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Measurement of Dielectric Loss by Phase Method

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Abstract

The measuring device for dielectric loss tangent of real insulating material (which is a capacitor having capacitance and active resistance) measurement has been considered. The device uses the phase shift method and the temporary separation of the measurement channel. Management of measurement process and processing of the measurement results is carried out by programmable microcontroller. The analysis of the device processing and measurement error estimation has been provided.

Keywords: dielectric; capacitor; dielectric loss; dielectric loss angle; phase method.

1. Introduction

Dielectric losses of energy in form of heat occurs in real dielectric materials under an applied voltage by both DC and AC. When DC voltage is applied to the insulating material the periodic polarization does not exist, however, leakage currents arise, since the values of bulk and surface electrical conductivities of the insulating material are not equal to zero. Leakage currents cause heating of the insulating material. With AC voltages, currents of periodic polarization are added to the leakage currents, this increases thermal energy allocated in material and may cause different defects that lead to a deterioration of the insulating properties of the material, and for large values of the thermal energy released, thermal destruction of the insulation material can occur. (Electrothermal breakdown).

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Therefore, in the manufacturing and exploitation process of electrical equipments, the quality of insulation material is tested in order to detect possible defects [1, 2].

Real insulation material is a capacitor having capacitance C_X and active resistance R_X. Capacitance C_X characterizes property of material to store electrical energy $W = C_X U^2/2$ by applying external electric voltage U.

The resistance R_X shows thermal energy $Q = \left(U^2/R_X\right) \cdot t$ allocated in the material by the leakage currents in the same conditions, for the time t.

In electrical equivalent circuit of capacitor the parameters R_X and C_X may be connected in series or in parallel, wherein serial circuit is preferable for small losses, parallel - for large ones. However, only calculation formulas depend on substitution scheme but the result of power measurement of dielectric losses remains unchanged. [3]. For example, the following formula is used to calculate the power dissipation of the parallel equivalent circuit (Figure 1).

$$P_a = U \cdot I_R = U \cdot I_C \cdot tg\delta = U \cdot \frac{U}{X_C} \cdot tg\delta = U^2 \omega C_X \cdot tg\delta \quad (1)$$

where $X_C = 1/\omega C_X$, δ is dielectric loss angle and ω is the angular frequency of the applied sinusoidal voltage U.

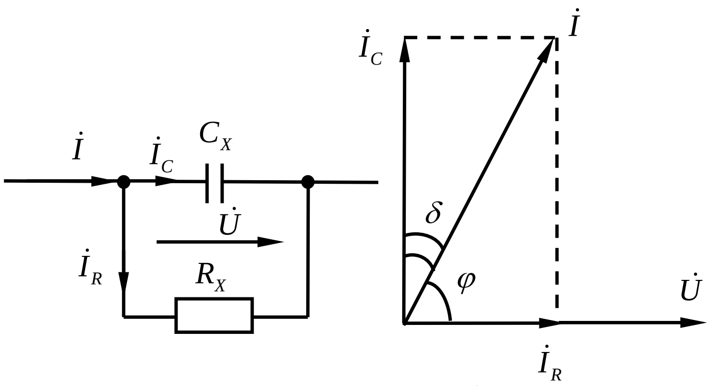

Figure 1: Parallel equivalent circuit of the real dielectric (capacitor)

From (1) it is clear that the dielectric losses are particularly important for materials used in high-voltage installations, in high-frequency equipment and especially in high voltage - high frequency devices, since the value of the dielectric loss is proportional to the square of voltage and frequency applied to the dielectric. Materials to be used in these conditions, must differ by small values of loss angle and dielectric constant, otherwise the power dissipated in the dielectric can reach unacceptably high values. High dielectric losses in the insulating material causes intense heating of the product manufactured from it and may lead to its failure.

From (1) it also follows that it is impractical to produce the assessment of the insulating properties of the dielectric by value of power of dielectric loss, as P_a also depends on the applied voltage. Therefore, the insulating properties of the insulator were evaluated by a value of $tg\delta$, which is equal to the ratio of active and reactive power, and can also be expressed in terms of parameters R_X and C_X (Figure 1.).

$$tg\delta = \frac{I_R}{I_C} = \frac{I_R \cdot U}{I_C \cdot U} = \frac{P_a}{P_p},\ tg\delta = \frac{I_R}{I_C} = \frac{U}{R_X \cdot U / X_C} = \frac{X_C}{R_X} = \frac{1}{\omega R_X C_X}$$

In contrast to the P_a, the value $tg\delta$ is also independent from geometric dimensions of the dielectric, which is easily proved by applying the concept of the complex permittivity [4].

To measure $tg\delta$, the sample of controlled dielectric (e.g., transformer oil) is placed in the space between the plates of a capacitive transducer (Figure 2). In the diagram: 1 - measuring circuit; 2 – capacitive transducer CT; 3 - programmable generator of sinusoidal signals; 4 - electronic switch; 5 - programmable microcontroller (MC); 6 - digital reading device (DRD); 7 - interface converter (UART-USB); 8 - the computer.

