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Research Article

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Measurement of Parameters of Active-inductive Elements of Electric Circuits by Phase Method

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Abstract The problem of separate measurement of the parameters of the inductance coil of alternating current is investigated. A comparative analysis of the methods for measuring the parameters of the coil of alternating current is carried out. The usage of alternating current voltage dividers applying the voltammetric method in combination with the phase method is preferable. The advantages of this technical solution are largely due to the possibility of using microcontrollers.

Keywords Inductance Coil, Inductance, Resistance, Measuring, Phase Method

Introduction

Inductance coil (IC) are widely used in most electrical and electronic devices as chokes for redistributing alternating current across circuits and creating inductive coupling between circuits. ICs are mandatory and main components of relays, contactors, transformers, electrical machines. When used together with capacitors, high-quality oscillating circuits are formed, which are part of the filters and high-frequency oscillators. In most electronic devices, along with RC-chains, RL-chains are also used to integrate or differentiate electrical signals. The properties of these chains form the working frequency band of electronic devices, which leads to a smoothing (integration) of the signal. A large group of devices with ICs are inductive sensors, which are a very affordable, simple, reliable, cheap element of drive control systems, machine tools, automatic lines, as well as systems for measuring physical quantities [1-3]. The advantage of inductive sensors is also a relatively large value of output power - up to several tens of watts [4, 5]. It is also important that ICs using appropriate insulation can successfully operate at temperatures up to 500 °*C*. The production of inductive sensors in the US and Europe alone is engaged in more than 35 companies [6, 7]. The widespread use of ICs requires the creation of high-speed, simple and reliable measuring instruments for ICs parameters compatible with modern microcontroller devices for information processing and measurement process control.

Object of Research

Inductance coils, with the exception of chokes, intended for use in power circuits, are not components, such as resistors and capacitors. They are made according to individual tasks with the required design and parameters necessary for a particular application. The main feature of IC is the use of magnetic cores in them. In IC operating at industrial frequencies, sheet steel is used as a magnetic core, perm alloy is commonly used at frequencies up to 1 *kHz*; at the same time the magnetic core is usually toroidal, assembled from thin rings ($h = 0,002...0,1$ *mm*) or wound from a tape of the same thickness. At higher frequencies, ferrites and magnetodielectrics are widely used, and their brand depends on the operating frequency range [4].

The substitution circuit IC is made taking into account the characteristics of the coil with a ferromagnetic core. In alternating magnetic fields in the IC magnetic circuit, active losses of electrical energy arise due to the phenomena of hysteresis and eddy currents. As a result, the relative magnetic permeability of the magnetic circuit becomes a complex value that has real (μ') and imaginary (μ'') components: $\dot{\mu} = \mu' - j\mu''$. Therefore, the resistance of the coil is determined by the expression

$$Z = R + j\omega L = R + j\omega \frac{W^2 \mu_0 \dot{\mu} S}{l} = R + j\omega \frac{W^2 \mu_0 S}{l} (\mu' - j\mu'') = R_E + j\omega L_E \,, \quad (1)$$

where $R_E = R + \omega W^2 \mu_0 \mu'' S / l$ is the active component of the coil's impedance, which reflects the active energy losses that arise from the alternating current in the coil wire with resistance R and in the magnetic core; $L_E = W^2 \mu_0 \mu' S / l$ - inductance of the coil, which characterizes the ability of the coil to accumulate magnetic energy; W - the number of turns of the winding; ω - the angular frequency of the current through the coil; l - the average length of the magnetic field line; S - cross-sectional area of magnetic field lines; $\mu_0 = 4\pi \cdot 10^{-7}$ *H/m* is the absolute magnetic permeability of a vacuum (air) - the physical constant.

For most IC, inductance is a useful parameter, and active resistance is parasitic, and therefore the quality of such IC is characterized by its good quality: $Q = \omega L_E / R_E$. The exception is eddy current inductive sensors, induction electricity meters, in which a nonmagnetic conducting body is placed in the air gap of the magnetic circuit. In the latter, eddy currents are induced from the alternating magnetic field created by the coil, causing active losses of electrical energy and, consequently, an increase in the active resistance of the coil.

