Traceability and Characterization of a 1000 kV HVDC Reference Divider

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***Abstract*— This paper presents the characterization of a resistive high-voltage dc (HVDC) reference divider and methods to establish traceability. The divider is designed for use as a laboratory reference for calibration of HVDC measuring systems up to 1000 kV. Targeting a measurement uncertainty of 20 μV/V at full voltage has put a focus on the temperature coefficients of the resistors, elimination of humidity dependence, and control of leakage currents in the high-voltage arm. A scale factor calibration against a 50 kV divider at 10 kV leads to an expanded uncertainty of 15 μV/V.**

***Index Terms*— High-voltage dc (HVDC) transmission, high-voltage techniques, measurement standards, uncertainty, voltage dividers.**

I. INTRODUCTION

INCREASING transmission voltages in high-voltage dc (HVDC) and incipient introduction of dc grids has accentuated the need for traceable calibrations of dc line voltage at levels exceeding a few hundreds of kilovolts. Stringent requirements are needed to ensure correct metering, where in many cases, the logical point to meter is at the interface between buyer and seller in a dc grid. This option is not used today, partly due to lack of traceable calibration of voltage transducers for metering purposes. This perceived need has formed the background of this paper.

To fulfill the needs of metering at these elevated voltages requires very good accuracy for dc. This has recently been achieved by the design of a new modular reference divider for calibration of metering class HVDC dividers up to the highest transmission voltages in use world wide [1], [2], [9]. For accuracy class 0.2%, a reference system should have an uncertainty less than 0.02%. Determination of losses in converter stations by direct measurement of ac and dc power [3] necessitates a performance of at least 0.01%. A system used for calibration of such reference systems should have a measurement uncertainty of less than 0.002%, which is met by the modular divider [2].

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Here, we present the design, characterization, and traceability of a 1000 kV resistive laboratory reference divider for SP's high-voltage laboratory, to be used for calibration of and intercomparison with the modular divider.

II. DIVIDER DESIGN

The target for the new divider assembly was a 1000 kV capability and an ambitious precision goal of 0.004%. The divider comprises 1000 precision resistors. The resistive current at nominal voltage is 100 μA, which leads to a total power dissipation of 100 W for the whole 1000 kV divider. Earlier work on reference dc dividers indicate that this current level was considered as a good compromise between problems caused by self-heating of the resistors and leakage currents bypassing through insulating structures [4]–[6].

The resistor chain is protected from the surrounding environment by a pressure-tight Fibre-reinforced plastic (FRP) tube filled with SF_6. The paint of the FRP tube showed a too low conductivity during the first calibration, which caused a buildup of charge in the middle flange (Fig. 2). The tube was repainted using semiconductive paint, leading to approximately a 20-μA current along the tube surface at nominal voltage.

A. High-Voltage Arm

The divider consists of a stack of modules with a nominal voltage of 25 kV each. Out of 40 modules, 37 modules are equipped with 25 pieces of the 10-MΩ Vishay–Mann precision-wire-wound resistors and three modules are equipped with 10-MΩ Caddock USF 370 precision resistors of the same type used in the design of a modular reference divider [1]. The capacitance of the polymethyl methacrylate (PMMA) center column support and stray capacitance to earth from the column form a parasitic capacitive divider that will put limitations in frequency response that is felt already in the millihertz range. The performance for a stable dc voltage is, however, excellent.

The modules (Fig. 1) are stacked on a bottom flange and encased in an FRP tube (Fig. 2) to provide a sealed environment for the high voltage arm. It is filled with SF_6 gas under a 150-kPa absolute pressure to provide increased dielectric strength. The sealed structure will ensure that the internal insulation surfaces remain clean and protected from humidity.

Stacking of the modules is shown in Fig. 2, where a 3-mm standoff disc of PMMA is visible. There are three such discs

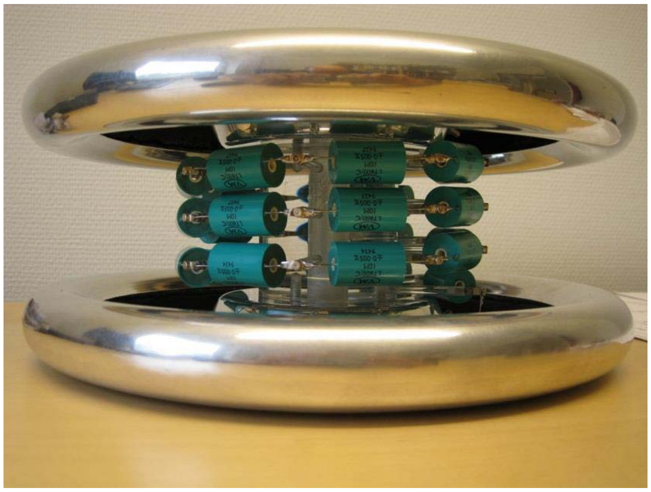

Fig. 1. 25 kV submodule equipped with the Vishay precision resistors.

