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Abstract

The report describes the methods used and results of a characterization of the voltage non-linearity of a 1200 kV HVDC divider at Aalto University high voltage laboratory. Measurements were performed in April 2012 and June 2013. Historical data from 1990 and 2007 were combined with new measurement results to gain good understanding of the voltage dependence and its reasons. The new more precise measurements confirm the findings of the 2007 measurements. The results show that the scale factor of the divider has a linear relative voltage dependence of −0.2 %/MV. It was also found that the oil-filled high voltage resistors have a thermal time constant of several hours.

Contents

1 Background

The traceable high voltage d.c. calibration infrastructure has been relative well established up to couple of hundred kilovolts. However, the increasing interest on HVDC power transmission on voltages up to c. 1000 kV has increased the need for traceable calibration of measurement dividers, especially those used for revenue metering, up to their full voltage. This report collects the results work performed on Aalto university 1200 kV HVDC divider between 1990 and 2013 for characterizing its voltage linearity.

The 1200 kV HVDC divider at Aalto University is part of the HVDC test system comprising of a Greinacher type d.c. cascade together with a voltage divider. Figure 1 shows the system and divider. The system is c. 8 m high. The high voltage arm of the divider consists of 4 sections in series, each rated for 300 kV.

All measurements presented in this report have been performed in Aalto University high voltage hall.

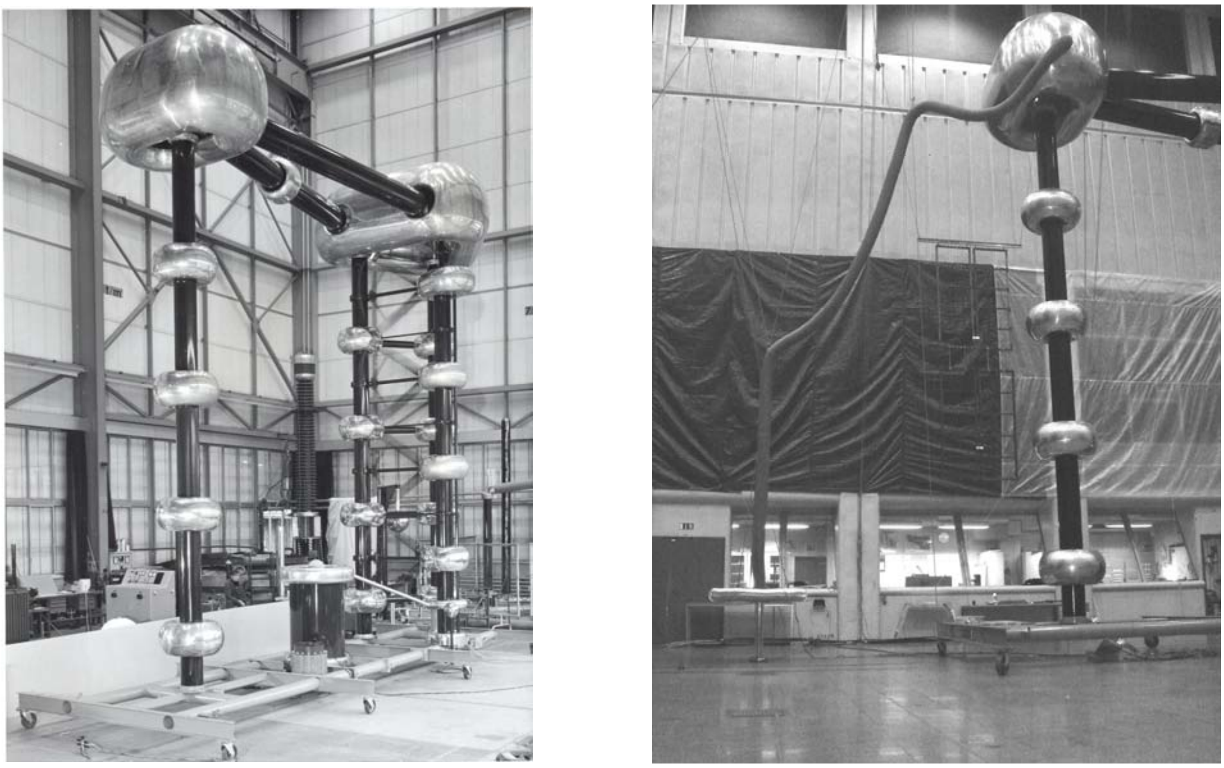


Figure 1. Left: The 1200 kV HVDC system at Aalto University. Generator on the back and the divider on the front. Right: Aalto divider on the right and MIKES 200 kV reference divider on the floor on the left.