ICs have, as a rule, cylindrical or spiral-shaped turns and are performed both single-layered and multi-layered. If the IC winding contains a large number of turns, and there is a potential difference between the individual turns and the layers of the turns, then the ICs will have some intrinsic capacity C_0 that will be connected parallel to the inductance of the coil itself. Own capacitance IC depends on the size of the coil, the material and shape of the frame, the type of winding, the presence of the screen and can be calculated by the simplified formulas [8] $C_0 = 0{,}5 D_F$ - for single-layer IC and $C_0 = \pi D_0 (8{,}5\varepsilon + 8{,}2) \cdot 10^{-1}$ - for multi-layer IC, where D_F is the diameter of the frame, *cm*; D_0 - average winding diameter, *cm*; ε - relative dielectric constant of the wire winding insulation. The smallest proper capacitance (several picofarads) is observed in single-layer coils wound with forced pitch. Multilayer coils have greater capacity. So, the capacity of coils with universal winding is 5...25 *pF*, and with ordinary multilayer winding it can be higher than 50 *pF* [9]. Own capacitance C_0 forms with the coil inductance a parallel oscillating circuit, the resonant frequency $f_0 = 1 / 2\pi \sqrt{L_E C_0}$ of which is the frequency of the intrinsic resonance of the IC. As a rule, the vast majority of ICs operate at frequencies much lower than the resonant.

Own capacitance reduces the Q-factor of IC, introducing additional loss resistance R_C, which leads to the release of active power in dielectric insulation

$$P_C = I^2 R_C = U^2 \omega C_0 tg\delta = I^2 \omega^3 L_E{}^2 C_0 tg\delta \,,$$

where $U = I\omega L_E$; $tg\delta$ - the tangent of dielectric loss of the insulation of the wire and frame IC. Hence follows the formula for calculating the serial loss resistance R_C in the coil's own capacity:

$$R_C = \omega^3 L_E{}^2 C_0 tg\delta \,.$$

Resistance R_C is relatively small. For example, at a frequency of $f = 5$ *kHz* with $L_E = 1{,}0$ *H*, $C_0 = 5$ *pF*, $tg\delta = 10^{-2}$ we get

$$R_C = (6{,}28 \cdot 5000)^3 \cdot 1{,}0^2 \cdot 5 \cdot 10^{-12} \cdot 10^{-2} \approx 1{,}25 \;\; Om.$$

In some cases, under certain restrictions, the use of a priori information about the model of an object of study allows one to reduce bipolar electrical circuits to a linear two-element bipolar electrical circuit, which greatly simplifies the separate determination of its parameters [10]. In the case of an IC with a relatively low current frequency (up to several hundred kilohertz), the IC full equivalent circuit can be replaced by a simplified equivalent circuit in the form of a series connection of a resistor R_X and inductance L_X (fig. 1).

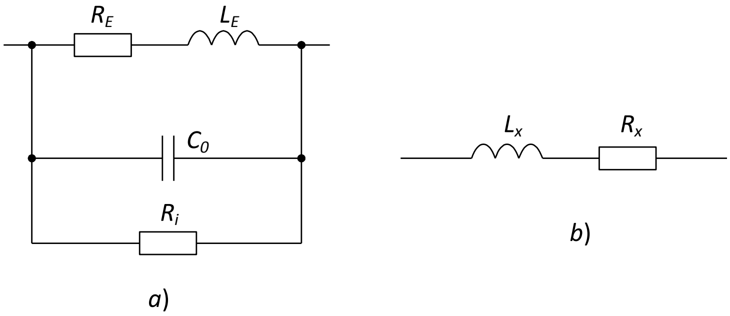

Figure 1: A substitution scheme IC:
a - full, b - simplified

Possible values of inductance of the coils of oscillating circuits, chokes, windings of transformers, electrical machines and other electromagnetic devices lie in the range from about 1 *nH* to 10 *kH* [4]. In particular, for power transformers, typical values of inductance and resistance of the primary winding are: $L_X = 10...100$ *H*, $R_X = 50...200$ *Om* [11]. Powerful chokes (filter coils, rectifiers, etc.), designed for small amplifiers, as a rule, have an inductance of 10...15 *H* and are designed for currents of 100...250 μA. For such chokes, the resonant frequency is from 3 to 12 *kHz*. At frequencies higher than the resonant value, the chokes cannot provide an effective barrier to the noise generated by the rectification of alternating current, or to the RF noise coming through the supply network. High-frequency ICs have a quality of about 300...400 [12]. Thin-film miniature ICs with ferrite cores are used in hybrid integrated circuits. They have a frequency range of 10...100 *MHz*, are made in the form of a circular or square helix and have a number of turns on the square of 1 cm^2 not more than 10, their quality factor is about 20...50.

