Anders Bergman

Absolute Calibration of a 100 kV DC Divider

SP
Swedish National Testing and Research Institute
Physics & Electrotechnics
SP REPORT 1996:05

Abstract

Anders Bergman

Absolute calibration of a 100 kV DC divider

An absolute determination of the ratio of a 100 kV DC divider has been made. A new Zener device that has recently become available has been used in a step-up mode to determine the ratio of a voltage divider. The uncertainty of the determination is ±6.6 ppm for a coverage factor k=1.

Key words: Calibration, intercomparison, high voltage, DC

SP - Sveriges Provnings- och Forskningsinstitut
SP RAPPORT 1996:05
ISBN 91-7848-609-2
ISSN 0284-5172
Borås 1996

Swedish National testing and Research Institute
SP REPORT 1996:05

Postal address:
Box 857, S-501 15 BORÅS
Sweden
Telephone +46 33 16 50 00
Telex 36252 Testing S
Telefax +46 33 13 55 02

Table of contents

Summary

High direct voltages are commonly measured by resistive voltage dividers with low operating current. Reference dividers have been developed by several national laboratories with uncertainties of the scale factor that are on the order of a few ppm. PTB in Germany [1] has reported 28 ppm at 2σ level, NPL in UK [2] has reported 5 ppm at 1σ level and IEN in Italy [3] has reported 3.5 ppm at 1σ level. International comparisons [4] of such dividers have ascertained the compatibility of the scale factors obtained in different labs.

Recently a new device, called DWINA, has become available. This device operates on a completely different principle, being in essence a high voltage DC zener reference. This device therefore permits an independent realisation of the scale factor of a DC measuring system. A major advantage of the DWINA is its low dynamic impedance leading to small influence of leakage currents on the voltage measurement.

The manufacturer of the DWINA, Megavolt Metrology in Moscow, has placed one unit at the disposal for a series of comparisons performed within the framework of working group 33.03 of CIGRE (Conference Internationel de Grand Reseau). The participating laboratories include a number of high voltage laboratories in the world, but no results are reported for comparisons with reference systems maintained in national laboratories. CESI (Italy) has however made a comparison between their own DWINA and the reference divider maintained by the Italian national lab IEN [5] and have obtained very good agreement even though the uncertainty cited for the comparison is an order of magnitude worse than the stated uncertainty for the reference divider.

The tests performed at the Swedish national laboratory for electrical quantities at SP (Swedish National Testing and Research Institute) aimed at using the DWINA to obtain an independent determination of the scale factor of the SP 100 kV divider at a level of uncertainty compatible with the best calibration uncertainties offered world-wide. A second goal was to obtain comparative data for the international comparison campaign in which the circulating DWINA is used. The results obtained gave a very satisfactory correlation between predicted and measured ratio for the SP 100 kV divider, with a difference of the same order of magnitude as the 1σ uncertainty.

1. The DWINA

A series connection of very stable zener diodes in series with a current generator forms the basis for the device called DWINA. The zener diodes are mounted on 100 circuit board strips with a nominal zener voltage of 1000 V each giving the device a nominal maximum voltage of 100 kV. The current generator maintains the diode current very close to the nominal zener current of 5 mA . The compliance voltage range of the current generator is 0 - 1000 V. The polarity of the current generator can be reversed for operation at negative voltage.

The dynamic resistance of the zener diodes is very low, 280 kohm for the entire stack. This resistance is very low compared to the resistance of voltage dividers used for similar voltages and the device is consequently quite insensitive to leakage currents.

The system may be used as a self-contained step-up system by measuring the zener voltage of all zener strips in the stack and using the calculated sum as the reference voltage for the high voltage calibration.

The long term stability of the diodes is however sufficiently good that the system can be used as a transfer standard, although with reduced accuracy.

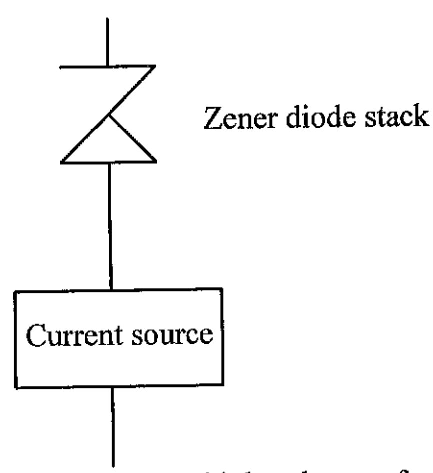

Figure 1. Basic circuit of the DWINA high voltage reference system

The zener diode circuit boards making up the zener diode stack are mounted on a fibre glass reinforced epoxy cylinder. The circuit boards are arranged in a helix around the cylinder with connection points at each board. Any voltage from 0 to 101 kV can therefore be measured with the DWINA by making the appropriate connections to the zener diode stack.

