DESIGN & DEVELOPMENT OF A STANDARD FOR HVDC VOLTAGE UP TO 50 kV

Márcio Thelio Fernandes da Silva [1], *Carlos Roberto Hall Barbosa* [2], *Luiz Carlos de Azevedo* [3]

[1] Cepel, Rio de Janeiro, Brazil, thelio@cepel.br
[2] PUC-Rio, PósMQI, Rio de Janeiro, Brazil, hall@ele.puc-rio.br
[3] Cepel, Rio de Janeiro, Brazil, luiz@cepel.br

Abstract: This work presents the prototype of a standard for HVDC, designed to be used in the range of 1kV to 50 kV and calibrated in low voltages. In HV, it will be the link in the chain of traceability between the INMETRO standard and the dividers used by industrial laboratories.

Key words: Metrology, Quality, Traceability, Standard, HVDC.

1. INTRODUTION

The National Institute of Metrology, Standardization and Industrial Quality (INMETRO) is the highest organism in Brazil that is responsible by the conservation and maintenance of base and derived units of the International System of Units (SI) in the country.

The quantity voltage, up to 1000 V, is traced to national standards in the Brazilian Calibration Network (RBC), but for voltages above 1000 V there is no laboratory in the country accredited by INMETRO to provide services for the electrical equipment industry in High Voltage Direct Current (HVDC). Thus, Brazil currently lacks the infra-structure in metrology with high voltage accreditation laboratories, high voltage alternating, continuous or impulse voltage/current, according to standard ISO/IEC 17025. [1]

Recent investments in the laboratory infrastructure of CEPEL, specifically through the project “LongDist”, with the construction of a laboratory for Ultra High Voltage (UHV) and also with the purchase of DC power supplies with $\pm$800 kV, have been made aiming at the development of new concepts of high-capacity lines for the transmission of large amounts of energy from the Northern region to the Southeastern and Northeastern regions. An example of investment in generation and transmission of energy is related to the transmission of the Madeira River and the construction of new hydroelectric power plants. [2]

It should also be considered that new investments in generation and transmission of large amounts of energy mobilize the industry and generates demand for testing of the new equipment to be installed. To perform these tests, so as to ensure reliability, accuracy and traceability, a metrology structure in high voltage is needed. Hence, it is necessary to create standards and encourage the accreditation of laboratories.

2. OBJECTIVE

The National Institutes of Metrology (NIMs) should perform the maintenance and conservation of the SI units in the country. However, specifically for the quantity voltage with magnitudes above 1000 V there is no laboratories in Brazil accredited by INMETRO to provide services for the electrical equipment industry in HVDC.

In this sense, the main purpose of this work was to build a prototype of a standard based on a High Voltage Divider (HVD), of the resistive type, with high impedance, for measurement of the quantity voltage above 1000 V. The standard was designed to be used in the range of 1kV to 50 kV and was calibrated in low voltages and traceable to the RBC. It will be the link in the chain of traceability between the INMETRO standard and the dividers used by industrial laboratories, according to standard IEC 60060-2 [3], and also to calibrate other working standards for HVDC, especially in the range of 1 kV to 250 kV.

The standard will be used in the chain of traceability in order to ensure HVDC accuracy, traceability and reliability to the electrical equipment industry, according to Figure 1.

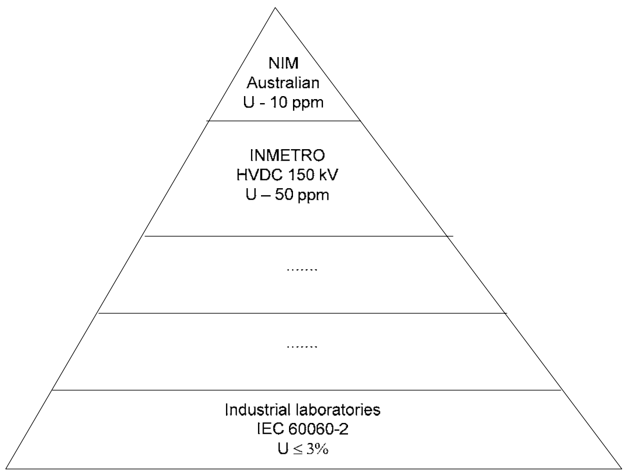

Fig. 1. Traceability structure for HVDC in Brazil.

