Determination of High-Resolution Digital Voltmeter Input Parameters

Ivan Leniček, Damir Ilić, and Roman Malarić

***Abstract*—High-resolution digital voltmeters (DVMs) can be widely used when precise measurements are needed, but input circuitry can contribute to the results of measurement. Therefore, to make uncertainty of measurement as small as possible for a particular measurement, it is necessary to characterize its input parameters. In this paper, the methods for the determination of input resistance, input capacitance, and input offset current of widely used precise DVMs HP 3458A with 8 1/2-digit resolution are presented. The method with voltage source and high-ohmic divider resistor has been developed for the determination of both input offset current I_S and input resistance R_V. The second method with the source of the linear voltage ramp and the picoampermeter is primarily used for the determination of input capacitance C_V. It was shown that the input offset current of voltmeters is in the range of picoamperes with relative instability of approximately $\pm$0.1, the input resistance is in the range of teraohms with the same relative instability of $\pm$0.1, and the input capacitance was measured to be in the range of a few hundred picofarads with uncertainty of a few picofarads.**

***Index Terms*—Digital voltmeter (DVM), input capacitance, input offset current, input resistance.**

I. Introduction

PRECISION digital voltmeters (DVMs) are currently used for a number of highly accurate methods of measurement, including those with Quantum Hall Resistance Standards [1]–[4]. In such measurements, there are many sources that contribute to measurement errors, such as environmental conditions (changes in temperature, RF signals, and electromagnetic fields), but it is also important to precisely know the values of the voltmeter's input parameters [5]. It is also evident in the precise determination of resistance by voltage ratio measurements, where the voltmeter input impedance is shunting the resistances being measured [6], [7]. Here, it should also be emphasized that DVMs can be used for low-frequency ac voltage (and voltage ratio) measurement when it is set on the DCV range, where its input capacitance influenced the measurement results [8]. The DVM input circuitry model on the DCV range, as shown in Fig. 1, contains the parallel combination of input resistance R_V and input capacitance C_V. The DVM also injects small current I_S to the device that is connected to its input terminals. If R_V, C_V, and I_S can be precisely determined, their influences on the measurement can be calculated [9].

In Section II, the aforementioned methods and experimental results for the determination of input offset current I_S, input resistance R_V, and input capacitance C_V are shown in Sections II-A–C, respectively.

Manuscript received July 6, 2007; revised March 21, 2008.

The authors are with the Faculty of Electrical Engineering and Computing, University of Zagreb, 10000 Zagreb, Croatia (e-mail: ivan.lenicek@fer.hr; damir.ilic@fer.hr; roman.malaric@fer.hr).

Digital Object Identifier 10.1109/TIM.2008.923786

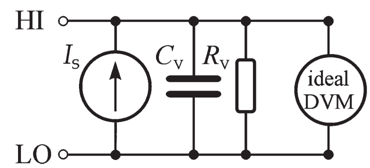

Fig. 1. Voltmeter input circuit parameters.

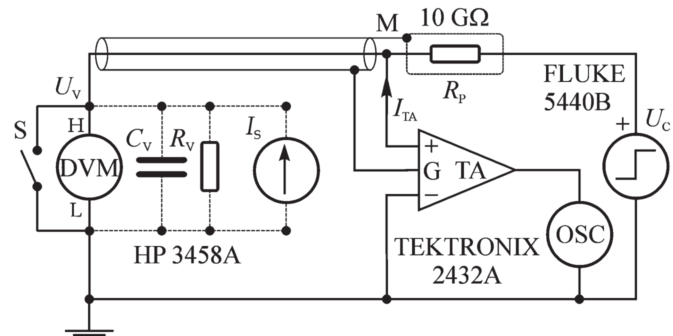

Fig. 2. Measurement circuit for the determination of the DVM's input parameters.

II. Determination of the DVM's Input Parameters

The measurement method for input resistance presented in this paper is done according to the brief explanation in [1] but with some modifications to achieve better accuracy and repeatability of measurements. The DVM selected for this paper is the HP 3458A, which is used in numerous high-precision measurements, but the presented methods for the determination of the input parameters of a voltmeter can be applied to any DVM. The scheme of the measurement circuit is shown in Fig. 2. DC-voltage calibrator FLUKE 5440B has been used as a very stable voltage source (with a long-term drift of less than 10 μV/V), which is connected to the DVM through a resistance R_P of 10 GΩ. The resistor R_P is of carbon-film type and placed in a thermally insulated metal enclosure that ensures low thermal drift during measurement, which is typically less than 10 $\mu\Omega/\Omega$ in 1 h. The enclosure of R_P is connected to the shield of the coaxial cable attached to the "high" input terminal of the DVM. The voltage drop across input resistance R_V is measured with the DVM itself, but it is also controlled with the electrometer transconductance amplifier TA having an input resistance of 10^{15} Ω and extremely low input offset current ($I_{TA} \cong 7$ fA). The active guard terminal G of the

