# Measuring device moisture content of transformer oil

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Summary. This paper deals by determination of moisture content of transformer-oil (TO). A method for rapid determination of moisture content of the TO is proposed. Developed by measuring circuit with flow measuring transducer for determining the quality factor of TO. Analytical dependences of capacitance and resistance measuring transducer with TO from the integral of the charge and discharge voltage are obtained.

Keywords. Transformer oil, moisture content, schema of substitution, function of Lambert, measuring transducer, quality factor

## INTRODUCTION

Now a lot emphasis is paid to improving the reliability of electrical installations as well as energy saving and improve the technical and economic indicators [12, 13, 16, 26, 27].

The influence of moisture on the degradation electrical insulation properties of transformer oil and the transformer insulating materials studied and characterized quite fully [3, 11, 22].

## OBJECTS AND PROBLEMS

Known methods of moisture testing TO have several of shortcomings and for the most part require of laboratory testing [8, 11]. Precision testing of moisture content in transformer oil is not high enough, some of the methods can not be attributed to the non-destructive testing, for example, chemical methods [5, 10, 22]. Up to now many scientists investigated the processes occurring at the testing of the moisture content in various solid and granular environments. The insufficiently studied is the non-destructive testing moisture content in liquids [5, 11, 23].

For operational testing of the moisture content TO, device is offered on principle of the high quality factor measurement of oil. The main element of the device is a sensor – measuring transducer of flowing type mounted on the transformer [9, 14, 15].

## RESULTS, DISCUSSION

**Functional diagram of device and measuring process of quality factor.** Measuring of quality factor TO, located in the converter executed by way determination of charge, amassed by a converter with TO, as shown on a Fig. 1.

Principle of action of this circuit consists of the following. The generator of *G1* generates rectangular impulses with frequency of *f1*, which supplied to on measuring transducer (MT) through high-precision resistance *R1*. The device of voltage registration (DVR) performs the cyclic measuring of voltage on MT from the moment of supply of the first impulse on MT. The charging process lasts to appearance of negative wavefront, after which a pause is formed and there is the parallel connecting of high-precision resistor *R2* by the switch *S*. Thus the process of discharge MT begins through *R2*, for which the cyclic measuring of voltage is also conducted on MT. This process lasts to appearance of positive wavefront of the pulse generator. Then all repeats in the loop.

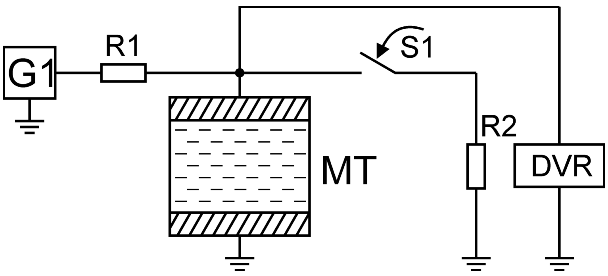


**Fig. 1.** Scheme of measurement quality factor

Since the structure measuring transducer is designed as a coaxial flowing condenser (Fig. 2.), the voltage on the MT, which is filled TO, will change along the curve 1 as shown in Fig. 3.

