THESIS ON INFORMATICS AND SYSTEM ENGINEERING C40

Development of National Standard for Voltage Unit Based on Solid-State References

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

/Andrei Pokatilov/

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INFORMAATIKA JA SÜSTEEMITEHNIKA C40

Pinge mõõtühiku riigietaloni arendamine Zener-tüüpi etalonpingeallikate baasil

ANDREI POKATILOV

Contents

Preface

The present work was carried out at the Estonian National Standards Laboratory for Electrical Quantities operated by Metrosert ltd, between 2004 - 2008. I thank the Director of Metrosert ltd, Mr Ain Noormägi for providing me the opportunity to conduct these studies.

I am most thankful to my supervisors Professor Toomas Rang (Tallinn University of Technology) and Dr Toomas Kübarsepp (Metrosert ltd) for their continuous guidance and valuable support during the years of this interesting research.

This work has been supported by several foundations and sources. I appreciate the financial support of the Information and Telecommunication Doctor School, the Estonian Information Technology Foundation and Tiger University.

The kind assistance and fruitful help of my collegues from Metrosert ltd are greatly acknowledged. Special thanks to Taima Adelbert and Toivo Kiibus for their contribution to the design of measurement procedures and analysis of the results.

I am thankful to Dr Gintautas Ambrazevicius from the Lithuanian Electrical Standards Laboratory of the Semiconductor Physics Institute (SPI) for arranging of the intercomparison described in this thesis.

Finally, my greatest and warmest thanks belong to my family for their continuous love and support within all these long years.

Andrei Pokatilov
Tallinn, September 2008

List of publications

I. A. Pokatilov, T. Kübarsepp, (2008) “Traceability of Voltage and Resistance Measurements in Estonia.” – Transverse Disciplines in Metrology: Proceedings of 13th International Metrology Congress, 2007 - Lille, France. London: ISTE, pp. 577–585.

II. A. Pokatilov, T. Kübarsepp, (2006) “Establishment of National Standard of Voltage Unit in Estonia,” Proceedings of 10th Biennial Baltic Electronics Conference BEC2006, October 2–4, 2006 Tallinn, Estonia. Tallinn: Tallinn University of Technology, pp. 157–160.

III. A. Pokatilov A, T. Kübarsepp, (2006) “Development of Automated Measurement Setup for Standard Resistors,” Proceedings of 10th Biennial Baltic Electronics Conference BEC2006, October 2–4, 2006 Tallinn, Estonia. Tallinn: Tallinn University of Technology, pp. 161–162.

IV. M. Pikkov, T. Rang, A. Pokatilov, (2006) ”SiC Schottky Diode for Use in Power Converters,” Proceedings of 10th Biennial Baltic Electronics Conference BEC2006, October 2–4, 2006 Tallinn, Estonia. Tallinn: Tallinn University of Technology, pp. 245–246.

Author’s contribution

The research work presented in this thesis has been conducted at the Estonian National Standards Laboratory for Electrical Quantities. Included publications are the results of a fruitful team work, where the author had a well-defined role.

For Publ. I, the author performed the measurements, analyzed the measurement results and estimated major sources of the measurement uncertainty.

In preparing Publ. II, the author developed a method for maintenance of solid-state voltage standards, performed the measurements, analyzed the measurement results and estimated the measurement uncertainty.

For Publ. III, the author had a major contribution in construction of the measurement setup, developing software, performing the measurements and analyzing of the measurement results.

For Publ. IV, the author did a part of work in analyzing of the measurement results and preparation of manuscript.

The author was the responsible person in preparing the manuscripts for Publications I, II and III.

Introduction

Many national metrology institutes (NMIs) employ the Josephson effect for maintenance of the representation of the voltage unit. The Josephson effect voltage standard (JVS) is the most stable and reproducible representation of the volt. In smaller national laboratories the voltage standards are frequently maintained in electrochemical cells or solid-state references, so-called secondary standards, which are less expensive for establishment and maintenance.

In 2002, an extensive questioning conducted among representatives from industry and science has indicated the high needs in accurate calibration services for electrical quantities with firmly confirmed traceability. In order to meet these requirements the Ministry of Economic Affairs has delegated to Metrosert ltd maintenance and development of the national standard of the volt with the relative expanded uncertainty of 1 µV/V at the 10 V level.

The targeted uncertainty can be achieved by means of thoroughly characterized electronic voltage references, which are operated in accordance with a well-designed maintenance procedure.

The main goal of the present work has been the development of a maintenance method for the Estonian national voltage standard, which ensures the relative expanded uncertainty of 1 µV/V at the 10 V level. To perform the measurement uncertainty analysis the metrological characteristics of the voltage standards were investigated. The obtained results have proved that the relative expanded uncertainty less than 1 µV/V is achievable in maintenance of the solid-state voltage standards. This was confirmed by comparison of the projection of the voltage output to the latest calibration point.

The measurement uncertainty of the laboratory achievable with new voltage measurement standards was evaluated by participation in the bilateral interlaboratory comparison with the standards laboratory for electrical quantities of National Metrology Institute in Lithuania.

The realization of the voltage scale in the range from 100 mV to 1 kV is implemented with a long-scale digital multimeter (DMM), which is used as a voltage divider. The performance of the DMM is checked by means of resistive voltage dividers.

The Estonian national standard for the voltage unit was appointed by the Minister of Economic Affairs in 2006.

1. Representations of voltage unit

1.1. Josephson effect voltage standard

The base electric unit of the International System of Units (SI) is still the ampere [1]. The volt, the ohm and the watt are derived units of the SI. The best realizations of the ampere are obtained from combination of realizations of the watt, the volt and the ohm with the best relative uncertainty of a few parts in 10^7. The realizations of these units according to their definitions are complicated and time consuming.

The discovery of the Josephson effect (JE) and quantum-Hall effect (QHE) allowed the ampere, the ohm and the volt to be determined from measurements of various combinations of physical constants. According to this approach, the Josephson constant K_J is assumed to correspond to the ratio of the elementary charge and the Plank constant $2e/h$ and the von Klitzing constant R_K is taken as fundamental value h/e^2.

The reference standards for volt and the ohm based on the JE and QHE are more stable and reproducible than a few parts in 10^7. Nowadays, many national laboratories use the JE and QHE to maintain representations of the volt and the ohm respectively [2, 3].

In 1962, British physicist B. Josephson predicted certain effects in two superconductors separated by a thin insulating layer, when electron pairs (Cooper pairs) tunnel from one superconductor to another [4]. The dc JE occurs, when a direct current of Cooper pairs flows through the junction with no voltage drop up to a critical value I_C. If a direct voltage V is applied to the junction, the current oscillates at a frequency f which depends only on the applied voltage and fundamental constants:

$$f = \frac{2eV}{h} \tag{1}$$

where e is the elementary charge and h is the Planck constant. During each cycle of the oscillation, a single quantum of magnetic flux $(h/2e)$ tunnels through the junction.

If an ac voltage at frequency f is applied to the junction, the current of Cooper pairs synchronizes with the frequency and steps of constant voltage are observed at the terminals of the junction (Figure 1), this called the ac Josephson effect:

$$V = n\frac{h}{2e}f \tag{2}$$

where n is an integer (the number of flux quanta transferred by each cycle), e is the elementary charge and h is the Planck constant.

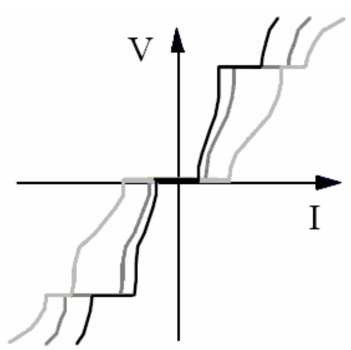


Figure 1. *I-V* characteristic for three different Josephson junctions with the same constant voltage step [2].

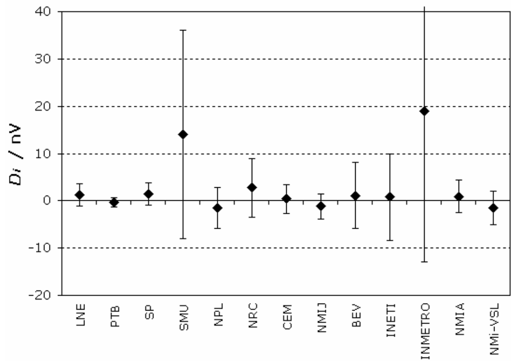


Figure 2. BIPM key comparison on dc voltage at 10 V nominal value BIPM.EM-K10.b. The JVS-s from different national standards laboratories were compared by means of a transfer JVS [6].

After discovery of ac JE the validity of the equation (2) was experimentally verified. It was shown, that the ratio $2e/h$ is independent of the type and geometry of the Josephson junction, magnetic field and microwave power. For the discovery of this effect the B. Josephson was awarded the Nobel prize in 1972.

In 1970s many national standards laboratories began to use the ac JE as the practical voltage standard. To ensure the consistency of national standards the conventional value of K_J was adopted by international agreement in 1990: K_{J-90} = 483 597,9 GHz/V [5]. The modern Josephson voltage standards (JVS) consist of large arrays of Josephson junctions capable to generate voltages from -10 to + 10 V with reproducibility better than 1 part in 10^9 [6]. The results of the comparison of the JVS-s at different national standards laboratories are shown in Figure 2.

Typically the JVS is operated every 2-6 months. In time between operation periods of the JVS, the maintenance and dissemination of the volt is conducted by using of solid-state references, so-called Zener diodes [7].

1.2. Secondary voltage standards

Since the beginning of the last century standard cells have been used by standards laboratories for maintenance of the volt [8, 9]. The standard cell is an electrochemical cell, which creates an electromotive force and electrical current from chemical reactions. Electrochemical cells are sensitive to temperature changes, vibration and small electrical current.

In the 1960s a new type of the voltage standard based on a solid-state device, so called Zener diode, was introduced. Zener voltage standards exhibit higher internal noise, but they are mechanically rugged and less sensitive to electrical current, as compared to electrochemical cells. Electronic standards have also lower temperature coefficients and can have higher output voltages to reduce the effect of the thermal emf in measurement leads. Nowadays, many standards laboratories maintain their volt in solid-state references it time between operations of the JVS [10-13].

The Zener device is a semiconductor diode that operates in the reverse-bias region of its *I-V* characteristics. In general, the breakdown current increases abruptly with the voltage when reverse-bias voltages exceed, see Figure 3. This phenomenon is known as breakdown of the *p-n* junction. There are two basically different mechanisms of junction breakdown: the Zener mechanism, due to tunneling, and avalanche breakdown.

The Zener mechanism occurs in heavily doped *p-n* junctions with the small depletion layer. It involves direct excitation of electrons from the valence band to the conduction band under the action of the high electric field in the junction depletion region.

Avalanche breakdown occurs in junctions having thicker depletion regions. The thermally generated minority carries injected into the space-charge region are accelerated by the field to energies higher than the gap energy can produce a secondary electron-hole pair by knocking out an electron from the covalent bond of a lattice atom in the depletion region. The secondary carriers produced by this process can produce further electron-hole pairs. Avalanche breakdown occurs when the number of carriers produced by this ionization process becomes very large.

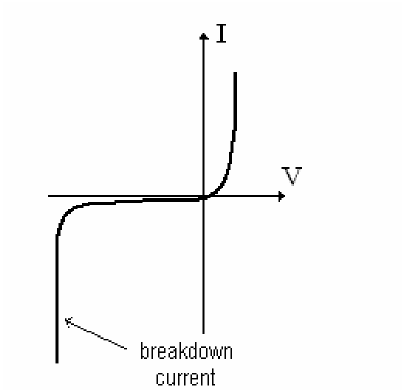


Figure 3. *I-V* characteristics of a p-n junction with breakdown current shown.

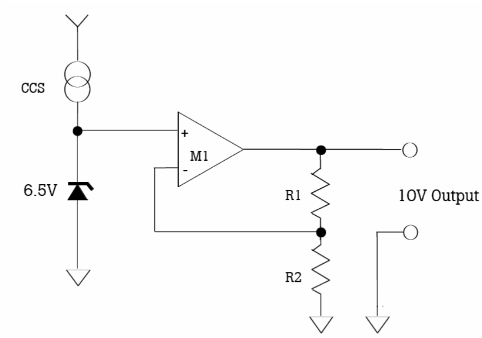


Figure 4. The circuit diagram of a Zener voltage reference.

The breakdown in *p-n* junctions is caused by the avalanche mechanism for breakdown voltages in excess of 8 V, and by the Zener mechanism for values of up to about 4 V. Because of the two effects have opposite thermal characteristics, the

Zener diodes operating between these two limits have stable performance with respect to temperature. The temperature coefficient is further reduced by adding the base-emitter junction of the series transistor with opposite temperature dependence. Then the Zener circuit is placed on the same substrate with a heater and operated at a stable temperature, which is above the maximum ambient temperature. The temperature control is achieved by varying the heater power without active cooling.

There is a trade-off between the Zener chip temperature and the temporal stability of its output at temperatures of about 50 ˚C. The higher chip temperature increases the long-term drift.

The simplified circuit diagram of a Zener voltage reference standard is shown in Figure 4. It consists of the Zener device, an amplifier and gain defining resistors. The voltage reference typically has an additional divided output at 1 V or 1,018 V. The resistors R1 and R2 are implemented in “statistical” resistor arrays and specially packaged to reduce effects of humidity and temperature changes [12].

The manufacturers have reduced influence of environmental variations on characteristics of the Zener references. Nevertheless, the best performance of the solid-state references is achieved when these parameters are considered for voltage references individually [11-16]. The uncertainty (*k=2*) of voltage standards maintained in electronic references is typically less than 1 µV/V.

2. Realization of scale of direct voltage

2.1. Maintenance of the volt

Laboratory

Electrical measurement standards and equipment are affected by changes of environment conditions. The best performance of the devices is achieved if the following parameters are taken into account: air temperature, relative humidity, barometric pressure and electromagnetic interference.

To minimize the environmental effects on measurement equipment the electrical standards are maintained in the specially designed laboratory - National Standards Laboratory for Electrical Quantities operated by Metrosert Ltd (Central Office of Metrology in Estonia).

The laboratory is constructed as a shielded room-within-room. Relative humidity and air temperature in the room are controlled by an air conditioner within ranges of (40 ± 10) % and (23,0 ± 1,0) °C respectively. Temperature, humidity and pressure are monitored either manually or automatically, which is shown in Figures 5, 6 and 7 respectively. The date (23.05.04) of the first calibration point of voltage references have been chosen as a starting point in all charts used in this work.