TABLE I
RESULTS OF DVM INPUT OFFSET CURRENT MEASUREMENT WITHIN A 10-MIN PERIOD; p_{Is} IS THE RELATIVE INSTABILITY

	I_{S}	p_{Is}
DVM 1	–0.7 pA	±0.1
DVM 2	3.3 pA	±0.1
DVM 3	–0.18 pA	±0.2

TA equalizes the potential of the cable shield with the potential of measurement point M, thus eliminating the influence of the parasitic cable impedance and leakage resistance of series resistor R_P. The calibrator and the DVM are connected to the PC using an IEEE-488 interface bus and are both program-controlled within an automated measurement procedure.

A. Determination of Input Offset Current I_s

First, the measurement step of the method is the measurement of offset voltage U_0 of the TA when the DVM's input terminals are shorted with switch S. The next step begins by opening switch S and setting the output voltage of the calibrator to 0 V. In that state, in the approximation scheme, the calibrator could be replaced by a shortcut, and the only current flowing through the circuit is the sum of input offset currents I_S and I_{TA}, causing noticeable voltage drop U_S across the parallel connection of R_P and R_V. Since R_V is in the range of teraohms and $R_P = 10$ GΩ, the minor influences of R_V and I_{TA} can be neglected, and input offset current I_S could be calculated as

$$I_S = \frac{U_S - U_0}{R_p}. \tag{1}$$

It has experimentally been found that an R_P of 10 GΩ is optimal for attaining significant reading as a compromise between the DVM's sensitivity and the thermal (Johnson) noise of the resistor. The uncertainty of I_S measured with this method is less than 1%, if approximation $R_P \cong R_P \| R_V$, together with the assumption that I_S is at least two orders of magnitude greater than I_{TA}, is taken into account.

The instability of the DVM's input offset current has been determined as the relative experimental standard deviation for a series of 100 voltmeter readings being taken within 10 min and marked as p_{Is}. For that purpose, the thermal stability and good insulation properties of R_P are very important. When the calibrator is shorted out, the voltage drop across R_P due to input offset current I_S has been monitored on the oscilloscope connected at measurement point M through electrometer transconductance amplifier TA. It can be seen that I_S is pulse shaped with the period of the voltage sampling rate as a consequence of the DVM integrator's switching when the AZERO (autozeroing) function is enabled. To avoid disturbances owing to the pulsed charging of TA input circuitry parasitic capacitance, the measurement was performed with the AZERO function disabled. The predetermined input voltage noise of TA was found to be approximately 5 μV peak to peak (when the inputs of TA are shorted only with a 10-GΩ resistor), but since measured voltage U_S is in the range of millivolts, this inherent noise of the measurement setup does not affect the instability of the internal current to be determined. The results are given in Table I for each of the three DVMs of HP 3458A type (marked simply as DVM1, DVM2, and DVM3): It can be seen that the measured input offset currents (mean values of the taken readings) of voltmeter HP 3458A are of picoamperes, as stated by the manufacturer. The slow cyclic changes of these currents within 10 min of the measurement period have been monitored, producing instability p_{Is} in terms of relative standard deviation of approximately ± 0.1 (i.e., $\pm 10\%$). It has to be mentioned that the input offset current of DVM is not influenced by the changing of sampling rate (command NPLC), even if the AZERO function is enabled. The differences between three DVMs of the same type are not significant but interesting, including the change of sign.

B. Determination of Input Resistance R_V

For the determination of input resistance R_V, the calibrator output must be set on voltage U_C (for example, 10 V). After the stationary state has been achieved, voltage U_V has been measured by DVM. Since $R_P = 10$ GΩ was chosen to be large enough in comparison with teraohmic R_V, the voltage drop across R_P would be enough that the calculation of the input resistance can be done by the following relation:

$$R_V = R_P \cdot \frac{U_V - U_S + U_0}{U_C - U_V + U_S - U_0} \tag{2}$$

where U_S and U_0 are the voltages measured in the previous step within the determination of I_S according to (1). The uncertainty of R_V, as determined by (2), mostly depends on the uncertainty of measured difference $U_S - U_0$, which was previously estimated to be less than 1%.

Input resistance R_V and its relative instability p_{RV} were measured at five voltages on the same 10-V range of the DVM. The results are shown in Table II, where it is noticeable that R_V of teraohmic value is not affected by changing the measurement voltage when the DVM is measured in the same range. It should be emphasized that the statement of the manufacturer is that the input resistance is higher than 10 GΩ on that voltage range, whereas the measured values are much higher for all tested DVMs of this type, which are uniform and very close to the input resistance values (1.4 TΩ and 0.76 TΩ) presented in [1].

