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## ВПЛИВ ПАРАЗИТНОЇ ІНДУКТИВНОСТІ ОБ’ЄКТУ КОНТРОЛЮ НА РОБОТУ ВИМІРЮВАЧІВ ЕЛЕКТРИЧНОЇ ЄМНОСТІ ІЗ ФАЗОВИМИ ДЕТЕКТОРАМИ

Проведено аналіз впливу паразитної індуктивності ємнісного об’єкту контролю та схеми вимірювання на результати контролю електричної ємності та тангенса кута діелектричних втрат при використанні вимірювальних схем, побудованих на використанні фазових детекторів та перетворювачів напруги в струм. Показано, що наявність паразитної індуктивності об’єкту контролю призводить до збільшення значень електричної ємності та тангенса кута діелектричних втрат і, крім того, до збільшення активної та реактивної компонент напруги на виході фазового детектора.
**Ключові слова:** діелектричні втрати, контроль зволоження, електрична ізоляція, вимірювання імпедансу, вимірювання напруги.

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## ВЛИЯНИЕ ПАРАЗИТНОЙ ИНДУКТИВНОСТИ ОБЪЕКТА КОНТРОЛЯ НА РАБОТУ ИЗМЕРИТЕЛЕЙ ЭЛЕКТРИЧЕСКОЙ ЕМКОСТИ С ФАЗОВЫМИ ДЕТЕКТОРАМИ

Проведен анализ влияния паразитной индуктивности емкостного объекта контроля и схемы измерения на результаты контроля электрической емкости и тангенса угла диэлектрических потерь при использовании измерительных схем, построенных на использовании фазовых детекторов и преобразователей напряжения в ток. Показано, что наличие паразитной индуктивности объекта контроля приводит к завышенным значениям электрической емкости, тангенса угла диэлектрических потерь и, кроме того, к увеличению активной и реактивной компонент напряжения, полученного на выходе фазового детектора.
**Ключевые слова:** диэлектрические потери, контроль увлажнения, электрическая изоляция, измерение импеданса, измерение напряжения.

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## THE INFLUENCE OF STRAY INDUCTANCE OF TESTED OBJECT ON TECHNICAL PERFORMANCE OF ELECTRICAL CAPACITANCE METERS WITH PHASE DETECTORS

Control of technical state of electrical insulation by means of applying of electrical capacitance and power loss factor as informative parameters is complicated by the presence of stray parameters of tested capacitive object. The influence of stray inductance of tested object on technical performance of measurement scheme based on applying of phase detector and voltage to current converter is considered in this paper. It was shown that the presence of inevitable stray inductance of tested object causes changes of active and reactive components of voltage on the output of phase sensitive detector. According to the results of carried out analysis, stray inductance can also lead to the existence of substantial frequency dependence of electrical capacitance of tested object even in case of applying non-polar dielectric materials and to the distorted values of power loss factor of tested dielectric material. Finally, it was shown that the presence of stray inductance causes difficulties in estimation of technical state of electrical insulation due to substantial discrepancy between the value of effective capacitance, which has been measured under the influence of stray inductance, and the exact value of capacitance which implies negligible stray inductance. Considered in this paper deleterious influence of stray inductance and resonant phenomena on accuracy of carried out appraisal of technical state of tested capacitive object should be taken into consideration in case of applying measurement schemes with phase detectors.
**Keywords:** dielectric losses; humidity control; electrical insulation; impedance measurement; voltage measurement.