The electrical connection of the divider is shown in Figure 2. An alternative low voltage arm of the divider has been added by Aalto University in order to get flat frequency response, and to enable measurement of the output voltage with a precision voltmeter on 10 V range.

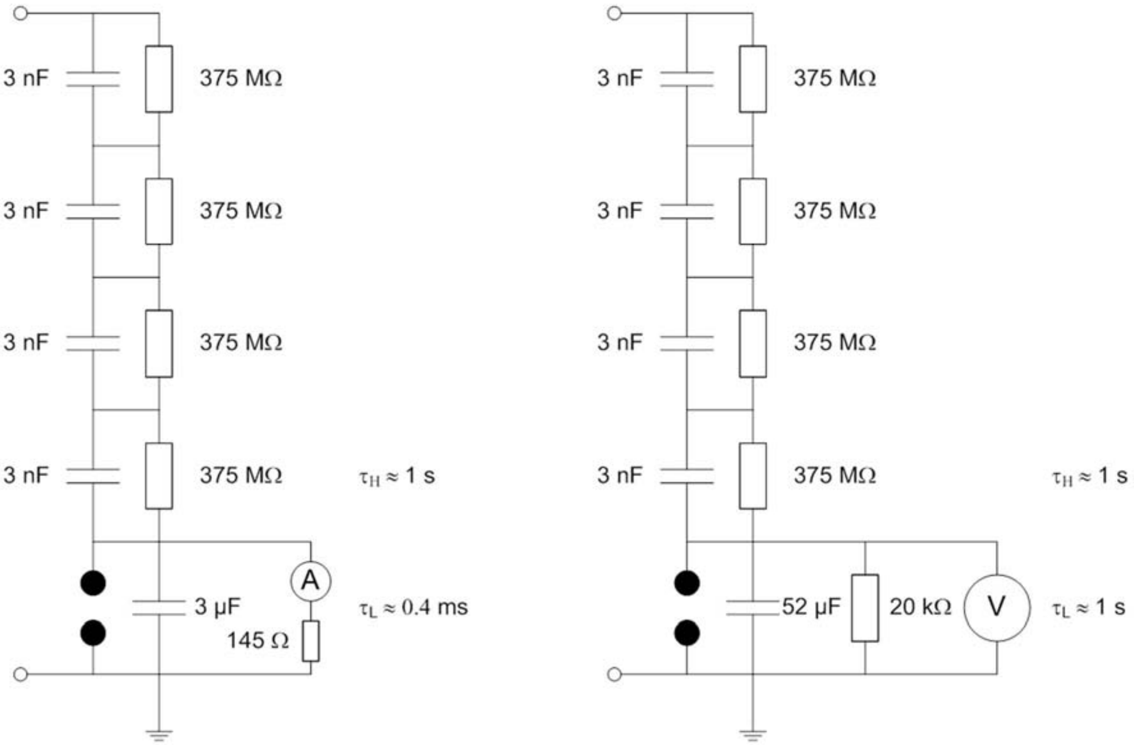


Figure 2. Left: Original divider configuration before 2007. Right: Divider configuration when using secondary low voltage arm.

2 Measurement methods and results

2.1 Comparison with rod-rod gap

IEC standard 60052 gives and empirical formula for the disruptive discharge voltage:

$$U_0 = 2 + 0.534 \times d,$$

where U_0 is in kilovolts and d is the gap spacing in millimetres. The standard quotes an uncertainty of 3 % (k=2) for absolute value after taking into account air density and humidity corrections. For relative measurement performed under stable conditions the uncertainty is somewhat lower.

Comparison with a rod-rod gap using the original low voltage arm configuration was performed in 1990; the result is shown in Figure 3. The built-in 3½-digit meter was used for measurement of the divider output; its resolution of this non-calibrated meter is limiting the resolution and thus uncertainty of measurement on lower voltage levels.

