NEW REFERENCE HVDC DIVIDER FOR THE CALIBRATION OF TESTING EQUIPMENT UP TO 1600 kV

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Abstract

An international metrology project named “EMPIR 19ENG02 FutureEnergy” started in June 2020, is developing, building, and evaluating measurement equipment and systems for the UHV level. This paper describes the work on a new reference UHVDC voltage divider for the calibration of testing equipment up to at least 1600 kV. This divider has a modular design and target expanded measurement uncertainty of 200 µV/V. The need for such measurement systems results from new measurement methods for future energy transmission grids. After the construction of the UHVDC voltage divider, the targeted measurement uncertainty of 200 µV/V was successfully at 1200 kV during a measurement campaign at PTB. The linearity and temperature dependence of the UHVDC divider modules as well as the overall results of this new divider are included in this work. This work will lead to new calibration and measurement capabilities (CMC) for traceability of the designed divider systems for participating national metrology institutes (NMI).

1 Introduction

Within the scope of an international research project, PTB is leading a work package for the development of metrological solutions for ultra-high DC voltages. In 2022, an international measurement campaign was carried out with RISE (Sweden) [1] and PTB (Germany) [2] with new voltage dividers. These components are the fundament for future calibration and testing services in the high-voltage range up to 2000 kV and the basics for the work of countless high-voltage test laboratories worldwide.

The increasing global demand for electrical energy, climate change and the resulting need to integrate renewable energies, as well as the current global political situation, show that a change in energy policy towards more independence from international markets is mandatory. Historically, electrical energy is still mainly generated centralised and transmitted over long distances by high-voltage three-phase power lines. The energy transition is already forcing a rethink at the national level. Electrical energy is generated where the natural regenerative energy supply is available, for example through wind power in offshore plants or in large hydroelectric reservoirs located far away from the consumers. In future, this electrical energy will be transported by high-voltage direct current (HVDC) transmission lines at operating voltages of several hundred kilovolts and in some cases voltages higher than 800 kV, which, according to current knowledge, is the only efficient and economically possible solution for transmission distances of more than 1000 km.

In order to ensure availability and supply quality beyond the voltage ranges that have been usual up to now, it is therefore necessary to test devices and components at the highest DC voltages. However, high-voltage tests and calibrations above 1000 kV DC were before this project started not available. The aim of PTB together with the other project partners is to extend the measurement possibilities up to 2000 kV DC within the EMPIR project "EMPIR 19ENG02 FutureEnergy" [3]. For this purpose, two different precision voltage dividers have been developed for PTB in the project. Two shielded precision voltage dividers are now available at PTB and RISE, which can be stacked from 200 kV to 1200 kV in 200 kV steps [4], as well as a newly designed modular universal voltage divider, based on a master's thesis at PTB, which can be used for voltages up to 2000 kV in five 400 kV steps [5].

Calibrations and high voltage measurements are mainly described in the IEC 60060 series - High voltage and high current test methods [6, 7]. However, system voltages are currently rising higher than the voltages covered by this standard and there is an urgent need to reliably extend the test methods into the ultra-high voltage range. Therefore, in the end of this project, the research results will contribute on an international level to the ongoing revision of the IEC 60060 series [6, 7] in the Technical Committee IEC TC 42 "High-voltage and high-current test techniques".

2. Characterisation

2.1 Ultra high voltage divider setup

The components of the 2000 kV high-voltage divider (PT400-1 up to PT400-5) [8] form a mixed voltage divider without an internal dampening resistance. Furthermore, it includes a shield arm, which counteracts parasitic capacitances. The precision divider was designed for this task because it is mainly used for HVDC calibrations and measurements [5]. The 10 MΩ precision resistors are in parallel with 100 nF capacitors. The schematic diagram of the precision divider is given in Figure 1. Red colour indicates the high-voltage arm and blue the low voltage arm. The pale colours (left) indicate the transient part of the divider, the medium colours (centre) the AC part and the strong colours (right) the DC part.

2.2 Temperature dependence

The separate resistances of a high voltage divider have a temperature coefficient T_K that depends on the kind of design. In the presence of a temperature increase, the total resistance and thus the scale factor change accordingly, so that the scale factor of the precision divider changes too [9]. When the temperature of a measuring divider increases, a differentiation is made between two causes, self-heating and the change in the ambient temperature outside the voltage divider.