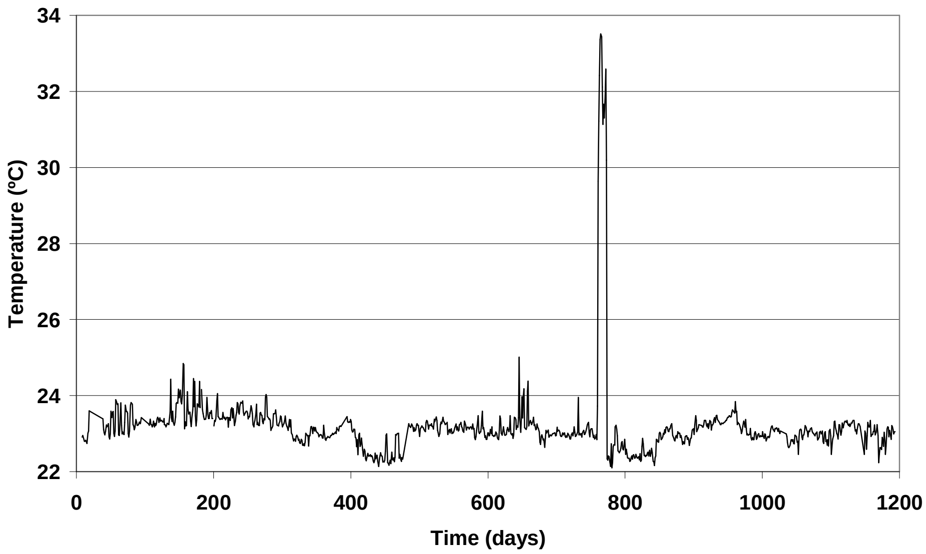


Figure 5. Air temperature monitoring in the standards laboratory for electrical quantities at Metrosert.

Temperature, humidity and pressure variations are due to finite regulation capabilities of the air-conditioner and natural pressure variations. The sudden peak at about 33 °C in Figure 5 was caused by a temporary failure in the air conditioner during summer months. However, this had a small influence on separately thermostatted voltage standards.

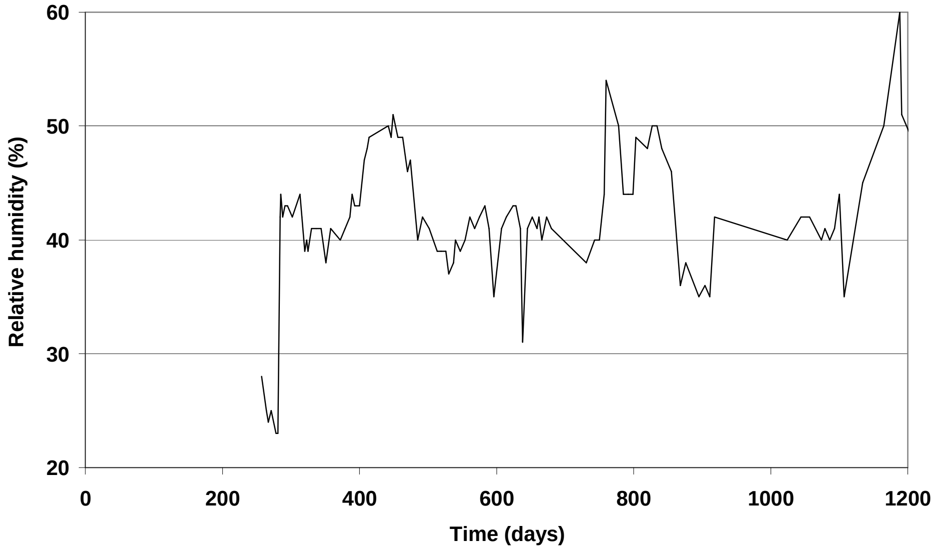


Figure 6. Relative humidity monitoring in the standards laboratory for electrical quantities at Metrosert.

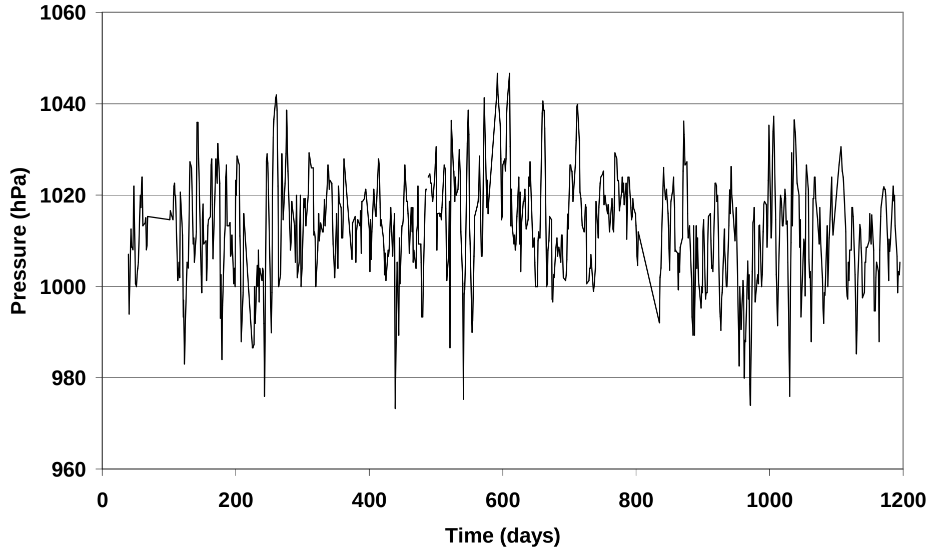


Figure 7. Pressure monitoring in the standards laboratory for electrical quantities at Metrosert.

Voltage standards and measurement equipment

The Estonian national standard of voltage is based on electronic voltage standards (so-called Zener diodes). Ten solid-state references are used in an automated system Fluke 7000-Series for maintenance and dissemination of the voltage unit, see Figure 8. Traceability of the standards is obtained from the JVS at periodic intervals.

Each voltage reference unit includes an ultra-stable 10 V source output and a 1 V divided output. The standards are divided into two modules.

The transfer module incorporates four units, which are annually calibrated against higher-level standards. After calibration, the voltage unit is transferred to the maintenance module.

The maintenance module permanently resides in the laboratory to avoid any effects due to change of the environment and battery to line power transitions. The module hosts six Zener units connected to the hardware average (HAV) of the system. Combining several references extends the predictability of the averaged output in time, reduces environmental effects and the level of noise.

Figure 8. The group of ten solid-state references divided into the transfer module (above) and the maintenance module (below).

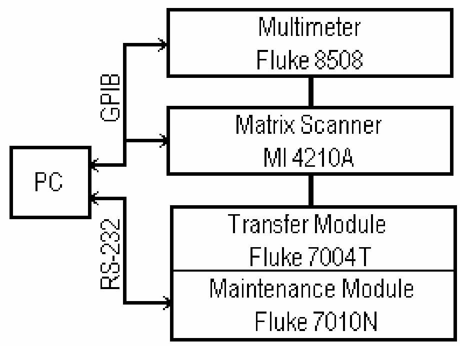


Figure 9. The automated system for maintenance of the voltage standards at 10 V and 1 V.

The maintenance module includes a built-in scanner, a null-detector and software to conduct automated inter-comparisons of 10 V level outputs of up to ten Zener units. The 10 V outputs of the Volt maintenance system are compared to the HAV on a regular basis to maintain surveillance over the voltage unit between calibrations.

Monitoring of 1 V-level outputs of the maintenance system is accomplished by means of a specially developed automated measurement setup (Figure 9). The automated measurement setup consists of a high-resolution multimeter Fluke 8508A, a matrix scanner MI 4210 and specially developed software in C++. Surveillance over outputs of 1 V level is maintained by measuring all possible differences between six standards and computing the variations of the individual references with respect to the group mean [8].

Automatically registered data allow to estimate stability of the standards. As an example, the Zener unit 10 V output relative to the HAV is presented in Figure 10. Unexpected changes beyond uncertainty limits of outputs of Zener units can be registered. The doubtful reference is excluded from the HAV and new drift-rate of the HAV is calculated based on known drift-rates of individual units.

The 10 V-level output is a primary voltage output exploited for maintenance of the local representation of the volt. Divided 1 V level outputs are mainly used for comparison with electrochemical cells and calibration of 10:1 ratio measurements of high resolution digital multimeters. Voltage references at 10 V level are investigated in present work.

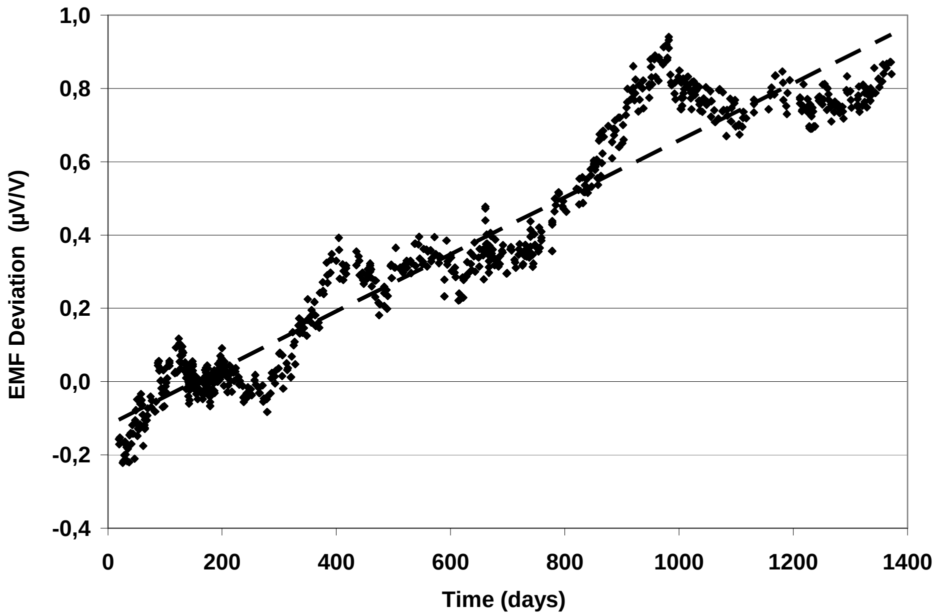


Figure 10. The 10 V output of the Zener at channel 1 as compared to the HAV output. The linear regression is shown for illustration purposes of the observed trend of change.

Maintenance and traceability

Traceability of dc voltage measurements in Estonia (Figure 11) is obtained by annual calibration of four Zener units fitted in the transfer module. Nominal values of 10 V and 1 V are calibrated at MIKES (Centre for Metrology and Accreditation, Finland) against the JVS or standards traceable to the JVS.

After calibration of the transfer module, the voltage unit is transferred to the maintenance module, which is used to represent the volt over the interval between external calibrations.

Voltage measurements in the range from 100 mV to 1 kV are related to 10 V HAV output of the maintenance module by means of a high resolution digital multimeter and multifunction calibrator.

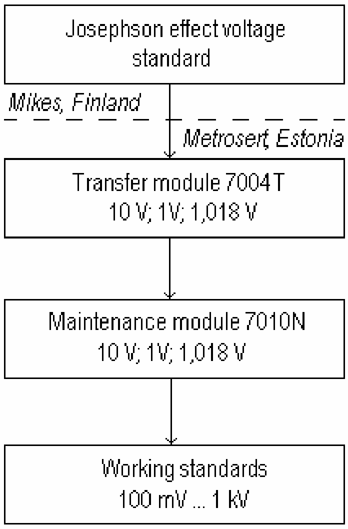


Figure 11. Traceability of direct voltage in Estonia.

2.2. Investigation of metrological characteristics of solid-state voltage standards

Model of output

The output of a solid state voltage standard may depend on time *t*, temperature *T*, humidity *H* and pressure *P*. The output voltage can be expressed as [19]:

$$V(t,T,H,P) = f(t-t_0,T_{ref},H_{ref},P_{ref}) + \alpha(T-T_{ref}) + h(H-H_{ref}) + \beta(P-P_{ref}) + \varepsilon(t) \qquad (3)$$

where $f(t-t_0,T_{ref},H_{ref},P_{ref})$ is a function which represents the long-term drift of the standard's output under reference environmental conditions, $\alpha(T-T_{ref})$ is a temperature coefficient with temperature correction, $h(H-H_{ref})$ is a humidity coefficient with humidity correction, $\beta(P-P_{ref})$ is a pressure coefficient with pressure correction and $\varepsilon(t)$ is an intrinsic noise of the voltage standard's output.

Environmental effects

The Zener references are known to be dependent on ambient temperature, humidity and pressure. These parameters may vary at the time of calibration among different laboratories or during transportation between laboratories.

The sensitivity to temperature, humidity and pressure of some commercially produced electronic voltage standards have been studied in [11, 14, 20, 21], but the influence of the effects may be dependent on the device construction even for identical models. Therefore effects of variable environmental conditions on performance of each standard should be investigated individually.

The methods for investigation of these effects are shown in Figure 12. The realization of the first method consists of measurement of standards placed in a specially designed chamber, in which an environmental parameter of interest is varied. This method may consume time from several hours (in measurements of effects of temperature and pressure) to several months (for humidity measurements).

The second method is so-called in-service characterization, where data from routine within-group comparisons and environmental records are analyzed.

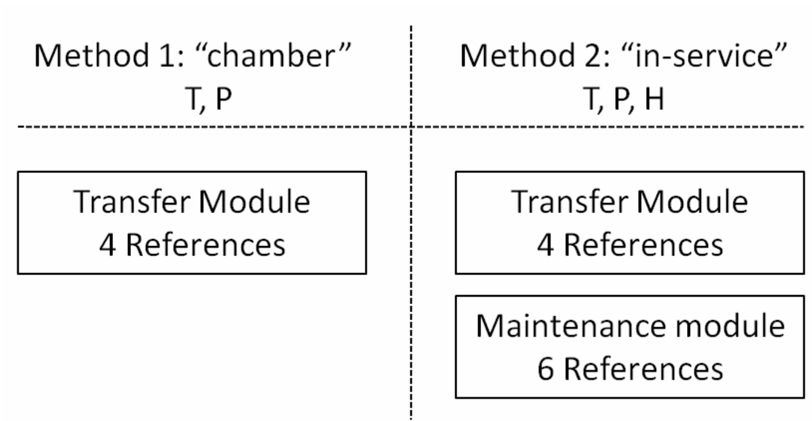
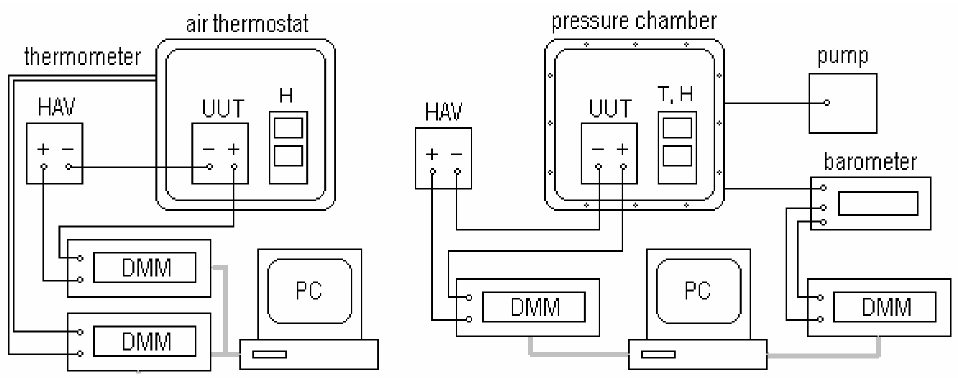


Figure 12. The methods used for investigation of sensitivity of voltage references due to variations in temperature (T), pressure (P) and humidity (H).