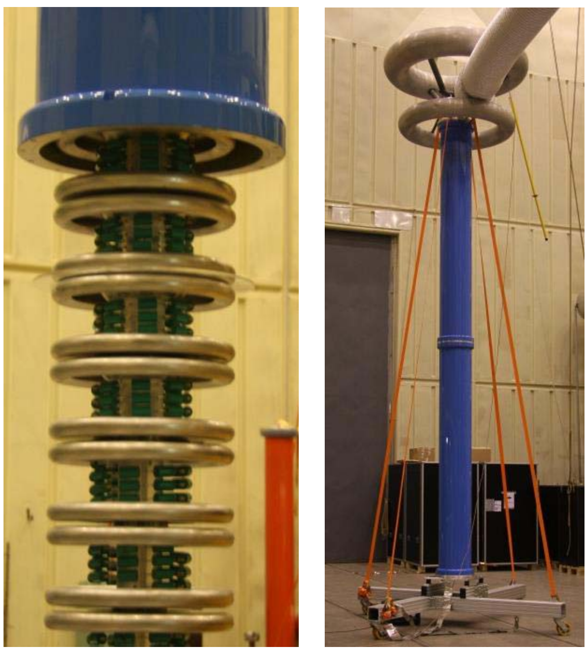

Fig. 2. Stacking of the divider with a PMMA standoff disc visible between modules 8 and 9 (left) and the full divider (right).

in the structure, on top of modules #8, #16, and #24, to prevent bending of the stack when it is put under pressure by springs under the top flange in the system.

The outer diameter of the divider is 480 mm. It is 6.9-m high, and weighs 600 kg. The top endplate houses a gas valve, a pressure gauge, and a feed through for the reference divider signal. The bottom plate has corresponding feed through to separate the resistive chain current from possible leakage current on the surface of the FRP tube.

B. Low-Voltage Arm

The low-voltage arm (Fig. 3), which comprises of the thick-film Vishay resistors of type S102, is encased in a vessel with SF6, similar to the high voltage arm, for protection against possible drift due to humidity. Humidity effects have been studied and a time constant of more than one week has

Fig. 3. Low-voltage arm in a sealed container filled with SF6.

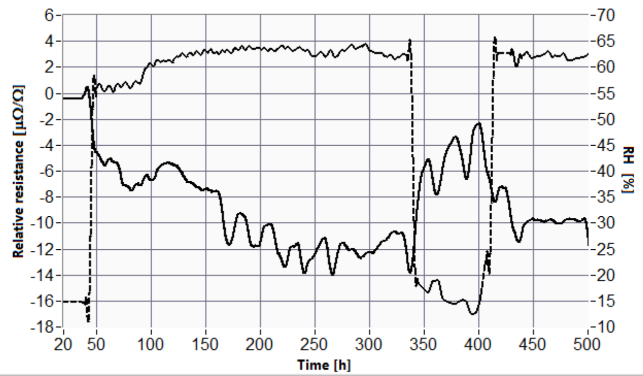

Fig. 4. Humidity plot. Solid curve—Caddock USF370 shows the relative change of the resistance (left vertical axis) as a function of time. Dashed curve—the relative humidity (right vertical axis).

been observed (Fig. 4). The temperature coefficient (TC) for the S102 is ±1 µΩ/Ω/K.

The ratio of the divider has been chosen to obtain a nominal output voltage of 10 V at rated input voltage, thereby permitting the use of high impedance (normally >70 GΩ and for some instruments >1 TΩ) Digital multimeter (DMM) input. This assures that performance is not compromised by uncertainty in the value of instrument input impedance.

III. Characterization

The HV submodules have been acquired from a precision voltage divider originally manufactured by Central Electricity Research Laboratory in U.K. for application to the calibration of the dividers for the cross-channel dc link to France [8]. That divider comprised of 24 modules for 25 kV each, i.e., a nominal of 600 kV at 100 µA. The divider was originally used at 160 µA, but this led to a fair amount of self-heating and unnecessarily large errors.