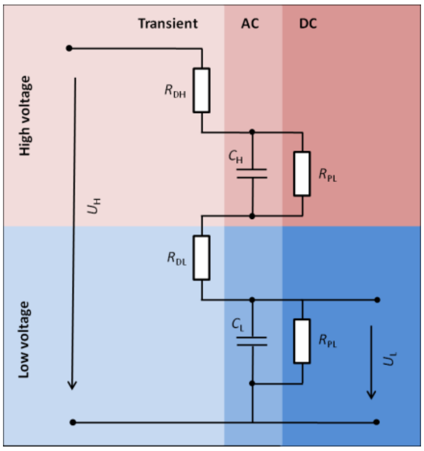

Fig. 1 Schematic diagram of the high voltage divider for superimposed measurements (PT400) [9]

The high-voltage resistors are housed in a polypropylene cylinder filled with air and enclosed at the top and bottom by flanges. The Joule heat rises to the top and increases the temperature there. At the same time, heat is released into the environment, so that after a while a temperature gradient is established in the voltage divider.

The stability behaviour of the reference (PT400.4) used is presented in Fig. 2 at 100 kV and show constant values after a short time. The reference was previously calibrated with the national standard divider MT100, whose temperature is 26.0°C (± 0.15 °C). This divider is thermally separated from the measuring laboratory and has a separate heater with which it is kept at a stable temperature value. The few outliers can have different reasons. On the one hand, the triggering of the measuring instruments can lead to minimal deviations if the readout routine shows slight shifts in the trigger synchronization. A non-simultaneous readout of the measuring instruments leads to voltage deviations in the nV range. Even the outliers are in the range of a few ppm.

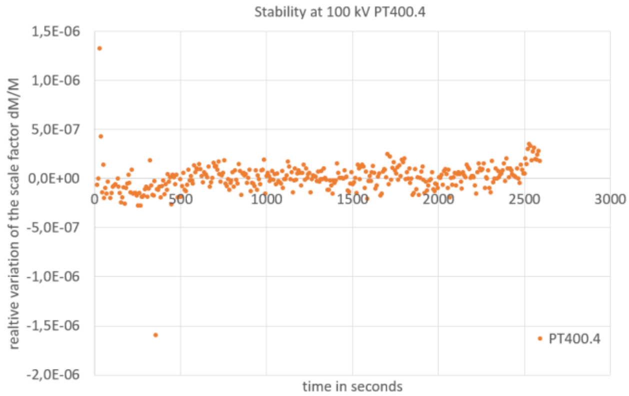

Fig. 2 Stability of high voltage divider at 100 kV for PT400.4

The influence of the external ambient temperature on the scale factor of all individual modules of the ultra-high voltage divider is described in the results chapter. Table 1 shows the scale factor of the modules at laboratory environment of 21°C

Table 1 Scale factor at 21°C

Module name	Scale factor
PT400.1	40002.54
PT400.2	39973.55
PT400.3	40002.94
PT400.4	40002.87
PT400.5	39762.15

The divider modules have traceability to the national references, Table 2 describes the most important technical details.

Table 2 Technical data of PT400 divider

Nominal scale factor	40.001:1
Nominal voltage	400 kV
Expanded uncertainty (*k*=2)	$1 \cdot 10^{-5}$ V/V
Resistance of precision arm	4 GΩ
Resistance of shield arm	2475 GΩ
Low voltage arm	100 kΩ

2.3 Setup for the measurement of the temperature coefficient

For measurements that are not carried out under ideal laboratory conditions of 21° C, the temperature coefficient is an important correction factor. This is indispensable for open area test site measurements, such as those carried out at PTB within the scope of the project. The dividers are exposed to temperature fluctuations during outdoor measurements. Therefore, temperature measurements for the DC measuring dividers are carried out with the help of the temperature laboratory for high-voltage devices at PTB. This temperature laboratory is equipped with a high-voltage bushing for voltages up to 300 kV. The chamber is 12 m high, has a diameter of 6.3 m and covers a temperature range of -35° C to +56.5° C. The temperature stability is 0.5° C in all temperature ranges.

The divider modules are tested from 0° C to 56.5° C in 10° C steps at a constant maximum voltage of U_{DC} = 100 kV. Even with large voltage dividers up to 8 m size, a homogeneous heat distribution in the temperature laboratory is achieved by a constant circulating air. This is also checked by temperature sensors mounted at different heights of the temperature laboratory (1.5 m and 7 m). Furthermore, the cylindrical structure of the laboratory can be seen in figures 3 and 4, which allows the examination of the dividers with always constant ambient geometries.

