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Research of Metrological Characteristics of the Phasometric Meter of Capacitance and Tangent of the Dielectric Losses Angle of Capacitors

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Abstract: The paper performs theoretical analysis of errors in the determination of capacitance and $tg\delta$ for low-voltage capacitors by the phase method. The main are two errors: a partial error from the instability of the parameters of the measuring circuit, and a partial error in measuring the phase shift angle between the two output voltages of the measuring circuit by the discrete counting method. It is established that the considered method of measurement is especially critical to the instability of values of voltage divider resistors. It is established that the limit of the basic relative error of measurement with a confidence probability of 0.95 does not exceed 0.012 % for capacity and 1.75 % for $tg\delta$.

Keywords: Capacitor, Measurement, Error, Measuring circuit, Phase signal, Microcontroller.

1. Introduction

In addition to capacitance C_X, real capacitors are also characterized by the active resistance R_X, which in AC circuits displays the active loss power that is released in the capacitor in the form of thermal energy from leakage currents and periodic polarization. The capacitor replacement electric circuit is a passive two-terminal two-ports network in which the parameters C_X and R_X can be connected in series or in parallel, wherein a sequential scheme is preferable for small losses, parallel - for large losses. However, only the calculated formulas depend on the replacement scheme, and the result of measuring the loss power remains unchanged [1]. When controlling the electrical parameters of capacitors, their insulating properties are estimated from the value of the dielectric loss tangent $tg\delta$, which is equal to the ratio of the active power of the capacitor to the reactive power, and is independent of the applied voltage [2]. With a parallel replacement scheme $tg\delta = \frac{1}{\omega R_X C_X}$, where $\omega = 2\pi f$, and f is the frequency of the sinusoidal voltage.

Many methods and schemes have been developed for measurement C_X and $tg\delta$ on AC current, they are discussed in detail in [3]. All of them have voltage or current as an intermediate value. These signals are known to be affected by various interference and noise, bias voltages, and drift of amplifier zero. In addition, when mating with the element base of digital technology and computing facilities, they require additional transformations, which complicates the measurement system.

A relatively new direction in the field of measurement C_X and $tg\delta$ is the use of AC voltage dividers with phase signals in combination with the method of time separation of the measurement channel. The development of this direction is largely due to the ubiquitous use of microcontrollers in measuring technology. This technical solution was used by us for a separate measurement of C_X and $tg\delta$ of capacitor [4].

2. Research Object

The essence of the meter is explained by the circuit in Fig. 1.

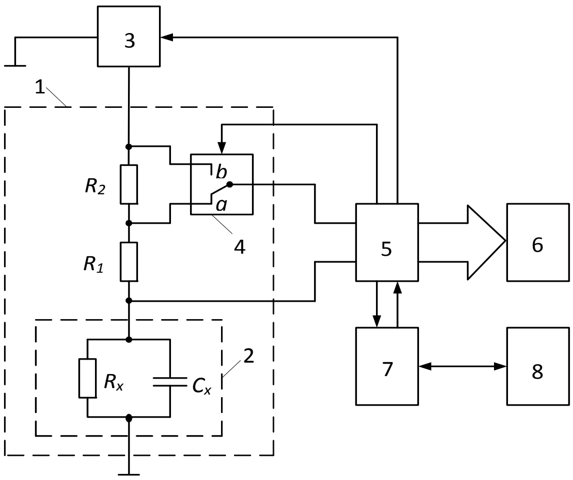

Fig. 1. Functional diagram of the phase meter of parameters of capacitors. 1 - measuring circuit; 2 - the investigated capacitor; 3 - programmable generator of sinusoidal signals; 4 - electronic switch; 5 - programmable microcontroller (MC); 6 - digital reading device; 7 - interface converter; 8 – personal computer.