A high voltage measurement is performed by choosing the appropriate number of zener diode circuit boards and connecting them to the high voltage source as in figure 5. The zener current is maintained by the current source at the correct level as long as the applied voltage is between the nominal zener voltage and the nominal zener voltage plus 1 kV. The calculated sum of the zener voltages plus the DC voltage across the current source constitutes the measured high voltage.

The manufacturers specification for the DWINA is ±0.01% of measured voltage under reference conditions, i.e. 25±5 °C and 65±15% RH as given in the instruction manual [6].

A calibration of the zener strips performed in direct conjunction with the use of the DWINA will increase the accuracy of the device substantially and this method has been utilised in the work performed at SP.

2. SP high voltage DC resources

SP owns two dividers of the type developed by NPL [2] and until lately manufactured and marketed by Vishay-Mann. One of the dividers is a multi-ratio divider for 50 kV and the other is intended for 100 kV and one ratio. Both dividers are designed for a rated current of 0.1 mA at full voltage. SP has also acquired components for a future extension of the divider range up to 500 kV.

A number of high quality digital multimeters are available for the measurement of the output voltage. In the present investigation three HP3458A multimeters have been used.

High voltage DC can be obtained from a dual polarity 500 kV source by Hipotronix and from a 145 kV positive polarity source by SAMES.

The Hipotronix source is based on voltage doubler rectifiers connected to the high voltage windings of two cascade connected transformers. Coarse stabilisation and regulation is obtained by magnetic stabilisers in the mains feed followed, by a motor driven regulating transformer. Fine stabilisation and fine regulation is obtained by a series electron tube in the high voltage circuit. The regulation is very good, better than ±0.05% at any voltage. The ripple is compensated by the electron tube and the level is less than 180 Vpp at the DWINA zener current of 5 mA at any voltage between 7 and 100 kV.

The SAMES source is an electrostatic generator with similar stability as the Hipotronix and a ripple that is less than 50Vpp at operating currents less than 5 mA. The maximum permissible load current is 10 mA.

3. Previous calibrations of SP voltage dividers

The 100 kV divider was manufactured in 1994 and it was calibrated at NPL (National Physical Laboratory, UK) prior to delivery. The correction for the output voltage was determined to -25 ±7 ppm at 100 kV. A low voltage calibration performed at SP in October 1995 gave a correction of -40 ±5 ppm at 1 kV, both results for a coverage factor k=1.

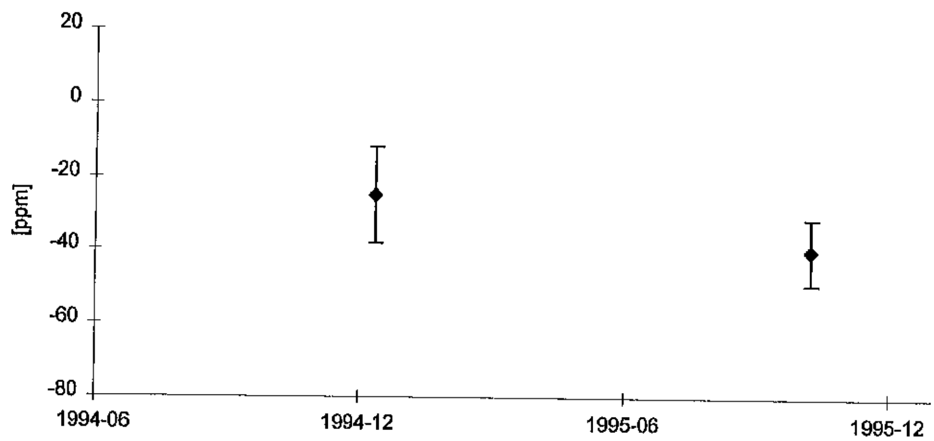

Figure 2. Previously recorded corrections for the Vishay 100 kV divider

The 50 kV divider was calibrated in 1993 at NPL prior to delivery to SP. It has since then been tracked by low voltage measurement of both resistance values and with a determination of the ratio at 1 kV. The initial calibration at NPL gave a correction of (40 ±15) ppm for the output voltage. The correction obtained from the NPL calibration and those from the subsequent low voltage calibrations are plotted in Figure 3. The plot indicates a small drift of the ratio with time.