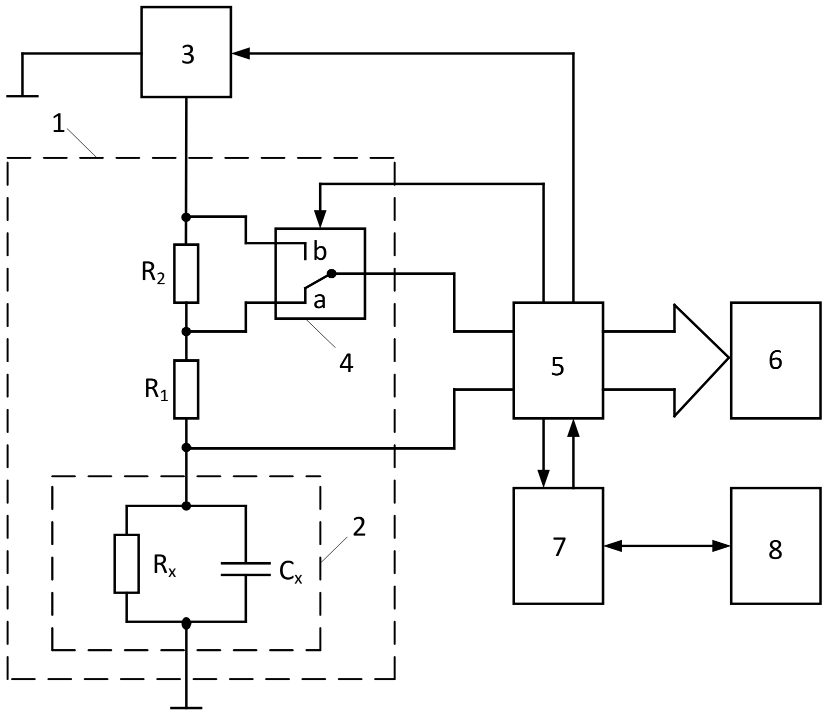

Figure 2: Simplified schematic diagram to measure the parameters of CT

In measuring circuit, in series with the CT, two model resistors are connected: base (R_1) and an additional (R_2

). The resulting circuit in the form of a voltage divider is connected to a generator of sinusoidal signals. The measuring circuit has two output voltages relative to the total point, which are input to the MC: the common voltage u_S of the voltage divider, taken from the general contact switch and voltage u_X from clamps of CT. The output signal of measuring circuit is a phase shift angle between the voltage u_S and u_X .

It should be noted that in most cases of measurement of $tg\delta$ it is also necessary to have appropriate values of parameters C_X and R_X , therefore when designing the meter has been tasked to provide separate measurements of these three parameters.

There are several methods and techniques for separate measurement of parameters of dual elements, two-terminal measuring circuits, but all of them use potentially-current signals, that are subject to various noise and interference effects, and therefore can not provide high measurement accuracy [5-9]. We have developed a phase method for the separate measurement of these parameters, in which only the phase shift angle between the two voltages of the measuring circuit must be measured to determine the values of these parameters [10, 11]. This method is used in this paper.

Let us find the relationship between the parameters of the CT and the angle φ. In the initial position a of switch for value of φ_1 of angle φ we can write:

$$tg\varphi_1 = \frac{\mathrm{Im}\left(\dot{U}_S/\dot{U}_X\right)}{\mathrm{Re}\left(\dot{U}_S/\dot{U}_X\right)} = \frac{\mathrm{Im}\left\{\dot{I}\left[R_1 + R_X/\left(1+j\omega R_X C_X\right)\right]/\dot{I}\left[R_X/\left(1+j\omega R_X C_X\right)\right]\right\}}{\mathrm{Re}\left\{\dot{I}\left[R_1 + R_X/\left(1+j\omega R_X C_X\right)\right]/\dot{I}\left[R_X/\left(1+j\omega R_X C_X\right)\right]\right\}} \quad (2)$$

The result is:

$$tg\varphi_1 = \frac{\omega R_1 R_X C_X}{R_1 + R_X} \quad (3)$$

In b position of switch

$$tg\varphi_2 = \frac{\omega\left(R_1 + R_2\right) R_X C_X}{R_1 + R_2 + R_X} \quad (4)$$

In these expressions ω is the angular frequency of the generator, I is the current of measuring circuit.

Using (3) and (4), we derive formulas for determining the parameters of the CT.