Due to the nominal scale factor of approx. 40.001:1 per module, it is necessary to perform this measurement at high voltage. Due to the fact that with a low-voltage measurement and an expected temperature coefficient in the ppm range, the measurement uncertainty of the measurement would be larger than the temperature coefficient. Therefore, the measurement is carried out module by module at a maximum voltage of U_{DC} = 100 kV (25 % of the nominal voltage per module). The voltage was supplied through a high-voltage coaxial cable connecting the temperature laboratory to the DC high-voltage laboratory where the reference divider is located. Furthermore, it must be taken into account that the steady state is only reached after several hours following a previous change in air temperature. The intervals between two measurements with different temperatures were 24 hours.

Fig. 3 Test set-up in the PTB temperature laboratory

It is important to note that temperature tests should always be started at the lowest temperature. Otherwise, condensation may occur in the divider, causing leakage currents and thus affecting the results. The specified temperature coefficient of the DC divider's high-voltage resistors built into the divider is 1.6 ppm/°C. Figure 3 and figure 4 show the test setup in the temperature laboratory for measuring the temperature coefficient of the four divider modules. These were measured in parallel at U_{DC} = 100 kV [5].

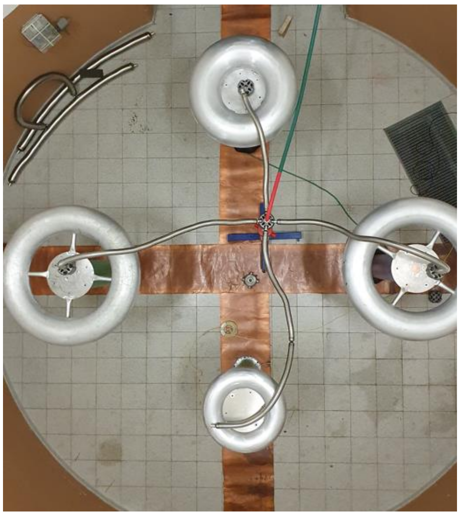

Fig. 4 Test set-up in the PTB temperature laboratory (view from the top) with high-voltage connection

For these precision measurements, a reliable reference divider including precision voltmeters is required for each measuring system. These are permanently installed in the DC measuring laboratory of the PTB. Therefore, a high-voltage cable connects the reference divider and the DC generator in the DC measuring laboratory to the test dividers in the temperature chamber. The low-voltage signal of the dividers is transmitted to the precision voltmeters in the DC laboratory via a 35 m long RG 58 cable. These measures ensure a temperature-stable environment for the reference, and, at the same time, the test divider is measured via the voltmeters in the temperature range from 0°C to 56.5°C. This provides a wide temperature range around the normal operating temperature of 21°C. The self-heating caused by the high-voltage measurement has only a minor effect, since the warm-up behaviour is known on the one hand and, on the other hand, the determined scale factor is measured over a period of at least one hour. After setting a new temperature value, the scale factor must be observed over a long period of time, as this is the only way to make a statement about the temperature inside the divider. This is the case because the divider reacts only very slowly (time constant approx. 5 hours) to temperature changes due to the insulating tube construction.

3 Results

A positive high-voltage source (type XP Glassman OS Series 2 kW, regulated high voltage DC power supplies, 450 kV) is used for the measurements. This is connected to the reference divider PT400.4 and the dividers under test PT400.1 / PT400.2 / PT400.3 / PT400.5. HP3458A voltmeters are used as measuring instruments. These measuring instruments are triggered and read out simultaneously via "LabView" software. The temperature of the standard measuring device during the measurement is 21.0 °C (± 0.5 °C) at a relative humidity of 40 % (± 10 %). Figure 5 shows an example of the change in the scale factor for a divider depending on the temperature. The temperature coefficients are determined from these values.