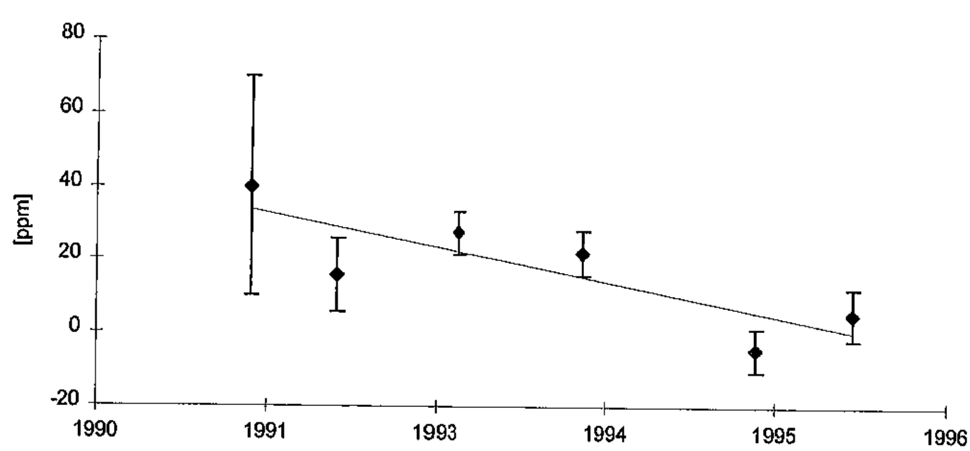

Figure 3. Previously recorded corrections for the Vishay 50 kV DC divider for the ratio 50 000:1

The correction for the 100 kV divider obtained from a low voltage calibration performed just prior to the high voltage calibrations was -40 ppm. A comparison between the 50 and the 100 kV dividers at 50 kV showed a difference of 46 ppm with the 50 kV divider having the lower output voltage. The low voltage calibrations of the two dividers resulted in a correction of 7 ±3.5 ppm for the 50 kV divider for the 30 000:1 ratio and -40 ±4.5 ppm for the 100 kV divider. The expected difference is thus 47 ±5.7 ppm with the 50 kV divider having the lower output voltage. The fit between the low voltage calibration and the high voltage comparison between the two dividers is thus excellent.

The ratio of the 100 kV divider as established by previous calibrations has been taken as 30 000:1 with a correction for the output voltage of -40 ±4.5 ppm for a coverage factor k=1.

4. Calibration of DWINA

4.1. Theory of operation

All the zener strips in the DWINA were calibrated both before and after the high voltage tests. Each calibration consisted of three separate runs with readings taken on each strip in turn. The readings were taken in 30 ±3 seconds after application of voltage. It is important that the readings are taken at a certain point in time since there is an appreciable drift in the zener voltage due to self heating.

The readings were taken with three HP 3458 digital multimeters controlled via a IEEE 488 bus by a computer running a custom Labview application. All readings were taken simultaneously and were stored in a file.

The current generator in the DWINA does not maintain the current perfectly constant. There is an internal current shunt available for the measurement of the zener current. This shunt can be used to monitor the current during tests, if the voltage drop across the shunt is added to the voltage measured across the current source. The zener current has been recorded during all calibrations of zener strips as well as during the high voltage tests. The value of zener voltage has been corrected to the nominal 5 mA, by applying a correction based on the known dynamic resistance of 2.8 kohms for each zener strip. The correction is small, in the present investigation on the order of 5 ppm.

The ambient temperature has been 21.7 ±1.0 °C throughout the test series including both the calibration of the DWINA strips and the high voltage tests.

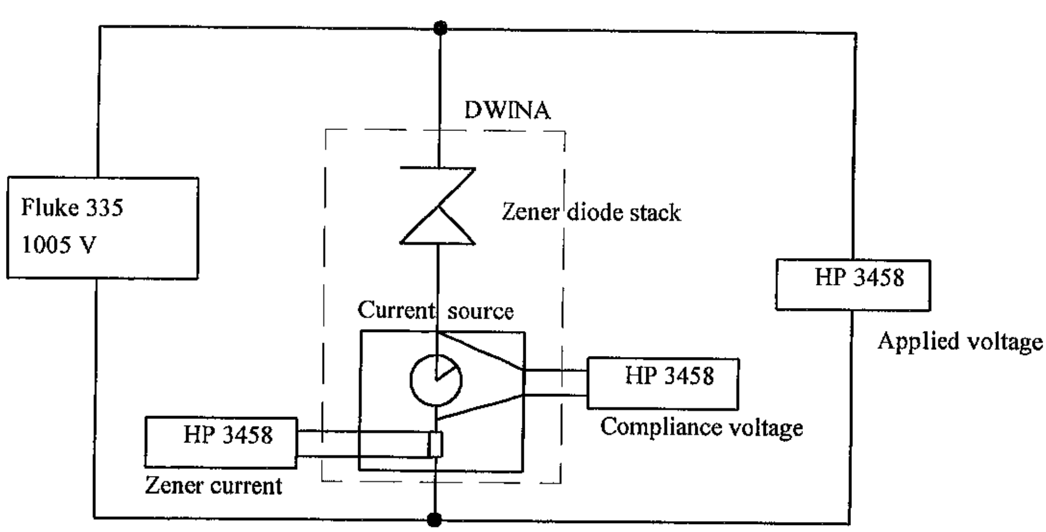

Figure 4. Circuit for calibration of DWINA strips

Each zener diode strip with a nominal voltage of 1000 V was connected in turn by short-circuiting all the other strips in the diode stack. A stable voltage of approximately 1005 V was applied and was measured by direct connection to the high voltage end of the zener diode strip and the earth point of the current source respectively. The compliance voltage of the current source and the shunt voltage are also measured. It is important that the multimeter for the compliance voltage is connected as shown in figure 4 since the current drawn by the multimeter otherwise will not be included in the regulation achieved by the current source. A current error will ensue and lead to a measuring error.