In our case, the first method was employed for measurements of temperature and pressure sensitivity of transfer standards. The maintenance module was not investigated by this method, because variation of environmental parameters exceeding laboratory conditions may cause significant recovery time for the Zener outputs. Humidity dependence was not measured, as there is no dedicated equipment available to maintain the stable humidity values during longer periods at the laboratory.

The temperature coefficients up to 0,3 µV/V/°C for 10 V outputs of some Zener standards are reported in [11, 14]. To determine temperature coefficients of transfer standards, a measurement system shown in Figure 13 (a) was constructed. An air thermostat is capable to maintain stable temperature within 50 mK in the range from 15 °C to 40 °C. The temperature inside the thermostat was monitored by a resistance thermometer, connected to a digital multimeter (DMM). Humidity was measured by a handheld digital hydrothermometer (H). The temperature in the thermostat was changed step-wise from 20 °C to 29 °C during a week, allowing at least 8 hours of stabilization for every temperature point. The 10 V voltage output of the unit under test (UUT) was compared with respect to the HAV (HAV) output by a high resolution digital multimeter, taking into account temporal drifts of standards. Temperature and voltage values were automatically collected to a personal computer (PC) using IEEE488 and RS-232 computer interfaces, and a specially developed data acquisition program in C++.

In Figure 14 effect of temperature on the 10 V outputs of the Z11, Z12, Z13 and Z14 measured against the reference maintained at stable temperature are shown. The output voltages vary linearly with temperature, coefficients are summirized in Table 1.



(a) (b)

Figure 13. Block diagrams of setups used to determine (a) temperature and (b) pressure effects on outputs of Zener references.

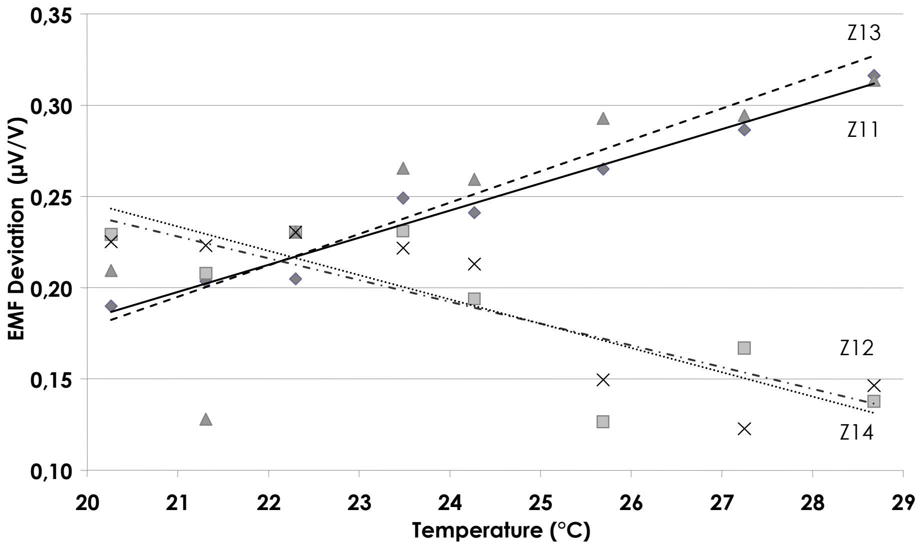


Figure 14. Linear least-squares fitted lines of change in 10 V output voltages of transfer standards against temperature change, with offsets normalized to zero.

Table 1. Temperature coefficients for transfer standards.

ID	Temperature coefficient, µV/V/°C	Standard deviation, µV/V
Z11	0,017	0,010
Z12	-0,012	0,025
Z13	0,015	0,011
Z14	-0,013	0,022

The pressure coefficients with the magnitude up to 0,020 µV/V/hPa were measured for some Zener references in specially constructed pressure chambers [18, 20 and 21] and from within-group measurements [19].

Sensitivity to normal variations in atmospheric pressure for transfer standards was investigated utilizing the measurement setup shown in Figure 13 (b). Zener standards were placed in a rectangular chamber, which is capable to maintain constant pressure within 4 hPa over several hours. The pressure was regulated by means of a manual valve and a pressure vessel. Temperature and humidity values were registered with a handheld digital hydrothermometer (T, H). Voltage outputs of test units were compared to the HAV (HAV) output by a high resolution digital multimeter (DMM). The similar multimeter was employed to monitor a current output of the barometer.

The pressure inside the chamber was changed gradually with the highest step of 250 hPa. Four transfer standards did not show any significant correlation between

10 V voltage outputs and pressure changes in the chamber. For example, measurement results for the Z12 are shown in Figure 15.

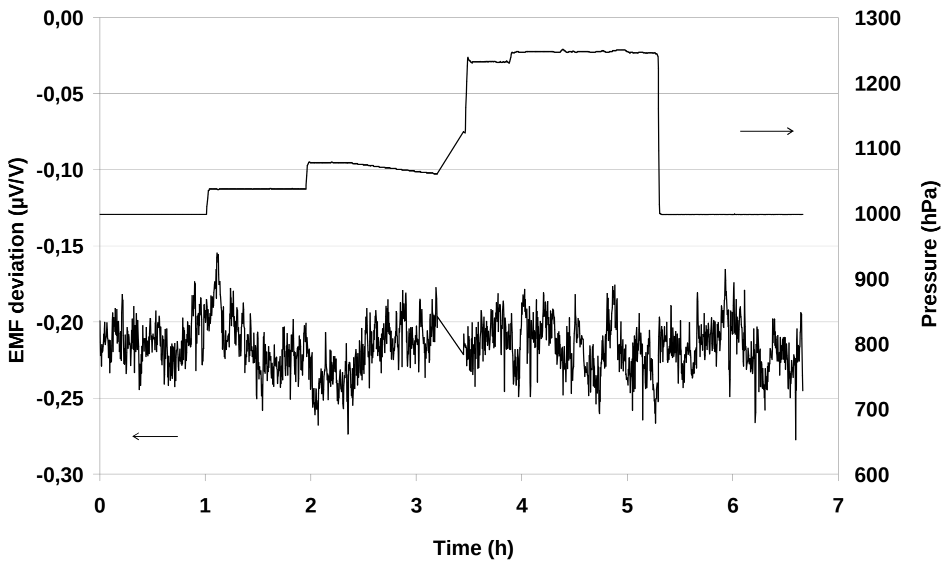


Figure 15. Pressure sensitivity measurement of the Z12 reference for 10 V output.

Sensitivity to environmental effects for voltage references is also analyzed from within-group comparisons, the second method called “in-service”. Outputs 10 V of all references in the system exibit no significant correlation to temperature and pressure variations, which is in agreemnet with results obtained for transfer standards measured in special chambers.

The influence of humidity changes on temporal characteristics of Zener references is observed from results of within-group comparisons.

The special environmental chambers were used to investigate humidity dependence of Zener references in [18]. However, effect of humidity on a voltage standard’s output may be observed from within-group measurements [19], as well. Some Zener references investigated in [11, 18 and 19] do not show clear correlation on humidity, but several standards exhibit humidity dependence up to 2 µV/V/%RH.

In Figure 16 4-year period results from within-group measurements for an individual voltage reference are depicted. The results were corrected for the HAV regression line. Although the magnitude of variations around the regression line is less than 0,15 µV/V, a marked correlation to humidity records is observed.

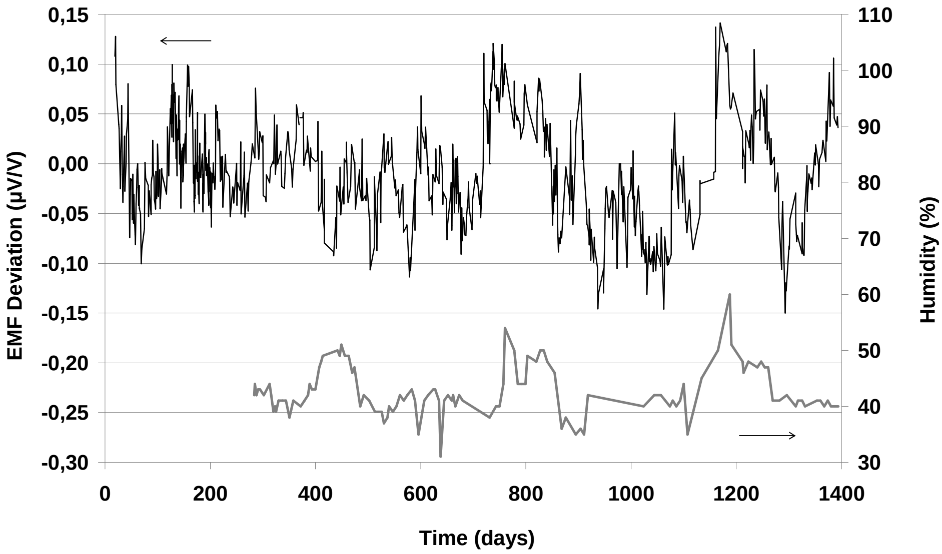


Figure 16. Effect of relative humidity on the Z6 10 V output. Voltage differences are measured against the HAV output.

Sensitivity to humidity changes of about 0,01 µV/V/%RH was observed only for items Z6 and Z2. The output response on humidity variations of the device Z2 10 V includes a time constant of 120 days.

Noise in voltage measurements

Noise in 10 V outputs measurements was investigated by means of the Allan variance (two-sample variance). This method is usually employed for measurements of stability of frequency standards in time and frequency metrology.

The Allan variance taken on the variable *y* is defined as:

$$\sigma_y^2(\tau) = \left\langle \frac{\left(\overline{y}_{k+1} - \overline{y}_k\right)^2}{2} \right\rangle \tag{4}$$

where 〈 〉 denotes averaging over time and τ is the sampling time.

We have characterized white and 1/*f* noises in digital multimeters and Zener standards with the Allan variance as described in [22, 23]. The Allan variance computation was implemented in MS Excel using MS Visual Basic for Applications programming language.

In Figure 17 the Allan deviations deduced from measurement results obtained using (a) the voltage difference between the HAV and the Zener 1 and (b) the short-circuit of the DMM 8508. The measurements series were performed in frames from 931 to 5120 measurements switching resolution of the DMM from 6 to 7 and 8 digits to combine faster measurement time at 6 digits and better sensitivity at 8 digits.

The Allan deviation of the Zener device reaches a nearly constant value after the sampling time of several seconds. This means the presence of the 1/*f* noise floor of about 90 nV for the Zener reference.

The value of the 1/*f* noise is well above the 1/*f* noise floor of the DMM, which begins from last two points on the curve (b). Measurements performed by two long-scale DMMs of different type (Wavetek 1281) resulted in nearly identical values of the Allan variances for the Zener standards, which ensure that noise originates in the standards.

The slope $\tau^{-1/2}$ in the curve (b) indicates the white noise process in the DMM short circuits measurements. A slight disagreement between the $\tau^{-1/2}$ and (b) in the two first points is due to the resolution switching of the DMM. Note that in case of white noise the Allan deviation is equal to the classical standard deviation.

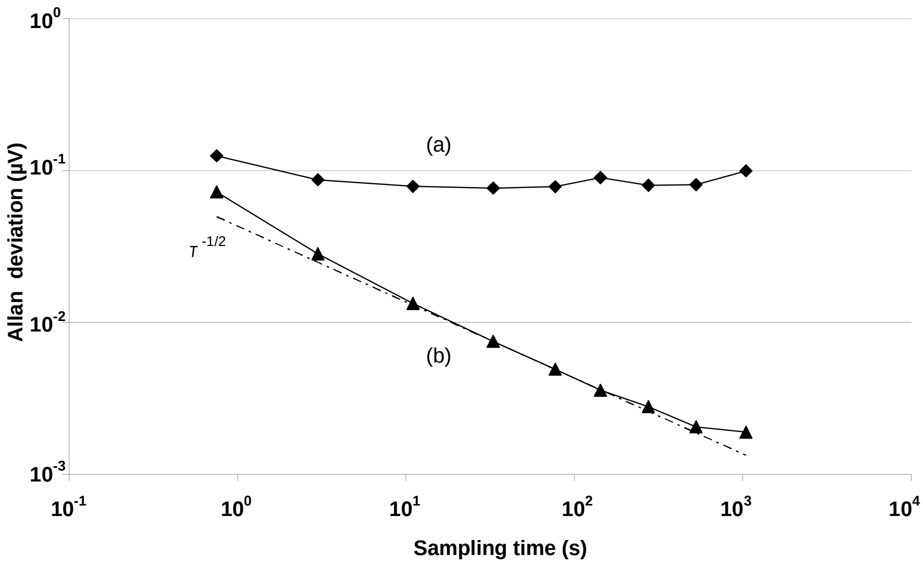


Figure 17. Allan deviations versus sampling time for (a) the difference between the HAV and the Zener 1 and (b) the short-circuit of the DMM.

References investigated in this work exhibit the 1/*f* noise floor in the range from 60 to 130 nV. The classical variance used in the uncertainty analysis (part 3.3) for the voltage references is a correct expression for the standard deviation as it is higher than the maximum observed 1/*f* noise floor of the Zeners.

Stability with time

The actual drift rate of the HAV and individual Zeners can only be estimated from external calibrations against higher level standards. The regular within-group comparisons give a degree of confidence in the reference standards, but unable to determine the drift rate.

The output of a solid-state reference during the calibration interval can be described by a certain mathematical model, which is based on analysis of previously obtained calibration data. The linear drift model is frequently used for periods of several months or more, where the least square estimates of regression parameters are found from calibration history. For some references a non-linear model may be more suitable, in particular for longer periods.

A model assuming that the output voltage exponentially approaches a constant value was employed for several standards for periods of 8-10 years [16]:

$$f(t-t_0, T_{ref}, H_{ref}, P_{ref}) = V_f - V_c \cdot e^{-(t-t_0)/T} \tag{5}$$

where V_f is the value that the output approaches, V_c is the total amount by which the output changes during its lifetime and T is a time constant characteristic of the standard.