3. DESCRIPTION OF THE PROTOTYPE

A high precision divider for high voltage direct current was designed and built to be used as a standard. The divider was designed to minimize the leakage current by insulating the structure. The high voltage electrode was designed to minimize the concentration of electric fields and the formation of coronas at high voltages. A reference measurement instrument (Fluke 8508A) with a resolution of 8.5 digits is used in conjunction with the divider, forming a Reference Measurement System (RMS). [4]

The divider is composed of 30 non-inductive film resistors, with a total resistance at the high voltage section (R_{HV}) of approximately 100 MΩ, and a film resistor with resistance of approximately 20 kΩ, as the low voltage section (R_{LV}) according to Figures 2 and 3.

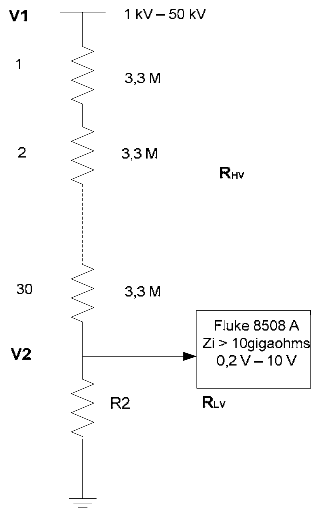

Fig. 2. Basic electric diagram of the standard for HVDC.

Fig. 3. Photo of standard divider for HVDC up to 50 kV.

3.1 Stability with temperature

The main objective is to have as low as possible a thermal coefficient for the divider Scale Factor (SF) within the temperature range specified for operation (22 °C ± 5 °C). The resistances of the high and low voltage (R_{HV} and R_{LV}) resistors were measured in 11 points within the operating range between 17 °C and 27 °C, as shown in Fig. 4.

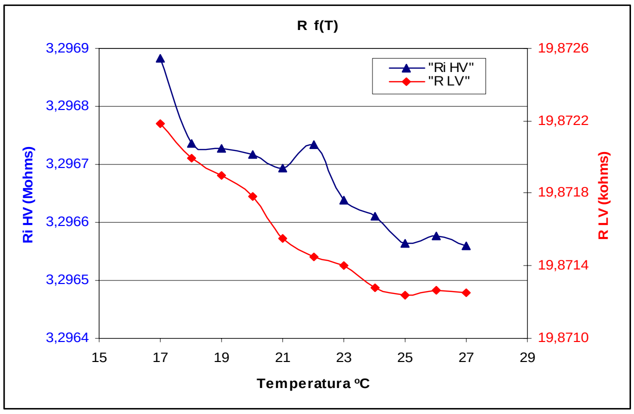

Fig. 4. Assessment of the resistors individual components thermal stability.

3.2 Voltage coefficient of the component resistors

Resistance is not always independent of the applied voltage. The voltage coefficient of resistance is the change in resistance per unit change in voltage, expressed as a percentage of the resistance at 10% of rated voltage [5]. The voltage coefficient is given by:

$$CV = \frac{R1 - R2}{R2} x \frac{1}{V1 - V2} x100$$

where:
R1 is the resistance at the nominal voltage $V1$;
R2 is the resistance in 10% of the nominal voltage $V2$.

3.3 Evaluation of the distribution and calculation of electric field

Leakage currents and small corona discharges cannot normally be fully eliminated, especially at high end of the operational range, and cause changes of the divider effective resistance. However, such effects can be substantially reduced, by choice of a physical arrangement that allow an approximately linear distribution of the electric field in the divider. [6] For those reasons, the resistors high voltage arm were arranged in helical shape and fixed in insulating columns, which in turn are mounted on a ground plane of copper. A ceramic bushing insulator isolates the structure of the active part of the divider, where the high voltage is applied.

This construction minimizes corona effects between the high voltage electrode and ground. In addition, a high voltage electrode was designed to prevent concentration of electric field and corona formation.

Low humidity absorption materials were used in insulated structures, which basically consist of six cylindrical plexiglass rods ϕ 3/16", also fixed in plexiglass plates with ϕ120 mm and fixed at 60 degrees intervals.

To design the electrode, the field calculations were performed using the software Phoenix 2D V3.0, developed in CEPEL and using finite element method. Figures 5 and 6 present the results of simulation and calculation of the field lines.