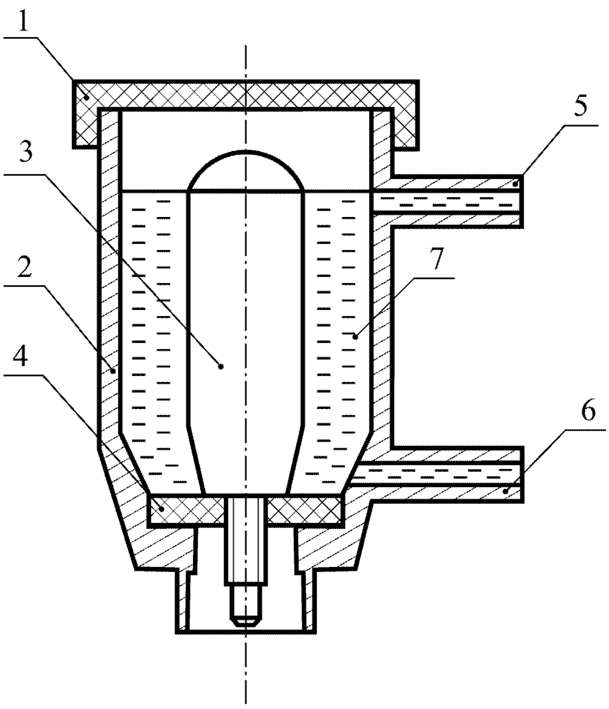


**Fig. 2.** Measuring flowing coaxial converter

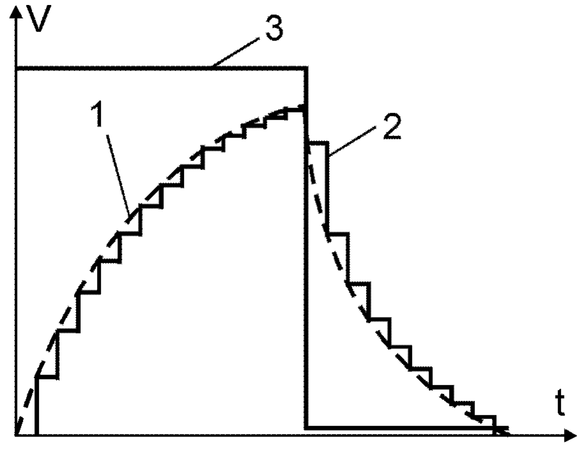


**Fig. 3.** Oscillograms of charge and discharge of capacity MT: 1 – voltage on MT, 2 – voltage, measured DVR, 3 – voltage from the return of generator of G1

Measuring flowing coaxial converter is a component design. Cover lid 1 made of plexiglass is screwed along the thread of corps 2 which is made of bronze. Inside the case 2 is installed insulating washer 4, wherein the central electrode 3 is fixed. Through the channel inlet tube 5, TO 7 is supplied in MT, and through the channel outlet tube 6 it are outputted from the MT. An influencing signal (voltage) is given on a central electrode 3 and corps 2.

Thus the device of DVR, which measuring voltage on MT must measure the instantaneous voltage with frequency far higher than frequency of generator $G1$, to get a stepped curve 2, which maximally is repeated as close to the curve 1.

The resistor R1 should be selected so that the maximum value of the curve charge was 90-95% of the output voltage of the generator $G1$. Resistor R2 must be selected so that the minimum value on the discharge curve was 5-10% of the generator output voltage $G1$. This is necessary because if the specified voltage will deviate from these limits, then with the same frequency f1, the testing accuracy decreases.

**Schema of substitution of the process of charge and process of discharge.** Quality factor of measuring transducer with TO depend of correlation from active conductivity to reactive conductivity. Thus, for determination of quality factor should be measure capacity and active constituting of conductivities of MT with TO. For this purpose in beginning necessary to get dependence of voltage of charge and voltage of discharge on time ($U_{ch} = f(t)$ and $U_{dis} = f(t)$).

Measuring of dependences of voltage of charge and voltage of discharge from time is made in accordance with a schema, shown on a Fig. 1.

The got results will directly correlate with a capacity and active conductivity of TM with transformer oil. However it is necessary obtain reverse dependencies capacity and active resistance TM integral voltage charge and discharge voltage $C_1 = f(U_{ch}, U_{dis})$ and $R_1 = f(U_{ch}, U_{dis})$.

Therefore were composed of the equivalent schemas of substitution for the charging and discharge process [17].

When during a 0.5 sec. there is a charge of capacity MT with transformer oil, then a circuit of discharge is disconnect, and transitional resistance of the switch $S1$ and internal resistance of generator $G1$ it is possible to ignore [25]. To accept, that in the process of charge of MT a generator will be the DC voltage source, because the charging process on duration is equal to time of impulse of generator $G1$ and equal 0,5 sec. Under the above assumptions was obtained the schema of substituting for the process of charge MT with transformer oil, shown in Fig. 4 [24].

