the average, an error of 1% will arise when the wavelength is displaced by 0.1 nm. It should be noted that up-to-date lasers possess a radiation wavelength stability of $\sim 10^{-5}$ nm [9].

Owing to the high resistance (tens of gigaohms) and the small capacitance of the modulator (several picofarads) the instrument produces an insignificant effect on the measured-voltage amplitude and phase. The linearity of the instrument's amplitude characteristic is obtained by a correct selection of the GaAs-crystal modulator operating conditions.

Experimental investigations of this installation have shown that it has a linear amplitude characteristic in the pulsed-voltage range of 1.5-10 kV. The error in measuring the pulse amplitudes then amounts to 3-5% and depends mainly on the recording-instrument precision. This system has a resolution with respect to time of 10^{-7} sec. The upper limit of voltage measurements can be extended by increasing the crystal linear dimensions.

Figure 2 shows oscillograms of high voltages with a complex form measured by means of the installation described above. A good agreement can be observed between the shape of the voltage fed to the modulator and the signal at the output of the optoelectronic system.

Thus, the Keldysh–Franz effect can be utilized successfully in optoelectronic high-tension measuring devices. The high resolution with respect to time and the small effect of the sensing element on the measured quantity make the application of this effect most promising for determining the parameters of high-tension short pulses.

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PRECISION COMPARATOR FOR MEASURING IN THE RANGE 1-10 mV

S. V. Gorbatsevich,* K. A. Krasnov, and V. P. Mazurov

UDC 621.317.52:537.312.62.089.68

The comparator used in measuring voltages in the range 1-10 mV with a relative error of 10^{-8}-10^{-7} is intended first of all for measuring the constant 2e/h in national or absolute units and for checking the measurements of the standard-cell (SS) emfs by means of the Josephson effect [1-3]. Even the best potentiometers (ZIP plant model R332 or Guildline Instrument 9930) cannot be used for this purpose. They have relative errors of $(1\text{-}5)\cdot 10^{6}$ and a sensitivity of 1-2 nV, whereas the SS emf drift amounts to 0.5-1 μV per annum and the maximum voltage at the Josephson junction is normally in the range 2-5 mV and has an instability of 10^{-8} [4-7].

The cascade voltage comparator specially developed for solving this problem represents a further improvement on designs used for similar purposes [8-10]. Its minimum voltage-range fsd amounts to 1 mV, and this corresponds to a ratio of about 1:1000. The comparator divider is provided with 80 ratios from 1024 to 64, thus making it suitable for comparing the SS emf with the same number of Josephson jucntion (JJ) voltages in the range 1-16 mV. The high precision in determining the comparator voltage ratios is achieved by a sequential comparison of the comparator-divider resistances and their precise adjustment. A simplified comparator circuit intended for measuring 2e/h is shown in Fig. 1.

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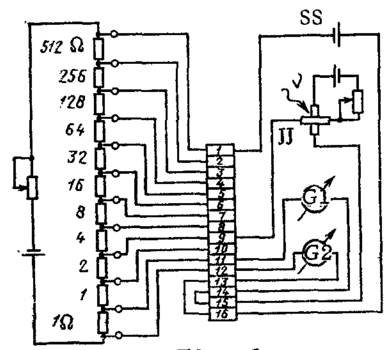

Fig. 1

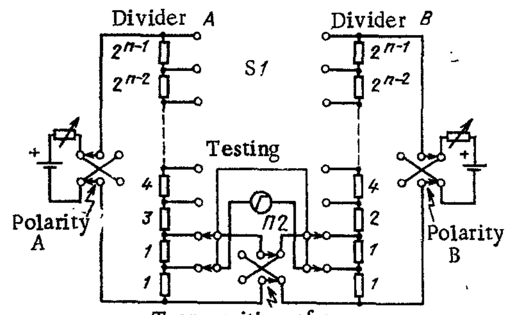

Fig. 2

In order to ensure autonomous testing, the comparator is provided with a second independently supplied iterative network of resistors. Its single resistance network is sufficient for comparing the JJ voltages with the SS emfs, whereas the second network can be used for checking the results obtained with the first one, since they are adjusted with virtually the same precision.