The same measurement sequence as for the determination of p_{IS} was used to find instability p_{RV}, which is also expressed here as the relative experimental standard deviation for a series of 100 voltmeter readings being taken within 10 min. Since voltage U_C and resistance R_P, in the circuit of formed voltage divider $R_P : R_V$, are stable within 10 μV/V and 10 $\mu\Omega/\Omega$, respectively, it is considered that the certain deviation of U_V

TABLE II
RESULTS OF DVM INPUT RESISTANCE MEASUREMENT

U_C	DVM1 $R_V(1 \pm p_{RV})$/TΩ	DVM2 $R_V(1 \pm p_{RV})$/TΩ	DVM3 $R_V(1 \pm p_{RV})$/TΩ
1 V	1.187•(1±0.15)	1.112•(1±0.11)	1.202•(1±0.12)
3 V	1.184•(1±0.11)	1.105•(1±0.11)	1.219•(1±0.07)
5 V	1.191•(1±0.09)	1.107•(1±0.04)	1.233•(1±0.11)
7 V	1.193•(1±0.08)	1.107•(1±0.06)	1.240•(1±0.08)
9 V	1.190•(1±0.08)	1.109•(1±0.08)	1.246•(1±0.05)

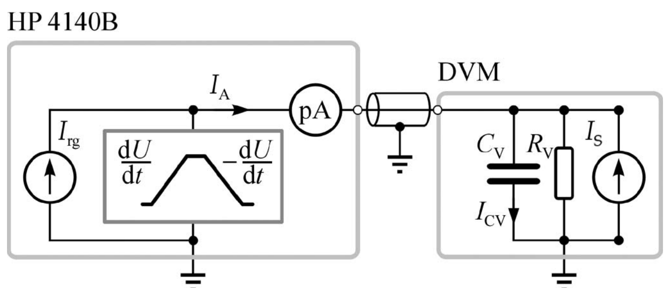

Fig. 3. Determination of the DVM input capacitance by means of the source of linear voltage ramp.

is caused by the instability of R_V. The obtained relative instabilities p_{RV} were no higher than ±0.15 and typically less than ±0.10.

C. Determination of Input Capacitance C_V

The measurement circuit in Fig. 2 can also be used for the determination of input capacitance C_V. A stepped voltage of 10 V was applied, and a faster sampling rate was used to scan the exponential growth of U_V. Using an appropriate exponential fitting function, time constant $R_P C_V$ has been determined, and then, the input capacitance is calculated. The values for the three DVMs are calculated to be 245, 263, and 256 pF, respectively. The estimated relative uncertainty of C_V, as a result of the fitting session, is less than ±0.5%.

However, input capacitance C_V can also be measured by means of the source of linear voltage ramp and precise low current meter. It is known that the linear voltage rise on the capacitor will produce constant capacitive current $I_C = C \cdot dU/dt$. If the ramp voltage is applied to the parallel combination of input resistance R_V and input capacitance C_V, the current that flows from the source will have two components: one with the constant value, which flows through the capacitor, and one with the linear rise, which flows through the resistor. If the voltage gradient is set to produce much higher capacitive current in comparison to the resistive current, the total current can be considered constant, and by measuring it, the input capacitance can be easily determined.

Fig. 3 shows the method of measurement of the DVM input capacitance by means of the source of linear voltage ramp and picoampermeter. The special voltage source HP 4140B is chosen as the generator of the voltage ramp. This device also includes the picoampermeter with a resolution of 10 fA, which can also directly show the value of the measured capacitance. The offset current I_S of the DVM and the current I_{rg} of the voltage source have to be taken into account. They contribute to measured current I_{CV}, but they can be regarded as constant and can be eliminated from the results of measurement by repeating the measurements with the changed polarity of the voltage gradient. Additionally, the picoampermeter reading is not influenced by parasitic current through the output impedance of the ramp generator, which has been checked by generating the voltage ramp with the output connector of the voltage source left open and producing a zero picoampermeter reading in that case.