Instead of the electronic switch 4, a switch integrated in the MC is used, when implementing the device. In the measuring circuit, two sample resistors are connected in series with the capacitor: a base resistor (R_1) and an additional resistor (R_2). The measuring circuit has two output voltages relative to the common point which are input to the MC: the total voltage taken from the common switch contact and the voltage of the capacitor terminals. The output signal of measuring circuit is the angle φ of phase shift between two indicated voltages. MC sets the frequency of the generator, controls the position of the switch, measures the φ angle in two positions of the switch, and determines C_X and $tg\delta$ by following algorithms [4]:

$$C_X = \frac{K_1}{ctg\varphi_1 - ctg\varphi_2}, \quad (1)$$

$$tg\delta = ctg\varphi_2 - K_2\left(ctg\varphi_1 - ctg\varphi_2\right), \quad (2)$$

where φ_1 - is the value of the angle φ in the position a of the switch, φ_2 - in the position b; $K_1 = \frac{R_2}{\omega R_1\left(R_1 + R_2\right)}$, $K_2 = R_1/R_2$.

The angle φ in the MC is converted into a time interval τ. The time intervals τ and T (frequency of the power supply of the measuring circuit) are measured by the discrete counting method by filling them with pulses of the reference frequency f_0 of the clock generator of MC with use of its integrated timer-counter. The procedure for calculating the resistance of resistors R_1 and R_2 of measuring circuit is described in [5]. The values of these resistances provide the required capacitance and tangent range of the capacitors to be investigated.

Obviously, the accuracy of the determination of C_X and $tg\delta$ is due to the stability of the Algorithms (1) and (2) and the accuracy of the φ angle measurement. From the known values of the possible deviations of the values included in (1), (2), and the accuracy of the φ angle measurement, it is possible to theoretically estimate the errors that can occur in the determination of C_X and $tg\delta$ with given device.

3. Research Methods

The absolute error of capacitance C_X measurement is determined by the total increment of the function (1), due to the instability (including the tolerances) of the parameters appearing in it. When determining the partial derivatives, it should be taken into account that the programmable generator of sinusoidal signals AD9833 [6] is used as the power source of the measuring circuit of the device, the frequency of which $f = 1000$ *Hz* is given from the MC. With each measurement, the MC sets the frequency of the generator and uses this frequency value in the calculation of C_X according to Formula (1), so that changing the generator frequency does not affect the accuracy of the C_X measurement, that is $\Delta(\omega) = 0$. Taking into account the total increment of the function (1) and the partial derivatives of (1), we find the expression for the relative error in determining the capacitance:

$$\gamma(C_X) = \frac{\Delta C_X}{C_X} = \gamma_R(C_X) + \gamma_\varphi(C_X), \quad (3)$$

where

$$\gamma_R(C_X) = -\left(1 + \frac{R_1}{R_1 + R_2}\right)\cdot\gamma(R_1) + \frac{R_1}{R_1 + R_2}\cdot\gamma(R_2), \quad (4)$$

$$\gamma_\varphi(C_X) = -\frac{ctg\varphi_1\cdot\gamma(ctg\varphi_1) - ctg\varphi_2\cdot\gamma(ctg\varphi_2)}{ctg\varphi_1 - ctg\varphi_2} \quad (5)$$

In obtained expressions:

- $\gamma_R(C_X)$ is the partial error of the determination of C_X from inaccuracy of resistance of resistors;
- $\gamma_\varphi(C_X)$ is the partial error of the determination of C_X from inaccuracy of φ angle measurement;
- $\gamma(R_1) = \Delta R_1/R_1$, $\gamma(R_2) = \Delta R_2/R_2$ are the relative changes in resistance of resistors (taking into account tolerances) under operating conditions;
- $\gamma(ctg\varphi_1) = \Delta(ctg\varphi_1)/ctg\varphi_1$, $\gamma(ctg\varphi_2) = \Delta(ctg\varphi_2)/ctg\varphi_2$ are the relative errors of the definition of $ctg\varphi_1$ and $ctg\varphi_2$ respectively, which, in turn, depend on the accuracy of the measurement of phase angles φ_1 and φ_2.