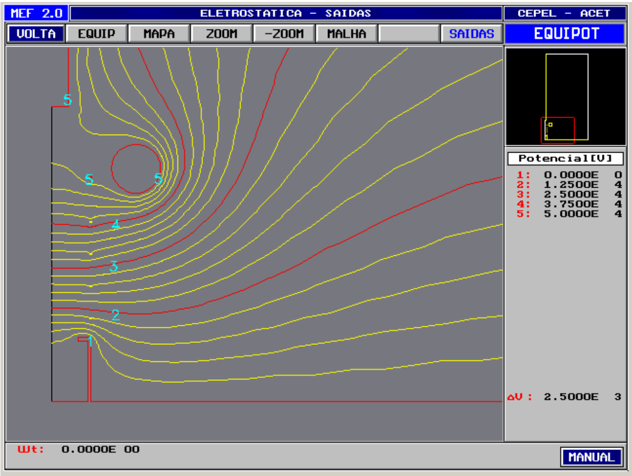

Fig. 5. Distribution of electric field lines in the divider.

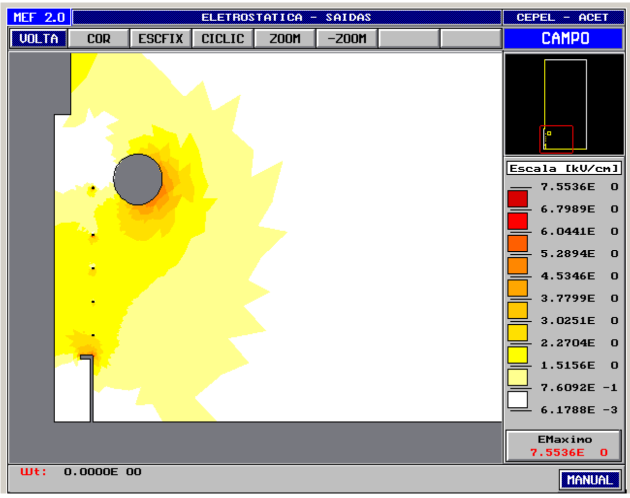

Fig. 6. Calculation of the distribution of electric field lines in the divider.

As the divider was designed with a symmetrical structure, it is sufficient to use a two-dimensional model for the field calculations. The above results show a maximum electric field strength at the terminals at the highest voltage of 7,5kV / cm in the first loop and of 4 kV / cm in the next. The low voltage resistor (≈ 20 kΩ) is located in a metal box with a BNC output connector. The upper electrode is made of aluminum with ϕ 75 mm and designed to generate a homogeneous field.

4. PERFORMANCE EVALUATION

A series of tests was performed on the standard to evaluate dielectric and dynamic characteristics for the measurement of HVDC up to 50 kV. The tests included: leakage current, thermal image, scale factor, step response, partial discharge, linearity and stability.

4.1 Leakage current

A ceramic bushing was used to connect the high voltage in order to minimize the leakage current by the structure of the divider. This assembly allows the measurement of current flowing through the divider and current through the insulator structure. To match the stability and accuracy of the resistive chain it is important that the design of the divider has a minimum value of leakage current. Leakage currents that occur between the bushing and the insulating materials cause measurement errors.

To measure the leakage current by insulating the structure of the divider, it was suspended and grounded through a 1MΩ resistor. A voltage of 50 kV was then applied. The leakage current in the divider insulator structure did not exceed 40ppm, or 20 nA for this applied voltage of 50 kV.

4.2 Partial discharge

To assess the level of partial discharge (PD) a test with AC voltage at industrial frequency (60 Hz) was performed, with values ranging from 7.07 kV to 35.4 kV, which corresponds to levels of 10 kV and 50 kV, respectively in DC. The test was performed with a 10 pC calibrator using a PD measuring instrument. The results shown in Figure 7 indicated a discharge level of less than 5 pC at maximum operating voltage.