The manual for the DWINA prescribes that the current shunt for the measurement of the zener current should be short-circuited during normal operation. This has not been done in the present investigation, where the zener current has been recorded in all measurements. It has in this way been possible to increase the accuracy of the measurement of the high voltage.

The zener voltage at the actual zener current is obtained as the applied voltage minus the compliance voltage and minus the zener current shunt voltage. The zener voltage that would be obtained at the nominal zener current is finally obtained by correcting for the zener current offset from 5.0 mA and for the small voltage drop in the lead between the diode strip and the current generator.

4.2. DWINA calibration uncertainty

The average value for the standard deviation of the distribution of values in each individual series of three measurements on one strip is 3.4 ppm. The least number of strips used in the high voltage tests is 7 (i.e. at 7 kV). The value for the zener voltage is based on the average value of the zener strip calibrations made before and after the high voltage tests. The zener voltage is therefore based on no less than 14 sets of measurements and the standard deviation for the contribution to the uncertainty is $3.4/\sqrt{14} \approx 1$ ppm

The time delay after voltage application until the reading is taken influences the zener voltage since the diodes are appreciably heated by the zener current. This effect was investigated by taking readings at 15, 30 and 45 seconds after voltage application. The average drift of the zener voltage from 15 seconds to 45 seconds after application of the test voltage was +34 ppm. This corresponds to a drift of 1.1 ppm/sec. The standard deviation for the contribution to uncertainty due to a variation of ±3 sec in the nominal delay time of 30 sec to the reading of the voltage has therefore been estimated to $\pm 3.3/\sqrt{3}$ ppm.

The applied voltage was measured with an HP 3458 which has been specifically verified for the measurement of 1005 V. The uncertainty of the measurement is estimated to ±4 ppm, for a coverage factor k=2.

The compliance voltage was measured with an uncertainty of ±15 ppm of reading or better. The compliance voltage was less than 0.5 % of the applied voltage. The influence on the uncertainty in the measurement of the zener voltage of the zener strip was negligible.

The zener current shunt voltage was measured with an uncertainty of ±15 ppm of reading or better. The influence on the measurement of the zener voltage of the strip ≈0.2 ppm since the dynamic resistance is 2.8 kohms for one strip. The contribution was neglected.

The DWINA was calibrated both before and after the comparisons at high voltage with the Vishay 100 kV divider. The change in the zener voltage from the calibration before and after the high voltage test was +3 ppm. The standard deviation for the contribution to uncertainty has therefore been estimated to 3/√3 ppm.

The total standard deviation for the contributions is obtained by summation of the variances

$$s = \sqrt{1^2 + \left(\frac{3.3}{\sqrt{3}}\right)^2 + \left(\frac{4}{2}\right)^2 + \left(\frac{3}{\sqrt{3}}\right)^2} \approx 3.4 \text{ ppm}$$

The total uncertainty in the calibration of the DWINA zener strips for a coverage factor k=1 was therefore 3.4 ppm.

5. High voltage comparison

5.1. Test set-up

For the high voltage tests an appropriate number of zener strips are short-circuited to obtain a zener voltage just below the prospective test voltage. The applied voltage is measured with a HP 3458 connected to the Vishay 100 kV divider. The compliance voltage and the zener current are measured with two further HP 3458 multimeters. The measurement procedure was to raise the voltage to the correct level and to read the three multimeters 30 seconds after reaching the zener voltage. The time delay to measurement is prescribed both by the manufacturer of the DWINA and in the procedures for the intercomparison. The voltage was lowered to zero after the reading. The DWINA was left to cool down for a period of at least 10 minutes between successive applications of voltage. The next reading was not taken until the exhaust air from the DWINA was less than 1°C above ambient. A reading was also taken from the multimeter connected to the Vishay 100 kV divider at zero voltage after each high voltage application. The zero reading has been used to correct for the offset error of the multimeter.

The correction for the offset in the reading of the Vishay 100 has been applied to the data obtained, but the uncertainty due to variation in the offset was regarded as accounted for by the dispersion in the ratio results.

