

## Simple and reliable system for accurate maintenance of voltage standards

Alan Šala, Damir Ilić, Ivan Leniček

*Department of Fundamentals of Electrical Engineering and Measurements  
Faculty of Electrical Engineering and Computing (FER), University of Zagreb  
Unska 3, HR-10000 Zagreb, Croatia  
Phone: +385-1-6129-753, Fax: +385-1-6129-616  
E-mail: [alan.sala@fer.hr](mailto:alan.sala@fer.hr), [damir.ilic@fer.hr](mailto:damir.ilic@fer.hr), [ivan.lenicek@fer.hr](mailto:ivan.lenicek@fer.hr)*

**Abstract-** A new automatic system is described whereby precise, simple and reliable intercomparison of electronic voltage standards is enabled by using a self-developed 16 channel low-thermal switch and digital nanovoltmeter, controlled by the computer. It enables faster and easier comparison, as well as optimisation of the whole procedure. The control software was developed using a LabVIEW, and the obtained parameters are pointed out.

### I. Introduction

At the Primary Electromagnetic Laboratory, which is a part of the Faculty of Electrical Engineering and Computing of the University of Zagreb, the maintenance of the unit of volt is one of its important tasks, due to its role as a holder of national standards of voltage. Although the best possible accuracy (or maintenance of the highest level) is attainable by means of Josephson voltage standards (JVS) [1-3], due to its costs and limited availability it is not the most practical, specially when the utmost level of accuracy is not essential. There are many laboratories that still use as reference of dc voltage the electronic (Zener) voltage standards. To ensure frequently calibrations of these DC reference standards (DCRS), the measurement procedure should be simple, highly reliable, ready for everyday use and preferably low cost. Such system is based on the comparison of  $n$  number of DCRS with unknown voltage on their outputs (usually 1 V, 1,018 V and 10 V) to the reference one, usually of the same type (Fluke 732A and 732B, Datron 4910, or similar), but with known values of maintained voltages [4]. Since for dc measurement very often the crucial influencing quantity is unwanted thermal EMF (TEMF), for measurement of voltage differences at a level of microvolts the crucial attention has to be paid to avoid any unstable and changeable TEMFs [5]. Therefore, in the construction of the mentioned multi-channel low-thermal switch and digital nanovoltmeter this was the very important task.

### II. Elements of the system

#### A. Method of measurement

The well known, simplest and the most precise method to compare two DCRS is when they are connected in series opposition [6], and the small voltage difference between them is measured by sensitive voltmeter (microvoltmeter or nanovoltmeter), as it is shown in Fig. 1. The voltages of sources A and B are marked as  $U_A$  and  $U_B$ , and their internal resistances as  $R_{inA}$  and  $R_{inB}$ , respectively; the nanovoltmeter is marked with nV, while different TEMFs in the circuit are marked with  $\varepsilon$ . From the scheme in Fig. 1a follows:

$$\varepsilon_{nV} + \varepsilon_B - U_B + \varepsilon'_B + \varepsilon'_A + U_A + \varepsilon_A - \delta_{AB} = 0 ; \quad (1)$$

or we can write that

$$U_A - U_B = \delta_{AB} + \sum \varepsilon_1 - \varepsilon_{nV1} ; \quad (2)$$

where  $\delta_{AB}$  represents the voltage difference measured by nanovoltmeter;  $\sum \varepsilon_1$  is the sum of residual TEMFs at the connection terminals of DCRS, and  $\varepsilon_{nV1}$  is residual TEMF of nanovoltmeter. The  $R_{inA}$  and  $R_{inB}$  are approx. 1 m $\Omega$ , and for this analysis their influences can be neglected due to the high

impedance of nanovoltmeter ( $>10 \text{ G}\Omega$ ), and low circuit currents ( $\sim 10 \text{ pA}$ ). Therefore, the errors due to the voltage drop on internal resistances of DCRS can be neglected.