For references exhibiting linear drifts in longer periods the time constant T is assumed to be much greater than the lifetime of the standard, which reduces Eq. (5) to a linear function.

In this work a linear regression is used to describe the voltage outputs of the standards in the time interval of about 3,5 years. There are two major criteria of evaluation for a model: the standard deviation of regression and the difference between the new calibration value and the value that was projected by the model. Applicability of non-linear models should be checked, as the number of calibration points increases with time.

Table 2 contains calibration history of the HAV obtained by external calibration of our transfer module consisting of four Zener units. The estimate of the uncertainty [17] for the maintenance module includes the uncertainty due to external calibration and transportation of the transfer module, and the components caused by calibration procedure of the maintenance module against the transfer module and environmental effects. The expanded uncertainties, U_c, achieved are listed in Table 2.

Table 2. Calibration history for the HAV output: EMF deviation is a deviation from the nominal value of 10 V and U_C denotes expanded uncertainty.

Date	EMF deviation, µV/V	U_c, µV/V
May 2004	0,00	0,50
December 2004	-0,14	0,25
April 2005	-0,19	0,50
June 2005	-0,27	0,25
August 2005	-0,29	0,25
September 2006	-0,44	0,25
November 2006	-0,45	0,25
February 2007	-0,49	0,25
November 2007	-0,54	0,25
December 2008	-0,57	0,25

Table 3. Values obtained for the HAV from comparison with SPI.

Date	EMF deviation, µV/V	Expanded Uncertainty, µV/V
April 2006	-0,36	0,25
May 2006	-0,39	0,25

The first three data points were omitted from the HAV output model, because in May 2005 an unexpected change in the Z5 10 V output was observed from within-group measurements, shown in gray line on the secondary vertical axis in Figure 18. Most probably, this is due to rearrangements in the laboratory, which took place at the same time. The new working tables were obtained and voltage standards were placed at their final location. Although, the clear deviation from the regression line was only observed for the Z5, the data points were excluded for all references in the HAV, as outputs of the references under the same conditions are expected to be correlated.

Starting from June 2005 the HAV output voltage can be expressed by a linear regression. Temperature, humidity and pressure coefficients are taken into account as uncertainty component. In this case equation (3) becomes:

$$V(t) = kt + b \pm U \quad (6)$$

where t is time in days, k is the drift rate, b is the offset term and U is the combined uncertainty, which includes components described in the part 3.3. The calculated regression line for the HAV output updated with the latest calibration points is shown in Figure 19. To improve quality of the calculated regression and to reduce related uncertainty, data obtained from the bilateral comparison with Electrical Standards Laboratory of the Semiconductor Physics Institute (SPI, Lithuania) was included in calculation (Table 3).

Evaluation of projection

The equation (6) is used to project 10 V outputs over 1-year calibration interval. Projections are evaluated by comparing the new calibration value to the value that was projected by the equation (6). The 1-year projection and calibration history for the HAV output is shown in Figure 18. The difference between prediction line and latest calibration points is 0,38 µV/V with the uncertainty ($k = 2$) of 0,51 µV/V. The uncertainty of difference is root-sum-of-squares (rss) of the prediction uncertainty (U_p in Table 4) and calibration uncertainty (U_c in Table 2).

Performance of the projection can be evaluated similar to that of applied in the determination of laboratory measurement performance by using equation [24]:

$$E_n = \frac{x_{lab} - x_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}} \tag{7}$$

where:

E_n – evaluation criteria,
x_{lab} – laboratory result,
x_{ref} – reference laboratory result,
U_{lab} – laboratory expanded uncertainty,
U_{ref} – reference laboratory expanded uncertainty.

In our evaluation, the 1-year projection value was used as a laboratory result x_{lab} and the new calibration value as a reference laboratory result x_{ref}. Performance of the projection is determined by the following criteria:

$|E_\mathrm{n}| \leq 1$ = satisfactory,

$|E_\mathrm{n}| > 1$ = unsatisfactory.

For the HAV and all individual Zeners, except the Z14, quality of the calculated projection is satisfactory, see Table 4. Differences between 1-year projections and new calibration points are less than 1 µV/V for all references.

Table 4. Relative drift rates for the HAV and individual references.

ID	2007			2008	
	Drift rate, µV/V/year	U_p, µV/V	$\|E_n\|$	Drift rate, µV/V/year	U_p, µV/V
Z1	-1,01	0,57	0,2	-0,95	0,51
Z2	-1,68	0,64	0,9	-1,43	0,78
Z3	-1,33	0,57	0,3	-1,24	0,54
Z5	-1,32	0,59	0,6	-1,17	0,62
Z6	-1,24	0,55	0,6	-1,10	0,55
Z7	-1,37	0,47	1,0	-1,13	0,70
Z11	-1,36	0,63	0,4	-1,24	0,55
Z12	-1,55	1,04	0,5	-1,35	0,97
Z13	-1,41	0,76	0,1	-1,35	0,58
Z14	-2,20	0,51	1,6	-1,94	0,88
HAV	-1,32	0,44	0,8	-1,17	0,54

The higher uncertainty calculated for the HAV in 2008 is due to the increased standard deviation of the regression. This can be caused by either systematic effects during calibration of the HAV or long-term fluctuations of the voltage output around its regression line. It is expected, that the standard deviation of regression should reduce with time, when more calibration points are obtained.

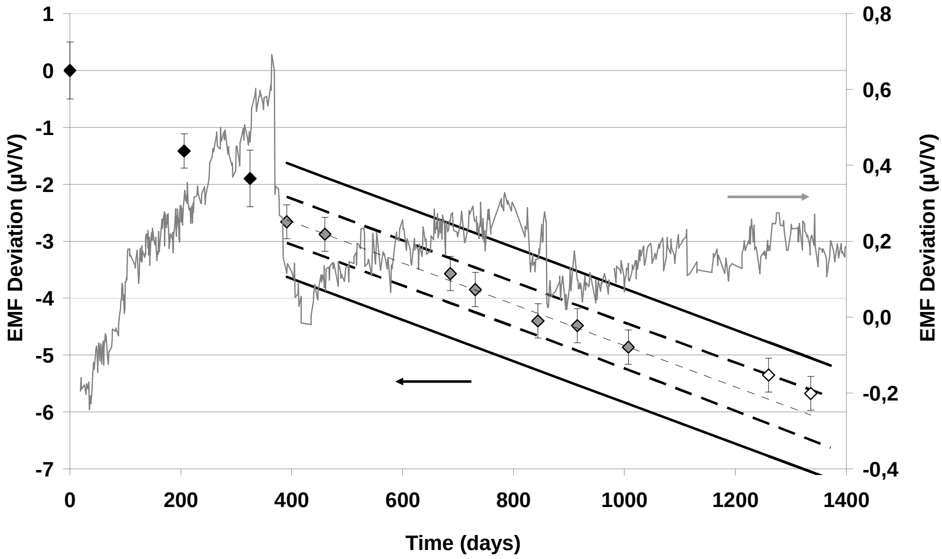


Figure 18. The calibration data for the HAV output: black markers – omitted points, gray markers – input values for the projection, white markers – latest calibration points, narrow dash line – projection, bold dash line – calculated expanded uncertainty, solid lines – 1 µV/V uncertainty limits, gray line on secondary vertical axis – in-service comparison results for the Z5.

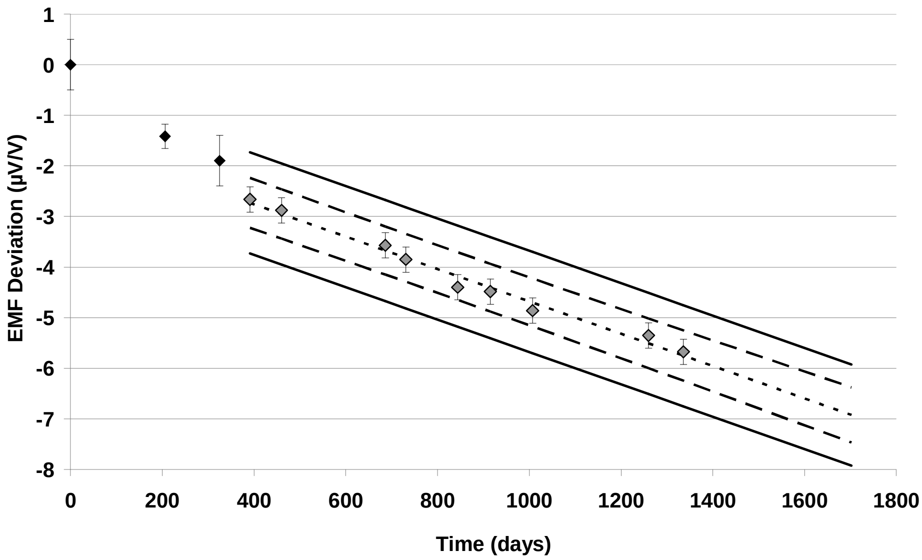


Figure 19. The calculated regression line for the HAV 10 V output containing the latest calibration points: black markers – omitted points, gray markers – input values for the projection, narrow dash line – projection, bold dash line – calculated expanded uncertainty, solid lines – 1 µV/V uncertainty limits.

2.3. Uncertainty estimate for national representation of the volt

The transfer standard is employed for importation of traceability from the JVS to the local representation of the volt. The standard is delivered from Mikes to Metrosert in several hours under power conditions, which ensures best repeatability in measurements. After that, the voltage unit is transferred to the HAV and individual laboratory references.

The voltage V_x of a laboratory voltage reference standard at the end of calibration period is obtained from the relationship:

$$V_x = V_{tr} + \delta V_{tr\_D} + \delta V_{tr\_R} + V_{A-B} + \delta V_{nd} + \delta V_{lb\_E} + \delta V_{lb\_D} \qquad (8)$$

where:

V_{tr} – voltage of the transfer standard,
δV_{tr_D} – drift of the value of the transfer standard,
δV_{tr_R} – reproducibility of transfer standard,
V_{A-B} – voltage difference between laboratory and transfer standards,
δV_{nd} – null detector gain error,

δV_{lb_E} – voltage variations of the laboratory standard due to environmental effects,
δV_{lb_D} – drift of the value of the laboratory standard.

Voltage of the transfer standard (V_{tr}): The calibration certificate for the transfer standard gives a voltage value of 9,999947 V with calibration uncertainty of 0,21 µV/V.

Drift of the value of the transfer standard (δV_{tr_D}): The short-term drift of the transfer standard since its calibration is estimated from measurement results performed at Mikes during calibration to be 0,03 µV/V ± 0,05 µV/V.

Reproducibility of transfer standard (δV_{tr_R}): Confidence in the transfer of the voltage unit is achieved by using of four transfer standards Z11, Z12, Z13 and Z14. The average of four voltage transfers is taken as the calibration value. The highest difference between any two transfer references is considered as the type B standard uncertainty 0,03 µV/V. This includes environment variations during transportation.

Voltage difference between laboratory and transfer standards ($V_{A\text{-}B}$): Measurements are performed using a reversal switching included in the reference to eliminate any thermal EMFs generated by interconnections in the system. Connections are switched in the sequence forward-reverse-reverse-forward, with thirty measurements in a series. The difference between the laboratory and transfer standards was -0,18 µV/V with standard deviation of 0,03 µV/V.

Null detector gain error (δV_{nd}): The measurement error specification for built-in null detector is ± 0,1 % ± 0,5 µV, which makes up the standard uncertainty of 0,03 µV/V for measured values. Differences in measurement results observed with the built-in null detector and an external digital multimeter are less than 0,05 µV/V.

Voltage variations of the laboratory standard due to environmental effects (δV_{lb_E}): Temperature and humidity in the laboratory are regulated by an air-conditioner within limits of (23,0 ± 1,0) °C and (40 ± 10) % respectively. Sensitivity of voltage standards to variations of environmental parameters was analyzed in the part 3.2 of the present work. Deviations from regression lines due to environmental effects are estimated to be within ± 0,20 µV/V.

Drift of the value of the laboratory standard (δV_{lb_D}): The drift of the HAV in the 1-year calibration interval is found from its calibration history to be -1,25 µV/V with the standard uncertainty of the regression line, u_{reg_HAV}, at the end of calibration interval [25] of 0,19 µV/V.

Correlation: For a group standard consisting of N independent references the standard uncertainty of the regression line, u_{reg_N}, is calculated as following [25]:

$$u_{reg\_N} = \sqrt{\frac{1}{N^2}\sum_{i=1}^{N} u^2(x_i)} \qquad (9)$$

where $u(x_i)$ is the standard uncertainty of the regression of the references making up the group standard. According to the equation (9) the u_{reg_N} should be equal to 0,09 µV/V, which is less than the u_{reg_HAV} - the standard uncertainty of the regression line of the physical output of the same group of standards. This is due to correlation between voltage outputs of the standards of the same type maintained under the same conditions.

When references are correlated, the standard uncertainty is expressed by [17]:

$$u(y) = \sqrt{\sum_{i=1}^{N} c_i^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{k=i+1}^{N} c_i c_k u(x_i) u(x_k) r(x_i, x_k)} \qquad (10)$$

where c_i and c_k are the sensitivity coefficients, and $r(x_i, x_k)$ is the correlation coefficient.

The standard uncertainty of the regression of the group of N = 6 individual standards u_{reg_N} calculated by the equation (10) is 0,19 µV/V and equals to the standard uncertainty of the regression line of the physical output of the same group of standards u_{reg_HAV}.

In Figure 20, the computations for the uncertainties maintained by a group of independent standards and the effect of correlation on the uncertainties are shown.

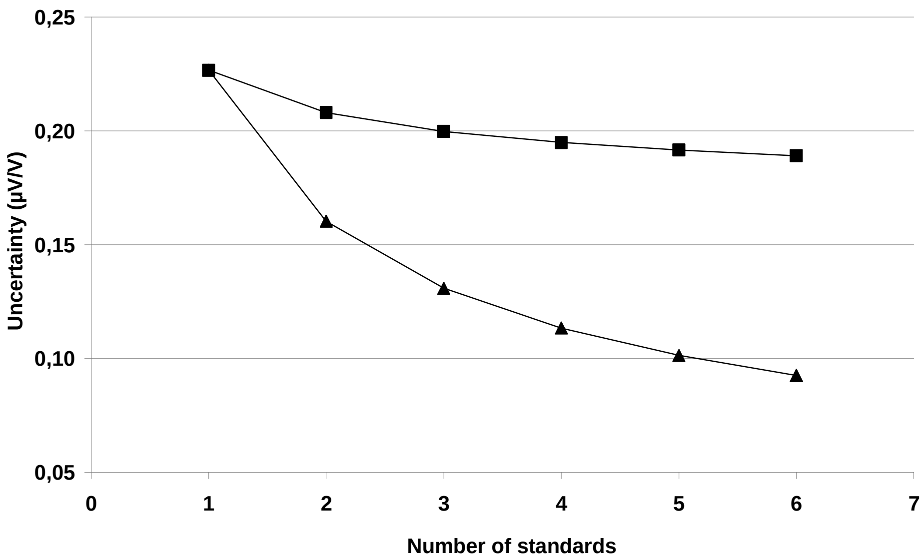


Figure 20. The standard uncertainty of the regression for the different number of standards in the group. Triangles denote uncertainties of independent references, calculated by equation (9). Rectangles denote uncertainties, which include the effect of correlation - equation (10).