Materials and Methods

From the above formula (1), it can be seen that the active resistance R_X of the IC also depends on the frequency of the current supplying the coil, therefore, the parameters of the IC should be measured with an alternating current (AC) of the frequency at which the use of the IC is envisaged. Moreover, considering the nonlinearity of the magnetization curve of the magnetic circuit, the measuring (test) current is also desirable to choose equal to the operating current IC. In addition, since the IC equivalent circuit is a complex impedance, the measuring circuit must provide separate measurement of the parameters R_X and L_X.

For separate measurement of the parameters of a two-element IC substitution circuit, balanced AC bridges and some of the resonance method circuits have become most common [13, 14]. The bridge method of measuring IC parameters is applied at relatively low frequencies - up to 1000 *Hz*, the measurement error is of the order of 1...3%, the limits of inductance measurement are 0,01...1000 *H* [14]. The resonance method is used at frequencies from 10 *kHz* to 1,5 *MHz*, since at low frequencies the resonance appears less sharply. The error of the resonant measuring instrument of the IC parameters is 2...5%, the limits of inductance measurements are from 0,05 μH to 100 *mH*.

The bridge and resonant methods for the separate determination of IC parameters on AC are well studied and continue to be successfully improved. Their main disadvantages are the complexity of implementation (balancing the AC bridge in two quantities requires at least two adjustable elements in its circuit), a long measurement time and the inconvenience of automation with the use of computer technology.

A relatively new direction in the field of measuring parameters of passive electric two-poles is the use of AC voltage dividers using the phase method in combination with the method of temporal separation of the measurement channel. In this case, the information carrier is only a phase signal. The development of this direction is largely due to the widespread use of programmable microcontrollers (PMC) in measurement technology. This technical solution was used by us for separate measurement of parameters of passive electric two-terminal networks [15-17].

Results

The essence of the separate measurement of the parameters of a sequential IC substitution scheme is explained in fig. 2, where: 1 - measuring circuit (MC); 2 - studied two-port; 3 - programmable generator of sinusoidal signals; 4 - electronic switch; 5 - PMC; 6 - digital readout device (DRD); 7 - interface converter; 8 - the computer.

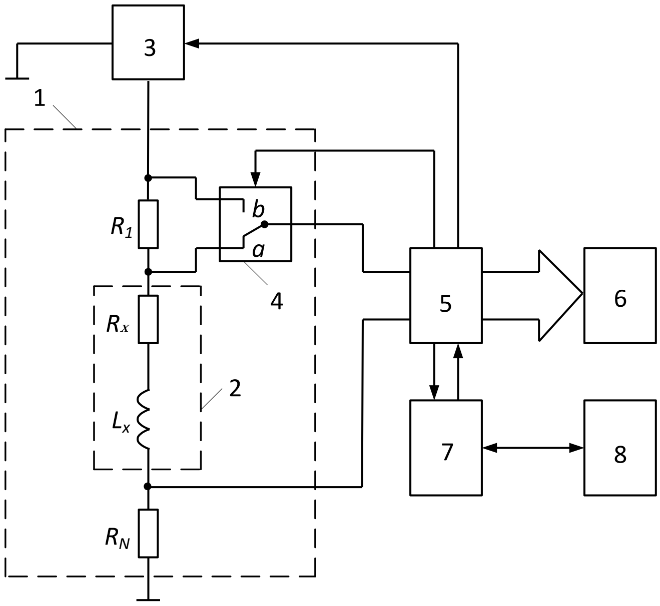

Figure 2: A simplified schematic diagram of the measuring parameters of the inductor

In MC, two reference resistors are connected in series with the IC: reference (R_N) and additional (R_1). The resulting MC in the form of a voltage divider is connected to a sinusoidal signal generator. MC has two output voltages relative to the common point, which are fed to the input of the PMC: the voltage u_S of the common contact of the switch and the voltage u_N of the reference resistor, while the informative signal is the angle φ of the phase shift between these voltages. During the measurement process, the PMC sets the required oscillator frequency ω, controls the position of the switch, and measures the values φ_1 and φ_2 angles φ in two positions of the switch. The relationship between the angle φ and the parameters of a two-port network is generally determined by the expression

$$tg\varphi_1 = \mathrm{Im}\left(\dot{U}_S/\dot{U}_N\right)\Big/\mathrm{Re}\left(\dot{U}_S/\dot{U}_N\right), \tag{2}$$

where $\mathrm{Re}\left(\dot{U}_S/\dot{U}_N\right)$ is the real part of the relation of voltages $\dot{U}_S/\dot{U}_N$, $\mathrm{Im}\left(\dot{U}_S/\dot{U}_N\right)$ is the imaginary part of this excuse. Using formula (2) we find:

- in switch a position

$$ctg\varphi_1 = \frac{R_N + R_X}{\omega L_X}, \tag{3}$$

- in switch b position

$$ctg\varphi_2 = \frac{R_N + R_X + R_1}{\omega L_X}. \tag{4}$$

Subtract from the expression (4) the expression (3): $ctg\varphi_2 - ctg\varphi_1 = R_1/\omega L_X$, whence we get

$$L_X = \frac{R_1}{\omega\left(ctg\varphi_2 - ctg\varphi_1\right)}. \quad (5)$$

Now divide the expression (4) into the expression (3):

$$\frac{ctg\varphi_2}{ctg\varphi_1} = 1 + \frac{R_1}{R_N + R_X},$$

where do we get

$$R_X = \frac{R_1}{\frac{ctg\varphi_2}{ctg\varphi_1} - 1} - R_N. \quad (6)$$

Formulas (5) and (6) show that a separate measurement of the parameters R_X and L_X is provided. It can be seen that it is required to measure only the phase shift angle between two output voltages of the MC. The PMC measures the angle φ values, calculates the parameters L_X and R_X according to the formulas (5) and (6) and displays the measurement results on a digital display, in which seven-segment LED indicators are used. To increase the reliability of the measurement result, the PMC at each point performs 10 measurements and displays the average result of these measurements on the indicator.

In the general case, the results of measuring the IC parameters also depend on the frequency of the supply current, therefore, a programmable generator of sinusoidal signals (for example, an AD9833 chip) is used as the IC power generator. At each measurement, the PMC sets the generator frequency and uses this value when calculating the IC parameters. The stability of the generator voltage is not significant, because in formulas (5), (6) the generator voltage does not appear. Thus, the accuracy of determining the IC parameters depends only on the accuracy of angle measurement, which is performed in the PMC by a discrete counting method; therefore, the measurement accuracy is significantly higher compared to methods using analog signals.

In PMC, the angle φ is converted into a time interval τ, the τ and period T is measured, according to the formula

$$\varphi = \frac{\tau}{T}\cdot 360^o = \frac{nf_0}{Nf_0}\cdot 360^o = \frac{n}{N}\cdot 360^o$$

the angle φ is calculated (f_0 - is the frequency of the quantizing pulses) and is determined by formulas (5), (6) R_X and L_X.

The development used a microcontroller PIC32MX695F512H, the central processor of which can operate up to a maximum frequency equal to 80 *MHz*. To improve the measurement accuracy, an external quartz resonator with a frequency of 8 *MHz* was used. This frequency is multiplied inside the PMC by 10, it turns out 80 *MHz*, on which the PMC, the core, the counters and all peripheral devices operate.

If necessary, it is possible to send digitized angle signals from the PMC to an interface converter (for example, AVR309) to send to the computer, process them there, output the measurement results to the computer monitor and save the measurement results base.

In the diagram of fig. 2 IC does not have a common point with a neutral wire, so it is not applicable for grounded ICs; in this case, IC should be applied according to the scheme of fig. 3*a*. Here the reference resistor is connected between the common wire and the second terminal of the generator, and through it current flows in the opposite direction with the current IC. Similar to the above formulas, in this case we get

$$\dot U_N = -\dot I R_1,\ \dot U_{S1} = \dot I\left(R_X + j\omega L_X\right),\ \dot U_{S2} = \dot I\left(R_2 + R_X + j\omega L_X\right),$$

$$ctg\varphi_1 = \frac{R_X}{\omega L_X},\ ctg\varphi_2 = \frac{R_2 + R_X}{\omega L_X},$$

$$L_X = \frac{R_2}{\omega\left(ctg\varphi_2 - ctg\varphi_1\right)},\quad R_X = \frac{R_2}{\frac{ctg\varphi_2}{ctg\varphi_1} - 1}. \quad (7)$$

From (7) it can be seen that in this case, the results of determining the IC parameters also do not depend on the resistance R_1.