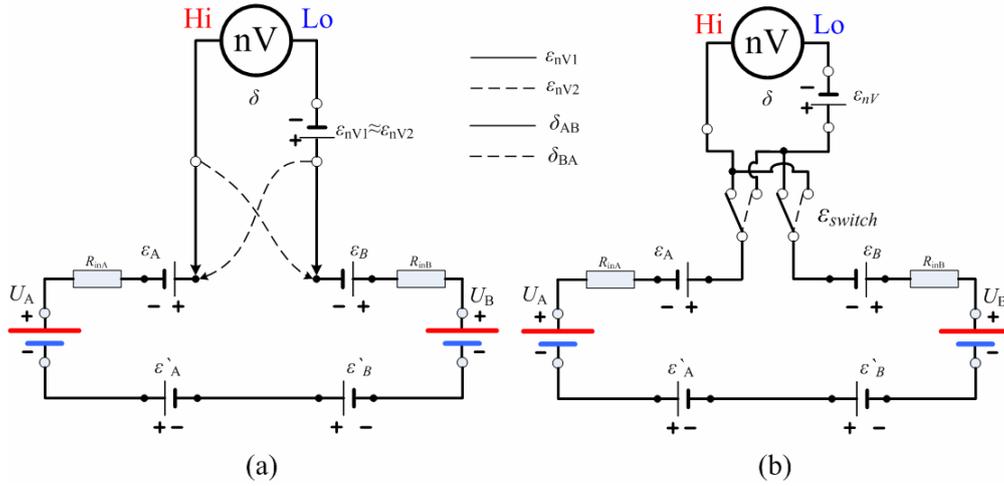


Fig. 1. Principle circuits for intercomparison of DCRS

When the Hi and Lo leads of nanovoltmeter are interchanged (Fig 1a, dashed line), the following equation is valid:

$$U_B - U_A = \delta_{BA} + \sum \varepsilon_2 - \varepsilon_{nV2}. \quad (3)$$

By subtracting (2) and (3), and taking into account that  $\sum \varepsilon_1 \approx \sum \varepsilon_2$  and  $\varepsilon_{nV1} \approx \varepsilon_{nV2}$ , the residual TEMFs tend to disappear and the final value of voltage difference between the reference and the calibrated standard is:

$$U_A - U_B = \frac{1}{2}(\delta_{AB} - \delta_{BA}). \quad (4)$$

To achieve this (i.e. for better matching between  $\varepsilon'_A$  and  $\varepsilon_A$ ,  $\varepsilon_B$  and  $\varepsilon'_B$ , and  $\varepsilon_{nV1}$  and  $\varepsilon_{nV2}$ ), the use of symmetrical two-line coaxial cables from voltage standard to the voltage comparator would be recommended. Furthermore, to obtain adequate cancellation of TEMFs, manual reversing of leads is not recommended, because such procedure is time consuming and can introduce larger nonstationary TEMFs.

## B. Construction of multi-channel low-thermal voltage switch

Keeping in mind mentioned above, the main task was construction of highly precise automated measuring system. To meet the performance criteria, a list of requirements [5] was established for the multi-channel low-thermal switch:

1. Random selection of DCRS, only two at a time, with either a normal or in inverted polarity.
2. Modular construction realized in such a manner that any accidentally wrong interconnection between two DCRS would be impossible.
3. Simplified connection within the system using only two line guardable coaxial cables.
4. Uncompensated thermoelectric voltages  $\varepsilon_{switch}$  (Fig. 1b), must be less than 50 nV.
5. Leakage resistance must be greater than  $10 \text{ G}\Omega$ .
6. Expected life must be greater than 10 years.

After evaluation of available switching methods and hardware [7, 8], it was found out that the very convenient method that fulfils the majority of mentioned requirements would be self-developed solution of multi-channel low-thermal switch presented in Fig. 2. The electromechanic relays have advantage considering their actuating power level and number of expected actuations during life time (up to  $10^7$  actuations, which might correspond to 100 years of use in such application). To overcome their major fault, which is the level of possible TEMFs, the relays must be actuated in special manner. Therefore, the developed switch named KomEta (from commutator of etalons) consists of magnetically latching relays powered only for 15 ms by the specially designed microprocessor digital input/output