Thus, only measured current I_{CV} changes direction, whereas currents I_{rg} and I_S remain unchanged (here, the current that flows through input resistance R_V is neglected, as mentioned before). Therefore, for positive voltage rise gradient dU/dt, the following relation is valid:

$$I_{A+} = I_{\text{rg}} - I_S + I_{\text{CV}}. \quad (3)$$

For the reversed polarity of voltage rise gradient, the measured current is calculated as

$$I_{A-} = I_{\text{rg}} - I_S + I_{\text{CV}}. \quad (4)$$

Current I_{CV} is calculated by averaging the difference of measured currents I_{A+} and I_{A-}, i.e.,

$$I_{\text{CV}} = \frac{I_{A+} - I_{A-}}{2}. \quad (5)$$

Measured capacitance C_{CV} forms the parallel connection of the input capacitance of the DVM C_V and the capacitance of the connecting cable C_C; thus, it can be written as

$$C_{\text{CV}} = C_V + C_C. \quad (6)$$

Finally, the input capacitance of DVM is calculated from the current I_{CV} determined by (5), the known voltage gradient dU/dt, and the measured C_C, i.e.,

$$C_V = \frac{I_{\text{CV}}}{dU/dt} - C_C. \quad (7)$$

The described method is used for the measurement of DVM input capacitance and cable capacitance that connects voltage source HP 4140B and voltmeter HP 3458A. The cable capacitance of the coaxial-cable-type RG-174 is measured by means of digital bridge GR 1689 and was determined to be $C_C = 45$ pF, with uncertainty better than 0.1 pF.

To measure the input capacitance on the 1-V range of the DVM, the end of the linear voltage rise must be under 1 V. By changing the voltage from 0 to 1 V, the maximum current that can flow through the input resistance is approximately $(1\ \mathrm{V}/1\ \mathrm{T}\Omega) = 1$ pA. If the input capacitance is on the order of 100 pF and if the capacitive current is one order higher than the resistive current, then the voltage rise must be at least 0.1 V/s. This allows the measurement of current I_A during the interval of 10 s, which is enough to estimate its stability. The total input capacitance for the positive voltage gradient is measured to be $C_{\mathrm{CV}} = 299$ pF, whereas the negative voltage gradient yielded $C_{\mathrm{CV}} = 327$ pF, with repeatability better than ± 2 pF. By averaging the results and inserting the measured value of C_C (which was mentioned before to be 45 pF), the input capacitance calculated by (7) for DVM2 was determined to be (268 ± 4) pF. This value is comparable and in agreement with the results pointed out in [10] but determined with uncertainty that is lower by one order of magnitude (only 4 pF with coverage factor $k = 2$).

The voltmeter input resistance can also be measured by this method. By applying the constant voltage from the source, capacitive current I_{CV} is equal to zero, and instead, only the current through resistance R_V flows. By obtaining two measurements of total current I_A, with the changed polarity of the voltage from the source, the input resistance of voltmeter DVM3 was determined to be approximately 1.2 TΩ, which is in good agreement with that of the first method.

III. Conclusion

The use of precise DVMs for high-accuracy measurements needs to address all possible sources of errors. The DVM input circuitry can contribute to the measurement uncertainty, and it is therefore important to characterize it. The methods presented in this paper can be used for accurate determination of DVM input parameters. The method with voltage source and high-ohmic resistor divider has been developed for the determination of both input offset current I_S and input resistance R_V. The second method with the source of linear voltage ramp and picoampermeter is primarily used for the determination of input capacitance C_V. It was shown that the input parameters are fairly stable during a period of 10 min.

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Ivan Leniček was born in Zagreb, Croatia, on October 25, 1972. He received the M.S. and Ph.D. degrees from the University of Zagreb in 2002 and 2006, respectively.

Since 2008, he has been an Assistant Professor with the Department of Fundamentals of Electrical Engineering and Measurements, Faculty of Electrical Engineering and Computing, University of Zagreb. In the framework of the Primary Electromagnetic Laboratory, which is functioning under the scope of department’s activities, his research interests are focused on highly accurate measurements and maintenance of Croatian national standards of basic electromagnetic quantities.

Damir Ilić was born in Zagreb, Croatia, in 1965. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the University of Zagreb in 1990, 1994, and 1999, respectively.

Since 1991, he has been with the Faculty of Electrical Engineering and Computing, University of Zagreb, first as a young Researcher, then as an Assistant in 1995, and as an Assistant Professor in 2002. He has been an Associate Professor since 2007, teaching different themes of electrical measurements and measurement techniques. He is the Technical Manager of the Primary Electromagnetic Laboratory, which maintains Croatian national standards of dc voltage, resistance, and capacitance. His main research interests are precise measurements of electric quantities, methods of comparisons of like and unlike impedances, PC-based measurement systems, and signal analysis.

Dr. Ilić is a member of the IMEKO TC4 Committee and the contact person of EURAMET TCEM.

Roman Malarić was born in Zagreb, Croatia, in February 1971. He received the B.S. degree in radio communications and the M.Sc. and Ph.D. degrees from the University of Zagreb in 1994, 1996, and 2001, respectively.

Since 2004, he has been an Assistant Professor with Department of Fundamentals of Electrical Engineering and Measurements, Faculty of Electrical Engineering and Computing, University of Zagreb, where his primary interest is the development of precise measurement methods for electrical quantities and the automatization of measurement methods by computers and virtual instrumentation.