2. The formula for the definition of C_X

From (3) and (4) we have: $ctg\varphi_1 - ctg\varphi_2 = \frac{R_2}{\omega R_1\left(R_1 + R_2\right)C_X}$ from which we obtain:

$$C_X = \frac{R_2}{\omega R_1\left(R_1 + R_2\right)} \cdot \frac{1}{ctg\varphi_1 - ctg\varphi_2} \qquad (5)$$

3. **The formula for the definition of** R_X

We divide formula (4) into formula (3): $\frac{tg\varphi_2}{tg\varphi_1} = \frac{\left(R_1 + R_2\right)\cdot\left(R_1 + R_X\right)}{R_1\left[\left(R_1 + R_2\right) + R_X\right]}$ which implies:

$$R_X = \frac{R_1\left(R_1 + R_2\right)m}{R_2 - R_1 m} \qquad (6)$$

where the notation $m = \frac{tg\varphi_2}{tg\varphi_1} - 1$

4. **The formula for the definition of** $tg\delta$

Let us transform the formula (3) and (4) as follows:

$$R_1 \cdot ctg\varphi_1 = \frac{R_1 + R_X}{\omega R_X C_X},\ \left(R_1 + R_2\right)\cdot ctg\varphi_2 = \frac{R_1 + R_2 + R_X}{\omega R_X C_X},\ \left(R_1 + R_2\right)\cdot ctg\varphi_2 - R_1 \cdot ctg\varphi_1 = \frac{R_2}{\omega R_X C_X}$$

Consequently,

$$tg\delta = \frac{1}{R_2}\left[\left(R_1 + R_2\right)\cdot ctg\varphi_2 - R_1 \cdot ctg\varphi_1\right] \qquad (7)$$

The resulting formulas (5), (6), (7) allow us carry out separate measurement of the three parameters of the CT on alternating current. This requires only to measure the angle of the phase shift between the two output voltages of the two-pole measuring equipment.

In the process of measuring MC controls the position of the switch and measures the values of the φ_1 and φ_2 angles in the corresponding switch positions. With the measured values of these angles MC calculates parameters C_X , R_X , $tg\delta$ according to the formulas (5), (6), (7), and outputs the measurement results on a digital display, as that seven-segment LEDs are used. To improve the reliability of measurement results at every point the MC performs 10 measurements and displays on the display the average result of these measurements.

If necessary, the digitized signals of φ_1 and φ_2 can be sent from the MC through the interface converter (*e.g.*, AVR309) to computer, where they can be processed and the measurement results are displayed on a computer monitor. Since, in general, the results of measurements of the CT parameters also depend on the frequency of the supply current of measurement circuit, there is a problem of stabilization of the frequency, or its control during the measurement process. With this in mind, as the power supply of the measuring chain programmable generator of sinusoidal signals AD9833 is used. At each measurement MC sets the generator frequency, and uses this value in calculating of CT parameters, whereby the generator frequency changes do not affect the measurement. Generator voltage stability is not essential, as in (5), (6) and (7) the generator voltage does not appear.

Thus, the accuracy of the CT parameters depends only on the accuracy of measurement of the angle φ that is performed in this device by discrete calculation method, so the measurement accuracy is significantly higher than with methods using potentially - current signals.

It should be noted that, without any restrictions while choosing parameters of measurement circuit we can provide condition $R_2 = R_1 = R$ and instead of formula (5), (6), (7) use the simplified formulas:

$$C_X = \frac{1}{2\omega R\left(ctg\varphi_1 - ctg\varphi_2\right)}, \quad R_X = \frac{2R\left(tg\varphi_2 - tg\varphi_1\right)}{2tg\varphi_1 - tg\varphi_2}, \quad tg\delta = 2ctg\varphi_2 - ctg\varphi_1$$

Voltage u_S and u_X inputs to the programmable MC, wherein the angle φ is converted to the time interval τ . The time intervals τ and T are measured by digital accounts by filling them with pulses of exemplary frequency of clock generator of MK with use of its integrated timer counter. Further, the angle φ is calculated by the obvious formula

$$\varphi = \frac{\tau}{T}\cdot 360^o \qquad (8)$$

Then, with the measured value of φ the MC calculates the values of C_X , R_X , $tg\delta$ according to the formulas (5) and (6), (7) and displays the results on the DRD.

To measure the angle φ in the MC, we consider two methods: the use of an internal ADC or internal comparators of MC.

5. The use of the internal ADC of microcontroller for digital converting of angle φ (Figure 3, 4)

Internal ADC of microcontroller converts the analog input signal into a digital signal (binary code). At the beginning, multiplexer transmits the voltage u_S to the input of ADC, which converts it to a digital code. ADC writes value of digital code ("Value 1") at the time t_1 in output register. MC starts the internal timer and via the multiplexer transmits the voltage u_X to the input of ADC. Then the MC considers the value of the output register until the moment t_2 when it receives on u_X the "Value 2" equal to "Value 1". At the moment t_2, the MC stores the timer value and again transmits the voltage u_S to the ADC input. Then twice receiving value equal to "Value 1" (the moment t_3), the MC again remembers the timer value and stops the timer.