board. Fig. 2 simply illustrates the main principle of actuating a bistable relays. The bistable latching relays are actuated prior to transition from “0” to “1” or vice versa coming from MC14515, 4-16 line decoder controlled by 8-bit MCU (Microcontroller PIC 18F452, Microchip). The impulse from decoder goes through the high-pass filter, formed by externally added capacitor  $C$  and internal winding resistance  $R$  of bistable relay. The main advantages of such actuation of relays are extremely low power dissipation and simplicity, due to the reduced number of components. Current which flows through relay winding causes negligible induced TEMF, while the generation of TEMF is further suppressed by the holding all of connection leads at the approximately same temperature. All inserted relays (NAIS Matsushita, S-Relays, 2 coil latching,  $R_{cont} = 50 \text{ m}\Omega$ ,  $U_{thermo}$  at nominal coil voltage  $\approx 1 \text{ }\mu\text{V}$ ,  $P = 200 \text{ mW}$ ) where carefully chosen to have the lowest possible TEMFs. They must be thermoelectrically matched to each other with less than  $250 \text{ nV/K}$ . All this was connected to the controlling computer via a serial connection isolated by optocouplers, and by supplying from the 12 V lead-acid battery makes a floating circuit.

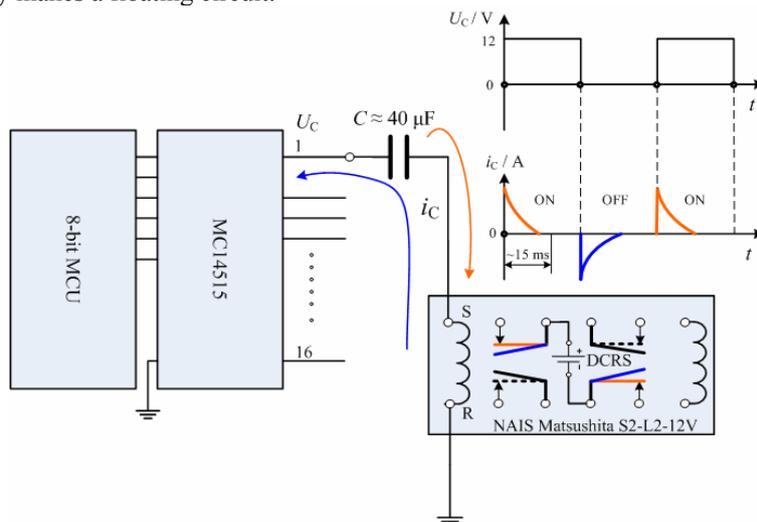


Fig. 2. Principle block diagram of relay actuator

The relays are wired in such a way that the difference voltage (between Line A and Line B) shown in Fig. 3 of every two voltage standards can be routed to a digital nanovoltmeter in forward or reversed polarity. At the decoder output it is impossible to have two outputs activated at the same time so wrong interconnections between DCRS would be almost impossible. Further protection is obtained through the series line that contains a line from serially connected free contacts at all relays on the one side. This will complete the series protection circuit only if all the relays on the line are in the open position. Thus, no relay on the A line can be closed if any other relay on the A line is already closed.