Similarly, from (2) we obtain:

$$\gamma(tg\delta) = \frac{\Delta(tg\delta)}{tg\delta} = \gamma_R(tg\delta) + \gamma_\varphi(tg\delta), \tag{6}$$

where

$$\gamma_R(tg\delta) = \frac{K_2(ctg\varphi_1 - ctg\varphi_2)[\gamma(R_2) - \gamma(R_1)]}{ctg\varphi_2 - K_2(ctg\varphi_1 - ctg\varphi_2)}, \tag{7}$$

$$\gamma_\varphi(tg\delta) = \frac{\Delta_\varphi(tg\delta)}{tg\delta} = \\ = \frac{-K_2 ctg\varphi_1 \cdot \gamma(ctg\varphi_1) + (1+K_2) ctg\varphi_2 \cdot \gamma(ctg\varphi_2)}{ctg\varphi_2 - K_2(ctg\varphi_1 - ctg\varphi_2)} \tag{8}$$

Calculations show that the considered phase-metric method for measuring the electrical parameters of capacitors is extremely critical to the stability of resistor resistances R_1 and R_2: even with the use of resistors of the C2– 29B type [7], which are sufficiently precise, changes in the permissible limits of their resistances cause unacceptably large measurement errors, not less than 20 %. Even if resistors R_1 and R_2 of the C2–29B type are chosen with precisely known resistances, only their temperature changes already cause practically unacceptable measurement errors for $tg\delta$. Therefore, it is advisable to use the most high-precision metal-fired resistors of type C5-61 as the resistors R_1 and R_2. They are manufactured with a minimum allowable deviation from the nominal resistance $\pm 0.005\%$ and with a minimum temperature coefficient of resistance $\alpha_t = \pm 10 \cdot 10^{-6}\ {}^0C^{-1}$ [8]. We determine the permissible change in the resistance of resistors R_1 and R_2 under normal conditions (at a temperature $20 \pm 5\ {}^0C$) taking into account that if the device is adjusted at $15\ {}^0C$ or $25\ {}^0C$, the temperature change may be equal to $\Delta t = \pm 10\ {}^0C$. Therefore, the temperature change of the resistance of the resistor will be

$$\Delta R_t = \alpha_t \cdot \Delta t \cdot R_N = 3 \cdot 10^{-6} \cdot 10 R_N = \pm 3 \cdot 10^{-5} R_N, \tag{9}$$

where R_N is the nominal resistance of the resistor. Then the total absolute change of resistance of the selected resistor under operating conditions for this tolerance value ($\pm 0.005\%$) will be

$$\Delta R_\Sigma = 5 \cdot 10^{-5} R_N + \Delta R_t = \pm 8 \cdot 10^{-5} R_N \tag{10}$$

Consequently, the relative changes in resistor resistances $\gamma(R) = \Delta R_\Sigma / R_N$ will be no more $\pm 0,008\%$. Bearing in mind that the relative changes in resistance of resistors $\gamma(R_1)$ and $\gamma(R_2)$ are independent random variables with almost normal distribution laws, with a confidence probability of 0.95 $\Delta R_\Sigma = 2\sigma_R$ can be taken, where σ_R is the standard deviation of the resistance of the resistor [9]. Therefore, for our case we will have $\sigma_{R_1} = \sigma_{R_2} = 0.5\Delta R_\Sigma = 4 \cdot 10^{-5} R_N$, and for the standard deviation of the relative changes in the resistance of the resistors, we obtain

$$\sigma[\gamma(R_1)] = \sigma[\gamma(R_2)] = \sigma[\gamma(R)] = 4 \cdot 10^{-5}$$

Then, taking into account (4) for the standard deviation of the partial error of the determination from the resistance of the resistors, we obtain

$$\sigma[\gamma_R(C_X)] = \sigma[\gamma(R)] \cdot \sqrt{1 + \frac{2R_1}{R_1 + R_2} + \frac{2R_1^2}{(R_1 + R_2)^2}}$$

Hence, the relative partial error C_X from the change in resistance of resistors R_1 and R_2 with a confidence probability of 0.95 will be

$$\gamma_R(C_X) = 2 \cdot 4 \cdot 10^{-5} \sqrt{1 + \frac{2R_1}{R_1 + R_2} + \frac{2R_1^2}{(R_1 + R_2)^2}}$$

For the scale $C_X = 0.001...0.1\ \mu F$, the resistance values of resistors $R_1 = 9\ kOhm$, $R_2 = 20\ kOhm$, means

$$\gamma_R(C_X) \approx 8 \cdot 10^{-5} \cdot 1.36 = 10.88 \cdot 10^{-5} \tag{11}$$