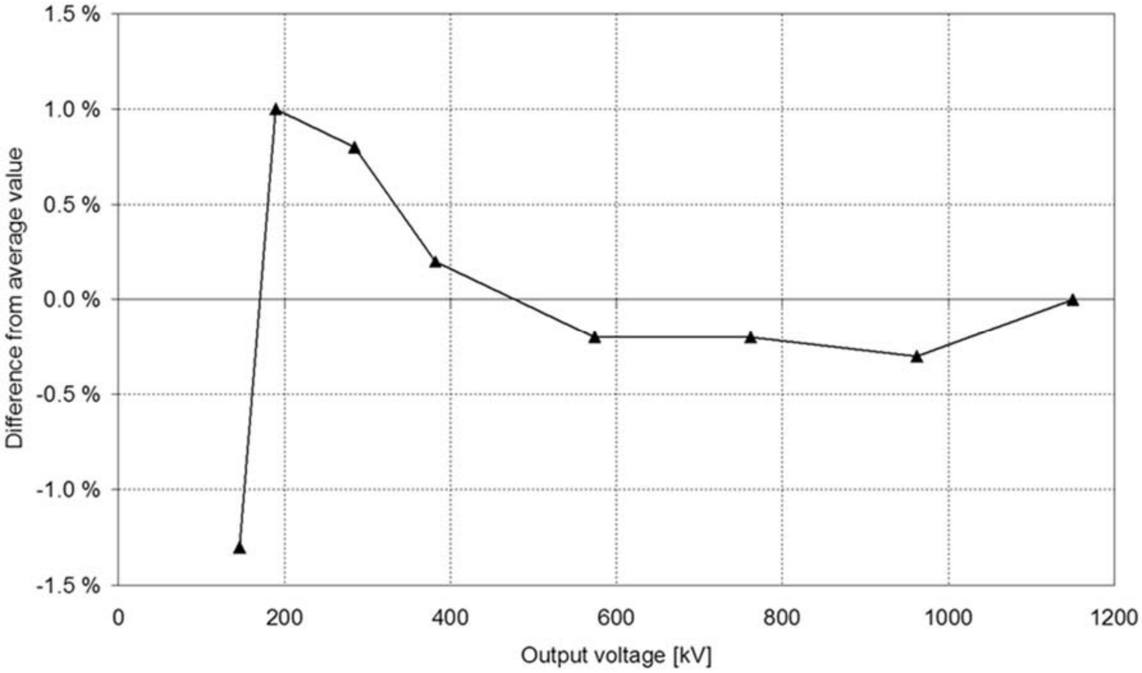


Figure 3. Non-linearity based on comparison with a rod-rod gap up to 1150 kV.

2.2 Comparison with generator excitation voltage

Comparison of the ratio of the measured direct voltage output to measured alternating voltage excitation of the generator was performed in 2007. The problem with this approach is the voltage dependent forward voltage drop of the rectifying diodes in the Greinacher cascade. This voltage drop is unknown.

However, some conclusions can still be made after some assumptions. When the voltage is high enough (in this case > 200 kV), the voltage drop can be assumed to be constant. Then a straight line can be fitted to the ratios measured on different voltages. Any deviation of the measured ratios from the fitted curve is a sign of non-linearity of the measurement system. Results of this measurement are shown in Figure 4. The estimated non-linearity based on this measurement is below 0.5 %.