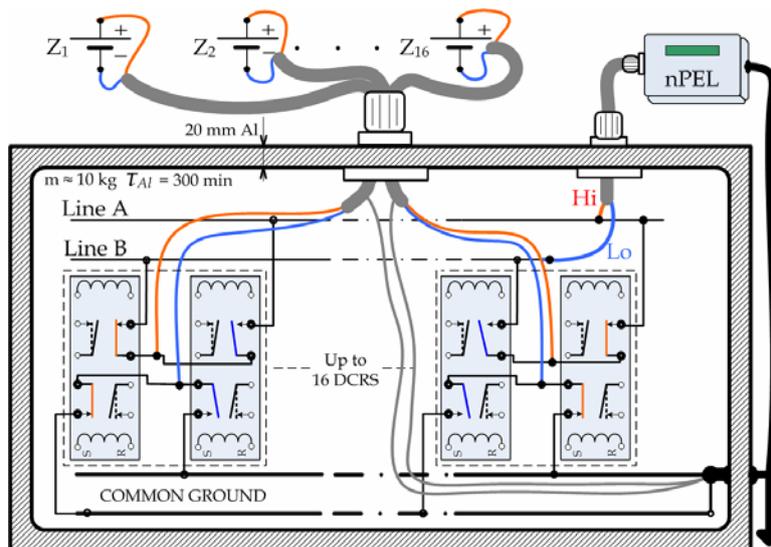


Fig. 3. The interconnections inside the multi-channel low-thermal switch KomEta

The switch features high leakage resistance and initially measurements gave resistance higher than 100 G $\Omega$ . Since all inputs of the switch carry about the same voltage, errors due to the leakage can be neglected. The TEMFs of the switch have been determined by applying 16 shorts to the inputs and measuring all possible difference voltages were found to be lower than  $\pm 50$  nV ( $s_{\max} = 4$  nV). Complete measurements have determined tendency of increased thermal voltages when the internal temperature of low-thermal switch is no more similar to ambient temperature  $T_{\text{AMB}}$ . This was because the relays at all channels were unusually more frequently actuated. The conclusion is that total TEMFs and their instability depend to some extent on the external temperature surrounding the switch. This is due to the uncompensated TEMFs in line A and line B inside low-thermal switch. For the range of temperatures usually encountered in the laboratory, voltages change as a linear function of temperature. At day 6 (Fig. 4.) the internal temperature of switch was intentionally increased at unusually high temperature point of  $T \approx 30^\circ\text{C}$ . Then temperature coefficients of input channels are determined to be approximately 3 nV /  $^\circ\text{C}$ . Value of TEMFs at day 10 has quickly returned at his present value when switch is operated in normal conditions.

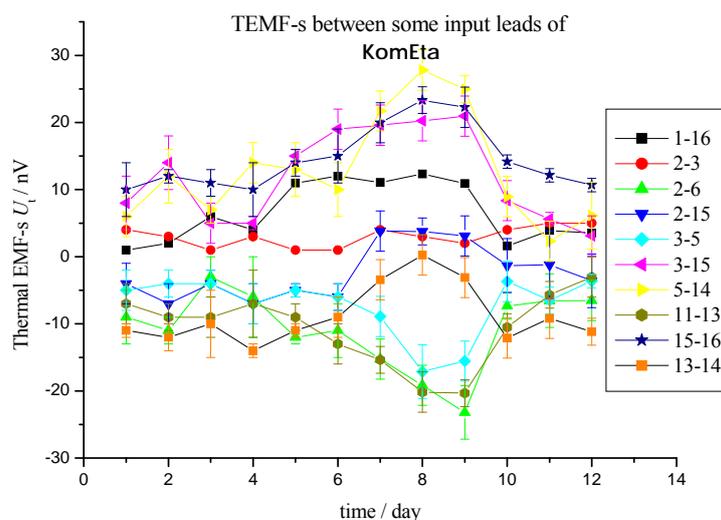


Fig. 4. Variation of TEMFs of some input channels of switch with short circuit at input. The voltages are clearly following an increase and decrease of internal temperature at day 6 and 10 respectively.

All DCRS leads and latching relays are housed in a heavy machined 20 mm thick aluminium isothermal box to maintain a uniform temperature at each of the relay contacts. Furthermore, all leads (made only from copper) are soldered to relays directly using Cd/Sn solder to prevent the thermal and noise voltages caused by connectors.

### C. Digital nanovoltmeter

The voltage differences are measured using the self-constructed digital nanovoltmeter  $\eta\text{PEL}$  operated in its 10 mV range. This nanovoltmeter was calibrated using the output of Josephson voltage standard. The zero stability was measured with short plugs applied to its input, and standard deviations between 8 nV and 10 nV were measured for a measurement period up to 5 minutes. The minimum achievable Allan variance and the time necessary to attain it [9] is valuable information for such sensitive instrument; it was measured to be 0,3 nV for a period of 1000 s. The tested linearity on 10 mV range was better than 1  $\mu\text{V/V}$ . All measurements should be performed at laboratory temperature conditions ( $\vartheta = 23^\circ\text{C} \pm 2^\circ\text{C}$ ) and for this type of nanovoltmeter no specially temperature-stabilized enclosure have to be used.