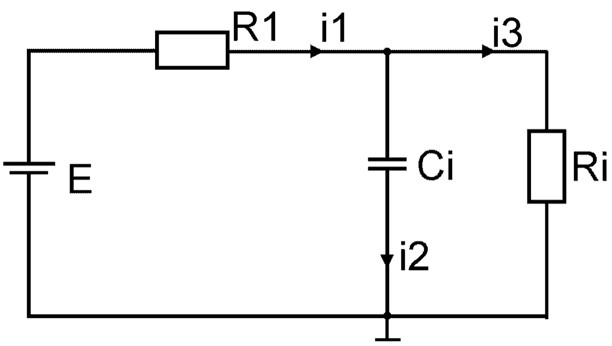


**Fig. 4.** Schema of substituting for the process of charge MT with transformer oil

When during a 0,5 sec. there is a discharge of capacity MT with transformer oil, then a circuit of charge is a disconnect, and transitional resistance of the switch $S1$ it is possible to ignore and consider that a condenser is charged to the maximal value of voltage [25]. Under the above assumptions was obtained the schema of substituting for the process of discharge MT with transformer oil, shown on a Fig. 5 [24].

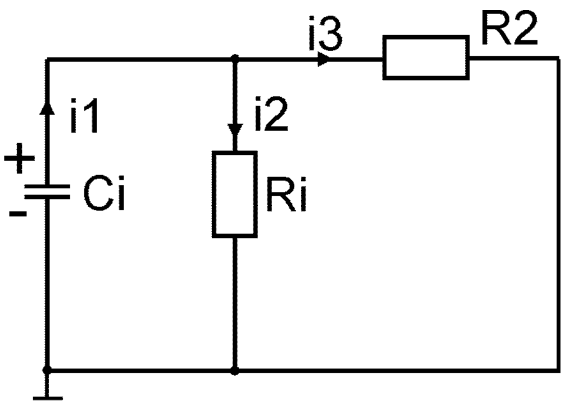


**Fig. 5.** Schema of substituting for the process of discharge MT with transformer oil

**Calculation of analytical dependences for the process of charge.** For determination of dependence of voltage of charge on MT $U_{ch}$ from a capacity $C_1$ and active resistance $R_1$ in the schema of substitution, shown on a Fig. 4, the system of equations was made by the system of equations on I and II Kirchhoff laws [2, 18] at zero initial conditions [6, 7]:

$$\begin{cases} i_1 - i_2 - i_3 = 0, \\ i_1 R_1 + \dfrac{1}{C_1} \int i_2 dt = E, \\ i_1 R_1 + i_1 R_1 = E. \end{cases} \qquad (1)$$

For free currents the system of equations will look like the following:

$$\begin{cases} i_1 - i_2 - i_3 = 0, \\ i_1 R_1 + \dfrac{1}{C_1} \int i_2 dt = 0, \\ i_1 R_1 + i_1 R_1 = 0. \end{cases} \qquad (2)$$

Passing to operator form, obtain [2, 18]:

$$\begin{cases} i_1 - i_2 - i_3 = 0, \\ i_1 R_1 + \dfrac{i_2}{C_1 p} = 0, \\ i_1 R_1 + i_1 R_1 = 0. \end{cases} \quad (3)$$

Completely decide the all system does not necessarily, because there is not necessary to obtain current values circuit, but it is necessary to define dependence voltage of charge on the parameters MT with transformer oil, therefore make up a matrix for the determinant of the system:

$$\begin{vmatrix} 1 & -1 & -1 \\ R_1 & \dfrac{1}{C_1 p} & 0 \\ R_1 & 0 & R_1 \end{vmatrix}. \quad (4)$$

From the obtained matrix define characteristic equation [2, 18]:

$$\frac{r1 + ri + C_1 \cdot p \cdot r1 \cdot ri}{C_1 p} = 0. \quad (5)$$

This equation has only one root of the equation is not equal to 0:

$$p = \frac{-R_1 - R_1}{R_1 \cdot R_1 \cdot C_1}. \quad (6)$$

For a root, not having imaginary part, it is possible to consider a process, which is described by equation for the current charge of condenser:

$$i_c = A_{ch} \cdot e^{pt}. \quad (7)$$

For a root, not having imaginary part, it is similarly possible to consider the process of charge of condenser, which is described by equation for voltage on a condenser [6, 7]:

$$U_c = A \cdot (1 - e^{pt}). \quad (8)$$

Solving the equation (Eq. 6) with the following parameters MT: $R_1 = 100000\,Ohm$, $C_1 = 10^{-6}\ F$, $R_1 = 1000000\ Ohm$, obtain:

$$p = \frac{-R_1 - R_1}{R1 \cdot RI \cdot CI} = \frac{10^5 - 10^6}{10^5 \cdot 10^6 \cdot 10^{-6}} = -11. \quad (9)$$