The resistors of the purchased divider are identical to the components of the Vishay dividers already in use at SP, and another 13 modules have been manufactured using spare Vishay resistors. The full set of 40 modules needed to reach a nominal voltage of 1000 kV at 100 µA was realized by equipping three modules with the same resistor type used in the modular divider designed for the on-site application [1].

A. Resistance Voltage Dependence

Since the divider purchased from the U.K. had been used at a much higher current than the nominal, a study of the stability of these resistor modules was carried out. By measuring the

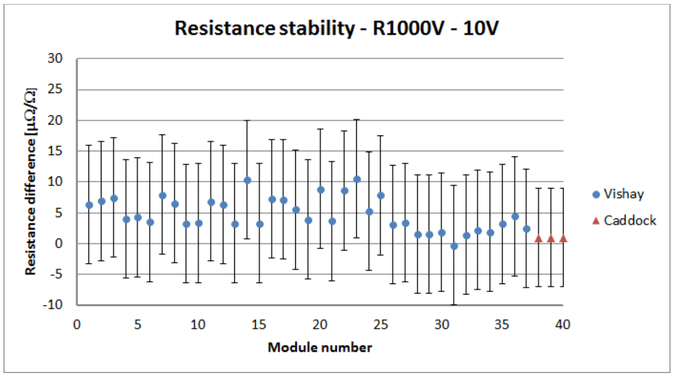

Fig. 5. Average resistance stability of the Vishay modules (blue dots) and the typical value of the Caddock resistors characterized elsewhere.

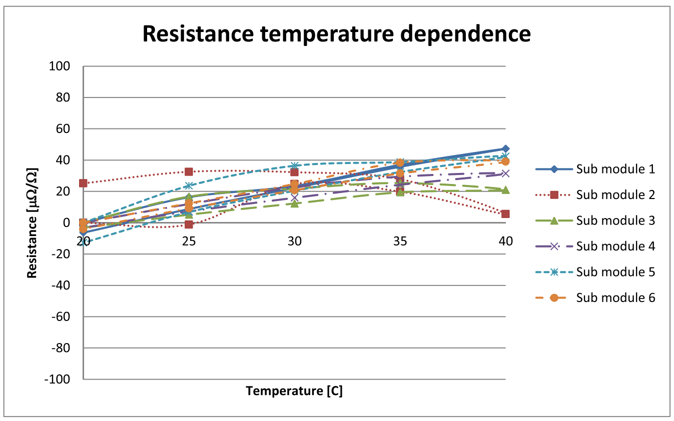

Fig. 6. Relative resistance as a function of temperature of the first six submodules.

resistance at 10 and 1000 V, the difference could be evaluated, as shown in Fig. 5. Any resistor deviating by more than 20 ppm was replaced. This screening was also done for the spare resistors, used in the other 13 modules, to ensure a stable operation after assembly. The last three modules built with the Caddock resistors have also been plotted with typical data for comparison.

B. Temperature Coefficient

A characterization of the TC was done on the first 24 modules, measuring the 250-MΩ resistance in a temperature chamber, using a Fluke 8508A. The resistance variation in a temperature variation for six of the modules has been plotted in Fig. 6.

From the measurement described in Fig. 6, using factory characterizations for the other 13 modules equipped with the Vishay resistors, and from a characterization of the Caddock resistors [9], the TC is plotted for all submodules in Fig. 7.

The TC from the first 24 submodules, with the Vishay resistors, has a clearly larger variation than the other 13 submodules. The combined TC for all Vishay resistors is $(+1.5 \pm 0.8)$ µΩ/Ω/K, and the Caddock resistors, with a TC of $(+1.1 \pm 0.2)$ µΩ/Ω/K, has only a marginal influence.

The ensuing overall TC for the full divider is $(+1.5 \pm 0.8)$ µΩ/Ω/K. This is closely matched with an estimated $(+0.6 \pm 0.2)$ µΩ/Ω/K for the type S102 Vishay resistors in the low-voltage arm.