For a measurement standard maintained on a group of references, the correlation term should be evaluated to avoid underestimation of the measurement uncertainty.

Uncertainty budget for a laboratory reference is presented in Table 5.

Table 5. Uncertainty budget for a laboratory reference at the end of calibration period.

quantity X_i	estimate x_i	standard uncertainty $u(x_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$	degrees of freedom, v_i
-	V	μV/V	-	-	μV/V	-
V_{tr}	9,999945	0,11	normal	1,0	0,11	∞
δV_{tr_D}	$-0{,}3 \cdot 10^{-6}$	0,03	rectangular	1,0	0,03	∞
δV_{tr_R}	0	0,03	rectangular	1,0	0,03	∞
V_{A-B}	$-1{,}8 \cdot 10^{-6}$	0,03	normal	1,0	0,03	29
δV_{nd}	0	0,03	rectangular	1,0	0,03	∞
δV_{lb_E}	0	0,12	rectangular	1,0	0,12	∞
δV_{lb_D}	$-12{,}5 \cdot 10^{-6}$	0,19	normal	1,0	0,19	7
V_x	9,999931				0,22	22

Expanded uncertainty:

$$U = k \times u(V_x) = 2{,}13 \times 0{,}22\ \mu\text{V/V} = 0{,}54\ \mu\text{V/V}$$

where k is the coverage factor corresponding to 22 effective degrees of freedom v_i, which is a measure of the reliability of the standards uncertainty [17].

2.4. Interlaboratory comparison between SPI and Metrosert

Measurement capability of a standards laboratory can be confirmed experimentally by participation in an interlaboratory comparison of measurement standards.

In 2006 a comparison of 10 V and 1 V voltage standards was conducted between the Estonian National Standards Laboratory for Electrical Quantities operated by Metrosert ltd (Metrosert, Estonia) and Electrical Standards Laboratory of the Semiconductor Physics Institute (SPI, Lithuania).

SPI maintains the representation of the volt based on the 10 V JVS system, installed at the end of year 2004. In time between operations of the JVS, the voltage unit is maintained in secondary voltage standards at 10 V and 1 V by means of a set of Zener references comprising Fluke 7004N Nanoscan System. The reference standards are periodically calibrated against the JVS system [27].

For comparison between two laboratories the most stable transfer standard Z13 was used. A model for the output voltage of the transfer standard was determined from measurements against the HAV output, as described in the section 3.2 of the present work. The model includes only time dependence. Variations in temperature, humidity and pressure between laboratories and during transportation are taken into account as an uncertainty component.

The Z13 was compared to the HAV output every day during one month (10.03 – 10.04.06) before it was delivered by hand to SPI. At SPI the measurements were conducted in two time series (19-21.04.06 and 15-18.05.06) against the JVS. After that the transfer standard was delivered again to Metrosert and compared to the HAV output during one month (23.05-22.06.06).

The transfer standard was delivered under power conditions, with temperature and humidity variations of (23,3...28,9) °C and (39...49) %RH respectively.

In Figure 21, the measurement results for the Z13 obtained at Metrosert (gray markers) and SPI (white markers) are shown. The difference between two laboratories was 0,94 µV/V with the expanded uncertainty of 0,89 µV/V. The major contribution to the uncertainty is from the measurement system of Metrosert. It is the calculated expanded uncertainty for the projection of the HAV output. The expanded uncertainty of measurements performed against the JVS of SPI was less than 0,05 µV/V.

Interpretation of obtained results is conducted according to ISO/IEC GUIDE 43-1:1997, „Proficiency testing by interlaboratory comparisons“ [24]. The equation (7) from this document was already used in the part 3.3 of the present work in estimation of quality of the projection for the HAV output. Although the criteria $|E_n|$ for the targeted uncertainty of 1 µV/V is less than 1, for the calculated uncertainty of 0,89 µV/V the $|E_n|$ is slightly higher than 1 ($|E_n| = 1{,}06$). This pointed to a need to re-evaluate the previously calculated uncertainty intervals.

The regression line and uncertainty intervals were updated after an unexpected change in the Z5 10 V output was observed, it is described in the section 3.2. The regression line of the HAV output was corrected, when a new calibration point was obtained in September 2006. According to the corrected projection shown in Figure 22, the difference between laboratories is 0,11 µV/V with the expanded uncertainty of 0,89 µV/V. The number $|E_n| = 0{,}13$, which means a satisfactory result of the bilateral comparison.

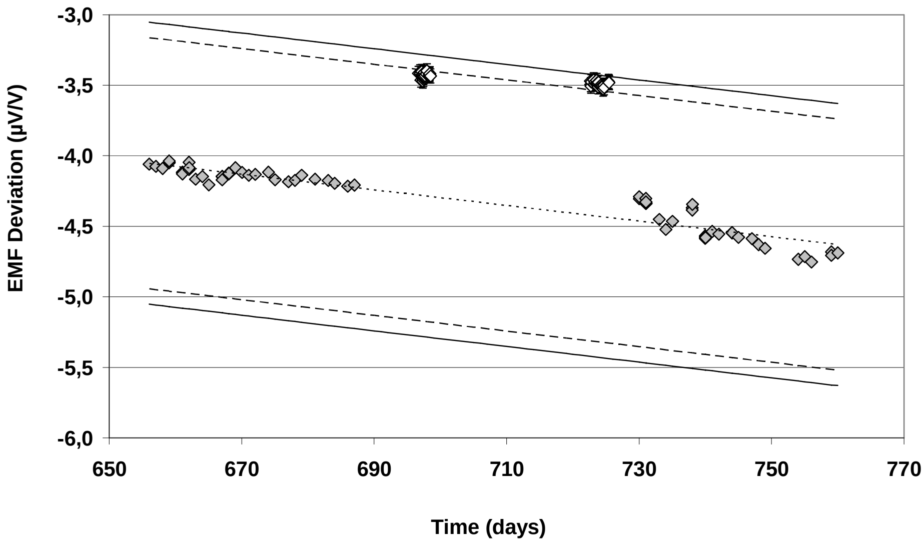


Figure 21. Measurement results of the bilateral comparison between SPI and Metrosert before the corrective action. Gray markers are results of Metrosert, white markers - results of SPI, narrow dash line – regression line for the travelling standard, bold dash line – calculated expanded uncertainty, solid lines – 1 µV/V uncertainty limits.

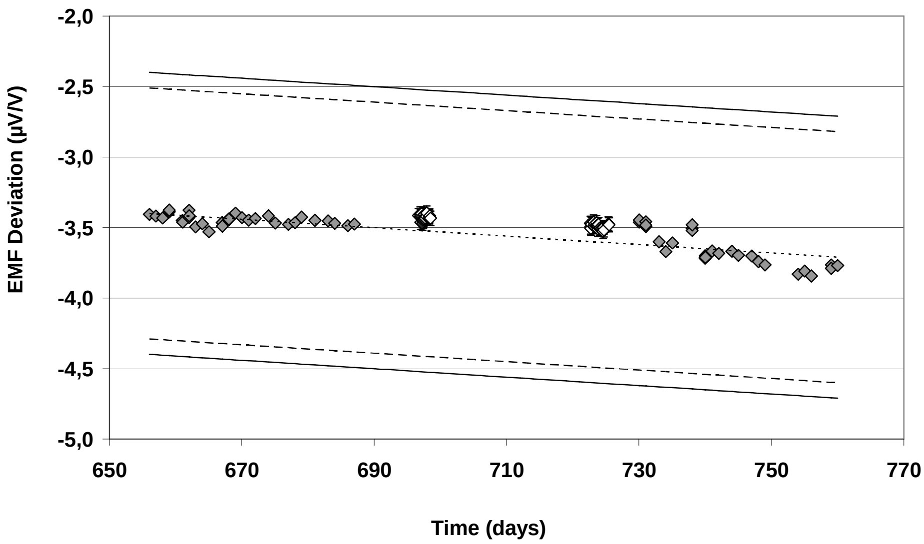


Figure 22. Measurement results of the bilateral comparison between SPI and Metrosert after the corrective action. Gray markers are results of Metrosert, white markers - results of SPI, narrow dash line – regression line for the travelling standard, bold dash line – calculated expanded uncertainty, solid lines – 1 µV/V uncertainty limits.

2.5. Measurement of direct voltage in range from 100 mV to 1 kV

Long-scale digital multimeter

A local representation of the voltage unit based on solid-state references is usually maintained at 10 V or/and 1 V voltage levels. Typical applications of voltage measurements extend the voltage range from 100 mV to 1 kV.

We have applied a method for scaling the basic voltage unit of 10 V by using of a modern long-scale digital multimeter (DMM) Fluke 8508 with a highly linear analog-to-digital converter [28]. Automated measurements with the DMM provide an accurate and easy to use solution for the scaling process.

The major sources of the uncertainty in voltage scaling with the digital multimeter are:

- linearity error of the DMM;
- stability of the voltage sources;
- repeatability of measurements.

The uncertainty component due to the DMM linearity error is normally estimated from specifications. In high-accuracy applications linear performance of DMM should be checked with external standards, ie a thoroughly characterized voltage standard, and resistive voltage divider. In the present work, the self-made Hamon-type [29] resistive voltage dividers (HRVD) are employed for calibration of the DMM ratio functions, using the Zener device Z13 and multifunction calibrator type Wavetek 4808 as voltage sources.

Resistive voltage dividers

In Figure 23, a principle of a self-made Hamon-type voltage divider is depicted, which is used at 0,1:1 V, 1:10 V, 10:100 V and 100:1000 V voltage ratio measurements. By using of this device the lower uncertainties can be achieved as compared to the DMM 8508.

The Hamon-type resistor consists of four resistors connected in a special way to reduce effects due to lead and contact resistances [29]. Three resistors R_1, R_2 and R_3 connected in parallel are compared to a fourth resistor R_4 as the 1:1 ratio. The value of three resistors connected in series is nine time of the value of R_4. The series combination of four resistors provides an accurate 1:10 ratio. The resistors are immersed in an oil bath for temperature stability during measurements.

Three build-up resistors at different nominal values are involved in scaling process to reduce the heating effects of resistors: 1 kOhm for 0,1:1 V and 1:10 V ratios (HRVD1), 10 kOhm for 10:100 V (HRVD2) and 100 kOhm for 100:1000 V ratio (HVRD3).

The 1:1 ratios of the HRVD1 and HRVD2 are compared by means of a high-resolution (9 digit) direct current comparator (DCC) resistance bridge [Publ. III] and a standard resistor R_S. The 1:1 ratio of the HRVD3 is measured by the potentiometric method employing the multifunction calibrator 4808 as a current source and digital multimeter 8508 as a voltmeter.

The HRVD1 can also be used to check the 10:1 resistance ratio of the DCC bridge. The agreement between the self-made Hamon-type resistor and the 1:10 kΩ range of the DCC bridge is better than 0,05 μΩ/Ω.

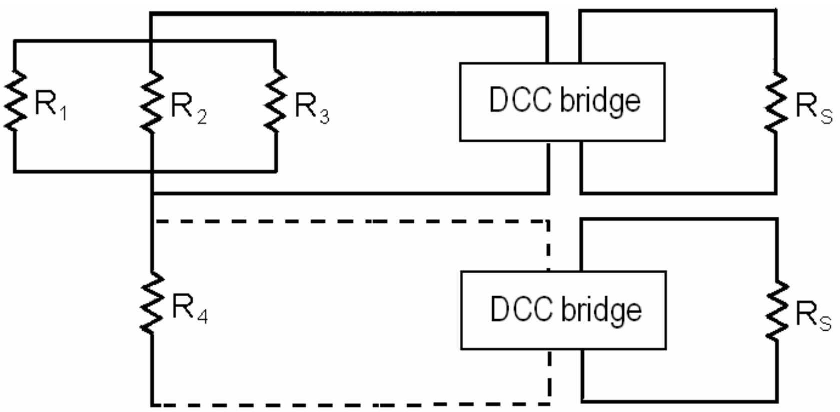


Figure 23. The simplified circuit diagram of the self-made Hamon-type voltage divider.

Measurement results

The measurement results along with the associated relative uncertainties are summarized in Table 6.

Table 6. Measurement results for voltage ratios: r_{8508} – is the ratio of the 8508, r_H – is the ratio of the self-made Hamon resistor. U_{8508} and U_H are the respective uncertainties.

	r_{8508}- r_H, μV/V	U_{8508}, μV/V	U_H, μV/V
0,1:1 V	1,1	3,3	1,6
1:10 V	0,8	2,2	0,7
10:100 V	0,9	2,6	0,8
100:1000 V	-1,6	6,7	1,0

The voltage ratio values normalized to the Hamon resistor ratio values are shown in Figure 24. The differences between the voltage dividers and the DMM ratio functions are within uncertainty limits.

From the analysis of the measurement results it can be concluded that the DMM 8508 is in conformance with its specifications and can be used as a voltage divider for realization of the voltage scale in the range from 100 mV to 1 kV. The uncertainties of the DMM can be reduced by taking into account the obtained corrections, resulting in the uncertainty ($k = 2$) of 3 µV/V for realization of the voltage scale.

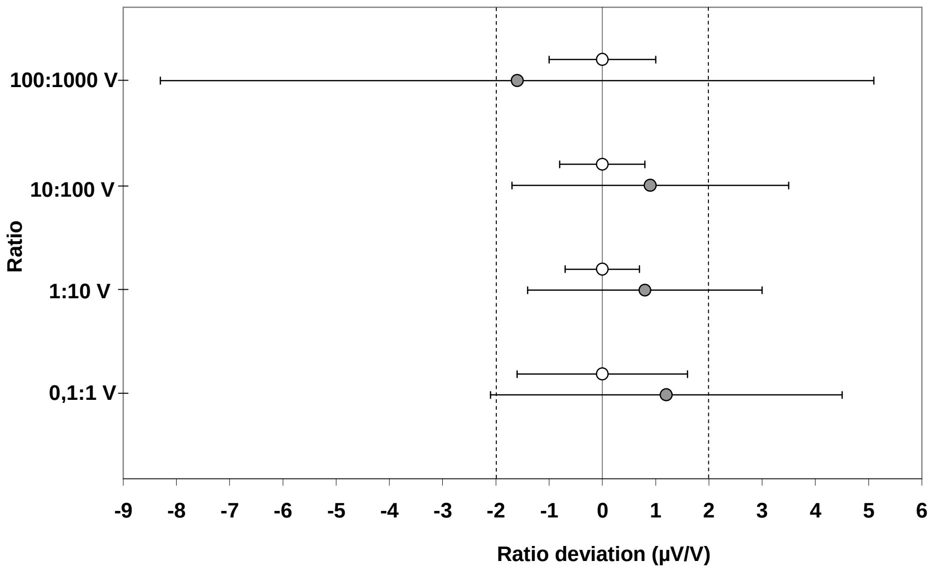


Figure 24. The voltage ratio values normalized to the Hamon resistor ratio values: filled circles - measured by the 8508, empty circles – by the self-made Hamon resistor. Horizontal bars indicate the measurement uncertainty.