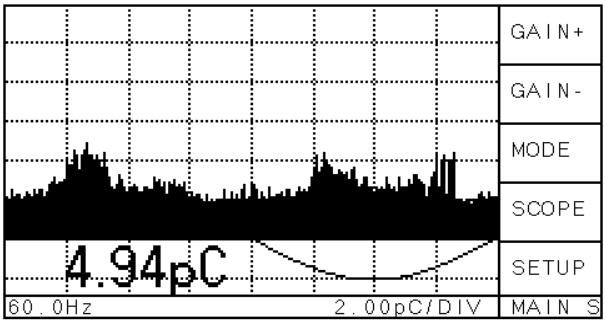

Fig. 7. Partial discharge test at divider.

4.3 Thermal image

To check the temperature distribution along the divider a thermal image test was performed at the nominal voltage of 50 kV. The results were considered normal with temperatures of ≅ 28 ^{o}C and they are shown in Figure 8.

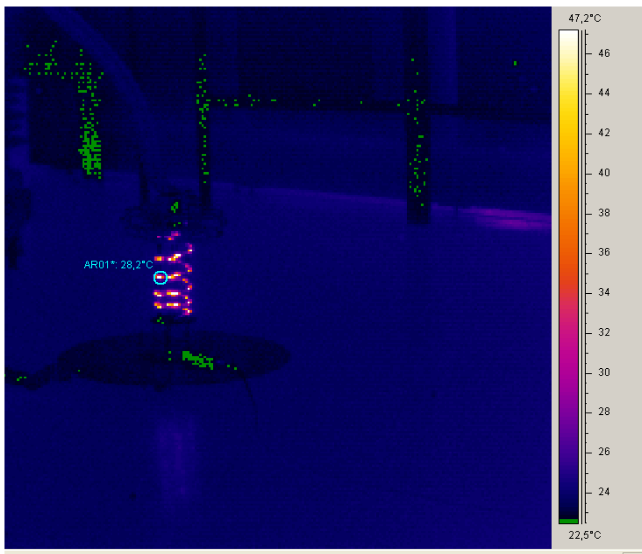

Fig. 8. Thermal image test.

4.4 Step response

To evaluate the dynamic performance a step response measurement was performed. A step voltage generator with rise time ≅ 5 ns and ninety voltage magnitude was used, applied to the high voltage terminal (V1). Figure 9 shows the step response and its calculated parameters.

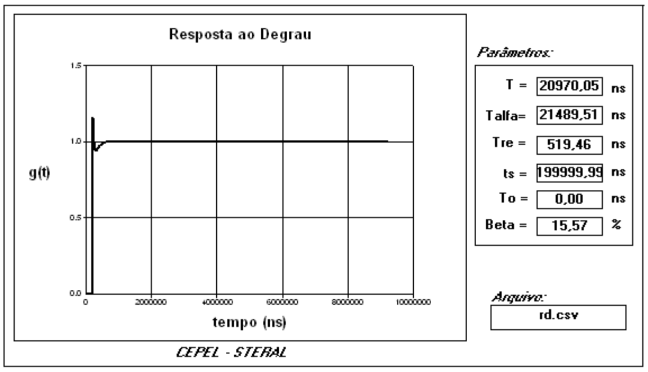

Fig. 9. Step response measurement.

4.5 Scale Factor (SF) determination

The results obtained in low voltage from the calibration in November 8 and 22, 2010, in CEPEL are shown in Table1. This Table also presents the results of the calibration performed at INMETRO.

Tabela 1. Scale Factor results of divider.

Aplication	SF CEPEL at 08/11/10	SF CEPEL at 22/11/10	SF INMETRO
1	4993,513	4993,102	4993,83
2	4993,498	4993,100	4993,83
3	4993,498	4993,097	4994,06
4	4993,493	4993,097	-
5	4993,491	4993,095	-
6	4993,491	4993,090	-
7	4993,484	4993,087	-
8	4993,484	4993,242	-
9	4993,479	4993,241	-
10	4993,484	4993,072	-

4.6 Uncertainty

For the high voltage divider described here the measurement uncertainty was calculated based on the tests performed, considering all the contributions of the system variables from the measurements at high and low voltage. [7]

To facilitate the identification of the input estimates it is shown in Figure 10 the location of the sources of uncertainty. The sources of u1 to u8 are shown in the diagram, while the sources u9 up to u11 are associated to the comparison with the INMETRO standard.