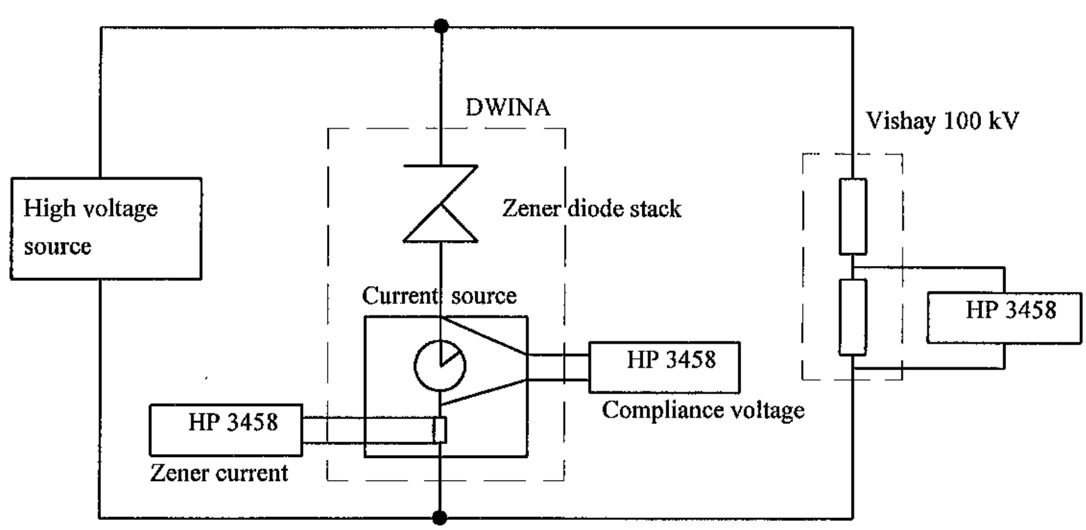

Figure 5. Test set-up for the high voltage tests

5.2. Influence of ripple content

SP has two high voltage DC sources available with different ripple content in the high voltage. A comparison of the error determined with the two sources gives a measure of the influence of the ripple on the results. The ripple amplitude is within the manufacturers specification for dynamic range of the DWINA current generator for both sources.

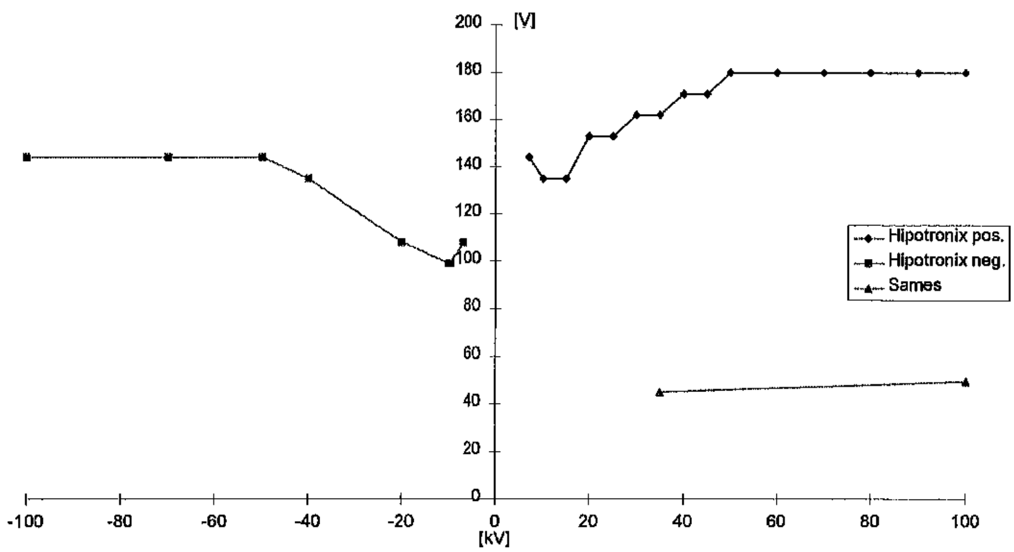

Figure 6. Ripple voltage as function of the DC voltage for the two high voltage sources measured at the zener current of 5 mA for the DWINA

The error of the Vishay 100 kV divider was determined at +35 and +100 kV with the SAMES source. The difference to the results obtained with the Hipotronix source was less than 2 ppm at 35 kV and zero at 100 kV. This difference is negligible in comparison to the uncertainty in the determination.

5.3. Short term stability

5.3.1. Stability of the Vishay 100 divider

A set of measurements were taken with the Vishay 100 kV divider connected to 100 kV for period of 18 hours. The voltage was raised to slightly above the DWINA zener threshold voltage to obtain readings and lowered to slightly below the threshold between measurements. This procedure ensures that the DWINA current was zero between readings and that the device was not further heated. In this way it was possible to evaluate the heating effects on the Vishay divider since the DWINA was always used in the cooled down mode.