Conclusions

In this thesis, the establishment of the national standard for voltage unit in Estonia is described.

A method developed for maintenance of the local representation of the volt is discussed. The voltage standard consists of ten references with 10 V and 1 V voltage outputs. Traceability is obtained from the Josephson effect voltage standard by annual calibration of the transfer standard at the Centre for Metrology and accreditation of Finland (Mikes). Confidence in voltage standards is ensured by regular intercomparisons of individual standards to the hardware average (HAV) of the system.

Metrological characteristics of the references were investigated. The most significant components contributing to the uncertainty estimate in maintenance of voltage standards are calibration uncertainty, environmental effects and long-term stability.

The uncertainty analysis indicates that the relative expanded uncertainty less than one part in 10^6 is achievable in maintenance of the national standard of the voltage unit. The output of a reference in time between external calibrations is described by a linear drift model, where the least squares estimates of regression parameters are found from calibration history.

The quality of the model describing the output of the voltage standard is evaluated by comparison of the projection of the voltage output to the latest calibration point. The criterion of evaluation $|E_n|$ is less than 1, which is the satisfactory result in modeling of the HAV output.

The measurement capability of the laboratory for new voltage measurement standards was confirmed by participation in the bilateral interlaboratory comparison with the standards laboratory for electrical quantities of National Metrology Institute in Lithuania. The difference between two laboratories was 0,11 µV/V with the expanded uncertainty of 0,89 µV/V.

The method for maintenance of voltage standards developed in present work was implemented in establishment of the reliable representation of the voltage measurement unit and realization of the voltage scale in Estonia. The uncertainty analysis and interlaboratory comparison confirmed that the voltage standard based on solid-state references at 10 V nominal value can be maintained with the expanded uncertainty better than at 1 µV/V.

The voltage scale in the range from 100 mV to 1 kV is realized by means of a long-scale digital multimeter and resistive voltage dividers with uncertainties less than 3 µV/V.

The national standard of the voltage measurement unit was appointed by the Minister of Economic Affairs in 2006.

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Publication I

TRACEABILITY OF VOLTAGE AND RESISTANCE MEASUREMENTS IN ESTONIA

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Résumé

Il s'agit d'une description d'amélioration de la capacité à mesurer le courant continu et la résistance électrique en Estonie. L'unité de courant continu, l'exécution du volt se base sur les sources du voltage d'étalon et sur l'unité de résistance électrique, l'exécution de l'ohm aux résistances d'étalon. Chaque année les étalons de toutes les deux mesures subissent un étalonnage selon les exécutions basées sur les fait de quantum. Dans le courant initial 10 V l'incertitude élargie calculée du courant continu est 1 µV/V et dans la zone de 1 Ω à 10 kΩ l'incertitude élargie calculée de la résistance électrique est 1 µΩ/Ω.

Abstract

The capabilities in measurements of direct voltage and electrical resistance were improved in Estonia. The standards for Volt and Ohm are based on electronic voltage standards and standard resistors, respectively. The reference standards are traceable to Josephson voltage (JVS) and Quantized Hall (QHR) effect resistance standards by means of annual calibration of transfer standards. The estimated expanded uncertainty is 1 µV/V for 10 V output of the volt maintenance system and 1 µΩ/Ω for standard resistors in the range from 1 Ω to 10 kΩ.

Introduction

Industry and science apply a number of measurements of direct current electrical quantities. The successful development in these areas requires uniform and accurate measurements, which are ensured by firmly established traceability.
In 2006 the standards for units of voltage and electrical resistance were appointed [1, 2] in Estonia. The standards are maintained in the specially designed laboratory of Metrosert Ltd (Central Office of Metrology in Estonia) in which relative humidity and air temperature are stabilised within ranges of (45 ± 5) % and (23.0 ± 0.5) °C, respectively.
In this paper new measurement capabilities in direct voltage and electrical resistance in Estonia are described.

Voltage standards

Maintenance and traceability

Ten solid-state references (so-called Zener diodes) [3]-[5] are used in an automated system for maintenance and dissemination of the volt. Standards are divided into two modules. The transfer module includes four units which are annually calibrated against the JVS or secondary standards traceable to the JVS at 10 V and 1 V nominal values at MIKES (Centre for Metrology and Accreditation, Finland) see Fig.1. After calibration, the voltage unit is transferred to the maintenance module, which is used to represent the volt in time between external calibrations. The maintenance module incorporates a null-detector, a built-in scanner and six Zener units connected to the hardware average (HAV). Averaging of outputs of several units is needed to reduce the influence of environmental effects [3]-[5], which gives higher degree of confidence in predictability of the HAV output.
The voltage measurements in the range from 10 mV to 1 kV are related to 10 V HAV output by means of the high resolution digital multimeter and multifunction calibrator.

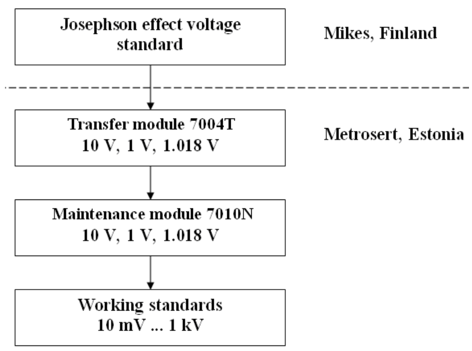

Fig.1 Traceability of dc voltage measurements in Estonia.

Measurement results

The standards are regularly compared to the hardware average of six units to identify any unexpected changes in 10 V outputs of individual references. Typical measured differences between outputs of the HAV and a

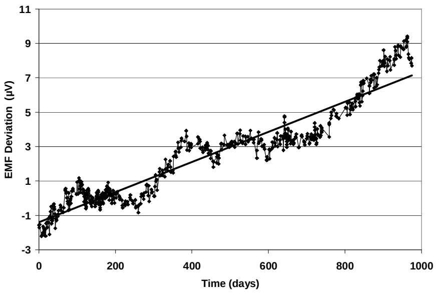

Fig.2 Typical measured differences between 10 V outputs of the HAV and single Zener unit. The regression is fitted to measurement results.

single Zener unit are shown in Fig.2. The linear regression line is fitted to the measurement data. The fluctuations near the regression line are estimated to be less than two parts in 10^7. The estimate of fluctuation is taken into account in uncertainty budget as a component due to long-term standard deviation of a regression.

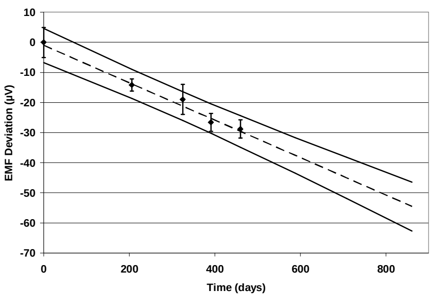

Fig.3. The calculated regression line for the 10 V output of the hardware average.

The linear drift model is used in [3, 4] to predict the 10 V HAV output in time between calibration points. The least square estimates of regression parameters are found from calibration history (Table I) for the HAV obtained by external calibration of the transfer module consisting of four Zener units.

Table I Calibration history for the HAV output.

Date	Value, V	Expanded Uncertainty, µV/V
May 2004	10.000000	0.5
December 2004	9.999985	0.2
April 2005	9.999981	0.5
June 2005	9.999973	0.3
August 2005	9.999971	0.3

The regression line (Fig.3) for the HAV 10 V output was calculated by applying the weighted least squares fitting method [6]. The associated uncertainty 1 µV/V (k = 2.67) for a 1-year calibration interval includes components due to:

- Calibration;
- Transportation;
- Long-term drift;
- Environmental effects;
- Noise.

Resistance standards

Maintenance and traceability

The Estonian national standard for resistance is based on the set of standard resistors in the range from 1 mΩ to 10 kΩ. Two reference nominal values at 1 Ω and 1 kΩ are maintained with a group of three standards.

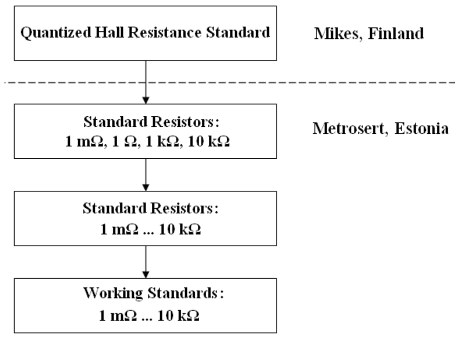

Fig.4 Traceability of resistance measurements in Estonia.

Traceability of the standard resistors is obtained by regular calibration of four standard resistors, Fig.4. Then the maintenance group of the resistance standards is calibrated with an automated measurement system based on the direct current comparator (dcc) bridge [7], Fig.5.

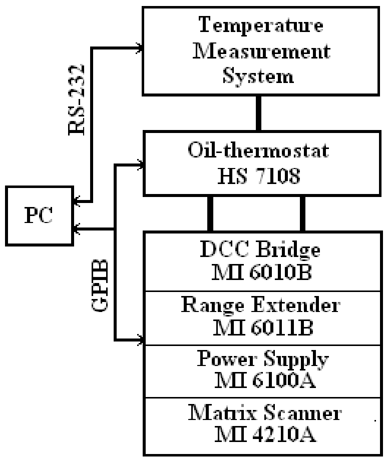

Fig.5. The automated system for measurements of the standard resistors.

The direct current comparator bridge, range extender and matrix scanner from Measurement International (MI) are used in regular comparison of standards, which allows tracking of relative drifts of the resistance values in time between calibrations. The resistors are immersed into the oil-thermostat to maintain the standards at temperature (23.00 ± 0.05) °C. The temperature is measured from inside of the resistors with sixteen fast response platinum resistance thermometers (PRT). The system is fully automated with measurement software developed at Metrosert ltd.

Measurement results

The monitoring of the stability of resistance values is conducted by regular inter-comparison of the standard resistors within the range from 1 mΩ to 10 kΩ. As an example, the measurement results for the 10:1 ratio of the 100 Ω and 10 Ω standard resistors are shown in Fig.6. During the period of more than 1.5 year the drift of the ratio is less than 1 part in 10^7.

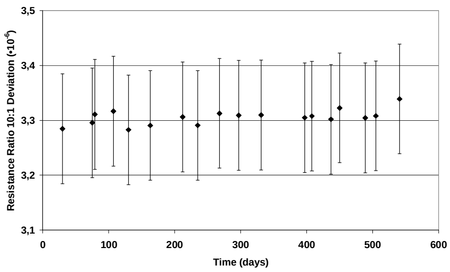

Fig.6 Measurement results for the 10:1 ratio of the 100 Ω and 10 Ω standard resistors. Vertical lines denote accuracy specification limits of the bridge.

The long-term stability of the temperature maintained in the oil-bath can be estimated from measurement history of the standard resistors, where temperature is registered for every standard during resistance measurements. The measurement results for nine platinum resistance thermometers are given in Fig.7. The drift less than 0.02 °C is observed for all PRTs. The total uncertainty in temperature measurements is 0.05 °C for the one-year calibration interval.

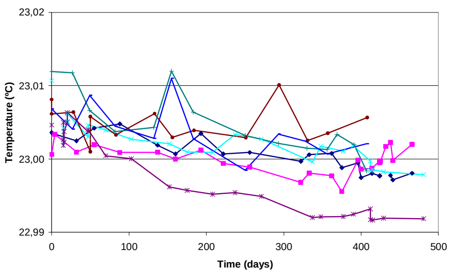

Fig.7 Results for nine platinum resistance thermometers measured from inside of the standard resistors.

The developed measurement setup and an air-thermostat allow determining the temperature coefficients of the resistors which are necessary to take into account effects of temperature on resistance values.

The maintenance of resistance unit and dissemination of traceable measurements require thorough characterization of the measurement bridge. We applied methods of complements checks and comparison with Hamon-type resistors [8, 9] to confirm the performance of our dcc bridge. The results of complements checks for 1:1 ratios with nominal values from 1 Ω to 10 kΩ are shown in Table II. Two measurement series are conducted by exchanging resistors R_X and R_S. The given measurement results indicate that 1:1 resistance ratios of our bridge comply with accuracy specification of the bridge, which is 1 part in 10^7.

Table II Complements checks results for dcc bridge.

Nominal value, Ω	Current, mA	Relative difference in ratio, $\cdot 10^{-6}$	Standard deviation, $\cdot 10^{-6}$
1	100	-0.012	0.0007
10	30	-0.002	0.0003
100	5	-0.015	0.0011
1 k	3	-0.024	0.0020
10 k	0.3	-0.067	0.0125

The measurements of the 10:1 ratios were performed by using of Hamon-type resistors [10, 11] see Table III. The ratios 100 Ω : 10 Ω and 10 Ω : 1 Ω were checked with the model SR1030 transfer standard. Also, two-decade steps of the bridge in the range from 100 Ω to 1 Ω were measured with the same device. The difference between 100 :1 (2nd row in Table III) and two 10 :1 (3rd and 4th rows in Table III) ratio measurement steps was 2 parts in 10^8.

Four (two for each range) home-made Hamon-type resistors were constructed to check the ratios 10 kΩ : 1 kΩ and 1 kΩ : 100 Ω of the bridge. The measurements of two Hamon-type resistors and 1 kΩ : 100 Ω bridge ratios were within 5 parts in 10^8.

Table III Comparison results with Hamon- type resistors.

Ratio, $R_X : R_S$	Relative difference in ratio, $\cdot 10^{-6}$	Relative expanded uncertainty, $\cdot 10^{-6}$
100 Ω : 1Ω	0.20	0.20
10 Ω : 1 Ω	0.09	0.20
100 Ω : 10 Ω	0.09	0.20
1 kΩ : 100 Ω	-0.05	0.20
10 kΩ : 1 kΩ	-0.61	0.30

The difference between two Hamon-type resistors in the range 10 kΩ : 1 kΩ was 16 parts in 10^8, resulting higher uncertainty of the measurement. The difference 61 parts in 10^8 observed between the bridge and Hamon-type resistor measurement results should be further investigated.