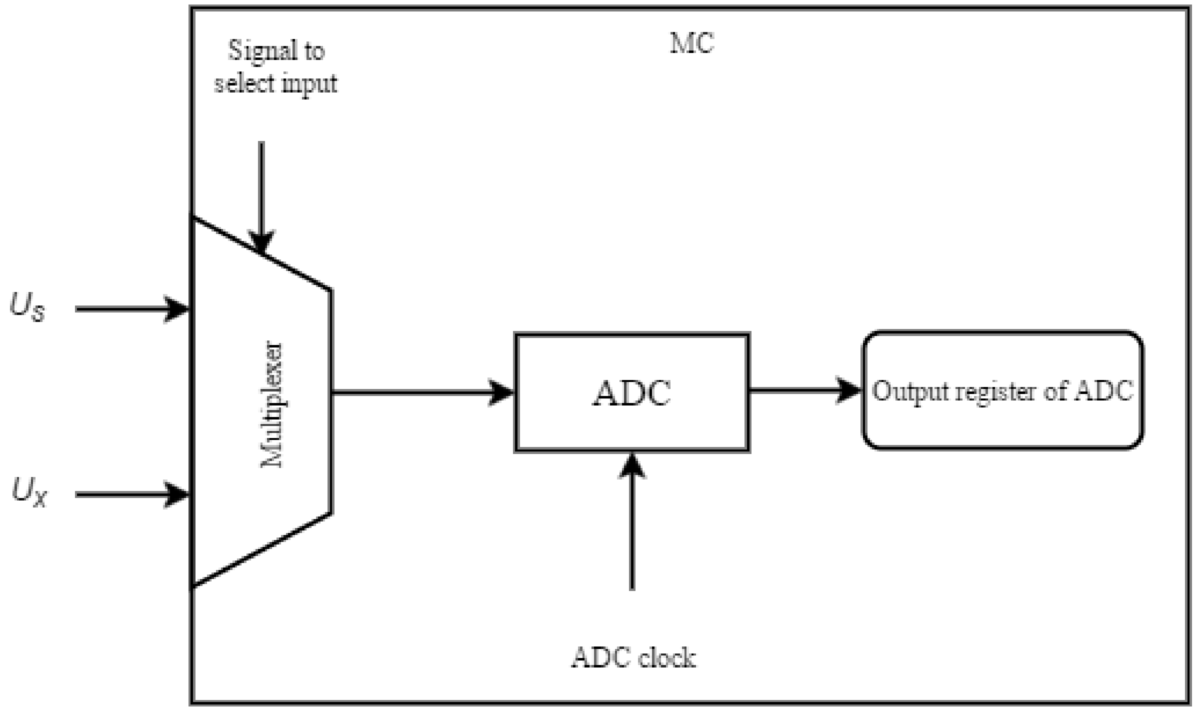

Figure 3: The block diagram of the method using ADC

By the number of the pulses of clock timer n for the time $t_2 - t_1$ and the value of the pulses N during $t_3 - t_1$, the angle φ is calculated by formula

$$\varphi = \frac{n}{N} \cdot 360^o \qquad (9)$$

obtained from (8) by substituting the values $\tau = n/f_0$ and $T = N/f_0$, where f_0 is clock frequency.

This method of measuring the angle φ has a significant limitation: the period of the ADC should not be more than the minimum value of τ. From condition $\tau_{\min} = 1/f_D$ where f_D is the ADC sampling rate, from (9) we find the minimum value of the angle φ, which can be measured by this method at the signal frequency f :