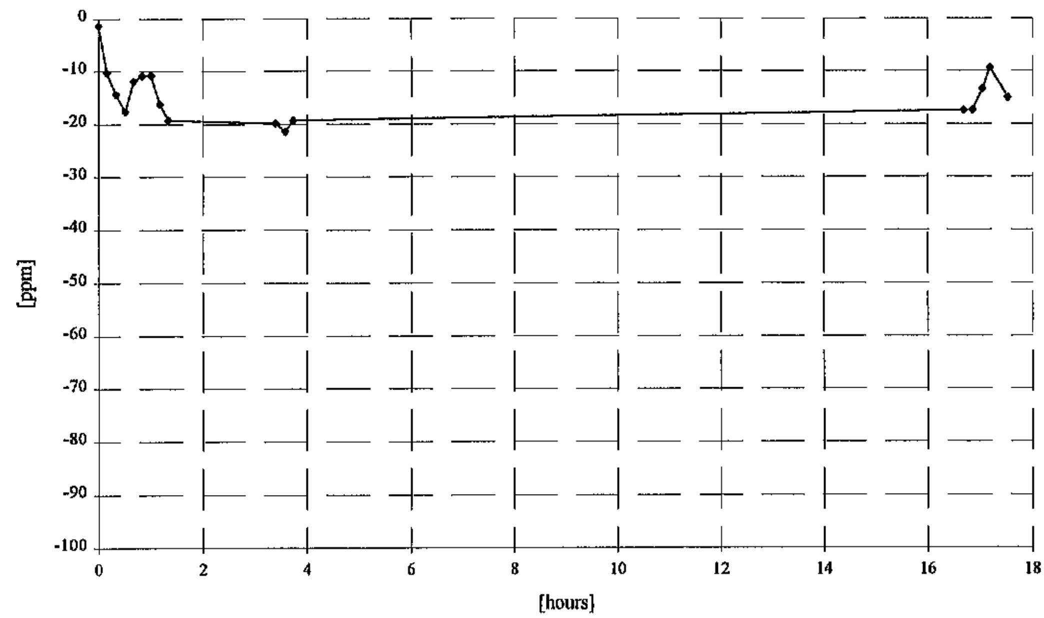

Figure 7. Short term stability of the Vishay 100 divider, error in output voltage.

There was an initial drift of approximately -19 ppm that levels off after approximately 1 hour. The dips in the curve around the 1 hour and the 17 hour points may be due to temperature transients caused by the change-over between day-time and night-time ventilation. The results show that the Vishay 100 divider has a negligible drift for the time span in the comparison with the DWINA.

5.3.2. DWINA short term stability

The short term stability of the DWINA device was determined in a direct continuation of the test performed where the Vishay 100 kV divider was connected to 100 kV during 18 hours. The Vishay 100 kV divider was therefore in thermal equilibrium and no change in its ratio should occur during the test.

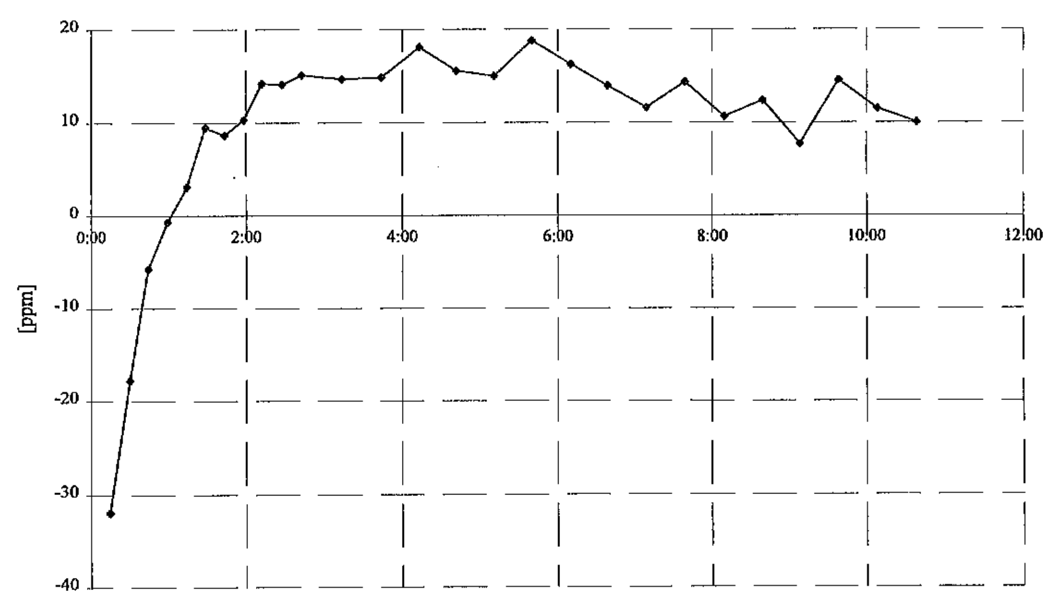

Figure 8. Short term stability of DWINA

The graph shows that the DWINA reaches a fairly stable equilibrium after 3 minutes. The reading in the high voltage tests has however been taken after 30 seconds of high voltage application. The slope is quite steep in this region and corresponds to 0.9 ppm/sec. This result is similar to the result obtained in the calibration of the individual strips, where a dependence of 1.1 ppm /sec was found.