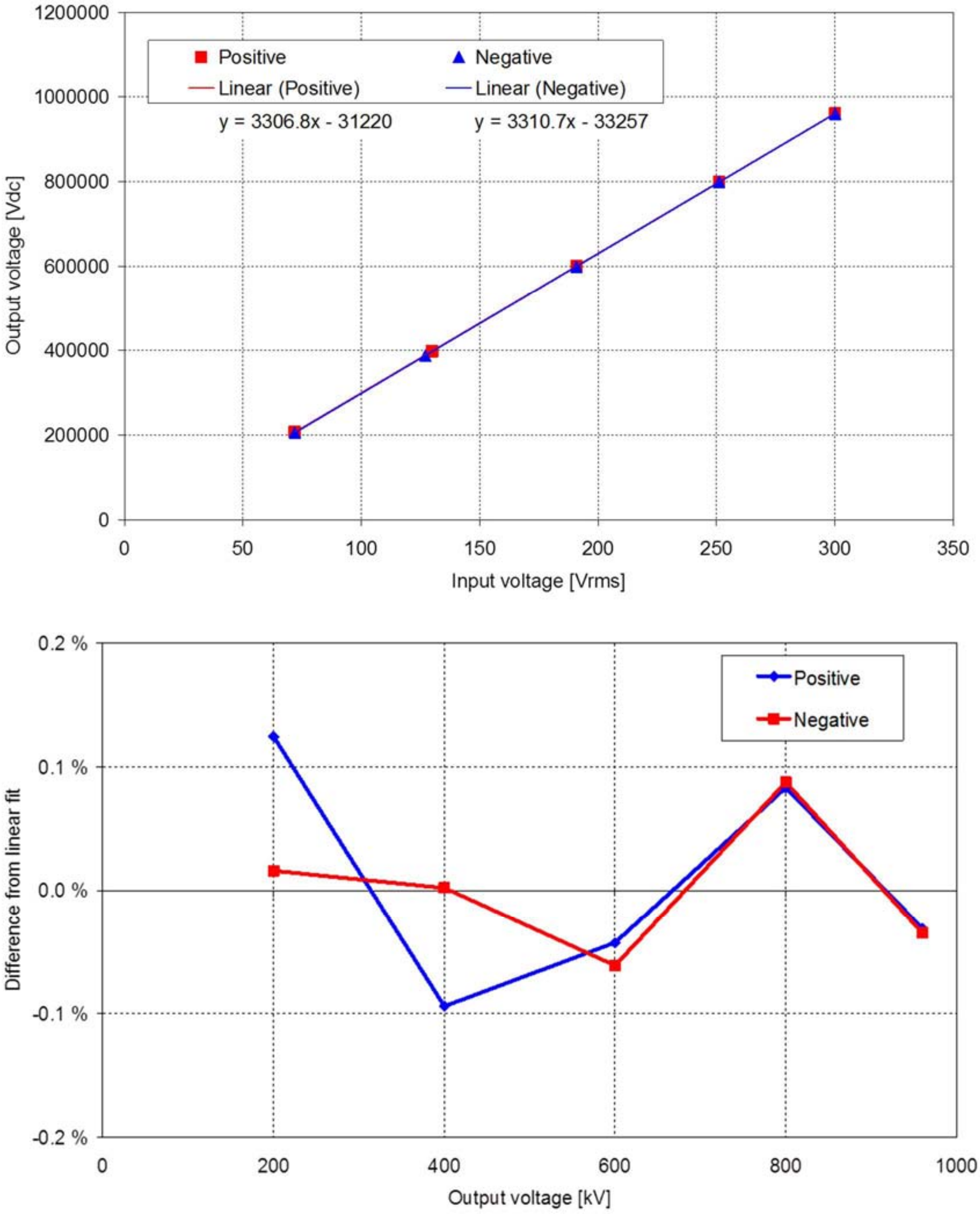


Figure 4. Non-linearity measured based on the measurement of the a.c. excitation voltage of the HVDC generator. Top: divider output voltage (d.c.) vs. generator excitation voltage (a.c. 400 Hz). Bottom: Difference from the linear fit.

2.3 Comparison with 200 kV reference divider in 2007

The high voltage arm of the divider has four 300 kV sections in series. The voltage linearity of each of these was measured against MIKES's 200 kV reference divider. The full voltage of one module is 300 kV, so conclusions can be made up to two thirds of the nominal full voltage of the divider, i.e. too 800 kV. This measurement was completed by comparing the complete 1200 kV stack with MIKES's 200 kV reference divider.

This measurement was performed for the first time in August-September 2007. A typical run for one divider section is shown in Figure 5. The scale factor of the divider was measured on four voltage levels from 50 kV to 200 kV, and repeated again on the lowest 50 kV level in order to reveal possible self-heating effects.