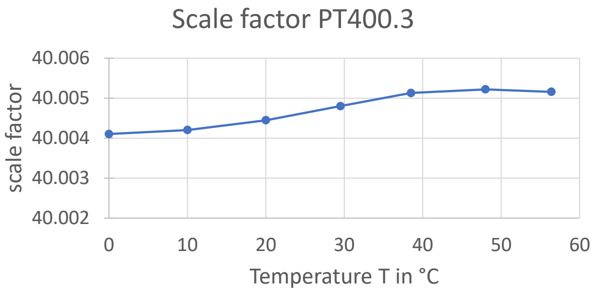

Fig. 5 Scale factor depending on temperature of PT400.3

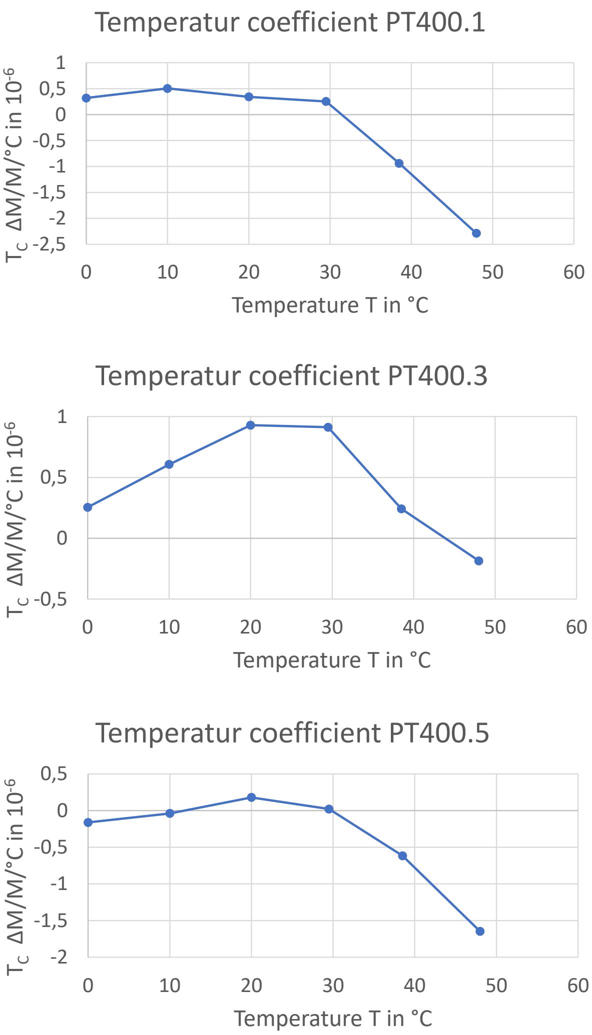

Fig. 6 Temperature coefficient of PT 400.1, PT400.3 and PT400.5

The diagram of the temperature coefficient for each individual divider module can be seen in Figure 6. The PT 400.2 showed internal corona or discharge processes during the measurements, so the measured values could not be evaluated. These measurements will be carried out at a later date, as the measuring divider must be completely disassembled and checked component by component in a time sensitive process.

For each temperature value, the measured values are combined to create a mean value of the scale factor (Figure 5). The temperature coefficients are related to the respective temperature range of two neighbouring temperature values and the corresponding scale factors (Figure 6). The standard deviation of all measurements is a maximum of ΔM/M = $2.5 \cdot 10^{-6}$/°C over the temperature range up to 56.5°C. Up to 30°C the temperature coefficients are smaller than $1 \cdot 10^{-6}$/°C so that a calibration can be carried out in the open area test site without any trouble in this range.

4 Intercomparison

With the characterisation of the UHVDC divider the two shielded precision voltage dividers of PTB were intercompared in a measurement campaign on the open field of the PTB together with an identical shielded precision 1200 kV voltage divider and an unshielded 1000 kV universal voltage divider from RISE [4] which design is presented in a separate paper at ISH 2023 [10]. The RISE modular voltage divider has been in use for on-site calibrations using five HV modules to reach 1000 kV since the original design and calibration launch in 2013. The stability of these HVDC divider systems is unprecedented with a scale factor drift of 0.7 µV/V/year [4]

The setup from the intercomparison is shown in Figure 7. The 2000 kV UHVDC divider can be seen on the left side, the two identical 1200 kV dividers on the right side. In the centre is the 2000 kV DC voltage generator and, in the background RISE universal RCR 1000 kV divider.

Fig. 7 Open area test site at PTB, high-voltage generator for 2000 kV DC (centre) and four precision voltage dividers for high DC voltages

Using the results from 150 kV to 1000 kV the scale factor (SF) stability is <1 µV/V (Table 3) with expanded uncertainty of 4.0 µV/V. A measurement with the UHVDC up to 1000 kV has an expanded uncertainty of 38 µV/V. Omitting the 1000 kV point, suffering from growing corona from the ring cage toroid of the UHVDC divider and the generator above 800 kV, the expanded measurement uncertainty of 28 µV/V. The SF stability points to an expanded measurement uncertainty for the UHVDC measurement system of 30 µV/V. However, to hold this limit two new corona rings have been prepared for the UHVDC divider, using a double toroid with larger diameters than the two 1200 kV HVDC dividers in Figure 7.