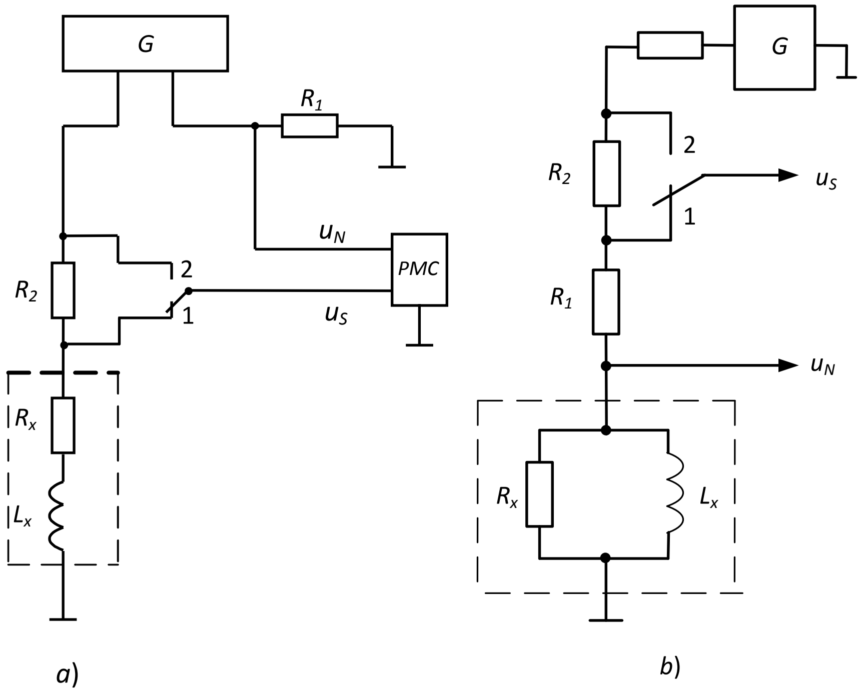

Figure 3. MC schemes for measuring the parameters of IC: a – for grounded IC;

Analysis of possible MC shows that in the case when the active-inductive two-port network is specified in the form of a parallel connection R_X and L_X, then it is necessary to choose the scheme of fig. 3*b* so that it is possible to provide separate measurement R_X and L_X. For positions 1 and 2 of the switch from the formula (2) it follows that $tg\varphi_1 = -\frac{R_1R_X}{(R_1+R_X)\omega L_X}$, $tg\varphi_2 = -\frac{(R_1+R_2)R_X}{(R_1+R_2+R_X)\omega L_X}$, taking into account which we get the formulas:

$$R_X = \frac{R_1(R_1+R_2)(tg\varphi_2/tg\varphi_1 - 1)}{R_2 - R_1(tg\varphi_2/tg\varphi_1 - 1)}, \quad (8)$$

$$L_X = \frac{R_1(R_1+R_2)}{\omega R_2}\cdot(ctg\varphi_2 - ctg\varphi_1). \quad (9)$$

In the formula (8) does not appear L_X, and in (9) - R_X, i.e. their separate definition is provided.

To measure the $Q = \omega L_X / R_X$ factor IC by the phase method, MC is used according to the scheme of fig. 4*a*. In this scheme $\dot U_0 = \dot I R_0$, $\dot U_X = -\dot I(R_X + j\omega L_X)$, $tg\varphi = \frac{\mathrm{Im}(\dot U_0/\dot U_X)}{\mathrm{Re}(\dot U_0/\dot U_X)}$,

$$\frac{\dot U_0}{\dot U_X} = \frac{\dot I R_0}{-\dot I(R_X + j\omega L_X)} = \frac{R_0}{-(R_X + j\omega L_X)} = -\frac{R_0(R_X - j\omega L_X)}{(R_X + j\omega L_X)(R_X - j\omega L_X)} = -\frac{R_0(R_X - j\omega L_X)}{R_X{}^2 + (\omega L_X)^2},$$

consequently,

$$tg\varphi = \frac{\omega L_X}{R_X} \text{ or } Q = tg\varphi,$$

where you can see that the resistance of the resistor R_0 does not affect the measurement result.