Similarly, using (7), we find the partial error in determining $tg\delta$ from the change in the resistance of the resistors R_1 and R_2. Since the standard deviation of the sum of independent random variables is

$$\sigma[\gamma(R_2) - \gamma(R_1)] = \sqrt{\sigma^2[\gamma(R_2)] + \sigma^2[\gamma(R_1)]} = \sqrt{2\sigma^2[\gamma(R)]}$$

for the standard deviation of the component $\gamma(R_2) - \gamma(R_1)$ we obtain

$$\sigma[\gamma(R_2) - \gamma(R_1)] = \sigma[\gamma(R)] \cdot \sqrt{2} = 5.64 \cdot 10^{-5} \tag{12}$$

Consequently, the partial absolute error of the measurement of $tg\delta$ the change resistance of resistors R_1 and R_2 with a confidence probability of 0.95 will be

$$\Delta_R(tg\delta) = 11.28 \cdot 10^{-5} K_2 (ctg\varphi_1 - ctg\varphi_2),$$

and the corresponding relative error will be

$$\gamma_R(tg\delta) = \frac{11.28 \cdot 10^{-5} K_2 (ctg\varphi_1 - ctg\varphi_2)}{ctg\varphi_2 - K_2(ctg\varphi_1 - ctg\varphi_2)} \quad (13)$$

For the scale of $tg\delta$ the resistance values of resistors $R_1 = 9$ $kOhm$, $R_2 = 14$ $kOhm$, hence $K_2 = R_1/R_2 \approx 0.643$, therefore,

$$\gamma_R(tg\delta) = \frac{7.25 \cdot 10^{-5} \cdot (ctg\varphi_1 - ctg\varphi_2)}{ctg\varphi_2 - 0.643 \cdot (ctg\varphi_1 - ctg\varphi_2)} \quad (14)$$

Table 1 presents the results of calculation $\gamma_R(tg\delta)$ by Formula (14) for the developed device with a measuring range $tg\delta = 0.0005...0.05$.

Table 1. Calculated error values $\gamma_R(tg\delta)$ for the measuring range $tg\delta = 0.0005...0.05$ at $R_1 = 9$ $kOhm$, $R_2 = 14$ $kOhm$.

$tg\delta$	φ_1	φ_2	$ctg\varphi_1$	$ctg\varphi_2$	$\gamma_R(tg\delta)$, %
0.0005	80^0	$86^0 2'$	0.1763	0.0693	1.55
0.001	$70^0 33'$	$82^0 6'$	0.3532	0.1389	1.40
0.002	$54^0 45'$	$74^0 28'$	0.7065	0.2778	1.44
0.004	$35^0 17'$	$60^0 57'$	1.4130	0.5555	1.50
0.005	$29^0 31'$	$55^0 20'$	1.7662	0.6944	1.48
0.01	$15^0 48'$	$35^0 45'$	3.5323	1.3889	1.45
0.02	$8^0 3'$	$19^0 48'$	7.0671	2.7778	1.51
0.04	$4^0 3'$	$10^0 12'$	14.1243	5.5555	1.35
0.05	$3^0 14'$	$8^0 10'$	17.6991	6.9444	1.32

The results of the calculation $\gamma_R(tg\delta)$ using Formula (14) are presented in Table 1 for the case of the use of resistors of type C5-61. Calculations show that in this case, the partial error of the determination of $tg\delta$ from the change in resistance of the resistors R_1 and R_2 with a confidence probability of 0.95 can be ensured no more than $\gamma_R(tg\delta) = 1.55\%$, and the definition C_X - $\gamma_R(C_X) \approx 0.011\%$.

Particular errors $\gamma_\varphi(C_X)$ in the determination of C_X by the Formula (5) and $\gamma_\varphi(tg\delta)$ in the definition of $tg\delta$ by the Formula (8) depend on the accuracy of the determination of $ctg\varphi_1$ and $ctg\varphi_2$, which in its turn depends only on the accuracy of measuring the phase angles φ_1 and φ_2. The relative error in measuring the phase shift φ has two components: $\gamma(\tau)$ the error of the φ angle transformation in the time interval τ and $\gamma(\varphi)$ the error in measuring the pulse signal duration: $\gamma_\Sigma(\varphi) = \gamma(\tau) + \gamma(\varphi)$. The error in forming the time interval τ depends on the zero-offset voltages of the comparators. The error $\gamma(\tau)$ can be practically eliminated by using a bipolar phase-meter circuit in which τ is determined by the four moments of the transition through zero values of the sinusoid in both directions (for one period of the input voltage, two time intervals τ are obtained) [10]. Consequently, the relative error $ctg\varphi$ in the determination will depend only on the accuracy of the phase shift φ measurement.