When: $p = -11$ obtain the following dependence of the current through the capacitor during the its charge:

$$i_c = A_{ch} \cdot e^{-11 \cdot t}. \quad (10)$$

Parameter $A_{ch}$ is the maximum current at the moment when a the voltage pulse edge supplied from the generator $G1$, and this current is defined:

$$A_{ch} = i_{max} = \frac{U_{out}}{R_1} = \frac{5}{100000} = 5 \cdot 10^{-5}\ A, \quad (11)$$

where: $U_{out} = 5V$ – a voltage output from the generator $G1$.

A result obtain graph of depending of the capacitor charge current from the time, which is represented in Fig. 6.

For the root, which has no imaginary part as it is possible to consider the charging of the capacitor, which is described by the equation for the voltage on the capacitor [6, 7]:

$$U_c = A \cdot (1 - e^{pt}). \quad (12)$$

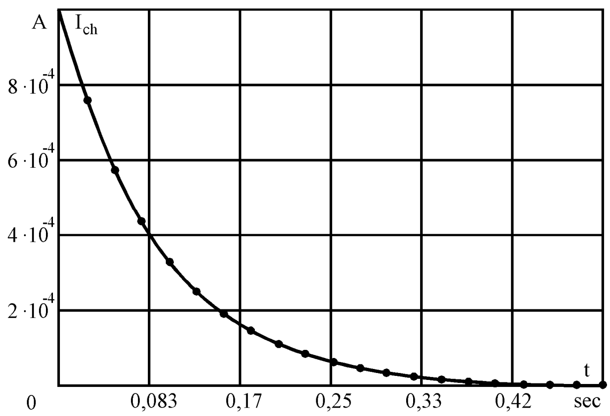


**Fig. 6.** Oscillograms of the capacitor charging current

As a result, obtain the following dependence of the voltage on the capacitor during the charge:

$$U_c = A_{ch} \cdot (1 - e^{-11t}). \quad (13)$$

The parameter $A$ is the maximum voltage supplied from the generator $G1$, which is defined:

$$A_{ch} = U_{max} = 5V. \quad (14)$$

A result obtain graph of depending of the capacitor charge voltage from the time, which is represented in Fig. 7.

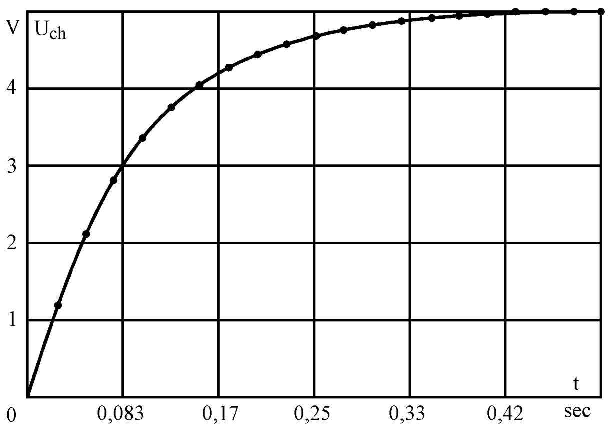


**Fig. 7.** Oscillograms of the capacitor charging voltage

An area under the curve charge of measuring transducer is determined for voltage:

$$S = A_{ch}\int(1 - \cdot e^{p \cdot t})dt = A_{ch} \cdot \left(t - \frac{1}{p} \cdot e^{pt}\right). \quad (15)$$

The size of this area can be got by adding up of voltages in times of a 0.5 s., while there is a discharge, and multiply this sum on the size of interval between measuring $dt$:

$$A_{ch} \cdot \left(t - \frac{1}{p} \cdot e^{pt}\right) = dt\sum_{n=1}^{m} U_n. \quad (16)$$

Hence obtain the value of $p$, using the Lambert $W$ [4]:

$$p = -\frac{1}{t} \cdot W\left(-A_{ch}\frac{t}{A_{ch} \cdot t - dt \cdot \sum_{n=1}^{m} U_n}\right). \quad (17)$$