The typical uncertainty budget in maintenance of resistance standards includes the following components due to:

- Calibration;
- Transportation;
- Long-term drift;
- Performance of the bridge;

- Connections;
- Temperature and power corrections.

The expanded uncertainty (k = 2) is 1 μΩ/Ω for the range from 1 Ω to 10 kΩ.

Conclusions

The reliable representations of the voltage and resistance units were established at secondary level of standards in Estonia.

The standards are traceable to Josephson voltage and Quantized Hall effect resistance standards.

The automated measurement systems were developed and thoroughly characterized to ensure, that the uncertainties in maintenance of standards are 1 μV/V for 10 V and 1 μΩ/Ω for the range from 1 Ω to 10 kΩ.

Acknowledgments

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Publication II

Establishment of National Standard of Voltage Unit in Estonia

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ABSTRACT: The national standard of volt in Estonia is based on the ten solid-state references and consists of maintenance and transfer modules. Traceability of the dc voltage standards is obtained by annual calibration of 4 Zener units fitted in the transfer module. The calculated expanded uncertainty is less than 10 µV, taking into account the component due to predicted annual drift of the 10 V system average.

1 INTRODUCTION

The most stable and reproducible representation of the voltage unit is based on the Josephson effect voltage standard (JVS) [1]. Typically the JVS is operated every 2-6 months. In time between operation periods of the JVS, the maintenance and dissemination of the volt is conducted by using of solid-state references, so-called Zener diodes [2]-[6].

To achieve the uncertainty of 10 µV for the 10 V output in maintenance of the voltage standard, the group of Zener references is used in an automated system. Periodical comparison of individual items to that of the average of the whole group enables tracking of the relative drifts of the Zener units in time between calibration points against the JVS or secondary level standards traceable to the JVS.

In this paper, the method developed for the maintenance of the standard of voltage in Estonia is described. Our system includes ten Zener units whose outputs are regularly compared to the average of the group of six references. The drifts of the system average and individual Zeners are determined from external calibrations. Measurement methods for prediction of the drift are presented.

2 MAINTENANCE

The solid-state references maintained in the specially designed laboratory of Metrosert Ltd (Central Office of Metrology in Estonia) were obtained in the beginning of 2004. To minimize environmental effects on the performance of the equipment, the relative humidity and air temperature in the room are controlled by an air conditioner within ranges of (45 ± 5) % and (23.0 ± 0.5) °C respectively.

To obtain traceability for dc voltage measurements in Estonia, four Zener units in the transfer module are annually calibrated at 10 V and 1 V nominal values at MIKES (Centre for Metrology and Accreditation, Finland) against the JVS or standards traceable to the JVS. Also, two calibration points were obtained from Fluke laboratory: along with purchased devices and when a Zener unit came from repair. Then the calibration values are transferred to the maintenance module. A 8½ digital multimeter and multifunction calibrator are used to determine voltage ratios relative to the traceable 10 V output of the reference standard. Traceability chain for dc voltage is shown in Fig. 1.

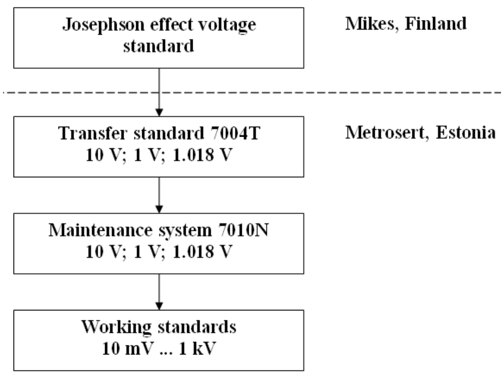

Figure 1. Traceability chain for dc voltage measurements in Estonia.

Output of a solid-state reference during the calibration interval can be described by a certain mathematical model. The linear drift model is frequently used [2]-[4], where the least squares estimates of regression parameters are found from calibration history. For some references a non-linear model may be more suitable, in particular for longer periods.

Environmental variations can influence the outputs of the standards [2]-[6]. To minimize temperature and humidity effects the gain/attenuation defining components within Fluke 7000 type instrument are made as "Statistical Resistor Arrays" and specially mounted [6]. Atmospheric pressure coefficients reported in [6] for a

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7004T module and in [2] for some 7001 units are negligible under normal use either as a transfer or stationary standard with the relative uncertainty of one part in 10^6.

Averaging of outputs of several standards further reduces environmental effects and makes the averaged output – hardware average (HAV) more predictable in time. For this purpose six references are hosted by the maintenance module with built-in scanning and inter-comparison capabilities.

Humidity and pressure coefficients were determined for some Zeners from within-group measurements during periods of several years in [5]. Our system has within-group measurements results for more than 1.5 years. The effects due to finite regulation capabilities of the temperature, humidity in the laboratory and natural pressure variations are reduced by factor of 1/6 for the hardware average of the system, as there are six units in the HAV. Humidity correction can not be estimated now due to relatively short measurement history and small humidity variations of (45 ± 5) %. It is supposed, that long-term fluctuations around regression lines for individual standards are coursed by seasonal effects. These fluctuations are estimated to be not more than two parts in 10^7 and it is used as a component in uncertainty calculations.

From periodical comparisons of individual Zeners against the HAV any reference with abnormal behavior may be registered and excluded from the system average. Also, the model of the regression (linear or non-linear) for individual standards may be estimated, which could be important for some references (Fig. 4) in one year calibration period when the regression model type is not always so evident from external calibration points.

3 MEASUREMENTS

The actual drift rate of the HAV and individual Zeners can be only estimated from external calibrations against higher level standards. Table I contains calibration history for the HAV obtained by external calibration of the transfer module consisting of four Zener units. The maintenance module is calibrated immediately after arrival of the transfer module.

The estimate of the uncertainty [7] for the maintenance module includes the uncertainty due to external calibration and transportation of the transfer module, and the components caused by calibration procedure of the maintenance module against the transfer module and environmental effects. Obtained uncertainty is listed in Table I.

As the number of calibration points will grow annually, the reliability of the standard uncertainty will increase and the expanded uncertainty will decrease. In this case more attention should be paid to the uncertainty components due to environmental effects.

In the regression line calculations the weighted least squares fitting method [8] was used to take into account different calibration uncertainties (Table I). The inversed standard uncertainties $1/(u_{std})^2$ were used to find standardized weights. Although one year stability specification for the 7004N model is ± 12 µV, the drift of the HAV output for the same period is – 24 µV, see Fig. 2.

Table I

Calibration history for the HAV output

Date	Value, V	Expanded Uncertainty, µV
May 2004	10.000000	5
December 2004	9.999985	2
April 2005	9.999981	5
June 2005	9.999973	3
August 2005	9.999971	3

Table II

Relative drift rates of the HAV and 7000 Zener standards

ID	Drift rate, $\cdot 10^{-6}$/year	U_p, $\cdot 10^{-6}$	s_{reg}, $\cdot 10^{-6}$
Z1	-2.16	0.78	0.13
Z2	-3.83	0.77	0.17
Z3	-2.69	1.00	0.19
Z5	-2.17	1.50	0.31
Z6	-1.49	0.69	0.11
Z7	-1.87	0.67	0.10
Z11	-1.97	0.62	0.09
Z12	-1.45	0.75	0.14
Z13	-2.31	0.93	0.19
Z14	-3.86	2.13	0.15
HAV	-2.37	0.88	0.15

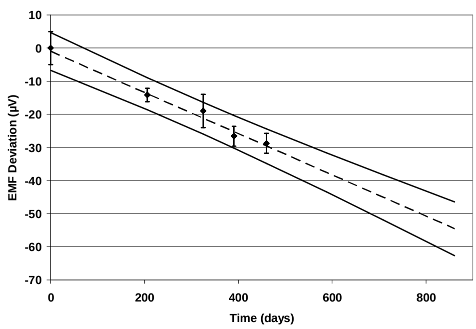

Figure 2. Regression curve for the HAV 10 V output of the system. Bars indicate expanded uncertainty associated to the HAV after traceability transfer from external calibrations. The linear regression line is indicated to guide the eye.

In modeling of the 10 V output of the maintenance system it is also important to study the performance of individual items in the system. All ten units in our system exhibit the negative drift rates, listed in Table II. The prediction uncertainty U_p (k = 2.87) and standard error of regression s_{reg} are calculated from external calibrations. The differences between individual 10 V outputs and hardware average of the system are measured weekly.

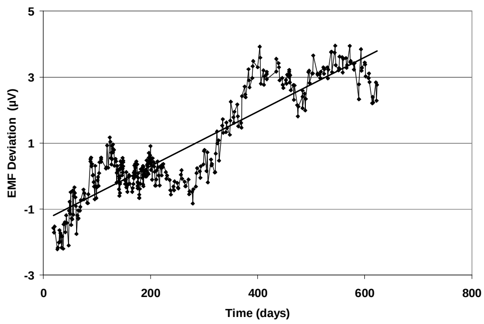

Figure 3. The 10 V output of the Zener at channel 1 as compared to the HAV output. The linear regression is shown for illustration purposes of the observed trend of change.

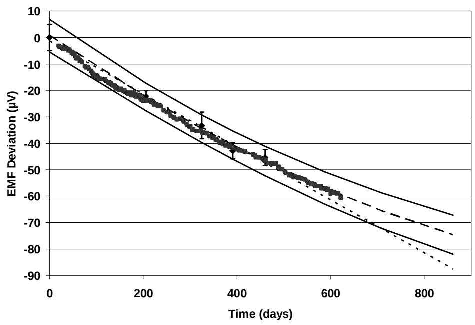

Figure 4. The non-linear regression and the linear regression curves obtained for the Zener 10 V output at channel 2. Filled symbols indicate the measured differences against the HAV output of the system.

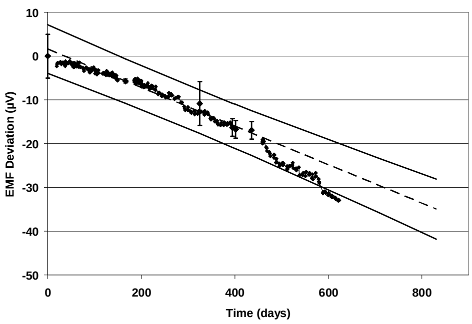

Figure 5. Measurement results of 10 V output of the Zener at channel 12. During external calibration the measurement points are missing. The sudden change in the output of the Zener can be noticed after transportation.

Automatically registered and stored data give information about general condition of every unit at any time. Also, fluctuations around the regression for individual references can be determined. As an example, a Zener unit output relative to the HAV is presented in Fig. 3.

The differences against the HAV regression line may be plotted for individual references, Fig. 4 and 5. The linear and non-linear regressions are given for the Z2 in Fig. 4. The measured differences against the HAV regression clearly follow the non-linear model.

Four references are used as transfer standards. One of transfer standards, the Z12 exhibited drop in output (Fig. 5). This may be due to the shipment, although, there were no extreme changes in humidity (41…46) % and temperature (23.5…27.2) °C during transportation. However, possibly drift rates of some Zeners are sensitive to battery to line power transitions.

It is convenient to compare regression curves rather than measured points of the individual Zeners. In Fig. 6, the measured differences between Z13 and Z1 are shown. The straight line is the differences calculated from regression curves based on external calibration points. Excluding systematic errors, the agreement between measurement results and modeled curves is within two parts in 10^7. This chart is usually expanded to next external calibration.

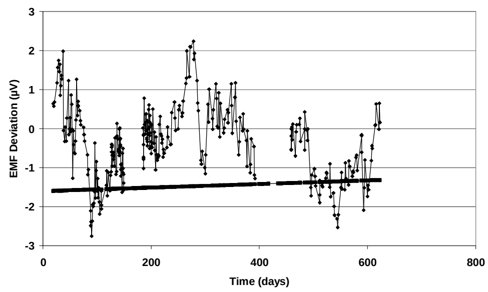

Figure 6. Comparison of the 10 V outputs of the Zeners at channel 13 and 1. The symbols indicate measured differences between the items. The straight line represents the differences calculated from regression curves based on external calibration points.

4 CONCLUSIONS

The reliable representation of the voltage unit based on the group of solid-state references is established in Estonia. The uncertainty analysis confirms that the 10 V level of our system can be maintained with the relative expanded uncertainty less than one part in 10^6. The national standard of voltage unit will be adopted by the Minister of Economic Affairs in 2006.

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Publication III

Development of Automated Measurement Setup for Standard Resistors

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ABSTRACT: An automated system for measurements of standard resistors has been developed. The system is based on high-accuracy direct current comparator bridge, range extender and current source. The setup is used for comparison, characterization and calibration of standard resistors in the range from 1 mΩ to 10 kΩ with relative uncertainties below (1…5) parts in 10^6.

1 INTRODUCTION

Resistance ratio bridges are the primary instruments used by National Measurement Institutes in resistance and temperature applications. In resistance measurements the bridges are used for scaling of the ohm from the quantized Hall resistance (QHR) standard [1] or resistance standards traceable to the QHR. The reliability of uncertainties obtained during scaling process of resistance is normally confirmed by performance assessment of the bridge.

For resistance measurements in the range from 1 mΩ to 10 kΩ, an automated system based on the commercially available direct current comparator bridge was developed. The performance of the setup was thoroughly characterized to confirm, that the maintenance of resistance standards with relative uncertainty 1 part in 10^6 is achievable in the electrical laboratory of Metrosert Ltd (Central Office of Metrology in Estonia).

2 DESCRIPTION OF SYSTEM

The measurement system (Fig. 1) consists of direct current comparator bridge from Measurement International (MI) type 6010B, 100 A range extender MI 6011B, DC power supply MI 6100A and four terminal matrix scanner MI 4210A. The standard resistors are immersed into the oil thermostat from Hart Scientific (HS) type 7108.

The main component of the automated system is the direct current comparator (DCC) bridge [2]. Along with the DC power supply and 100 A range extender, the measurements of resistors in the range from 0.1 mΩ to 10 kΩ with measurement currents from 10 μA to 100 A can be carried out. The same DCC bridge was previously used in Estonian National Temperature Laboratory, but without 100 A range extender and DC current source [3].

The stability of temperature in the oil bath is within (23.00 ± 0.01) °C. Sixteen fast response platinum resistance thermometers (PRT) HS type 1522-16 are inserted into resistors to monitor the temperature. Temperature values of the thermometers are recorded by using the thermometer readout type HS 1529 and two selector switches from Isotech.

Two subsystems, one for resistance and another for temperature measurements operate under control of a personal computer. The supporting software was developed at Metrosert Ltd. The devices for resistance measurements and oil thermostat are connected through the GPIB (General Purpose Interface Bus). In temperature measurements the RS-232 serial interface is used for the purpose of flexibility in other applications, where the GPIB is not present.