$$\varphi_{\min} = \frac{f}{f_D} \cdot 360^0 \qquad (10)$$

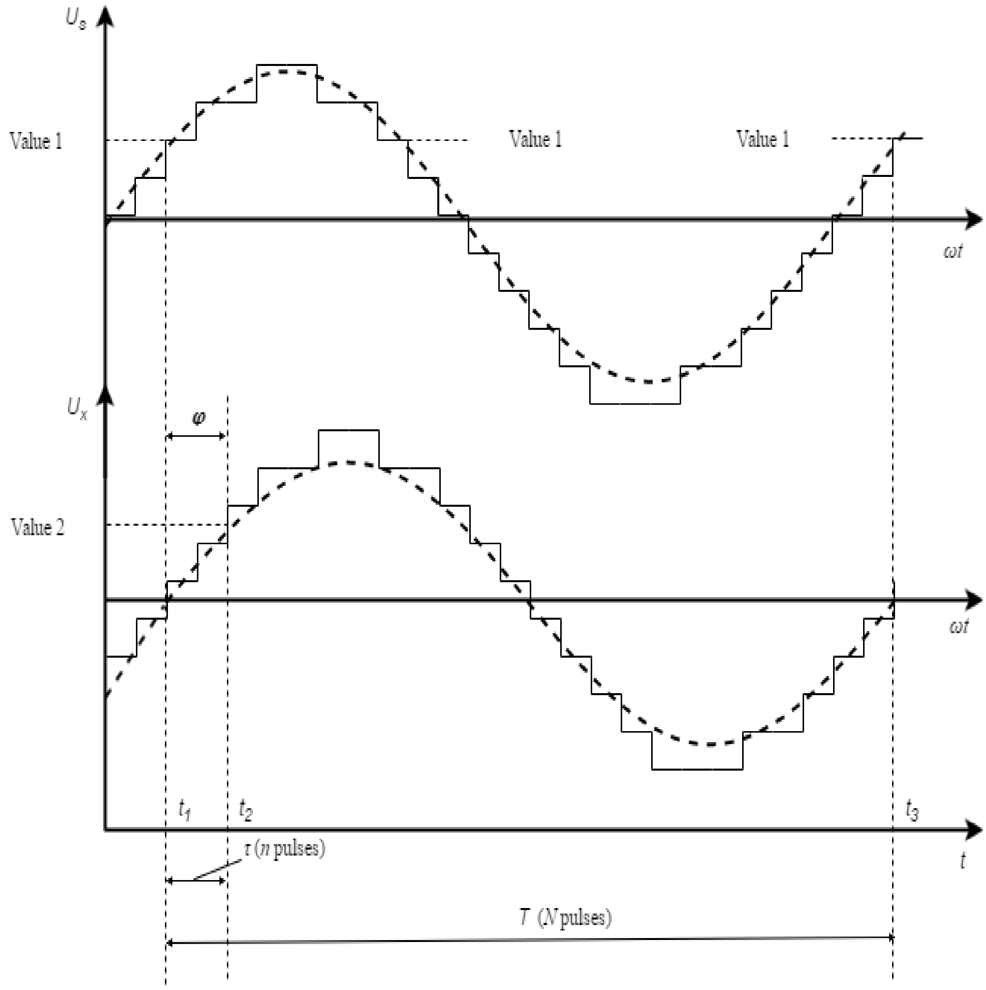

Figure 4: Signal conversion graphs for ADC

In device developed according to the scheme in Figure 2, the measuring circuit is supplied by sinusoidal current with frequency $f = 50$ kHz. Even if you use the MK LPC4370FET100 type [12], the ADC of which has a sufficiently high sampling frequency $f_D = 80$ MHz, from (10) we obtain for $\varphi_{\min}$ the value $\varphi_{\min} = 0,225^0$. In addition, for the nominal value of the measuring range $\varphi_N = 45^0$ the sensitivity threshold of error will be $\delta_S = \frac{\varphi_{\min}}{\varphi_N} \cdot 100 = 0,5\%$. Accordingly, in the present problem, the use of the internal ADC of microcontroller for digital conversion of angle is inappropriate.

6. The use of internal comparators of MC for digital converting of angle φ (Figure 5, 6)

To implement this method, we need MC with two internal comparators. Inverted inputs of comparators are grounded, and the direct inputs are connected to u_S and u_X , and thus forming a zero voltage comparators. As a result, each of the comparators can perform three types of interrupts:

- "Transition 0-1" (Rising edge) - when the signal at the direct input passed through 0 up;
- "Transition 1-0" (Falling edge) - when the signal at the direct input passed through 0 down;
- "Transition 1-0 / 0-1" (Toggle) - when the signal at the direct input passed through 0 up or down.