The results obtained clearly show that the time at which the measurement is made is chosen in the steepest portion of the curve for the short term stability. A considerably better point would be at 2 or 3 minutes. Information from the manufacturer hints however that such a procedure may be disadvantageous due to accelerated ageing of the DWINA zener diodes.

5.4. Calibration of SP DMMs

The multimeters used are all HP3458 8½ digit multimeters with the high stability option offered by the manufacturer. In DC mode the best accuracy is ±4.2 ppm plus the traceability for 1 year. The multimeters are tracked by annual calibrations in-house at SP. The calibrators used at SP are calibrated against Josephson effect arrays with a traceability of $\pm 5 \cdot 10^{-9}$.

The most critical measurement in the present series is the measurement of the voltage applied on the 1 kV zener diode strips in the DWINA high voltage block. The uncertainty of the HP3458 is stated as ±14 ppm for 1 kV. In this case a detailed study of the stability of the measurement of 1 005 V was made in direct conjunction with the DWINA calibration. The HP3458 was checked in a calibration circuit over a period of several days and the correction for the measurement was determined with an uncertainty of ±2 ppm for a coverage factor k=1.

The multimeter used for the measurement of the output voltage from the Vishay 100 kV divider is used at 1 V and 10 V ranges to measure voltages from 0.25 V to 3.3 V. The uncertainty has been estimated for the worst case to be ±4 ppm for a coverage factor k=1.

The uncertainty for the multimeters used to record the zener current and the compliance voltage has been taken as better than ±8 ppm of reading.

5.5. Error budget and total uncertainty

The uncertainty in the calibration of the 1000 V zener strips in the DWINA has been estimated at ±3.4 ppm for a coverage factor k=1.

The heating effect in the Vishay 100 is negligible for the 30 second time span used in the comparison.

The ripple on the high voltage has been shown to have negligible influence.

The nominal delay time of 30 seconds until the digital multimeters were read may vary by a small amount. The short term instability caused by heating of the DWINA, see section 5.3.2, means that there is an uncertainty due to the exact time the reading is made. The variation in time is certainly less than ±3 seconds and with the slope of the heating effect established to 0.9 ppm/sec, the standard deviation for the contribution to uncertainty is 2.7/√3 ppm.

The digital multimeter HP 3458 used for measurement of the Vishay 100 divider contributes with ±4ppm for a coverage factor k=1

The manufacturer has investigated the combined effect of leakage along the mounting cylinder for the zener strips and corona currents and has determined that it is less than he $2 \cdot 10^{-6}$ A. The standard deviation for the influence on the zener voltage is estimated to 5.6/√3 ppm. The estimate is based on the zener dynamic resistance being 280 kohm for the entire stack.

The variation in the ambient temperature is very small and the effect has been regarded as included in the variation in the results.

Summation of the variances for the influence factors gives

$$s = \sqrt{(3.4)^2 + \left(\frac{2.7}{\sqrt{3}}\right)^2 + (4)^2 + \left(\frac{5.6}{\sqrt{3}}\right)^2 + \left(\frac{0.3}{\sqrt{3}}\right)^2} \approx 6.4 \text{ ppm}$$

The total uncertainty in the comparison due to measurement uncertainties is thus ±6.4 ppm for a coverage factor k=1.

There was a variation in the three readings obtained at each voltage level. The variation is in most cases on the order of 0.5 V in the calculated high voltage. The influence is most marked for the lower voltages. The standard deviation of the mean value is from 1.4 to 55 ppm.

The total uncertainty in the comparison between the DWINA and the Vishay 100 voltage divider is from 6.6 to 55 ppm for a coverage factor k=1. The uncertainty bars in figure 9 are drawn to show this total uncertainty.

5.6. Variation over voltage range

A comparison was made ranging from 7 kV to 100 kV for both positive and negative polarity. Each voltage level was measured three times with cooling down of the DWINA device to ambient temperature before the next application of the high voltage. The voltage was reduced to zero during the cooling down period.

The uncertainty related to the measurements, excluding the variation between measurements is estimated to ±6.4 ppm for a coverage factor k=1, see section 5.5. The variation observed between measurements is of the order of 0.5 V in the high voltage. The influence of the dispersion is therefore most marked at the lower voltages The best accuracy was obtained for positive polarity where ±6.6 ppm for a coverage factor k=1 was obtained at 100 kV. The plot in figure 9 of the error shows the estimated total uncertainty in each point based on the standard deviation of the observed variation and on the basic uncertainty of the measurements. Note that the plot gives the error in the measured high voltage and that the correction for the ratio of the Vishay 100 has the opposite sign.