Figure 2 shows the connection of two iterative resistor networks intended for the first testing stage. Each basic resistor, with the exception of the first one in each network, is provided with parallel-connected adjustment resistors which serve to vary the values of the basic resistors within small limits. The switches shown in the position of Fig. 2 form an equal arm Wheatstone bridge with each arm having a resistance of 1 Ω. The basic resistors are adjusted until the galvanometer G has a minimum reading in both positions of the switch S2 (transposition of arms), and then the value of resistors forming pairs in each network will be the same. The next position of the switch S1 (Testing) is used for forming an equal-arm bridge with an arm resistance of 2Ω. These resistors are aligned with the series-connected pairs of 1-Ω resistors. Subsequent resistors are aligned in a similar manner with the previously aligned resistor combinations right up to the last, tenth testing step when the eleventh resistor with a nominal value of 512 Ω is aligned with the series-connected resistors whose values range from 1 to 256 Ω. The effect of compensation connections is reduced by using separate supply sources for each basic-resistor network.

Despite the relative complexity of the testing process, the selection of this method is justified by a larger set of voltage ratios and the constant power dissipated by resistors in the course of checking and measuring.

The total divider resistance of 1024 Ω was selected on the basis of thermal-noise considerations, the required ratio of 1:1000, the low-value arm resistance of 1 Ω required for matching to the small resistance of the galvanometer G1 (see Fig. 1), and the reduction of the leakage-resistance effects.

The two dividers with 11 basic resistors each consist of two identical printed-circuit boards. The nominal values of the basic resistors are shown in Fig. 1. Relative deviations of resistors from their nominal values do not exceed $\pm 1\cdot 10^{-4}$. The resistor temperature coefficients lie in the range of $(2\text{-}7.3)\cdot 10^{-6}\,°\mathrm{K}^{-1}$; and the temperature coefficient of the ratio 1:1000 amounts to $3\cdot 10^{-7}\ °\mathrm{K}^{-1}$.

The trimming iterative network for each basic resistor consists of a fixed resistor MLT with a large value and two type SL5-14 variable resistors for "rough" adjustments in the range up to $5\cdot 10^{-6}$ and for "fine" adjustments in the range up to $1\cdot 10^{-7}$. The printed circuits are provided with potential and current leadouts, as well as with leadouts for trimming the iterative networks. The printed-circuit boards are connected to the switches, trimming resistors, etc., by means of copper multiconductor leads in fluoroplastic insulation. They are soldered with a special solder which has a small thermal emf when paired with copper [11]. The comparator uses for assembling bridges and mutual transposition of arms in the course of testing the same switches as in the R348 instrument.

The divider is arranged structurally in the following manner: The two printed-circuit plates are joined with a Manganin base and are clamped between two copper sheets through a fluoroplastic insulation in order to reduce temperature gradients. This unit is placed in a red copper casing which serves as a passive thermostat. The outer casing is also made from red copper and provided with a heating element and a contact thermometer for maintaining a given temperature. This casing has a thermal insulation inside it together with the required switches, resistors, etc., which are placed in a lagged jacket. The printed-circuit plates temperature variations in the course of measurements do not exceed 0.005°C.

Two supply sources were used in checking the divider, namely, a PTs-85 1.34-V battery with a capacity of 2.5 A·h (divider working current of 1 mA) for testing the 64-512-Ω resistors and measuring 2e/h; and for testing 1-32-Ω resistors PTs-85 four batteries were used in a parallel connection through 1-kΩ resistors (divider working current of 4 mA). In order to reduce the working-current instability the batteries are thermostatically controlled and always connected either to the divider network or the load resistors.

The null indicator used in testing consisted of a photocompensated NFK-2 nanovoltmeter with a scale factor of 0.2 nV on the most sensitive range; its output signal is recorded on the N320-1 printer.

Let us now see how the comparator is tested for determining its actual ratio. Figure 3 shows a simplified schematic of an arbitrary testing step. The resistors R_i comprise trimming resistors; they are shown only for the stages R_p and R_p'. When the supply sources are connected the voltage drop across both dividers amounts to E_p. The voltage drop across the resistors R_p and R_p' when the current flows through them in the forward and inverse directions amounts to U_{p+}, U_{p-}, and U_{p+}', U_{p-}', respectively. The relative deviations of resistor ratios from their nominal values can be calculated from the formula

$$\delta_p = \frac{2}{E_p}\left[(U_{p+} - U_{p+}') + (U_{p-} - U_{p-}')\right]. \tag{1}$$

The true ratio is equal to

$$N^* = 2^n\left(1 + \frac{1}{2}\sum_{p=1}^{n}\delta_p\right). \tag{2}$$

In order to calculate δ_p it is convenient to provide R_p with a small change by shunting it with an additional calibrated resistor R_{cp}, which is connected by means of the push button K_p. The known change in R_p is then used for determining the difference $U_p - U_p'$ without measuring E_p directly.