The relative error in the determination of $ctg\varphi$ can be calculated from the following expression

$$\gamma(ctg\varphi) = \frac{\Delta(ctg\varphi)}{ctg\varphi} = -\frac{\varphi}{ctg\varphi \cdot \sin^2\varphi} \cdot \frac{\Delta\varphi}{\varphi} = -\frac{2\varphi \cdot \gamma(\varphi)}{\sin 2\varphi}$$

or

$$\gamma(ctg\varphi) = -\frac{2\pi\varphi \cdot \gamma(\varphi)}{180 \cdot \sin 2\varphi} = \beta \cdot \gamma(\varphi), \quad (15)$$

where $\beta = -\frac{0.035\varphi}{\sin 2\varphi}$, φ - in radians, $\gamma(\varphi) = \Delta\varphi/\varphi$ is the relative error in measuring the phase angle.

Consequently, $\gamma(ctg\varphi_1) = \beta_1 \cdot \frac{\Delta\varphi_1}{\varphi_1} = \beta_1 \cdot \gamma(\varphi_1)$; $\gamma(ctg\varphi_2) = \beta_2 \cdot \frac{\Delta\varphi_2}{\varphi_2} = \beta_2 \cdot \gamma(\varphi_2)$.

The errors $\gamma(ctg\varphi_1)$ and $\gamma(ctg\varphi_2)$ are random and independent, so with a confidence probability of 0.95, we can assume that $\gamma(ctg\varphi_1) = 2\sigma_{\gamma(ctg\varphi_1)}$, $\gamma(ctg\varphi_2) = 2\sigma_{\gamma(ctg\varphi_2)}$. Since the standard deviation of the sum of independent random variables is

$$\sigma_\Sigma = \sqrt{\sigma_1{}^2 + \sigma_2{}^2},$$

taking into account expression (5), for a relative change in the sum of the random errors, we obtain

$$\gamma_\varphi(C_X) = \frac{\sqrt{\beta_1^2 \cdot \gamma^2(\varphi_1) \cdot ctg\varphi^2{}_1 + \beta_2^2 \cdot \gamma^2(\varphi_2) \cdot ctg^2\varphi_2}}{ctg\varphi_1 - ctg\varphi_2}$$

Because angles φ_1 and φ_2 are measured by the same hardware almost simultaneously, it can be assumed that $\gamma(\varphi_1) \approx \gamma(\varphi_2) = \gamma(\varphi)$, hence

$$\gamma_{\varphi}\left(C_X\right)=\frac{\gamma(\varphi)\sqrt{\beta_1^2\cdot ctg\varphi_1^2+\beta_2^2\cdot ctg^2\varphi_2}}{ctg\varphi_1-ctg\varphi_2} \qquad (16)$$

Taking into account the expression β, we have:

$$\beta_1\cdot ctg\varphi_1=-0.0175\cdot\frac{\varphi_1}{\sin^2\varphi_1},$$

$$\beta_2\cdot ctg\varphi_2=-0.0175\cdot\frac{\varphi_2}{\sin^2\varphi_2},$$

therefore, from (16) we obtain

$$\gamma_{\varphi}(C_X)=\frac{0.0175\cdot\gamma(\varphi)}{ctg\varphi_1-ctg\varphi_2}\cdot\sqrt{\left(\frac{\varphi_1}{\sin^2\varphi_1}\right)^2+\left(\frac{\varphi_2}{\sin^2\varphi_2}\right)^2} \qquad (17)$$