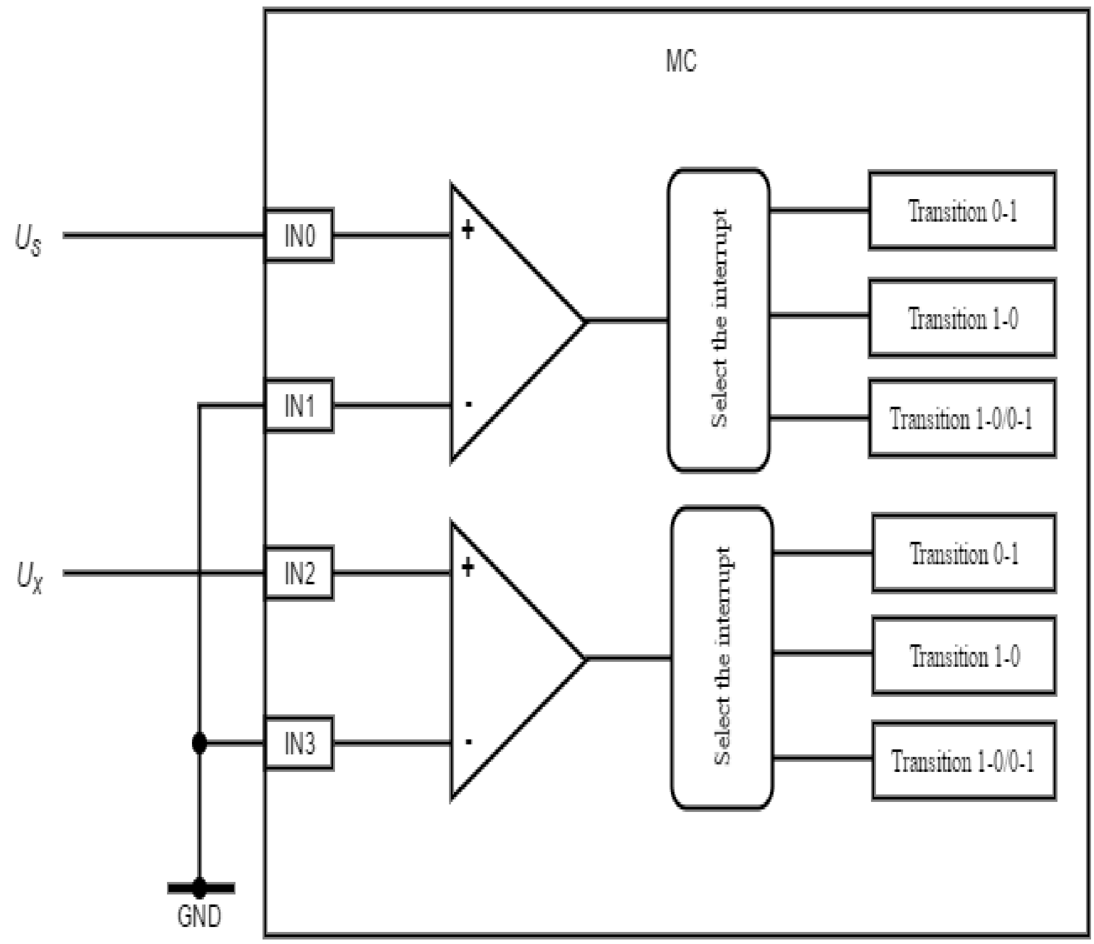

Figure 5: The block diagram of the method using comparators

At the moment t_1, the MC receives an interrupt "Transition 0-1" from the first comparator and starts a timer. Then at the moment t_2, again the MC receives an interrupt "Transition 0-1" from the second comparator. At this moment, the MC saves the value of the timer.

When for the second time (at the moment t_3) the MC receives an interrupt "Transition 0-1" from the first comparator it again stores the value of the timer and stops the timer. By the obtained numbers of pulses n and N , the angle φ is calculated as in the first method.

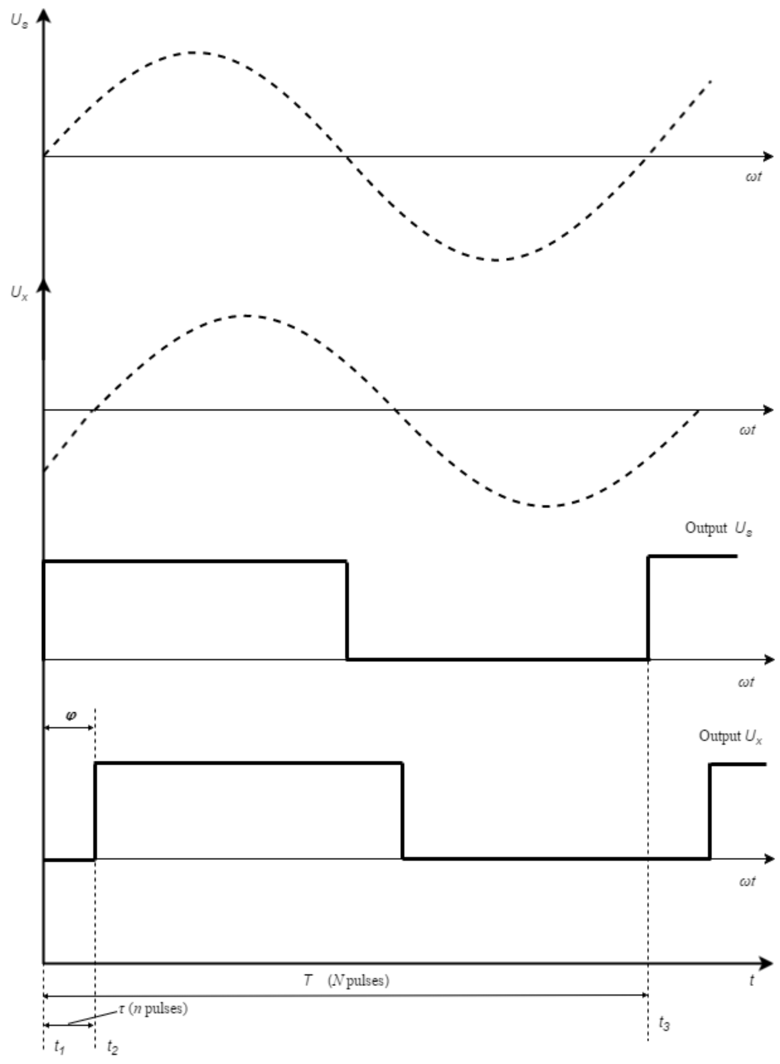

Figure 6: Signal conversion graphs for comparator

7. Evaluation of φ angle measurement error

It follows from (9), that the φ angle measurement error is caused by the error in determining the number of pulses n and N. This error is the sum of the random error of discreteness, i.e. the possibility of loss in numbers n and N with one count pulse. Absolute measurement error

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

and the relative error

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

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

$$\delta(\varphi) = \frac{1}{n} + \frac{1}{N} = \frac{1}{\tau f_0} + \frac{1}{T f_0} = \frac{1}{f_0} \cdot \left(\frac{1}{\tau} + \frac{1}{T} \right) \qquad (10)$$

Equation (10) shows that the error of measurement of the angle φ can be reduced by increasing the frequency f_0 of the timer of MC. Based on the analysis performed in this paper, preference is given to the use of internal comparators of MC for digital conversion of angle φ.