Obviously, in the considered circuits, the studied two-port circuit with R_X and L_X can also be a single inductive primary converter (IPC). In the case of a differential IPC, we applied MC according to the scheme in fig. 4*b*, where inductance (classical IPC) and active resistance (eddy current type IPC) can be sensitive parameters. In this scheme, for the phase shift angle between the output voltages $\dot{U}_S$ and $\dot{U}_X$ in the first (initial) and second switch positions, you can write, respectively

$$tg\varphi_1 = \frac{\omega L_1}{R_1 + R_N}, \tag{10}$$

$$tg\varphi_2 = \frac{\omega L_2}{R_2 + R_N}. \tag{11}$$

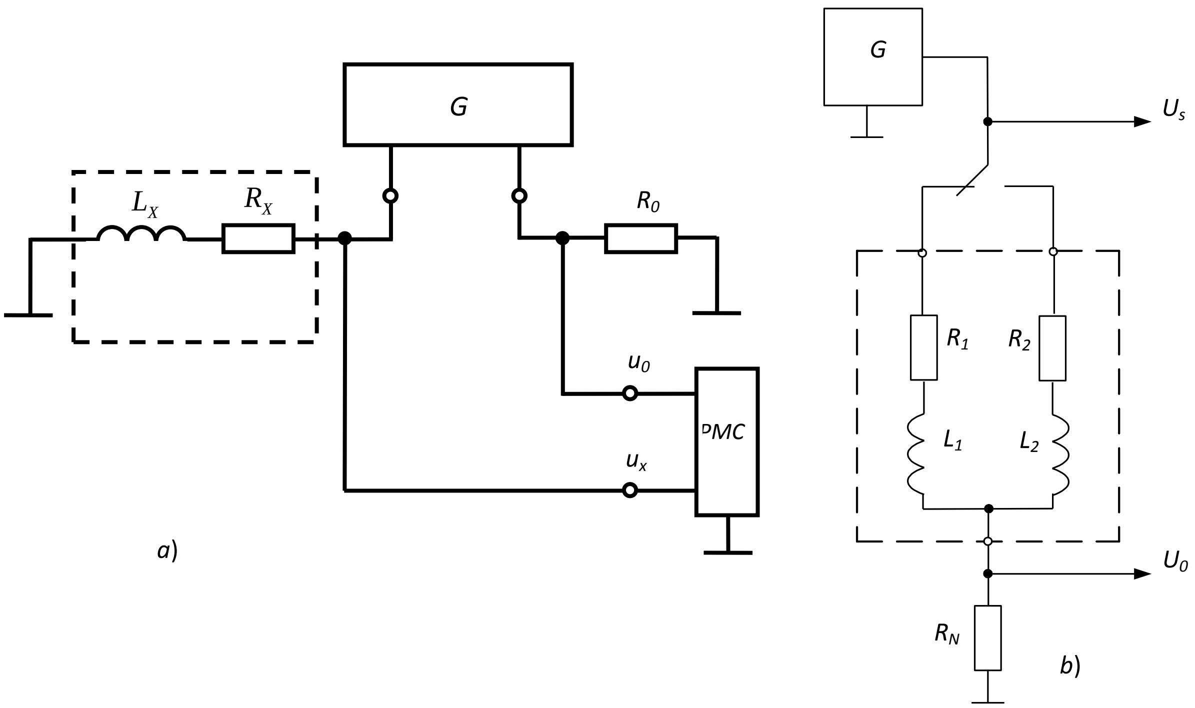

Figure 4: MC schemes for measurement: a – quality factor of the IC; b - parameters of differential IPC

If the informative parameter is unbalance of inductance (ΔL), then $L_1 = L_0 + \Delta L$, $L_2 = L_0 - \Delta L$, $R_1 = R_2 = R_0$, where R_0 and L_0 are the initial values of these parameters, which are constant and known (indicated in the passport data of the IPC). For this case, from (10) and (11) follows:

$$tg\varphi_1 - tg\varphi_2 = \frac{\omega(L_1 - L_2)}{R_0 + R_N} = \frac{2\omega\Delta L}{R_0 + R_N}, \qquad tg\varphi_1 + tg\varphi_2 = \frac{\omega(L_1 + L_2)}{R_0 + R_N} = \frac{2\omega L_0}{R_0 + R_N},$$

where we get the formula for determining the informative parameter IPC:

$$\Delta L = L_0 \cdot \frac{tg\varphi_1 - tg\varphi_2}{tg\varphi_1 + tg\varphi_2} = L_0 \cdot \frac{\sin(\varphi_1 - \varphi_2)}{\sin(\varphi_1 + \varphi_2)}. \tag{12}$$