Performing similar actions with the Expression (8) we finally obtain

$$\gamma_{\varphi}\left(tg\delta\right)=\frac{0.0175\cdot\gamma(\varphi)}{ctg\varphi_2-K_2\left(ctg\varphi_1-ctg\varphi_2\right)}\cdot B, \qquad (18)$$

where

$$B=\sqrt{\left(1+K_2\right)^2\cdot\left(\frac{\varphi_2}{\sin^2\varphi_2}\right)^2+K_2^{\,2}\cdot\left(\frac{\varphi_1}{\sin^2\varphi_1}\right)^2}$$

To calculate the relative errors from Expressions (17) and (18), it is necessary to find a value of $\gamma(\varphi)$. The digital measurement of phase shift φ is based on a digital method for measuring the length of the time interval τ, corresponding to the phase shift, wherein $\varphi=(\tau/T)\cdot 360^o$, where T - is the sinusoidal voltage period. In the MC, the time intervals τ and T are measured by the discrete counting method by filling them with pulses of the reference frequency f_0 of the clock generator of MC with use of its integrated timer-counter. The meter reading will be

$$\varphi=\frac{\tau}{T}\cdot 360^o=\frac{nT_0}{NT_0}\cdot 360^o=\frac{n}{N}\cdot 360^o, \qquad (19)$$

where n and N are the number of pulses received on the meter during τ and T respectively.

It follows from (19) that the measured value of the phase shift is independent of frequency, if the period of the sinusoidal signal is measured simultaneously. The error in measuring the angle φ is mainly determined by the quantization errors of τ and T, since the frequency of the quantizing pulses f_0 generated from the MC clock is maintained continuously with high accuracy, and the change of f_0 equally affects the numerator and denominator of Expression (19). The quantization error consists of a random discreteness error, that is, the possibility of loss in numbers n and N by one counting pulse. In this case, the absolute error of measuring the angle φ

$$\Delta\varphi=\frac{\partial\varphi}{\partial n}\Delta n+\frac{\partial\varphi}{\partial N}\Delta N=\left(\frac{\Delta n}{N}-\frac{n}{N^2}\Delta N\right)\cdot 360^o,$$

and the relative error

$$\gamma(\varphi)=\frac{\Delta\varphi}{\varphi}=\frac{\Delta n}{n}-\frac{\Delta N}{N}.$$

The worst case occurs, when $\Delta n=1$, $\Delta N=-1$:

$$\gamma(\varphi)=\frac{1}{n}+\frac{1}{N}=T_0\left(\frac{1}{\tau}+\frac{1}{T}\right)=\frac{f}{f_0}\left(1+\frac{360^0}{\varphi}\right) \qquad (20)$$

Equation (20) shows that the error of measurement of the angle φ increases with the frequency $f=1/T$ of the generator of the supply of the measuring circuit, the clock frequency of the generator MC is smaller, and the measured angle φ is smaller. At the selected values of $f=1$ *kHz*, $f_0=80$ *MHz* we get

$$\gamma(\varphi)=\pm 1,25\cdot 10^{-5}\cdot\left(1+\frac{360^0}{\varphi}\right) \qquad (21)$$

4. Results

Table 2 shows the values of the variables and the errors $\gamma_{\varphi}\left(C_X\right)$, corresponding to the range of capacitance measurement $C_X=0.001...0.1$ *mkF*, calculated by formulas (17) and (21), where the notation

$$A=ctg\varphi_1-ctg\varphi_2,\ B_1=\sqrt{\left(\frac{\varphi_1}{\sin^2\varphi_1}\right)^2+\left(\frac{\varphi_2}{\sin^2\varphi_2}\right)^2},$$

and in the Formula (21) the values $\varphi=\varphi_1$, are substituted, since always $\varphi_1<\varphi_2$, and we are interested in the limit of the permissible measurement error. From Table 2 it can be seen that the error is minimal in the middle part of the scale of the angle φ and increases along the edges of this scale.

Table 3 shows the values of the variables and the error $\gamma_{\varphi}\left(tg\delta\right)$, corresponding to the measuring range of $tg\delta$, calculated from Formulas (18) and (21), where the notation,

$$B_2=\sqrt{\left(1+K_2\right)^2\cdot\left(\frac{\varphi_2}{\sin^2\varphi_2}\right)^2+K_2^{\,2}\cdot\left(\frac{\varphi_1}{\sin^2\varphi_1}\right)^2}$$

Table 2. The calculated values of the variables and the error $\gamma_\varphi(C_X)$ for the capacitance measurement range at $f = 1000\ Hz,\ f_0 = 80\cdot10^6\ Hz,\ R_1 = 9\ kOhm,\ R_2 = 20\ kOhm$.

