Diseño y construcción de un generador de impulso de voltaje de 10 KV,” *Tecnura*, vol. 12, pp. 4–13, 2009.

[5] A. Velázquez, “Sonda de medición para alto voltaje y alta frecuencia,” INstituto Politécnico Nacional, 2015.

[6] E. Kuffel, W. . Zaengl, and J. Kuffel, *HIGH VOLTAGE ENGINEERING FUNDAMENTALS*, SECOND. Great Britain: Butterworth - Heinemann, 2000, p. 539.

[7] J. V. C. Benítez, S. Charry , S. Gómez, “Diseño Y Construcción De Una Fuente De Media Tensión.,” p. 6.

[8] K. Feser, “Transient Behaviour of Damped Capacitive Voltage Dividers of Some Million Volts,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-93, pp. 116–121, 1974.

[9] a. J. Schwab and J. H. W. Pagel, “Precision Capacitive Voltage Divider for Impulse Voltagge Measurements,” *IEEE Trans. Power Appar. Syst.*, vol. PAS-91, pp. 2376–2382, 1972.

[10] K. Feser, “A new type of voltage divider for the measurement of high impulse and a.c. voltages,” *Haefely Test AG*. 1971.