If the informative parameter is the unbalance of active resistances, then $R_1 = R_0 + \Delta R$, $R_2 = R_0 - \Delta R$, $L_1 = L_2 = L_0$. From (10) and (11) we determine

$$ctg\varphi_1 = \frac{R_1 + R_N}{\omega L_0} = \frac{R_0 + \Delta R + R_N}{\omega L_0},\ ctg\varphi_2 = \frac{R_2 + R_N}{\omega L_0} = \frac{R_0 - \Delta R + R_N}{\omega L_0},\ ctg\varphi_1 - ctg\varphi_2 = \frac{2\Delta R}{\omega L_0},$$

$$ctg\varphi_1 + ctg\varphi_2 = \frac{2(R_0 + R_N)}{\omega L_0},\ \frac{ctg\varphi_1 - ctg\varphi_2}{ctg\varphi_1 + ctg\varphi_2} = \frac{\Delta R}{R_0 + R_N},$$

where do we get

$$\Delta R = (R_0 + R_N)\cdot\frac{ctg\varphi_1 - ctg\varphi_2}{ctg\varphi_1 + ctg\varphi_2} = (R_0 + R_N)\cdot\frac{\sin(\varphi_2 - \varphi_1)}{\sin(\varphi_2 + \varphi_1)}. \quad (13)$$

From formulas (12) and (13) it follows that MC according to the scheme of Fig. 4*b* provides a separate measurement of the parameters of the differential IPC.

Estimation of Measurement Error

A method has been developed for a theoretical study of the error of measurement of the two-poles parameters by the phase method, which can be applied to all MC considered here [18]. In particular, in relation to the MC, Fig. 4*b* for the case of formula (12), the following expression of the relative measurement error is obtained:

$$\delta(\Delta L) = \frac{f}{f_0}\cdot(\varphi_1 - \varphi_2)\cdot ctg(\varphi_1 - \varphi_2). \quad (14)$$

It is seen that the measurement error is smaller, the greater the frequency of the PMC clock generator and the smaller the frequency of the MC power generator. In this case, with an increase in the difference $(\varphi_1 - \varphi_2)$, the error decreases. We estimate the possible values of the error by the formula (14). Let in the scheme of Fig. 4*b* differential IPC has parameters $L_0 = 10\ mH$, $R_0 = 3\,Om$, $\Delta L = 0...5\ mH$, $f = 10\ kHz$, $f_0 = 80\ MHz$. To ensure the conditions of maximum sensitivity, which is the case $\varphi_0 = 45^o$ when, the reference resistor must have an $R_N = 628\,Om$

$$\delta(\Delta L) = 0{,}125\cdot10^{-3}\cdot(\varphi_1 - \varphi_2)\cdot ctg(\varphi_1 - \varphi_2)\cdot$$

The increments $\Delta L = 0...5\ mH$ correspond to changes in angles within the limits $\varphi_1 = 45^o...56^o18'$, $\varphi_2 = 45^o...26^o34$ and changes in the relative error within $\delta(\Delta L) = 0{,}0125...0{,}0114\%$, which is a sufficiently high accuracy.

The phase method is used to measure the mutual inductance M of two magnetically coupled coils. Currently, there are two classical methods of M measurement. The first of these is the method of an ammeter, a voltmeter, and a wattmeter [19]. Investigated two coils are connected in series, according to and in series with; in both cases, the current I, voltage U, and active power P of the circuit are measured. According to the measurement results, the reactance of the circuit is determined: $X = \sqrt{z^2 - R^2} = \sqrt{(U/I)^2 - P^2/I^4}$ and, using the dependences $X_A = \omega(L_1 + L_2 + 2M)$, $X_B = \omega(L_1 + L_2 - 2M)$, where X_A is the value X with the coils turned on consistently, and X_B with the opposite, the mutual inductance is calculated:

$$M = (X_A - X_B)/4\omega,$$

where ω - the angular frequency of the current supply circuit; L_1 and L_2 - inductance of the first and second coils, respectively. The method is complicated and time-consuming, has low accuracy due to the need to measure many quantities, each of which, of course, is accompanied by its own error; a single output signal is not provided for conjugation of MC with computer equipment for automated processing of measurement information.

The transformer idling method is simpler [19]. With the help of the investigated coils form the primary and secondary windings of the transformer. The primary winding is fed with AC I_1, this current and the voltage $U_2 = E_2$ of the secondary winding terminals are measured in idle mode and the mutual inductance of the coils is determined by the formula

$$M = U_2/\omega I_1 \,. \tag{15}$$

As can be seen from (15), in this case also it is not possible to provide a single output signal for transmitting over a distance or interfacing an MC with information processing means. To eliminate this drawback, the MC circuit for measuring the mutual inductance by the phase method has been developed (fig. 5a).