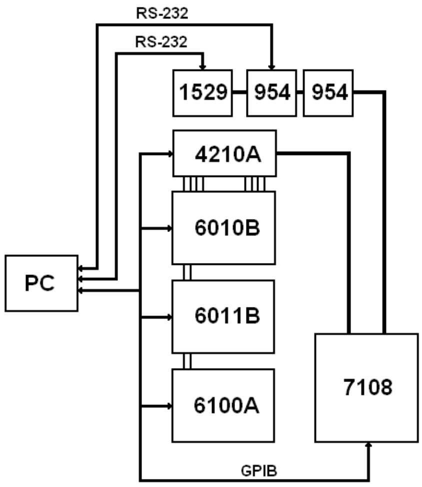

Figure 1. The automated measurement system for standard resistors.

3 MEASUREMENTS

The automated measurements are performed regularly to investigate the stability of individual standard resistors. As an example, the measurement results for 10 Ω standard resistor are shown in Figure 2. The same setup allows to determine the temperature coefficients of the resistors which are necessary to take into account the temperature effects on resistance values at the accuracy level of 1 part in 10^7.

To confirm the performance of our DCC bridge we applied methods of complements checks and comparison with calibrated standard resistors [4, 5]. The results of complements checks for 1:1 ratios with nominal values from 1 Ω to 10 kΩ are shown in Table I. Two measurements are conducted by exchanging resistors R_X and R_S. The given measurement results indicate that 1:1 resistance ratios of our bridge are within ±1 part in 10^7, which complies with accuracy specification of the bridge.

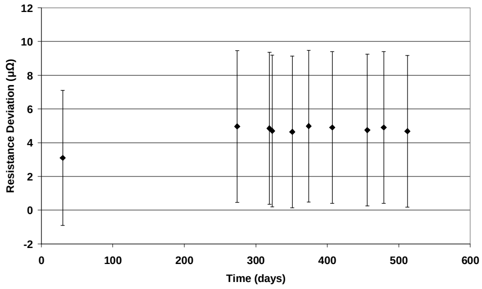

Figure 2. Stability of the 10 Ω standard resistor.

Table I

Complements checks results for DCC bridge

Nominal value, Ω	Current, mA	Relative difference in ratio, $\cdot 10^{-6}$	Standard deviation, $\cdot 10^{-6}$
1	100	-0.012	0.0007
10	30	-0.002	0.0003
100	5	-0.015	0.0011
1 k	3	-0.024	0.0020
10 k	0.3	-0.067	0.0125

Table II

Results of comparisons with calibrated resistors

Ratio, $R_X : R_S$	Cal. Date, R_S	Relative difference in ratio, $\cdot 10^{-6}$	Relative expanded uncertainty, $\cdot 10^{-6}$
1 Ω : 1 mΩ	2005	-0.62	20.0
1 Ω : 10 mΩ	2004	0.57	2.00
1 Ω : 100 mΩ	2004	0.23	0.91
1 kΩ -> 1 Ω	2005	0.25	0.61
1 kΩ -> 10 Ω	2004	-0.17	0.61
1 kΩ : 100 Ω	2004	-0.11	0.45
10 kΩ : 1 kΩ	2005	0.25	0.58

To check 10:1 resistance ratios, the calibrated reference resistors are compared to the values obtained with the resistance bridge. The results are presented in Table II. The symbol "->" denotes, that the measurements were performed in decade steps. Three resistors have been calibrated abroad in 2005: 10 kΩ, 1 kΩ and 1 Ω with relative uncertainty 4 parts in 10^7. One resistor with nominal value of 1 mΩ was calibrated at the relative uncertainty of 20 parts in 10^6. For other resistors, the differences in ratio and the related uncertainties were found from calibration history and measurement results.

The accuracy specification of the bridge for the decade ratios in the range from 1 Ω to 10 kΩ is 1 part in 10^7, which is smaller than the calibration uncertainties of the resistors. For that reason, it is difficult to estimate the conformance of the measurement results with bridge specifications. However, the differences in ratio are less than 3 parts in 10^7 being smaller as compared to the calibration uncertainties. The differences larger than specifications of the bridge can be due to the calibration uncertainty and stability of the resistors and/or inaccuracy of the bridge.

For the higher degree of conformance with the bridge specification, either smaller uncertainty of the reference resistors or Hamon-type device should be used.

3 CONCLUSIONS

The automated setup for measurements of standard resistors was developed. The new system is used in high-accuracy resistance measurements and calibration of customers' standard resistors demanding low uncertainties.

The characterization of the bridge was carried out to verify, that the uncertainties of resistance scaling using our system are less than (1…5) parts in 10^6 in the range from 1 mΩ to 10 kΩ.

ACKNOWLEDGMENTS

The authors would like to thank prof. T. Rang, who is the supervisor of the author's[1] PhD studies.

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Publication IV

SiC Schottky Diode for Use in Power Convertors

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Abstract. **The specification characteristics of power electronic applications can be improved by use of recent high-speed power devices. The Schottky structure has been developed for direct type converter circuits. The description of real layout and testing methodology of an experimental sample of 4H-SiC Schottky barrier diode manufactured by diffusion welding. Presented results of timing for reverse recovery time are described according to the sample of the direct current regulator.**

I. INTRODUCTION

The sample power silicon-carbide diodes were fabricated on CVD grown low-doped 4H-SiC epitaxial layer without edge termination. Double layer Ni-Au and triple layer Ti-Ni-Au sputter metallization were used for Schottky contacts fabrication. Non-rectifying bottom contacts were provided by Ni-Au metallization. Diodes were tested on-wafer and delivered for dicing, and packaging. To decrease the parasitic spreading resistance the thickness of initial sputter metallization was increased by diffusion welded 30 µm metal foil. Such way combined thick and plane metal layers makes it possible to perform the clamp mode package in the cases usually used in power electronics. This scheme of packaging ensures current takeoff from the whole contact area and increases operating temperature up to 600°C. The forward current-voltage characteristics up to 75 A measured for packaged diodes give 250 A/cm^2 (70A) at 1.9 V forward voltage [1]. However, the diode's behavior can be more interesting while in a switching mode. Insufficient continuous backward off-state voltage U_D and essential continuous forward voltage U_F make the trial and the measurement of the operating speed difficult using classical analysis, as described in [2]. Nevertheless, it is possible to estimate the dynamic characteristics, namely the speed of switching on, if to force the diode to work as a part of some real power electronics application. The step-down switching regulator particularly matches the mentioned application. The operating mode of the regulator was chosen in accordance to the parameters of the diode.

II. DESCRIPTION OF APPLIANCE

The simple switching regulator circuit is shown in Fig. 1. The application is supplied with power source V_{IN} = +45V. Switch Q based on MOSFET works for the load consisting of resistive and inductive parts R_L and L_L. The value of resistive part of the load is exactly selected to provide the value of diode's current I_{FM} right before the switching off with I_{FM} = 30A. The control signals for transistor Q come from impulse generator G. The diode under the test D is connected parallel to the load and plays its part as free wheeling diode. Into the circuit of D (series D) is attached a measuring shunt R_{SH}, which is used to gather the information about current flowing through the diode. In order to decrease strongly the self-inductance of the shunt, it is implemented as a bubble construction [3].

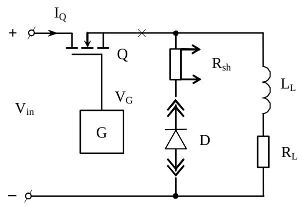

Fig. 1. Switching regulator circuit.

The oscilloscope is used to measure the timing waveforms for the diode's current. Corresponding graphs reflecting the work of the appliance are shown in Fig. 2.

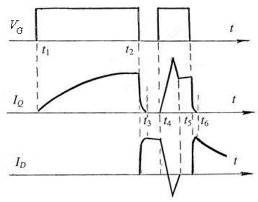

Fig. 2. Several processes of test circuit.

Transistor Q gets couple of control impulses following one another (t_1-t_2 and t_4-t_6). The inductance value L_L, the length of impulse (t_1=t_2) and delay timeout are conditioned in such a way to achieve the diode's current I_D before switching off phase would be as close as possible to the value of load's current $I_{L\ MAX}$. To reduce the heating of a diode under the test all impulses follow the low frequency of 120…150 Hz.

The work is conducted by following way. At the moment t_1 the transistor Q activates and some energy starts accumulating in the inductance L_L. For the moment t_2 diode's current is completely set up. At the moment t_3 transistor Q is switching off and the load current goes to the diode D. At the moment t_4 transistor Q is switched on again and the diode D is about to be deactivated. This is accompanied by surge of backward current I_R.

At the moment t_5 the switching off phase is over and the load current flows again through the transistor. The interval between t_4 and t_6 should be certainly longer than the time of diode's deactivation (the switching off phase). At the moment t_6 Q is deactivating and the load current goes back to the diode and while the inductance L_L is discharging it is dropped to zero.

The speed of transistor Q current's growth at the activating phase at the moment t_4 and correspondingly speed of drop of diode's current at the deactivating phase are controlled by additional linear throttle with a variable inductance, which is linked up with source of the transistor Q (point X). Throttle is supplied with the charge tapping circuit, which was accumulated while the transistor Q was switched on. Full discharge of energy of additional throttle takes place in a time of $t_3 - t_4$. Additional throttle reduces the time t_{ON} required to activate the transistor, and therefore increases the speed of growth for drain's current.

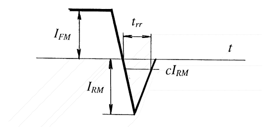

Fig. 3. Classical definition of parameters.

By the rule reverse recovery time t_{rr} is determined according to the graphs in Fig. 4 according to the recommendation of [4] where degree C is usually assumed as C=0,25. Experimental regulator layout research however has shown significant differences in deactivation proceeding between real applications and shown in Fig. 5. In addition to its already mentioned static characteristics diode D also has comparatively big its own capacity. This and also high speed of current change lead to the condition when the whole process of the diode's deactivation looks like having an oscillatory nature. Fig. 4 shows approximate deactivation proceeding. In order to estimate deactivation capabilities in such conditions it is suggested to step back from generally used way of evaluation the t_{rr} [4]. If to admit the time shown in Fig. 3 for the time t'_{rr} then standard deactivation characteristics can be produced for the diode under the test. Measurements obtained from the results based on experimental layout and diode under the test are shown in Fig. 5 and Fig. 6.

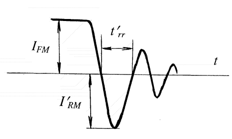

Fig. 4. Assumed definition of parameters.

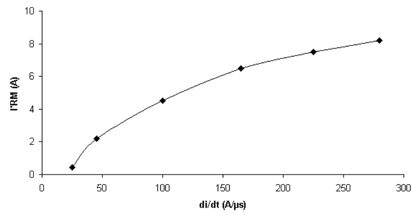

Fig. 5. Recovery current I'_{RM} versus current fall rate.

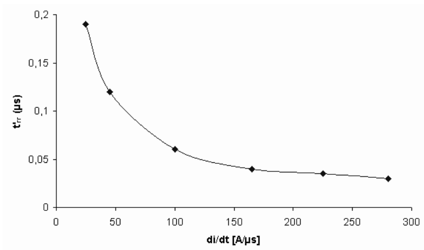

Fig. 6. Reverse recovery time t'_{RR} versus current fall rate.

III. Conclusions

The 4H-SiC Schottky structure has been developed for direct type converter circuits. The timing measurements made for reverse recovery show that a sample diode produced by the diffusion welding posses sufficient operating speed. In case the trend is worked out to improve the static operation factors the diode can perfectly be used in power electronic applications.

IV. Acknowledgement

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Pinge mõõtühiku riigietaloni arendamine Zener-tüüpi etalonpingeallikate baasil

Lühikokkuvõte

Väitekirjas esitatava töö eesmärgiks on pinge mõõtühiku riigietaloni arendamine. Voldi esitamiseks kasutasime kuut Zener-tüüpi etalonpingeallikat automaatses süsteemis tugiväärtusel 10 V.

Nelja samasugust pingeallikat kasutame ülekandeetalonina voldi seostamiseks Josephsoni efektil põhineva etaloniga mõõtevahendite transpordist ning sellega kaasnevate keskkonnatingimuste järsust muutusest tulenevate mõjude vähendamiseks riigietaloni mõõtevõimele.

Riigietaloni mõõtevõime säilitamisel jälgitakse kuue kalibreeritud etalonpingeallika väljundpingeid võrreldes üksikute Zenerite väljundeid keskmise tugiväärtusega, mida arvestatakse määramatuse panusena väliskalibreerimiste vahelisel perioodil. Mitme etalonpingeallika kasutamine on vajalik ümbritseva keskkonna parameetrite mõju vähendamiseks kogumi keskmisele väärtusele.

Pingeühiku säilitamisel ja edastamisel saavutatava mõõtemääramatuse hindamiseks uuriti pingeallikate mitmeid metroloogilisi omadusi: tundlikkust temperatuuri, õhurõhu ja õhuniiskuse muutustele, ajalist triivi jms. Pingeühiku esitamist kirjeldavat matemaatilist mudelit kontrolliti viimase väliskalibreerimise suhtes. Väliskalibreerimiste vahelises intervallis kasutame projektsiooni kirjeldamisel laboris valideeritud lineaarset regressioonikõverat. Mõõtetulemuste analüüs näitas, et meie poolt arendatud meetodiga saavutatav laiendmääramatus Zener-tüüpi pingeallikatega kasutamisel on väiksem kui 1 µV/V.

Elektriliste suuruste riigietaloni labori (AS Metrosert) uue etalonibaasiga realiseeritav mõõtevõime on kinnitust leidnud rahvusvahelises võrdlusmõõtmises Leedu alalispinge ja elektrilise takistuse riigietaloni laboriga.

Pinge skaala realiseerimiseks piirkonnas 100 mV kuni 1 kV kasutasime digitaalsel täppismultimeetril ning multifunktsionaalsel kalibraatoril rajanevat mõõtesüsteemi. Täppismultimeetril põhinev pingejagaja on automaatne ja kasutamises lihtne lahendus pinge skaala realiseerimisel. Multimeetri kalibreerisime isetehtud Hamon-tüüpi pingejagajate abil. Väljatöötatud meetodi laiendmääramatus piirkonnas 100 mV kuni 1 kV on väiksem kui 3 µV/V.

Elektriliste suuruste riigietalon alalispinge grupietaloni tugiväärtusel 10 V ja alalispinge väärtustel 100 mV kuni 1000 V kinnitati majandus- ja kommunikatsiooniministri määrusega aastal 2006.

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Metroloogia, alalispinge ja takistuse etalonid, AC-DC ülekanne, aja ning sageduse metroloogia, elektlise juhtivuse mõõtmised, mõõtmiste automatiseerimine.

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