Nanovoltmeters that have been tested in above application for comparisons of zener voltage standards yield approximately same results (deviation was much smaller than overall measurement uncertainty) but only after correct sampling time  $\tau$  was chosen. Summary of all compared nanovoltmeters and minimum achievable Allan variance can be seen in Fig. 5 (short-circuited inputs) and Fig. 6. (input resistance is 1 k $\Omega$ ). The Allan variance provides a way of characterising measurement processes in the time domain [10]. It is related to the power spectral density and can reveal correlations in time series. For a given nanovoltmeter the characteristic time bandwidth  $B$  has been deduced over which the

measurement noise is white and Allan variance decreases. The key issue in measurement setup is to attain that the standard deviation of the measured mean is just the standard deviation divided by the square root of the number of measurements. Only for white noise time series the Allan deviation is equal to the standard deviation of the mean which means that for example digital nanovoltmeter  $\eta^{PEL}$  in Fig. 5 has white noise process up to 1000 s measurement bandwidth. For sampling times below 1000 s, the Allan deviation decreases nearly as  $\tau^{-1/2}$ , indicating that in this range the noise is white. For Agilent 34420A this time  $\tau$  is much smaller and range from 30s to 70s. With more measurements (larger  $\tau$ ) Allan deviation begins to increase and predominant action of flicker ( $1/f$ ) noise excludes the use of formula in which  $var(\bar{x}) \neq var(x) / n$  and standard deviation of the result of measurement become equal (or even greater) to standard deviation of result of one measurement. Further results showed that the most important factor which limit precision of digital and analog nanovoltmeters are the stability of ambient temperature (what is already investigated in [9]) and source resistance.

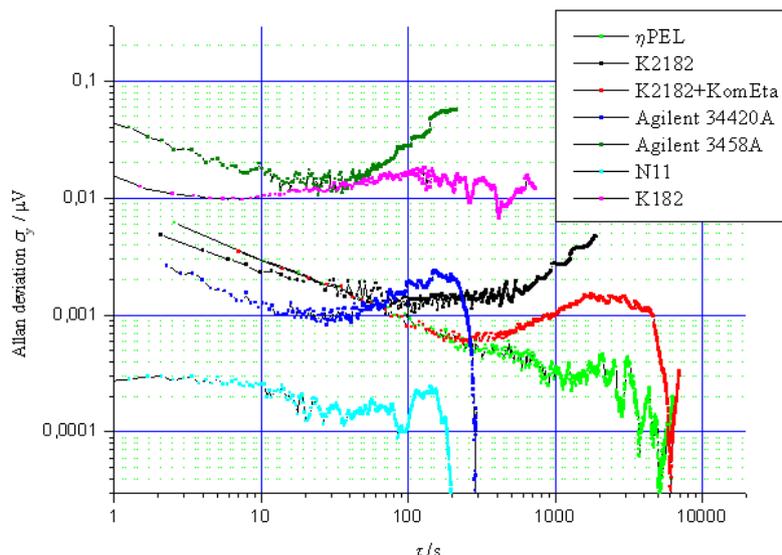


Fig. 5. Allan deviation versus sampling time  $\tau$  for some commercial nanovoltmeters with short-circuited inputs (Keithley 182, Keithley 2182, EM N11...)