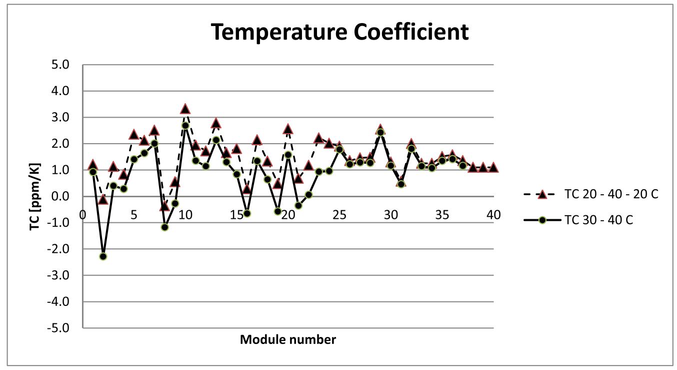

Fig. 7. Measured TC is plotted for all 40 modules. The data for the last three modules are typical values from another characterization.

C. Voltage Coefficient

The Vishay wire-wound resistors are considered to have negligible voltage coefficients, which have also been verified here. The Caddock film resistors have been characterized to (-10 ± 4) µΩ/Ω/kV. In the modular divider described in [1], this has an influence. However, in this reference divider with only three out 40 submodules using the Caddock resistors, the contribution is less than 0.8 µΩ/Ω/kV and therefore negligible.

IV. Calibration and Traceability

The determination of the scale factor was performed using three methods. The first method uses resistance calibration of the high-voltage arm using a voltage bridge method and the low-voltage arm using a DMM. The second method is a scale factor calibration against another well characterized voltage divider at 50 kV. The third method uses a modular divider [2] for a scale factor comparison at full 1000 kV.

A. Resistance Based Calibration

The voltage bridge method utilizes two precision calibrators to form one branch, and the other branch containing a reference resistor and the unknown resistor. The balance current is zeroed between the branches.

Before assembly, the resistance of each of the 25 kV modules was calibrated in the precision lab of SP Technical Research Institute of Sweden using the voltage bridge method at 1 kV. A high-voltage module resistance of 250 MΩ could be determined with an expanded uncertainty below 5 µΩ/Ω. For this case, the total measurement uncertainty is presented in Table I. An alternative approach, relying on the voltage-current method, with a reference resistor has a slightly larger uncertainty.

The resistance of the low-voltage arm is calibrated using a properly calibrated DMM with a typical uncertainty of a few microohms per ohm.

The resistance can now be calculated for the series connection of the 40 HV modules, and together with the known Low voltage (LV) arm resistance, the scale factor is calculated from

$$s.f. = \frac{\sum R_H + R_L}{R_L}$$

TABLE I

UNCERTAINTY BUDGET FOR A 1000-kV DC MEASUREMENT ($k = 2$) (DIVIDER RESISTANCE CALIBRATED BEFORE ASSEMBLY AT 1 kV)

	Type	Contribution in 10^{-6}
Statistical spread	A	5
Determination of LV arm resistance	B	1
Determination of HV module resistance @ 1 kV	B	2.5
Uncertainty of voltage coefficient correction	B	0.1
Uncertainty for (23 ± 2) ºC temperature range	B	1.5
Non-linearity due to leakage currents	B	2.5
Self-heating effect and stratification	B	2
Uncertainty of DMM reading	B	1.6
Contribution of DMM input impedance	B	1
Combined Standard uncertainty		6.9
Combined expanded uncertainty		**14**

TABLE II

UNCERTAINTY BUDGET FOR A 1000-kV DC MEASUREMENT ($k = 2$) (COMPLETE DIVIDER RESISTANCE CALIBRATED AFTER ASSEMBLY AT 1 kV)

	Type	Contribution in 10^{-6}
Statistical spread	A	5
Determination of LV arm resistance	B	1
Determination of HV arm resistance @ 1 kV	B	7.5
Uncertainty of voltage coefficient correction	B	0.1
Uncertainty for (23 ± 2) ºC temperature range	B	1.5
Non-linearity due to leakage currents	B	2.5
Self-heating effect and stratification	B	2
Uncertainty of DMM reading	B	1.6
Contribution of DMM input impedance	B	1
Combined Standard uncertainty		9.9
Combined expanded uncertainty		**20**

TABLE III

UNCERTAINTY BUDGET FOR A 1000-kV DC MEASUREMENT ($k = 2$) (DIVIDER SCALE FACTOR CALIBRATED AT 10 kV)

	Type	Contribution in 10^{-6}
Statistical spread	A	5
Determination of reference divider SF	B	3.5
Uncertainty for (21 ± 2) ºC temperature range	B	1.5
Non-linearity due to leakage currents	B	0.5
Self-heating effect and stratification	B	0.5
Uncertainty of DMM 1 reading	B	1.6
Contribution of DMM 1 input impedance	B	1
Uncertainty of DMM 2 reading	B	1.6
Contribution of DMM 2 input impedance	B	1
Combined Standard uncertainty		7.5
Combined expanded uncertainty		**15**