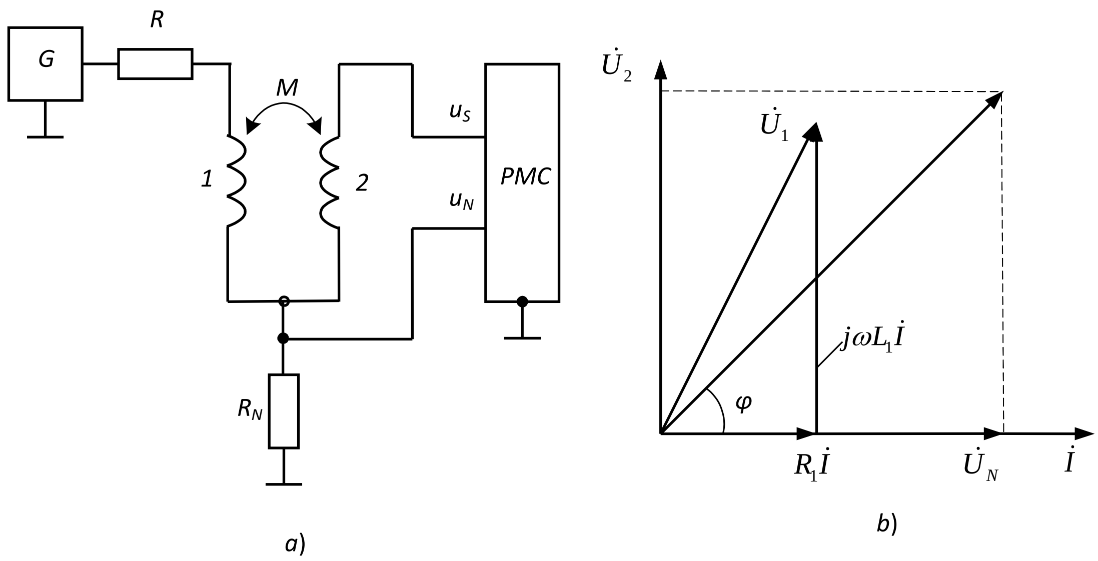

Figure 5: Measuring circuit for measuring mutual inductance by phase method:
a – scheme; b – vector diagram of current and voltage

Here, coils *1* and *2* also form the transformer windings, to the common output of which a reference resistor R_N is connected. The primary winding *1* of the transformer is powered by a sinusoidal current I of the generator (directly or through a current-limiting resistor R), and the secondary winding *2* operates at idle mode. The output signal of the MC is the phase shift angle φ between the voltages u_S and u_N relative to the common wire of the circuit, which are applied to the input of the PMC (directly or through buffers).

In the vector diagram (fig. 5*b*) through R_1, L_1 and U_1 marked active resistance, inductance and voltage of the primary winding of the transformer respectively, $\dot{U}_N = \dot{I}R_0$, $\dot{U}_2 = j\omega M\dot{I}$, $\dot{U}_S = \dot{U}_N + \dot{U}_2$, $tg\varphi = \dfrac{U_2}{U_N} = \dfrac{\omega MI}{IR_0} = \dfrac{\omega M}{R_0}$, therefore,

$$M = \frac{R_0}{\omega} \cdot tg\varphi \,,$$

Whence it is seen that the measurement result does not depend on the generator voltage and the IC supply current.

Conclusions

The analysis of the considered meters shows that the proposed method for separate measurement of active-inductive two-pole parameters on alternating current, based on the application of the phase method in combination with the time division of the measurement channel, provides a digital invariant measurement of the parameters of active-inductive two-pole network, has simple practical implementation and can provide high measurement accuracy. At the same time, the main advantage is the elimination of potential-current signals, the conversion and measurement of which is accompanied by inevitable errors due to the influence of external and internal interference and noise, the bias and shift voltages of operational amplifiers, the instability of their gain factors, the influence of cable line parameters, etc. An estimate of the measurement error was made for all the considered MCs, and it was found that by appropriate selection of the MC parameters and the generator frequencies, the required measurement accuracy can be ensured. A technique has also been developed for the experimental study of the metrological characteristics of devices with the described MCs. Measured parameters R_X and L_X are modeled by high-precision model resistance and inductance magazines. The absolute measurement error is estimated as the difference between the readings of the digital reading device connected to the output of the PMC and the values R_X, L_X at the indicated stores. Theoretical and experimental research of the metrological characteristics of the developed microcontroller meters, multiple measurements and analysis of the results showed that it is possible to provide separate measurements of the parameters of two-element active-inductive two-pole devices with a limit of permissible basic relative error not exceeding 0,1%.

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