C_X, μF	φ_1	φ_2	$\gamma(\varphi)\cdot10^4$	$\gamma_\varphi(C_X)\cdot10^3\%$
0.001	$3^0 14'$	$10^0 19'$	14.0425	3.749
0.002	$6^0 28'$	$20^0 1'$	7.0837	2.010
0.004	$12^0 45'$	$36^0 5'$	3.6544	1.102
0.006	$18^0 44'$	$47^0 32'$	2.5271	0.765
0.008	$24^0 19'$	$55^0 32'$	1.9756	0.651
0.01	$29^0 28'$	$61^0 15'$	1.6696	0.608
0.02	$48^0 30'$	$74^0 34'$	1.0528	0.599
0.05	$70^0 31'$	$83^0 44'$	0.7631	1.108
0.1	80^0	$86^0 2'$	0.6875	2.344

Table 3 shows the values of the variables and the error $\gamma_\varphi(tg\delta)$, corresponding to the measuring range of $tg\delta$, calculated from Formulas (18) and (21), where the notation,

$$B_2 = \sqrt{(1+K_2)^2\cdot\left(\frac{\varphi_2}{\sin^2\varphi_2}\right)^2 + K_2^{\ 2}\cdot\left(\frac{\varphi_1}{\sin^2\varphi_1}\right)^2}$$

It is seen that in this case also the error is minimal in the middle part of the scale of the angle φ and increases along the edges of this scale

Table 3. The calculated values of the variables and the error $\gamma_\varphi(tg\delta)$ for the measurement range of $tg\delta = 0.0005...0.05$ at $R_1 = 9\ kOhm,\ R_2 = 14\ kOhm,\ K_2 = R_1/R_2 \approx 0.643$.

$tg\delta$	φ_1	φ_2	$\gamma(\varphi)\cdot10^4$	$\gamma_\varphi(tg\delta)$,%
0.0005	80^0	$86^0 2'$	0.6875	0.636
0.001	$70^0 33'$	$82^0 6'$	0.7628	0.341
0.002	$54^0 45'$	$74^0 28'$	0.9469	0.204
0.004	$35^0 17'$	$60^0 57'$	1.4004	0.158
0.005	$29^0 31'$	$55^0 20'$	1.6495	0.156
0.01	$15^0 48'$	$35^0 45'$	2.9731	0.199
0.02	$8^0 3'$	$19^0 48'$	5.7151	0.338
0.04	$4^0 3'$	$10^0 12'$	11.2361	0.639
0.05	$3^0 14'$	$8^0 10'$	14.0425	0.796

The results of the calculations presented in Tables 2 and 3 show that the partial error of the determination of C_X, due to the error in measuring the angle φ, does not exceed $\gamma_\varphi(C_X) \approx 0.00375\%$, and the definition of $tg\delta$ - $\gamma_\varphi(tg\delta) = 0.796\%$.

The total errors in the determination of C_X and $tg\delta$ are equal to the sums of the partial errors $\gamma_R(C_X)$ and $\gamma_\varphi(C_X)$, $\gamma_R(tg\delta)$ and $\gamma_\varphi(tg\delta)$ respectively. Bearing in mind that these partial errors are random and independent, for the limits of the allowed total basic relative errors with a confidence probability of 0.95, we obtain

$$\gamma(C_X) = \sqrt{\left[\gamma_R(C_X)\right]^2 + \left[\gamma_\varphi(C_X)\right]^2} \approx 0{,}012\%,$$

$$\gamma(tg\delta) = \sqrt{\left[\gamma_R(tg\delta)\right]^2 + \left[\gamma_\varphi(tg\delta)\right]^2} \approx 1{,}75\%$$

We note that these errors can be reduced by narrowing along the edges of the φ angle scale.

5. Conclusion

The development of devices for measuring capacitance and tangent of the dielectric loss angle of capacitors with the use of time separation of the measurement channel and phase signals is a promising direction that allows to provide the necessary measurement accuracy.

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