Since the root of the characteristic equation is $p = \frac{-R_1 - R_I}{R_1 \cdot R_I \cdot C_I}$, then putting (Eq. 6) in (Eq. 17) get next equality:

$$\frac{-R_1 - R_I}{R_1 \cdot R_I \cdot C_I} = -\frac{1}{t} \cdot W\left(-A_{ch}\frac{t}{A_{ch} \cdot t - dt \cdot \sum_{n=1}^{m} U_n}\right). \quad (18)$$

Hence find the value $C_I$ and $R_I$

$$C_I = \frac{(R_1 + R_I) \cdot t}{W\left(-A_{ch} \cdot \frac{t}{A_{ch} \cdot t - dt \cdot \sum_{n=1}^{m} U_n}\right) \cdot R_1 \cdot R_I}. \quad (19)$$

$$R_I = \frac{t \cdot R_1}{W\left(-A_{ch} \cdot \frac{t}{A_{ch} \cdot t - dt \cdot \sum_{n=1}^{m} U_n}\right) \cdot R_1 \cdot C_I - t}. \quad (20)$$

**Calculation of direct and reverse analytical dependences for the process of discharge.** For determination of dependence voltage of charge on MT $U_{dis}$ from a capacity $C_I$ and active resistance $R_I$ in the schema of substitution, shown on a Fig. 5, the system of equations was made by the system of equations on I and II Kirchhoff laws [2, 18] at zero initial conditions[6, 7]:

$$\begin{cases} i_1 - i_2 - i_3 = 0, \\ \frac{1}{C_I}\int i_1 dt + i_2 R_I = 0, \\ \frac{1}{C_I}\int i_1 dt + i_3 R_2 = 0. \end{cases} \quad (21)$$

Passing to operator form, obtain [2, 18]:

$$\begin{cases} i_1 - i_2 - i_3 = 0, \\ \dfrac{i_1}{C_1 p} + i_2 R_1 = 0, \\ \dfrac{i_1}{C_1 p} + i_3 R_2 = 0. \end{cases} \quad (22)$$

Completely decide the all system does not necessarily, because there is not necessary to obtain current values circuit, but it is necessary to define dependence voltage of charge on the parameters MT with transformer oil, therefore make up a matrix for the determinant of the system:

$$\begin{vmatrix} 1 & -1 & -1 \\ \dfrac{1}{C_1 p} & R_1 & 0 \\ \dfrac{1}{C_1 p} & 0 & R_2 \end{vmatrix}. \quad (23)$$

From the obtained matrix define characteristic equation [2, 18]:

$$\frac{r2 + ri + Ci \cdot p \cdot r2 \cdot ri}{Ci \cdot p} = 0. \quad (24)$$

This equation has only one root of the equation is not equal to 0:

$$p = \frac{-R_2 - R_1}{R_2 \cdot R_1 \cdot C_1}. \quad (25)$$

For a root, not having imaginary part, it is possible to consider a process, which is described by equation for the current charge of condenser:

$$i_c = A_{dis} \cdot e^{pt}. \quad (26)$$

For a root, not having imaginary part, it is similarly possible to consider the process of charge of condenser, which is described by equation for voltage on a condenser [6, 7]:

$$U_c = A_{dis} \cdot e^{pt}. \quad (27)$$

An area under the curve charge of measuring transducer is determined for voltage:

$$S = A_{dis} \int e^{p \cdot t} dt = \frac{A_{dis}}{p} \cdot e^{pt}. \quad (28)$$

The size of this area can be got by adding up of voltages in times of a 0.5 s., while there is a discharge, and multiply this sum on the size of interval between measuring $dt$:

$$\frac{A_{dis}}{p} \cdot e^{pt} = dt \sum_{n=1}^{m} U_n. \quad (29)$$

Hence obtain the value of $p$, using the Lambert $W$ [4]:

$$p = -\frac{1}{t} \cdot W\left( -A_{dis} \frac{t}{dt \sum_{n=1}^{m} U_n} \right). \quad (30)$$

Since the root of the characteristic equation is $p = \frac{-R_2 - R_1}{R_2 \cdot R_1 \cdot C_1}$, then putting (Eq. 25) in (Eq. 30) get next equality:

$$\frac{-R_2 - R_1}{R_2 \cdot R_1 \cdot C_1} = -\frac{1}{t} \cdot W\left( -A_{dis} \cdot \frac{t}{dt \sum_{n=1}^{m} U_n} \right). \quad (31)$$