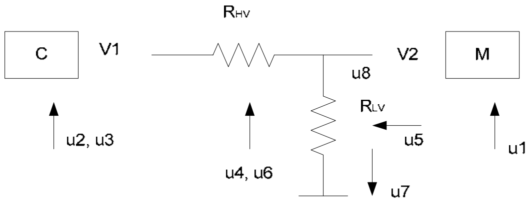

Fig. 10. Diagram to identify the sources of uncertainty.

where:
C – Calibrator e M – Multímeter.

4.6.1 Low voltage

The divider output voltage (V2) is measured using a 8.5 digit multimeter. This device is a reference and tracked the Brazilian Calibration Network (RBC). The measurement uncertainty of this device was determined within the range of 0,15 V to 10 V. The uncertainty of the device up to 10 V with long term stability according to the calibration certificate is,

$u1 = 51x10^{-6}$

4.6.2 Scale factor

The Scale Factor of the divider was determined at low voltage through a DC voltage calibrator and a 8.5 digit multimeter, measuring the input voltages (V1) and output (V2) of the divider to the level of 1 kV.

SF = (V1/V2) = 4993,491:1

$u2 = 10x10^{-6}$ (calibrator)

$u3 = 2,0x10^{-6}$ (standard deviation / mean)

4.6.3 Thermal coefficient

The thermal coefficient (TC) was calculated from Fig. 4. For the high voltage arm it results in 30 ppm / ^{o}C and for the low voltage arm in 17 ppm / ^{O}C.

$u4 = 30x10^{-6}$

$u5 = 17x10^{-6}$

4.6.4 Voltage coefficient

The voltage coefficients (VC) were determined for five randomly selected resistors. The measurement was performed in four terminals with 100V and 1000 V and for a very short time to avoid thermal stress. The relative uncertainty due to the voltage coefficient is,

$u6 = 91x10^{-6}$

4.6.5 Leakage current

The leakage current on the insulator structure did not exceed 40 ppm or 20 nA for an applied voltage of 50 kV, corresponding to an uncertainty of;

$u7 = 40x10^{-6}$

4.6.6 Partial discharge

The partial discharge test (PD) was made in AC, at a high voltage level of 35.4 kV, equivalent to 50 kV DC and using a PD detector. In addition, the test circuit was calibrated with a 10 pC PD calibrator. The discharge level measured was considered negligible (<5 pC).

4.6.7 Short time stability

The high voltage divider was checked twice within a period of one month in order to determine its short time stability (see Table 1). The contribution to this uncertainty is,

$u8 = 74x10^{-6}$

4.6.8 Linearity

A comparison with the standard was performed with INMETRO to determine the SF of the divider in the operation range of 1 kV to 50 kV. This component of uncertainty (u9) was quantified and used to calculate the uncertainty of the standard. The results described in the linearity are shown in Figure 11.

SF_c = 4993,491:1 (CEPEL at 1 kV with calibrator);

SF_I = 4993,91:1 (High voltage with INMETRO standard)

$u9 = 62x10^{-6}$ (Uncertainty of INMETRO = 0,31/4993,91)
$u10 = 228x10^{-6}$ (Linearity)
$u11 = 84x10^{-6}$ ΔSF between CEPEL and INMETRO = $(SF_I – SF_c)/SF_c$).

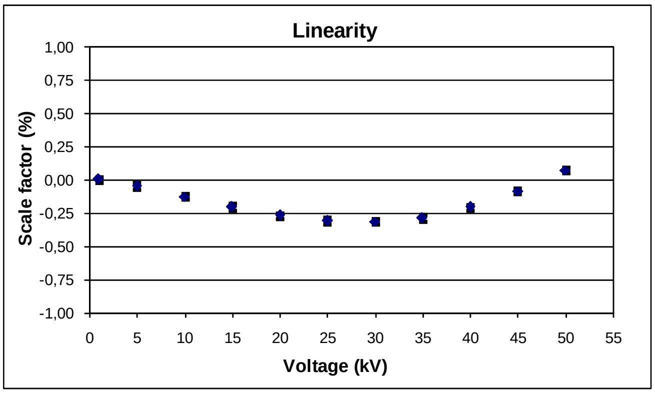

Fig. 11. Linearity of standard to HVDC up to 50 kV.

4.7 Combined uncertainty calculation

The combined uncertainty (Uc) of the RMS for HVDC is derived from the individual uncertainties and also the source of comparison with the INMETRO standard.

$$Uc = \sqrt{\sum_{i=1}^{n} u_i^2}$$

Table 2 shows the sources, the uncertainty calculation and analysis of the probability distribution.