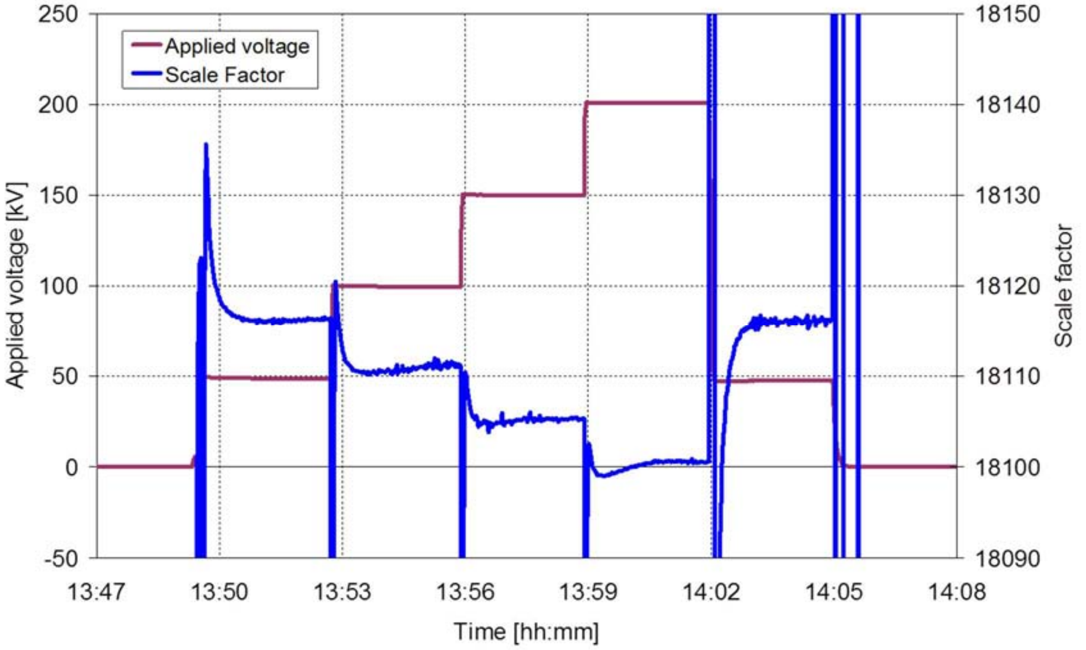
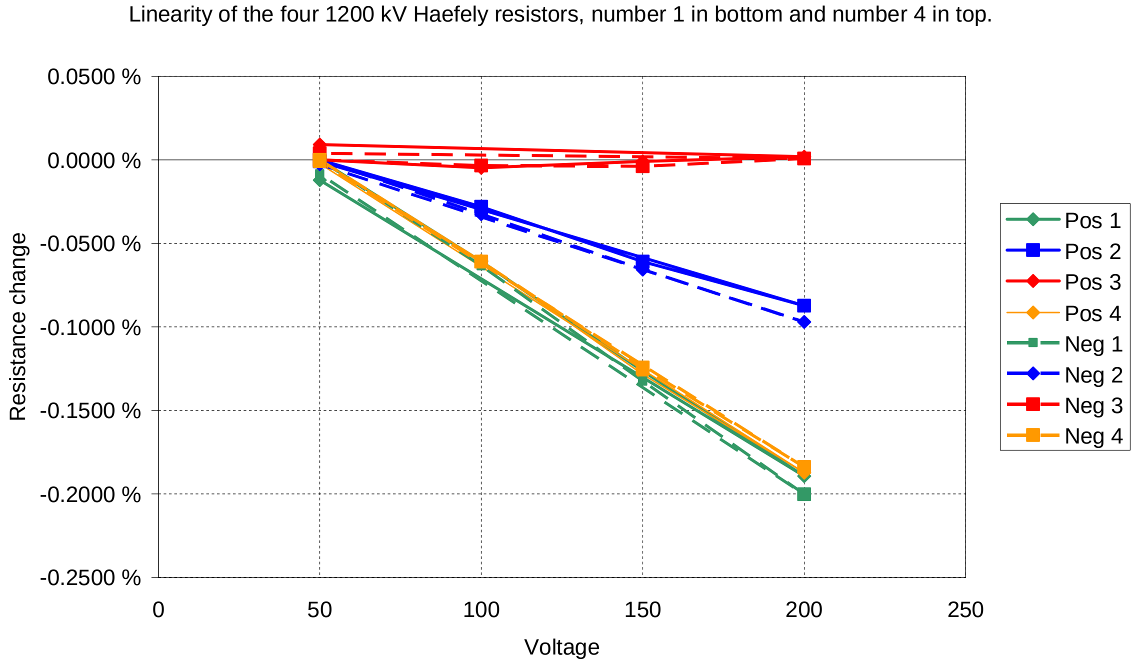


Figure 5. Typical run for the measurement of the voltage dependence of one 300 kV section of the 1200 kV divider.