Hence find the value $C_1$ and $R_1$

$$C_1 = (R_2 + R_1) \cdot \frac{t}{W\left( -A_{dis} \cdot \dfrac{t}{dt \sum_{n=1}^{m} U_n} \right) \cdot R_2 \cdot R_1}, \quad (32)$$

$$R_1 = t \cdot \frac{R_2}{W\left( -A_{dis} \cdot \dfrac{t}{dt \cdot \sum_{n=1}^{m} U_n} \right) \cdot R_2 \cdot C_1 - t}. \quad (33)$$

Supposing that $C_1$ unchanging and for the process of charge and for the process of discharge will equate (Eq. 19) and (Eq. 32)

$$\frac{(R_1+R_I)\cdot t}{W\left(-A_{ch}\cdot\frac{t}{A_{ch}\cdot t-dt\cdot\sum_{n=1}^{m}U_n}\right)\cdot R_1\cdot R_I}=\frac{(R_2+R_I)\cdot t}{W\left(-A_{dis}\cdot\frac{t}{dt\sum_{n=1}^{m}U_n}\right)\cdot R_2\cdot R_I}. \tag{34}$$

Since the maximum charging voltage equals the maximum voltage of the discharge, i.e. $A_{ch}=A_{dis}$, from (Eq. 34) determine the active resistance of MT:

$$R_I=\frac{R_1R_2\left(W\left(\frac{-A\cdot t}{A\cdot t+dt\sum_{n=1}^{m}U_{n\,ch}}\right)-W\left(\frac{-A\cdot t}{dt\sum_{n=1}^{m}U_{n\,dis}}\right)\right)}{-W\left(\frac{-A\cdot t}{A\cdot t-dt\sum_{n=1}^{m}U_{n\,ch}}\right)R_1+W\left(\frac{-A\cdot t}{dt\sum_{n=1}^{m}U_{n\,dis}}\right)R_2}. \tag{35}$$

Supposing that $R_I$ unchanging for the process of charge and for the process of discharge will equate (Eq. 20) and (Eq. 33)

$$\frac{R_1\cdot t}{W\left(-A_{ch}\cdot\frac{t}{A_{ch}\cdot t-dt\cdot\sum_{n=1}^{m}U_{n\,ch}}\right)\cdot R_1\cdot C_I-t}=\frac{R_2\cdot t}{W\left(-A_{dis}\cdot\frac{t}{dt\sum_{n=1}^{m}U_{n\,dis}}\right)\cdot R_2\cdot C_I-t}. \tag{36}$$

Since maximal voltage of charge is equal to maximal voltage of discharge, i.e. $A_{ch}=A_{dis}$, then from (Eq. 36) determine the capacity of MT:

$$C_I=\frac{-t\cdot(R_1-R_2)/R_1\cdot R_2}{\left(W\left(\frac{-A\cdot t}{A\cdot t-dt\cdot\sum_{n=1}^{m}U_{n\,ch}}\right)-W\left(\frac{-A\cdot t}{dt\sum_{n=1}^{m}U_{n\,dis}}\right)\right)}. \tag{37}$$

Thus, first measured the voltage of the charge $U_{n\,ch}$ and discharge $U_{n\,dis}$ after a fixed period of time $dt$ (equal to the time single conversion of ADC [20]) during the charge equal to the time of discharge, i.e. 0.5 sec.

Then, knowing $R_1$ and $R_2$, with the use of function of Lambert calculated $R_I$ on (Eq. 35) and $C_I$ on (Eq. 37). On these parameters of measuring transducer the quality factor is calculated on the known formula:

$$Q=\omega R_I C_I. \tag{38}$$

where: $\omega$ – frequency of generator $G_1$, equal 1 Hertz.

Should be noted that the function Lambert is calculated by recursion formula:

$$W_{j+1}=W_j-\frac{W_je^{W_j}-x}{e^{W_j}(W_j+1)-\frac{(W_j+2)(W_je^{W_j}+x)}{2\cdot W_j+2}}. \tag{39}$$

where: $x$ – argument of function of Lambert [4], $W_j$ – the value calculated of the function of Lambert on a previous iteration, $W_{j+1}$ – the value calculated for the current iteration of the Lambert function.