The following sequence of operations is used in testing the comparator and determining the actual ratios.

Each testing stage is set with the switch S1 (see Fig. 2). In the first position of the switch, the current in both branches is set so that the voltage drops on the resistors 1 + 1 + 2 + 4 + ... + 32 Ω are equal. The next six switch S1 positions are used for testing the resistors of 1, 2, 4, 8, 16, and 32 Ω. In the eighth position of the switch S1, equal voltages are set in both dividers. The next four switch S1 positions serve to assemble bridges with arm resistances ranging from 64 to 512 Ω.

The galvanometer deflections recorded in testing 2-Ω resistors are shown in Fig. 4, which comprises notation 1 corresponding to a bridge with the same sequence of resistors in its arms and a supply-source polarity of "+" (at the current leadout of the 512-Ω resistor); notation 2 corresponding to a bridge with transposed resistors and a supply-source polarity of "+"; notation 3 to the same resistance sequence as in 1, but with a "-" polarity; notation 4 to a version of 2 with a "-" polarity; and calibration signal K for deflecting the galvanometer. All the ten arms are tested (and if required adjusted) in the same manner. The testing lasts about 1 h.

In processing recordings we first drew straight lines "by eye" in order to average out the galvanometer deflections with respect to noise. We then measured the distances between pairs of deviations and calculated the ratio error by means of the calibrated signal. The values thus obtained were inserted into the expressions (1) and (2).

Let us examine the basic sources in determining the comparator voltage ratios for 1:1024 and 1:128 and voltages of 1 and 8 mV, respectively.

1. The response threshold of the null detector NFK-2 amounts to 0.4 nV, which produces comparator-testing errors equal of 10^{-7} and $1.2 \cdot 10^{-8}$, respectively.

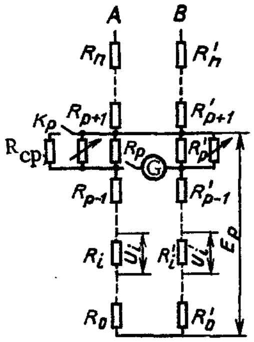

Fig. 3

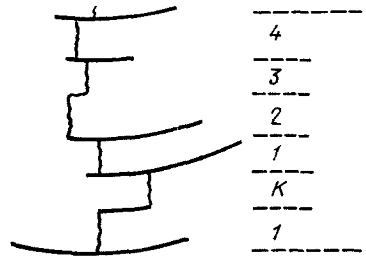

Fig. 4

2. The thermal emf between any two comparator potential leadouts does not exceed 1 nV and its variation in the course of testing a single ratio does not exceed 0.05 nV, and this leads to errors of $5 \cdot 10^{-8}$ and $6 \cdot 10^{-9}$, respectively.

3. It is possible that in the course of testing the voltage drops across the compensation connections may vary due to unequal resistances of the compensation conductors and changes in the switch-contact resistances, as well as to the instability of supply currents in the basic-resistor circuits. The compensation-connection resistance changes do not exceed 3 mΩ, and the relative current drift does not exceed 10^{-5} during testing. Thus, the error due to the compensation connections effect does not exceed, for the ratios under consideration, $3 \cdot 10^{-8}$ and $4 \cdot 10^{-9}$, respectively.

4. The calibration-signal error is produced by the aging of calibration resistors. Changes in the value of these resistors do not exceed 3% per annum, and this leads to an error of $2 \cdot 10^{-8}$.

5. Since temperature variations of the divider basic resistors do not exceed 0.005°K in the course of testing and the ratio temperature coefficients do not exceed $3 \cdot 10^{-7}\,°K^{-1}$, the error ratio due to temperature variations can be evaluated as $2 \cdot 10^{-9}$.