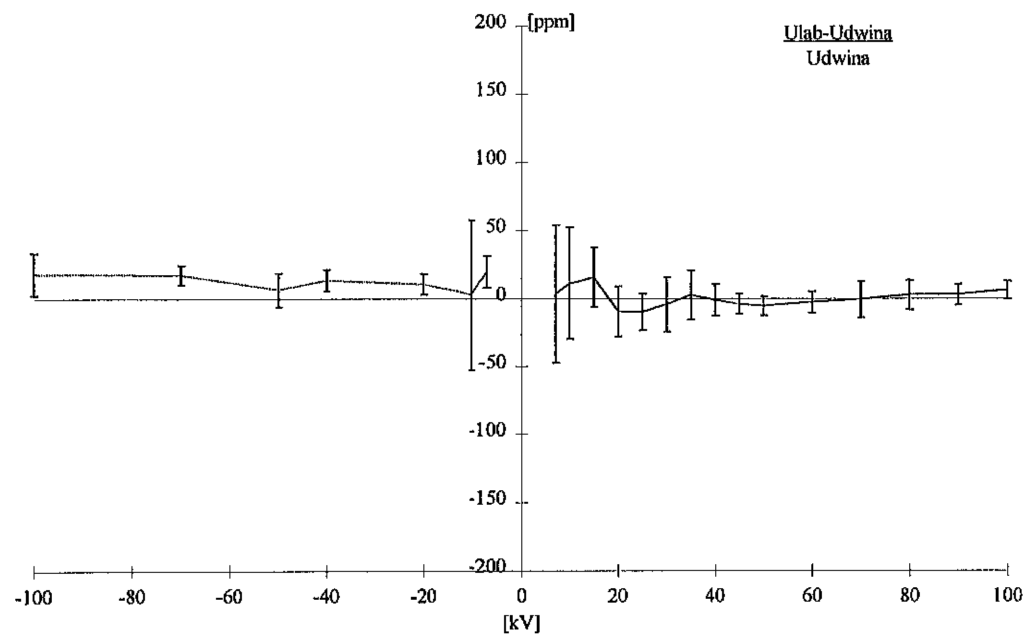

Figure 9. Difference between the previously established ratio for the Vishay 100 and the results obtained with the DWINA. Ulab and Udwina refers to the high voltage as measured with each system.

5.7. Other observations

The current generator of the DWINA was not operational on receipt of the equipment from the pilot lab. The operational amplifier in the feedback circuit of the current generator was broken on both channels and had to be replaced. Satisfactory operation was obtained after the replacement.

The oscilloscope output was not operational on channel two (the channel used in the high voltage tests). The failure was traced to a 100 ohm series resistor between the operational amplifier and the output socket. The resistor had varying resistance in the Mohm range. The failure was not noted during initial calibration since the digital multimeter used had an input resistance of 10 Gohm. The failure had no influence on the results since the ripple amplitudes were measured with a separate voltage divider for AC. The output circuit was repaired and was functional before the DWINA was sent on to the next laboratory.

6. Conclusions

The correction for the Vishay 100 kV divider as established by previous calibrations was -40 ±5 ppm. The results obtained with the DWINA at 100 kV gave a correction for positive polarity of -47 ±6.6 ppm and -58 ± 16 ppm at negative polarity, all three results for a coverage factor k=1.

The obtained result agrees well with previous results and with the ratio obtained by low voltage calibrations. The result is especially valuable since it has been obtained with a method that is entirely different from the methods used at other national laboratories to establish the ratio of the high voltage dividers.

7. References

[1] PEIER, D., GRAETSCH, V. A 300 kV DC measuring device with high accuracy. Third International symposium on high voltage engineering (August, 1979 : Milan, Italy), Proceedings. Paper 43.08. 1979.

[2] KNIGHT, Brian, MARTIN, Philip. A high voltage divider having an uncertainty of 5 ppm at 100 kV. IEEE Transactions on Instrumentation and Measurement, vol. 42, April, 1993, pp. 568 - 570.

[3] D'EMILIO, S, ... Calibration of DC dividers up to 100 kV. IEEE Transactions on Instrumentation and Measurements, vol. IM-34, June 1985, pp. 224-227.

[4] MARX, R., SCHON, K. Internationale Vergleichsmessungen an einem Gleichspannungsteiler bis 100 kV. PTB-Mitteilungen 96, 3/86, pp. 165-168.

[5] BOLOGNESI, F, ... reference measuring system for high direct voltages. Ninth international symposium on high voltage engineering (August 28 - September 1, 1995 : Graz, Austria), Proceedings. Paper 4915. 1995.

[6] High voltage measurement standard DWINA -100, Instruction manual. 2, Andrewskaja nab., GSP-1, Moscow, 117965, Russia : Megavolt Metrology.