Table 3 Intercomparison of PTB 1200 and PT 1600 measurement systems

U [kV]	SF error [µV/V]	k	υ_{eff}	Exp. unc. [±%]
100 kV	6.7	2.0	110	± 0.00149
200 kV	5.1	2.0	190	± 0.00183
400 kV	-0.9	2.0	140	± 0.00150
600 kV	-6.3	2.0	120	± 0.0023
800 kV	-1.9	2.0	100	± 0.0052
1000 kV	-2.6	2.0	60	± 0.0065
Average	-0.5			
Exp. unc. (k=2)	4.0			± 0.0028

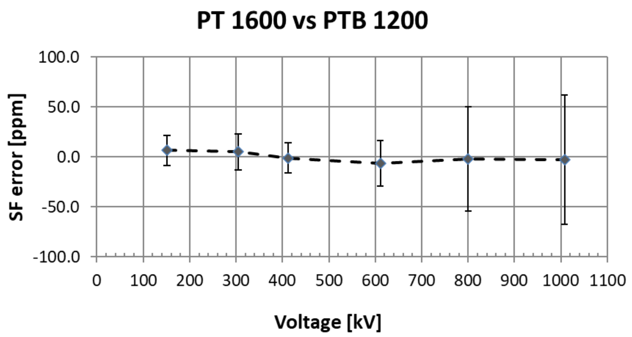

Fig. 8 Plot of the values in Table 3

5 Conclusion

The maximum measured temperature coefficient is T_c = 2.5 ppm/°C. According to the data sheet information of the supplier of the high-voltage resistors, they have a temperature coefficient of maximum $T_{c,R}$ = 1.6 ppm/°C. The determined value is therefore reasonable and other influences, such as the parallel capacitors, the low-voltage divider, as well as the self-heating, only have a minor effect at different temperatures. Based on this result, the voltage divider can be used both in a controlled stable laboratory environment with minimal temperature influences and low uncertainties and in open area test site measurements with large temperature changes. In the second case, a correction of the scale factor must be made based on the obtained measured values if the outdoor temperature exceeds 30°C or the dividers are heated up by the sun. Through the comparison between the modular PTB HVDC 1200 kV divider and the PTB UHVDC 1600 kV divider it has been shown to have an extremely low scale factor difference between the systems, within 1 µV/V, and an expanded measurement uncertainty of below 30 µV/V.

The two dividers of PTB, HVDC 1200 kV and UHVDC 2000 kV, have a scale factor agreement with the RISE HVDC 1200 kV voltage divider during the measurement campaign of several weeks and they are now ready to be used for future calibration services. New CMC claims will be made for both PTB dividers, and the PTB HVDC 1200 kV divider is identical to the RISE 1200 kV measurement system which has a claimed expanded measurement uncertainty of 20 µV/V. The results presented here points toward an expanded measurement uncertainty of 30 µV/V for the new PTB UHVDC measurement system.

6 Acknowledgements

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7 References

Conference Paper

[4] Elg, A.-P., et al.: “On the Stability of a Modular 1000 kV HVDC divider design”. Conference on precision electromagnetic measurements, Wellington 12 – 16 Dec, 2022

[5] Passon, S., et al.: “Modular Wideband High Voltage Divider for Metrological Purposes”. The 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, 2017

[10] Alf-Peter Elg, Tatu Nieminen, Joni Klüss, Stephan Passon, Frank Gerdinand and Johann Meisner “A Modular Universal Divider for Calibration of UHVDC, and Composite Waves up to 1400 kV” Submitted to ISH 2013

Book, book chapter and manual

[9] Schon, K.: 'Hochspannungsmesstechnik – Grundlagen – Messgeräte - Messverfahren', Springer Verlag, 2016

Standard

[6] IEC 60060-1, „High-Voltage Test Techniques - Part 1: General definitions and test requirements“, 2010

[7] IEC 60060-2, „High-Voltage Test Techniques - Part 2: Measuring systems“, 2010

Thesis

[8] Passon, S.: ' Metrological infrastructure for the measurement of superimposed impulse voltages in HVDC systems'. PhD thesis, Technische Universität Braunschweig, 2021

Websites

[1] RISE: https://www.ri.se/en, accessed 27 February 2023

[2] PTB: https://www.ptb.de/cms/en.html, accessed 27 February 2023

[3] EMPIR 19ENG02 FutureEnergy: https://www.ptb.de/empir2020/futureenergy/home/, accessed 27 February 2023