TABLE IV

UNCERTAINTY BUDGET FOR A 1000-kV DC MEASUREMENT ($k = 2$) DIVIDER CALIBRATED AT 1000 kV

	Type	Contribution in 10^{-6}
Statistical spread	A	5
Determination of reference divider SF	B	8
Uncertainty for (21 ± 2) ºC temperature range	B	1.5
Non-linearity due to leakage currents	B	2.5
Self-heating effect and stratification	B	2
Uncertainty of DMM 1 reading	B	1.6
Contribution of DMM 1 input impedance	B	1
Uncertainty of DMM 2 reading	B	1.6
Contribution of DMM 2 input impedance	B	1
Combined Standard uncertainty		10.4
Combined expanded uncertainty		**21**

where R_H are the HV module resistances and R_L is the resistance of the LV arm.

After assembly, the complete stack, i.e., the 10-GΩ high-voltage column, was again calibrated with the voltage bridge method. In this case, the expanded uncertainty for resistance increases to 15 μΩ/Ω for the full stack, since the spread of measurements (type A) will dominate. In this case, a higher total expanded measurement uncertainty of 20 μV/V is the result, as presented in Table II.

B. Scale-Factor-Based Calibration

This method is based on a comparison with another divider that has a well-known scale factor. Measuring the ratio of the two output voltages permits determination of the scale factor.

During a calibration at Aalto University in Espoo, Finland, a 40 kV reference divider from MIKES was used at 10 kV, and smaller wide band reference divider from SP was used at 1 kV to calibrate the scale factor (Table III).

C. Intercomparison at Full Voltage

A series of comparison measurements with the modular 1000 kV divider [2] was performed in a measurement campaign at Aalto University in Espoo, Finland, in May and June 2013 (Fig. 3). The systems were studied at voltages ranging from 10 to 1000 kV. During the campaign, the HVDC scale factor references of three different national laboratories, MIKES, Physikalisch-Technische Bundesanstalt and SP, were compared with each other.

The expanded measurement uncertainty for the modular divider, determined in a series of experiments in several configurations [1], is presented in Table IV.

D. Comments on Instrumentation

The DMMs used for measurement of the signal from the low-voltage arms of all dividers were of the type Agilent 3458A (high-stability option). These were calibrated within 90 days before the measurement, which gives an expanded measurement uncertainty of (2.6 + 0.05) μV/V (reading + range), and is included in the previous uncertainty estimate. The scale factors of both 1000 kV dividers are approximately 100 000, which permits the use of the 10 V, which is the most accurate range of the instruments.

All low-voltage arms have a resistance close to 100 kΩ, which puts the instruments' guaranteed input impedance of >10 GΩ in focus. A 10-GΩ impedance would affect the

Fig. 8. Setup with the reference divider (in front), the generator with divider (in the middle), and the modular divider (in the background) [9], during the intercomparison at Aalto University's high-voltage laboratory.

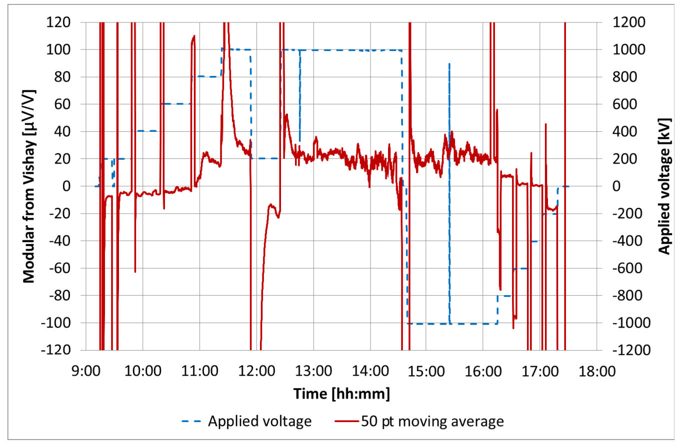

Fig. 9. Plot showing a 6-h comparison run between the modular divider and the reference divider.

divider signal by 10 µV/V. However, the impedance has been measured for various Agilent 3458A DMMs at SP, where one of the instruments used in the campaign (high stability option) showed an impedance exceeding 1 TΩ. In such a case, the effect is 0.1 µV/V. Other observations have shown at least $Z > 70$ GΩ, which shows why we add a conservative 1 µV/V to all uncertainty estimates.