At first set by the arbitrary value of function of Lambert [4], for example $W_j=0$, calculated $x$ on a formula:

$$x=W_je^{W_j}. \tag{40}$$

Then on (Eq. 39) is calculated the following approximation for the function Lambert $W_{j+1}$ and are checked: if $\Delta<W_{j+1}-W_j$, then $W_j=W_{j+1}$ and the calculation function is repeated.

In view of the foregoing, has been developed a block-scheme of the device transformer oil moisture testing with microprocessor system (Fig. 8).

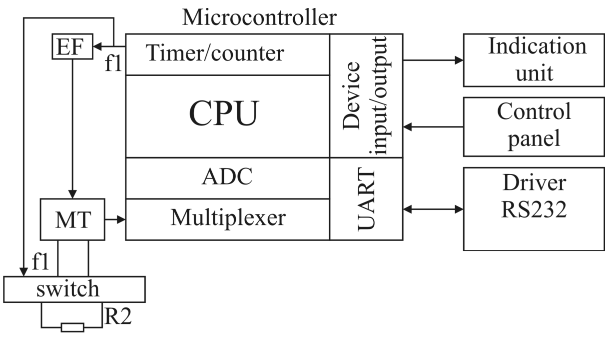


**Fig. 8.** Block-scheme of the device moisture content testing transformer oil

The timer-counter, which is part of the microcontroller is configured to operate as a generator of issuing rectangular pulses with a frequency f1 = 0.5 Hz.

These rectangular pulses at a frequency f1 coming to an emitter follower EF and to the controllable inputs of switch.

EF performs amplification function signal input of timer-counter for current, which allows to significantly increase the loading ability of the generating device.

Thus, the timer-counter, which is part of the microcontroller and EF perform the function generator G1 (Fig. 8) [1, 19].

With the emitter follower signal of amplification current is applied to measuring transducer MT, where there are processes of charge and discharge capacity of MT.

When the negative edge of the input signal comes to the MT, then at the same time the switch connects the resistance R2 for the discharge capacity of MT.

Voltage of MT through a programmable-controlled multiplexer is supplied to analog-to digital converter (ADC), which, as well as a multiplexer, is part of microcontroller [21].

ADC digitizes the input voltage and supplies a result the central processing unit (CPU) for further processing.

The CPU calculates quality factor from the obtained data and transformer oil moisture content, correspondingly, and saves the results in RAM or in non-volatile memory data.

Through built-in interface UART microcontroller connected to a PC through the driver RS232 with the PC, which evens of logic levels [1].

Using the interface connection allows you to transfer measurement results to a PC for further processing.

After computing the result of moisture content periodically displayed on the indicating unit, which is an alpha-numeric liquid crystal display (LCD).

Control of device the measuring of moisture content of TM implemented by the keys on the control panel, which is a matrix keyboard.

Using the keypad, the operator controls the operation of the device may specify the type of the investigated TO transmit testing results to a PC, perform testing for faults, save, and view the results of testing.

## CONCLUSIONS

1. The proposed method of determination of quality factor of MT on the integral value of the measured voltage of charge allows directly through calibration characteristics relate the value of quality factor Q with a moisture content of transformer oil.

2. Use of the function of Lambert in analytical dependences $C_I = f(U_{ch}, U_{dis})$ and $R_I = f(U_{ch}, U_{dis})$, for a moisture testing device of transformer oil necessitates the use microprocessor, able to realize the algorithm of decision these recurrent formulas.

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## ИЗМЕРИТЕЛЬНОЕ УСТРОЙСТВО ВЛАГОСОДЕРЖАНИЯ ТРАНСФОРМАТОРНОГО МАСЛА

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А н н о т а ц и я . В работе рассматриваются вопросы определения влагосодержания трансформаторного масла (ТМ). Предложен метод оперативного определения влагосодержания ТМ. Разработана измерительная схема с проточным измерительным преобразователем для определения добротности ТМ. Получены аналитические зависимости емкости и активного сопротивления измерительного преобразователя с ТМ от интегрального напряжения заряда и разряда.

К л ю ч е в ы е с л о в а : трансформаторное масло, влажность, схема замещения, функция Ламберта, измерительный преобразователь, добротность.