The four sections were found not to be identical. The measured voltage dependencies are shown in the top part of Figure 6. Discussions with manufacturer's representatives revealed that most probably different types of resistors–based on availability at the time of manufacture–have probably been used. Section 3 probably has wirewound resistors, sections 1 and 4 film resistors, and section 2 about 50 % of both.

The complete divider was also compared with the reference. These results are shown in bottom part of Figure 6. They are well in line with the voltage non-linearity measured for the sections (the derivative is the same), but the absolute value does not match with the measurements performed on sections (the level changes at 200 kV). These measurements, for sections and complete divider, were performed during a period of about 2 weeks. The temperature in the laboratory fluctuated by several degrees during this period, and the difference was attributed to the temperature coefficient of the high voltage resistors. The final proof of this was however left open.

The scale factor changes from 50 kV to 200 kV are −0.20 %, −0.09 %, −0.00 % and −0.19 % for the four modules, with an average of −0.12 %. This leads to c. −0.24%/MV for the series connection.



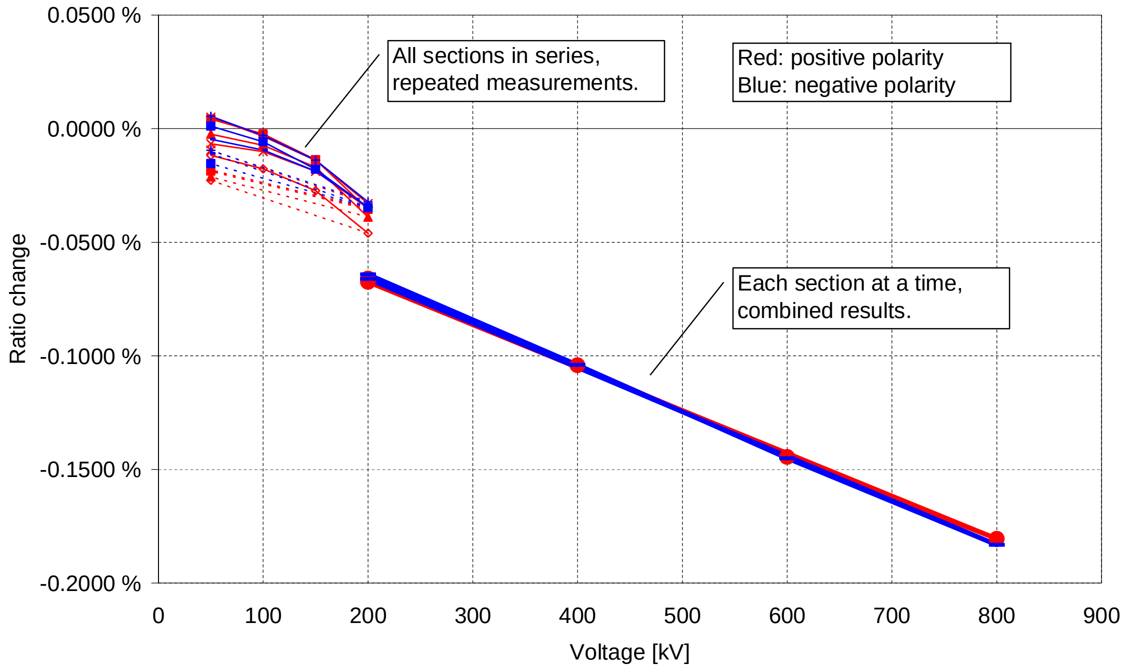


Figure 6. Non-linearity of the 1200 kV divider by comparison with 200 kV reference divider. Top: Four 300 kV sections measured separately. Bottom: Complete 1200 kV divider measured up to 200 kV, complemented with combined results of the four sections measured separately.