Tab. 2. Uncertainty calculation of the scale factor.

Source	Value (ppm)	DP	vi	FD	Up	Up2
u1	51	Nor.	∞	2	2,55E+01	6,50E+02
u2	10	Nor.	∞	2	5,00E+00	2,50E+01
u3	2,0	Nor.	9	3,1623	6,32E-01	4,00E-01
u4	30	Rec.	∞	1,732	1,73E+01	3,00E+02
u5	17	Rec.	∞	1,732	9,82E+00	9,63E+01
u6	91	Rec.	∞	1,732	5,25E+01	2,76E+03
u7	40	Rec.	∞	1,732	2,31E+01	5,33E+02
u8	74	Nor.	9	3,1623	2,34E+01	5,48E+02
u9	62	Nor.	∞	2,1	2,95E+01	8,72E+02
u10	228	Nor.	10	3,3166	6,87E+01	4,73E+03
u11	84	Rec.	∞	1,732	4,85E+01	2,35E+03
Combined uncertainty Uc ⇒ $\sqrt{Up^2}$						115
Uncertainty U = k * Uc						235

5. RESULTS

The development of a standard for HVDC made it possible to create a link in the chain of traceability and collaborated with the Metrology and industry development. It also meets the growing demand for services of accredited calibration/testing of electrical equipment for HVDC, improving the metrology structure in high voltage in the country, considering also the demand of the domestic industry resulting from recent investments and advances in HVDC transmission lines.

The standard presented here will be used to calibrate other standards for HVDC and also in the calibration of measurement systems to ~~the~~ industrial laboratories up to 250 kV, ensuring reliability according to the traceability chain described in Figure 12.

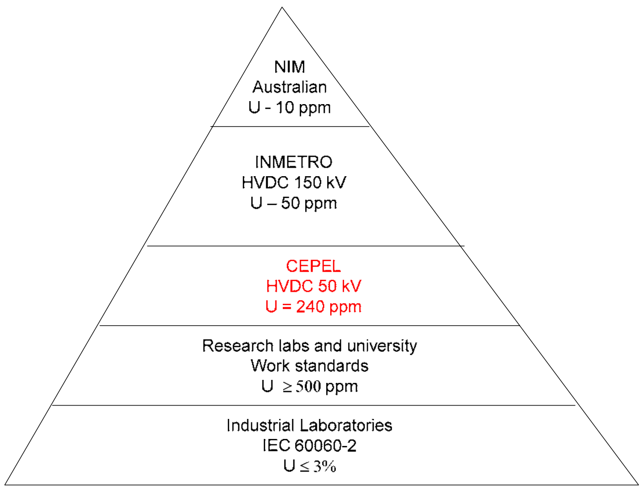

Fig. 12. Chain of traceability for HVDC in Brazil.

A summary of the standard operational characteristics is shown below.

HVDC standard for 1 kV up to 50 kV;
RMS composed of HVD + Fluke 8508A;
Scale Factor = 4993.491:1; U=240 ppm; k=2.05; with 95.45% of confidence.

Environmental conditions:
Temperature: 22^{o}C ± 5^{o}C
Relative Humidity: 55% ± 20%.

6. REFERENCES

[1] ABNT NBR ISO 17025/05 - General requirements for the competence of calibration and testing laboratories;

[2] Ten Year Plan for expansion of energy MME – 2008 / 2017. www.mme.gov.br;

[3] IEC 60060 "High-voltage test techniques, Part 2: Measuring systems" - 2010;

[4] Journal of Electrostatics 67 (2009) 741-745 – "The construction of a DC high voltage precision divider" – 2009, Ahmet Merev a, O¨ zcan Kalenderli b;*.

[5] Journal of Electrostatics 67 (2009) 741-745 – "The construction of a DC high voltage precision divider" – 2009, Ahmet Merev a, O¨ zcan Kalenderli b;*

[6] J. Rungis and D. E. Brown, "Modular dc resistance divider for 500 kV," J. Elect. Electron. Eng., vol. 5, Dec. 1985.

[7] ISO GUM / 2003 – Guia para a expressão da incerteza de medição – Terceira edição.