8. Block diagram of the measurement program

The algorithm of the device provides averaging for measurement results to programmatically exclude the occasional errors. For simplicity, the overall program is divided into four functional blocks (Figure 7).

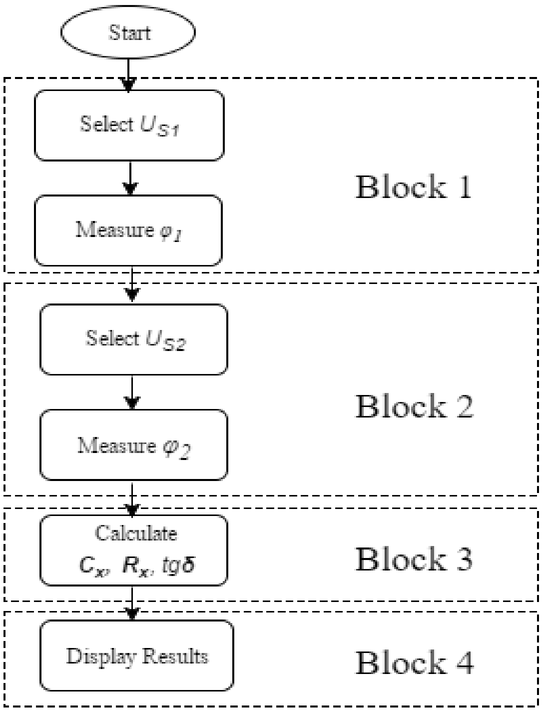

Figure 7: Function blocks of the program

The first block performs the choice of the first measuring circuit Figure 2 (switch position a) and the calculation of the angle φ_1.

The second block performs similar to the second circuit (switch position b) and calculates the angle φ_2. The third block calculates the values C_X, R_X, and $tg\delta$. The fourth block displays the values or transmits data to a computer via USB port. Algorithms of blocks are shown in Figures 8, 9.