2.4 Comparison with 200 kV reference divider in 2012

In order to confirm the findings of 2007, the comparison with MIKES's 200 kV reference divider was repeated in April 2012. With the experience from the 2007 session it was this time possible to perform all measurements during one day. The new measurement were in line with old ones, nicely confirming the earlier measured voltage dependence. This time the measured change was −0.16 % / 750 kV, which leads to voltage coefficient of −0.2 %/MV.

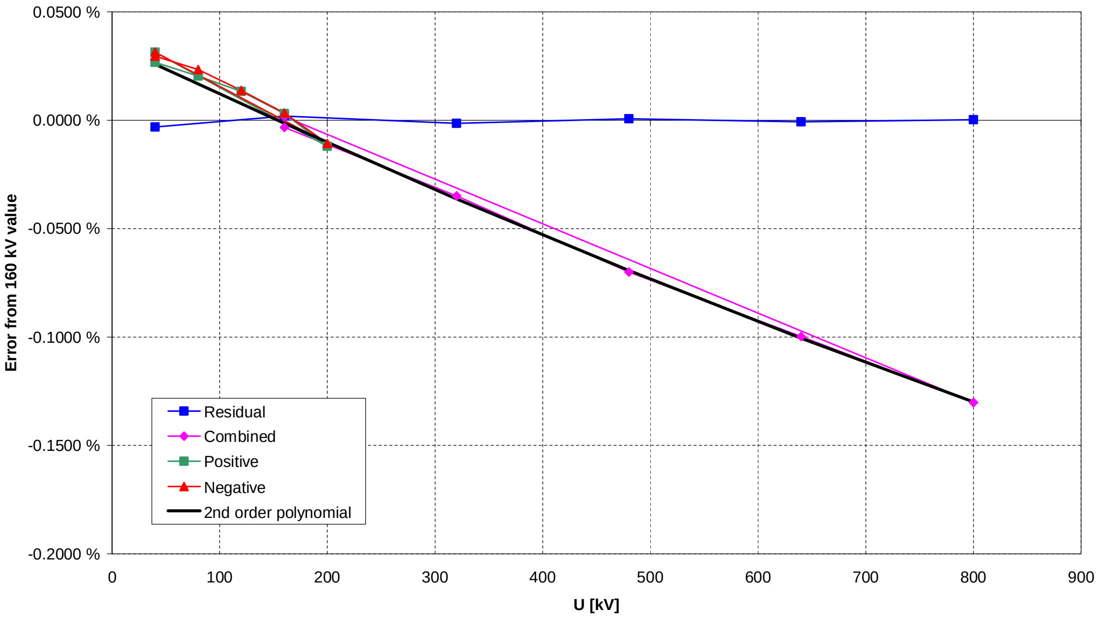


Figure 7. Non-linearity of the 1200 kV divider by comparison with 200 kV reference divider. Results of the by section and complete divider measurement combined as in Figure 6.

2.5 Comparison with 1000 kV reference divider in 2013

The 1200 kV divider was compared directly with the modular 1000 kV divider built in EMRP HVDC -project in June 2013.

A one day measurement run is shown in Figure 8. During the first two hours the scale factor of the 1200 kV divider does not drift significantly. It only follows the voltage changes. The scale factor changes from about 70700 to 70650, i.e. c. −0.07 %. The respective voltage change is 0.4 MV. This leads to voltage dependence of about −0.18 %/MV, which confirms again the earlier measurement

However, after continuous application of voltage higher than 400 kV, the scale factor starts to steadily increase. This effect is more significant as the voltage is increased, and it is most probably due to self-heating of the resistors and subsequently warming up of the insulating oil. During the four hour application, from 12:30 to 16:30, first on +1000 kV and later on −1000 kV, the scale factor continuously changes from 70640 to 70710, i.e. about + 0.1 %.

An opposite effect, with shorter time constant, can be seen on each step when the lowering the voltage after 16:30. The cooling effect is most prominent on the step from

−400 kV to −200 kV. This is superimposed with the voltage dependent change of the scale factor.