V. Intercomparison

The scale factors of the dividers, by calibration of the resistance of the high- and low-voltage arms, were studied before the assembly and intercomparison in June 2013. The scale factors were also determined at 1, 10, and 200 kV before the intercomparison commenced, varying the voltage up to 1000 kV. Fig. 8 shows the 1000 kV reference divider and a 1000 kV modular divider in Aalto high-voltage hall.

During the comparison measurements, audible and visible corona was present at voltages above 600 kV, increasing the standard deviation of the measurements. Evidence was found of charge build-up on the surface of the laboratory reference insulator tube, which may lead to a nonlinearity by possible leakage currents. The surface has now been repainted with a semiconducting paint to minimize this effect. The temperature gradients are expected inside the 6.9-m long FRP tube, in which the loss power is 100 W at full voltage.

In addition to calibration of the dividers and their components, the measurements in the high-voltage hall included studies on voltage dependence and self-heating, and nonlinearity due to possible leakage currents.

A. Scale Factor Comparison

The result of a 6-h long run comparison between modular 1000 kV and SP reference dividers is shown in Fig. 9. The applied voltage was varied between -1000 and $+1000$ kV. No polarity effect can be seen after a 10 min break that was required for the polarity change of the HVDC generator. The transients observed during the changes of the voltage level are due to the slow response of the purely resistive reference divider. Here, the building up of charge on the outer skin of the reference divider is evident from the higher noise level at high voltages in Fig. 9.

The rise of the scale factor quotient just before 11:00 and the drop at the end of the run was caused by the degradation of three wire-wound resistors, discovered after disassembly of the reference divider. The difference in the observed scale factor between 200 and 1000 kV is approximately 30 µV/V. This is consistent with a 31 µV/V difference measured after disassembly and traced to the three damaged resistors.

B. Self-Heating

A self-heating effect test started with heating of the modular divider 1000 kV divider [2] to steady state by applying 1000 kV for 3 h. After heating the modular divider, the reference divider was quickly (within 10 min) inserted into the circuit. The difference settles around 37 µV/V. By subtracting the change in scale factor of 31 µV/V and a TC of 1.5 ppm/K, we conclude that the self-heating is 4 ± 2 K. This temperature change is reasonable compared with the modular divider result of 6 K [2], having the double heating of 200 W.

VI. Experience

The reference divider showed an unacceptable susceptibility to interference from corona in the high-voltage hall. It has subsequently been modified by painting the outer surface of the insulating cylinder with semiconducting paint, intended to bleed off any charge on the surface. Excessive corona in the high-voltage hall will otherwise lead to charge carriers accumulating on the fiberglass tube.

During the lasts tests, an increase in the scale factor of the reference divider indicated a degradation of resistors in the high-voltage arm. Three were found and replaced after disassembly. The new-resistance-based scale factor is at hand, and is currently being calibrated against a 50 kV Vishay divider, and will further be compared with the complete modular divider at hand in the laboratory of SP.

VII. Conclusion

A high-accuracy HVDC divider for traceable calibration in SP's high voltage laboratory has been constructed and verified. Thorough characterizations of the TC and voltage coefficient of two different types of precision resistors were performed and it was shown that the total assembly had an average TC of $(+1.5 \pm 0.8)$ μΩ/Ω/K and a negligible voltage dependence.

Three calibration methods were used for determination of the scale factor of the divider. One method was based on calibrating the resistance of each of the HV modules and the LV arms, and the second method a scale factor calibration at 10 kV, followed by a series of divider comparison measurements up to full voltage.

A best overall measurement uncertainty of 14 μV/V for the laboratory reference at 1000 kV has been demonstrated using the voltage bridge method before assembly. However, after assembly using the resistance method, the expanded uncertainty will increase to 20 μV/V. The scale factor calibration against a 50 kV divider at 10 kV gives the best practical expanded uncertainty of 15 μV/V. For comparison at full voltage with the modular divider [1], an expanded measurement uncertainty of 21 μV/V is achieved.

Further work on measurements of stratification inside the divider is ongoing, and a new semiconductive painting has been applied to further suppress the effect of corona. A conservative Calibration and Measurement Capability-entry has been given for this divider of 50 μV/V, and considering the work presented here the value is expected to be revised in the near future.

Acknowledgment

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