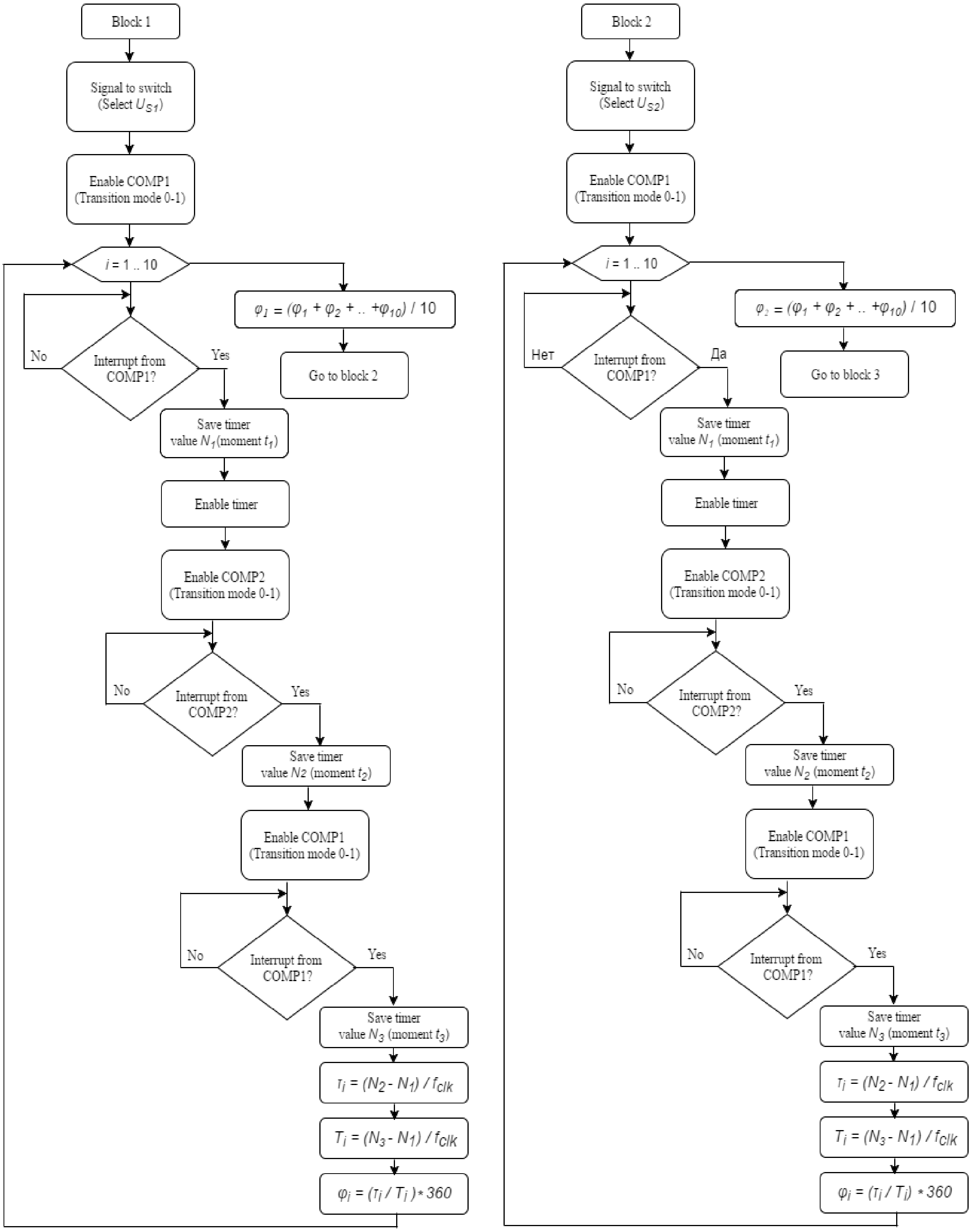

Figure 8: Scheme of the functional blocks 1 and 2

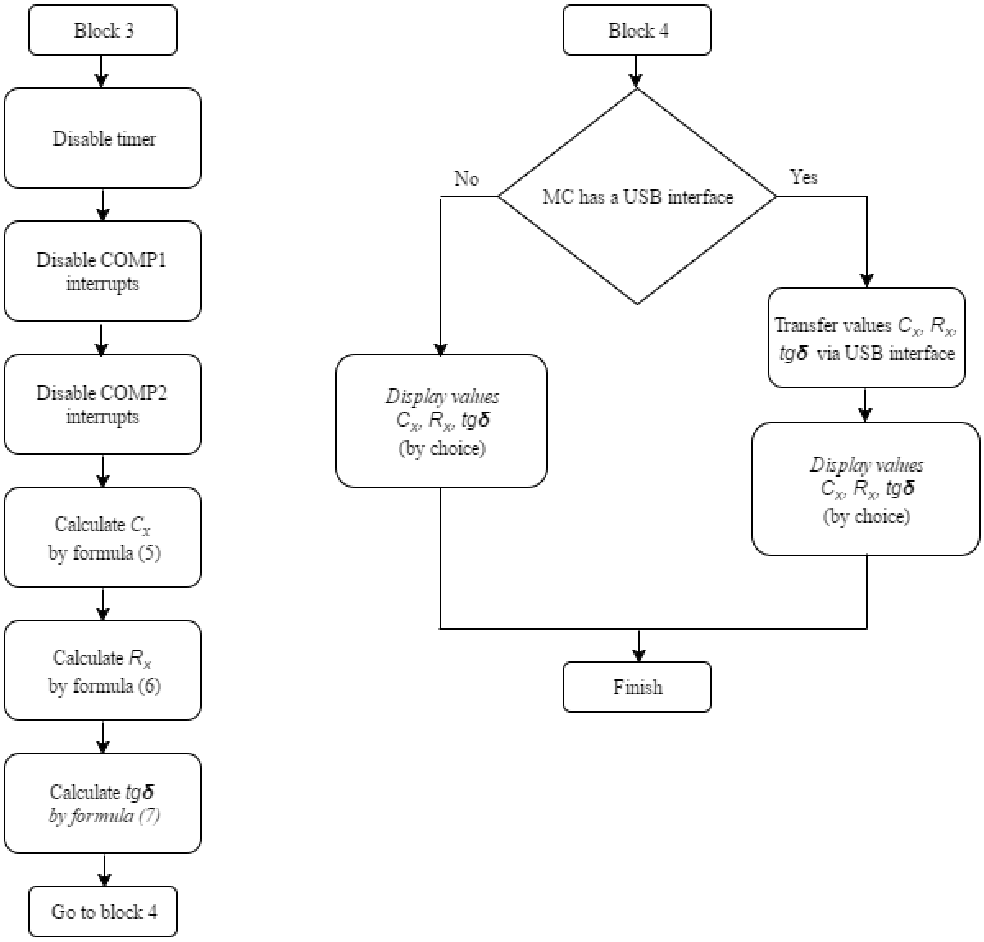

Figure 9: Scheme of the functional blocks 3 and 4

9. Conclusions

Designed by the authors, the phase method for dielectric loss measurement, makes it relatively easy to implement invariant parameters measuring of capacitance of the primary transducer without the use of potentially-current signals. You need to measure only the angle of the phase shift between the two output voltages of measuring circuit. The microcontroller controls the process of measurement and processing of the measurement results. To convert the measured phase shift angle to a digital code, it is advisable to use the internal comparators of microcontroller instead of embedded ADC. This significantly reduces the error from the threshold sensitivity of the device, in addition ADC is more sensitive to noise and interference.

Also a technique for experimental study of the metrological characteristics of the described dielectric loss meter was developed. In the circuit of Figure 2 the measured parameters R_X and C_X are modeled by a high-precision resistance box P4851 and capacities box P544. Absolute measurement error is estimated as the difference between the output results in digital reading device 6 (Figure 2) and the values of R_X and C_X in P4851 and P544. The results of the experiments shows that the developed device can provide a separate measurement of the parameters C_X , R_X , $tg\delta$, with a basic relative error of measurement not exceeding 0.2%.

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