6. The insulation resistances of various comparator components were measured directly several times after the comparator manufacture in order to detect the effect of leakages on its operation. The insulation resistance amounted to at least $5 \cdot 10^{-11}$ Ω, and its variations in the course of testing produced an error not exceeding 10^{-9}.

Thus, the error in determining the comparator voltage ratios equal to 1:1024 and 1:128 calculated in accordance with error-accumulation formulas amounted to $1.2 \cdot 10^{-7}$ and $0.2 \cdot 10^{-7}$, respectively.

The null detector of the voltages equality in the lower arm of the cascade comparator also consisted of an NFK-2 photocompensation nanovoltmeter. This provides an additional error which is due to the NFK-2 response threshold and amounts to $4 \cdot 10^{-7}$ and $0.5 \cdot 10^{-7}$ for voltages of 1 and 8 mV, respectively.

Conclusions. Investigations of the cascade comparator have shown that the error in measuring the ratio of the SS emf to the JJ voltage (∼1 mV) does not exceed $4 \cdot 10^{-7}$. For larger JJ voltages the error decreases, and for 8 mV it does not exceed $5 \cdot 10^{-8}$. This error is determined mainly by the response threshold of the NFK-2 nanovoltmeter which serves as a null detector in comparing the measured voltage to voltage drops across the comparator lower arm. When this voltmeter is replaced by more sensitive instruments the above error can be reduced to 10^{-7} and $2 \cdot 10^{-8}$, respectively.

The comparator can be used for precise measurements in various physical investigations, e.g., in measuring temperature by means of platinum resistance thermometers, etc., when the error must not exceed 10^{-7}.

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DEVICE FOR MEASURING SURFACE POTENTIALS

A. P. Kal'nitskii and A. I. Fainshtein

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Surface potentials are extremely sensitive to such phenomena as adsorption and desorption of gases, oxidation, and changes in the chemical and phase composition. Therefore, measurements of this quantity can provide extensive information on various physicochemical processes occurring on the surface of solid bodies.

Usually dynamic capacitors are used for measuring surface potentials (Kelvin method) [1, 2]. Its essence consists in the fact that the surfaces of the measured sample and the electrode form an air capacitor, one of whose plates vibrates at a given frequency with respect to the other. If the surface potentials differ, a current will be produced in the external circuit due to changes in the capacitance:

$$j=\frac{dQ}{dt}=(\varphi_1-\varphi_2)\frac{\varepsilon_0 S}{l^2}\frac{dl}{dt}=(\varphi_1-\varphi_2)\frac{\varepsilon_0 S}{l^2}=a\omega\cos\omega t, \tag{1}$$

where φ_1 and φ_2 are the surface potentials of the sample and the electrode; S is the surface area; l is the distance between them; $l = l_0 + a \sin \omega t$; and ω and a are the frequency and amplitude of electrode oscillations.

It will be seen from (1) that the sensitivity of this method increases with a reduction in the distance between the plates. However, considerable difficulties arise in reducing this distance without disturbing the parallelism of the air capacitor surfaces. Moreover, since sensitivity is proportional to the plate area, it is difficult to measure small sections of the surface.

In the method suggested below these deficiencies are eliminated. The electrodes are made in the shape of metal rods covered with a thin layer of a dielectric and they do not oscillate, but remain in contact with the tested surface. In such a construction the distance between the surface and the electrode is determined by the thickness of the dielectric and can amount to 5-10 μm. This makes it possible to reduce the electrode area to 0.3 mm^2 without decreasing the capacitance of the measuring device (in the dynamic capacitor method this area amounts to 20-50 mm^2). Thus it becomes possible to carry out local measurements and investigate not only plane, but also curved surfaces.

The difference of potentials across the measuring capacitor plates in the contact area is due to the difference in the surface potentials of the electrode and the tested surface. Figure 1 shows a schematic illustrating the principle entailed in measuring this quantity. The signal is fed from the bipolar pulse generator PG to the measuring capacitor C, where the measured quantity is added to the pulse amplitude. The amplitude of positive pulses is thus increased, and that of the negative ones reduced by the same amount. The pulses of each polarity are then amplified separately and fed to the comparison circuit, where the measured quantity is separated, having been already amplified in each channel. The signal thus obtained is transmitted to the dc amplifier DCA and then to the measuring instrument MI.

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