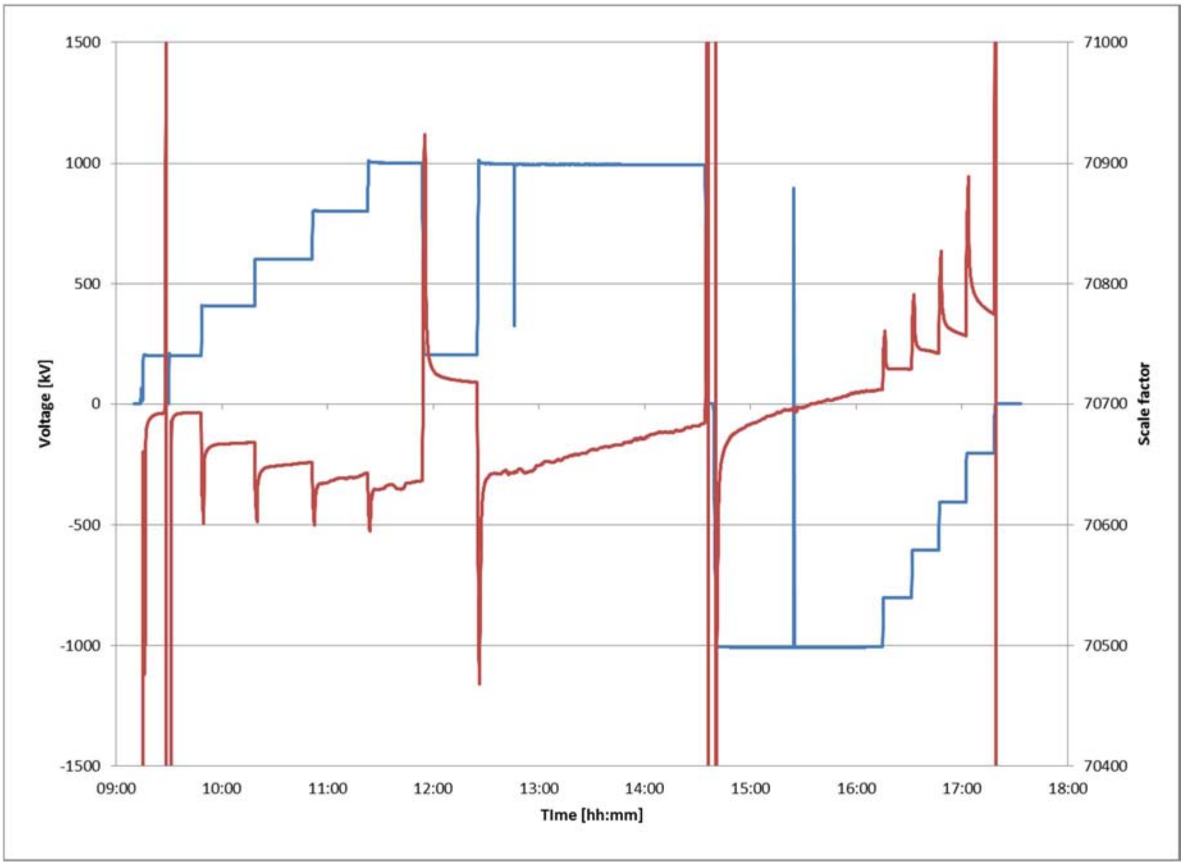


Figure 8. A full day comparison measurement with modular 1000 kV divider of EMRP HVDC -project. Blue line shows the output voltage of the modular divider; here 10 V corresponds to 1000 kV. Red line is the original measurement result and the black its 20 point moving average.

3 Conclusions

The voltage non-linearity of a 1200 kV dc divider and its modules have been checked, and the results have been compared with earlier measurements.

The results of three different measurements lead to values of −0.2 %/MV, −0.2 %/MV and −0.18 %/MV. The last one based on direct comparison with 1000 kV modular reference divider can be considered the most accurate. The influence of the voltage dependence and self-heating of the 200 kV reference divider that was used for the first two evaluations limit the accuracy of those measurements.

The divider high voltage arm of the 1200 kV divider is immersed in oil. This structure leads to good short term stability, i.e. the self-heating time constant is very long. Both long time application of high voltage and ambient temperature in the high voltage hall change the scale factor with very long time constant, which could even be measured in days rather than in hours.

With careful design of the calibration procedure can be used for calibration with 0.05 % measurement uncertainty up to 800 kV. This requires that the scale factor is checked for each calibration.

4 Acknowledgements

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