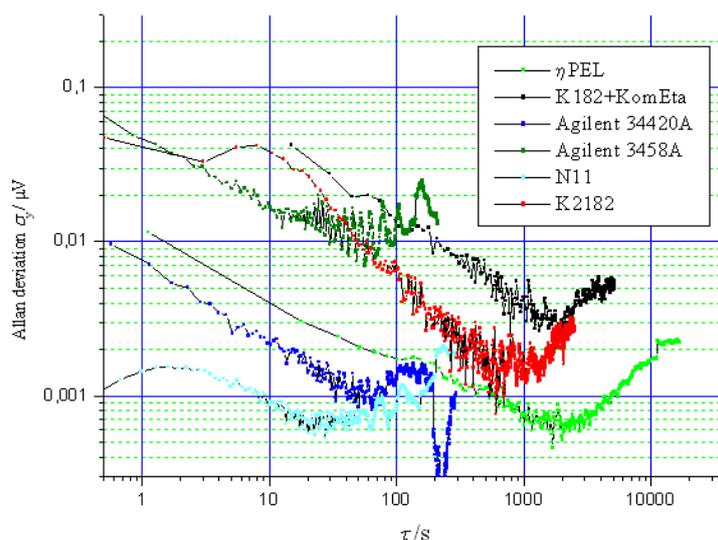


Fig. 6. Allan deviation versus sampling time  $\tau$  for some commercial nanovoltmeters when the source resistance of 1 k $\Omega$  is inserted into the circuit

## D. Software

The application software is designed in the graphical language LabVIEW. The whole measurement process is performed automatically under GPIB and RS232 control and has two parts: in the first one, the main VI program selects the combination of electronic voltage standards to be compared, and in the second one all differences of the output voltages of DCRS are measured and stored. Each difference is measured over about two minutes in both forward and reversed polarity and the mean value of voltage difference  $U_A - U_B$  is taken in order to cancel the voltage offset of the digital nanovoltmeter and stationary TEMFs. All results are stored in files on the computer for later evaluation.

The calibration of a voltage standard is finished when at least ten measurements for each voltage level have been performed. Then the results are copied into a spreadsheet program where the final evaluation is carried out. From the raw data, the mean value and standard deviation are determined and a plot of the voltages versus time is generated. The numbers needed for the calibration certificate are computed and stored in a data file readable by the word processing program used to print the certificates.

## III. Conclusion

Direct calibrations of electronic voltage standards via a Josephson voltage standard are possible with uncertainties of some  $10^{-8}$ , but when the short-term random fluctuations of the output voltages are taken into account, the accuracy of the dissemination of the volt using electronic voltage standards is limited to values in the order of  $10^{-7}$ . Described measurement system, with the developed multi-channel low-thermal switch and digital nanovoltmeter is sufficient and convenient for such purpose.

## References

- [1] R. Pöpel, "The Josephson effect and voltage standards", *Metrologia*, vol. 29, pp. 153-174, 1992.
- [2] J. Kohlmann, R. Behr, T. Funck, "Josephson voltage standards", *Meas. Sci. Technol.*, vol. 14, no. 8, pp. 1216-1228, August 2003.
- [3] J. P. Lo-Hive, D. Reymann, G. Genevès, "Using 10V Josephson voltage standards to estimate the uncertainty of Zener voltage references as travelling standards", in *Conference Digest CPEM'98*, pp. 349-350, Washington D.C., July 6-10, 1998.
- [4] D. Vujević, D. Ilić, "Stability of Some DC Reference Standards", *IEEE Trans. Instrum. Meas.*, vol. IM-48, no. 6, pp. 1081-1084, December 1999.
- [5] D. W. Braudway, R. E. Kleimann, "A High-Resolution Prototype System for Automatic Measurement of Standard Cell Voltage", *IEEE Trans. Instrum. Meas.*, vol. IM-23, no. 4, pp. 282-289, February 1974.
- [6] A. F. Dunn, "Maintenance of Laboratory Unit of Voltage", *IEEE Trans. Meas.*, vol. IM-20, no. 1, pp. 2-10, February 1971.
- [7] Dataproof Low Thermal Scanner, <http://www.dataproof.com/>
- [8] T. Funck, E. Pesel and P. Warnecke, "Calibration of electronic voltage standards at the PTB", *PTB Berichte*, Physikalisch Technische Bundesanstalt, Braunschweig, Germany.
- [9] T. J. Witt, "Using the Allan Variance and Power Spectral Density to Characterize DC Nanovoltmeters", *IEEE Trans. Instrum. Meas.*, vol. IM-50, no. 2, pp. 445-448, 2001.
- [10] T. J. Witt, D. Reymann, "Using power spectra and Allan variances to characterise the noise of Zener-diode voltage standards", *IEE Proc. - Sci. Meas. Technol.*, Vol. 147., No. 4., July 2000.