**Introduction.** The quality of electrical insulation in various types of electrical equipment can be determined by means of applying various diagnostic parameters, obtained by using diverse measurement techniques. Typical electrical tests can imply measurements of resistance of electrical insulation [1] and various high voltage tests [2]. Another wide spread approach for electrical insulation quality estimation implies carrying out of measurements of electrical capacitance [3], power loss factor [4] and quality factor [5]. In majority of practical cases undertaking of such measurements implies the applying of series or parallel equivalent schemes of capacitive tested object. Such schemes usually contain electrical capacitance, caused by polarization processes in dielectric material and resistance, caused by power losses in tested object. However, in practice, due to quite complicated construction, the majority of tested objects can contain various parasitic parameters, which, in some cases, can cause a substantial impact on accuracy of carried out measurements. The presence of parasitic inductance of tested object usually is not taken into consideration in mentioned types of equivalent schemes [6]. In some cases such discrepancy causes substantial inaccuracy in carried out appraisal of technical state of tested object. The extent of such deleterious influence on accuracy of carried out appraisal depends on applied measurement technique. This circumstance causes the necessity of study of stray inductance impact on accuracy of the most spread measurement techniques which are used in practice of carrying out measurements of electrical capacitance and power loss factor. In this paper such analysis will be carried out with respect to measurement techniques which are based on the applying of phase detectors.

**The objective of this paper** is to carry out an analysis of the influence of stray inductance of tested object on technical performance of electrical capacitance meters based on applying of phase detector and voltage to current converter.

**Impact of stray inductance on the output voltage of phase sensitive detector.** The applying of measurement schemes with phase detectors usually implies usage of different types of current to voltage and voltage to current converters which are used in order to obtain signals analyzed by phase detector. Fig. 1and Fig. 2 present two usual basic types of measurement schemes which imply the applying of phase detectors. Technical performance of both schemes under the assumption of negligible stray inductance has been described in [7, 8]. For the purposes of current study both schemes have been complemented with stray inductance of tested object $L_s$, equivalent scheme on Fig. 2 has also been complemented with shunt resistance due to power losses in dielectric material.

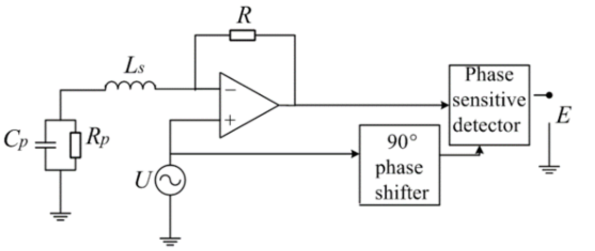


Fig.1. Principle scheme for the analysis of technical performance of capacitance meters with phase detectors based on applying of voltage to current converter in case of testing capacitive object with significant stray inductance: $E$ – output signal of phase sensitive detector, $U$ – the value of voltage generated by external source, $R$ – load resistance of voltage to current converter.

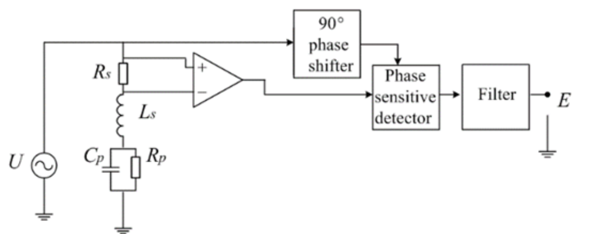


Fig. 2. Principle scheme for the analysis of technical performance of capacitance meters with phase detectors based on applying of current to voltage convertor in case of testing capacitive object with significant stray inductance: $R_s$ – resistor of current to voltage converter.

For both principle schemes the value of voltage generated by the source of tested voltage is used as a reference signal of phase detector due to the same values of voltage applied to the part of scheme which contains power loss resistance $R_p$ and unknown capacitance of tested object $C_p$. In the simplest case phase sensitive detector can be built by using simple correlometer which consists of block of multiplication of reference and analyzed signals and *RC* circuit with sufficiently high time constant. Despite the ability of taking into consideration the influence of stray inductance in capacitive tested objects by using equivalent schemes with distributed parameters, which have been elaborated for example in [10], this analysis will be hold in simplified form, by means of applying equivalent schemes with lumped parameters and by considering parallel equivalent scheme of tested capacitive object with power losses, as parallel equivalent scheme usually is more suitable for the analysis of various processes in dielectric materials with taking into consideration power losses in dielectric materials. Under the assumption of applying operational amplifier with idealized properties, the value of voltage on the inverting input of the operational amplifier will be equal to the value of voltage on the non-inverting input, generated by the source of testing voltage, as the voltage across the inputs to the amplifier is equal to zero. In this case the value of current through the part of electrical circuit on Fig. 1 which consists of stray inductance $L_s$, load resistor $R$ and impedance of tested object $Z_p$ can be determined as:

$$I = \frac{U}{Z_p + j\omega L_s} = \frac{U(j\omega C_p R_p + 1)}{R_p + j\omega L_s(j\omega C_p R_p + 1)}, \qquad (1)$$

where $Z_p$ denotes the value of impedance of tested object. In current study the determination of $Z_p$ implies parallel connection of electrical capacitance of tested object and shunt resistance caused by power losses. Therefore, here $Z_p$ represents the value of impedance of tested object which is determined for the case of negligible stray inductance. Consequently, $Z_p$ can be determined by using the following expression:

$$Z_p = \frac{R_p}{j\omega C_p R_p + 1}. \qquad (2)$$

The expression for the value of impedance $Z_1$ for current which flows through the part of electrical circuit on Fig. 1 which consists of stray inductance $L_s$, feedback resistor $R$ and impedance of tested object $Z_p$ can be obtained in the following form:

$$Z_1 = \frac{R(j\omega C_p R_p + 1) + j\omega L_s(j\omega C_p R_p + 1) + R_p}{j\omega C_p R_p + 1}. \qquad (3)$$

By taking into consideration previously obtained expressions, the value of output voltage on the output of voltage to current converter can be determined as a result of multiplication of expressions (1) and (3)

$$E = \frac{U(-jR\omega C_p R_p - R + \omega^2 L_s C_p R_p - j\omega L_s - R_p)}{\omega^2 L_s C_p R_p - R_p - j\omega L_s}. \qquad (4)$$

After the appropriate selection of reference signal, the value of constant component of voltage on the output of phase sensitive detector depends on product of amplitudes of reference signal and input signal of phase detector and the value of phase shift between these signals. Therefore, the applying of phase detector with further filtering of obtained signal by using *RC* circuit with sufficiently high time constant after the appropriate selection of initial phase of reference signal allows to determine real and imaginary components of voltage on the output of voltage to current convertor. Assuming negligible voltage drop on inner resistance of generator of testing voltage, further analysis will be hold in the context of the influence of stray inductance on active and reactive components of voltage on the output of phase sensitive detector. In is necessary to emphasize, that in this case the exact value of voltage components on the output of phase sensitive detector will differ only by the value of constant multiplier, equal to 0.5. Under the assumption of absence of accuracy loss caused by such operations as multiplication of reference signal and signal on the output of voltage to current convertor and also by filtering, the value of real component of voltage on the output of voltage to current converter can be determined by using the following expression:

$$\mathrm{Re}(E) = \frac{(\omega^4 L_s^2 C_p^2 R_p^2 - 2A + R_p R + R_p^2 + \omega^2 L^2)E}{R_p^2 - 2A + \omega^4 L_s^2 C_p^2 R_p^2 + \omega^2 L_s^2}. \qquad (5)$$

where $A$ can be determined by using the following expression:

$$A = \omega^2 L_s C_p R_p^2. \qquad (6)$$

The expression for the value of imaginary component of voltage on the output of voltage to current convertor can be obtained in the following form:

$$Im(E) = -\frac{RE\omega(L_s + L_s\omega^2 C_p^2 R_p^2 - R_p^2 C_p)}{R_p^2 - 2\omega^2 L_s C_p R_p^2 + \omega^4 L_s^2 C_p^2 R_p^2 + \omega^2 L_s^2}. \qquad (7)$$

Obtained expressions can be used for the determination of real and imaginary components reveal the influence of stray inductance on technical performance of capacitance meters based on applying of voltage to convertors and phase detectors. While under ideal conditions of operation such phase detector is supposed to detect the exact values of active and reactive components of voltage on the output of voltage to current convertor, the existence of stray inductance leads to certain loss of accuracy due to the presence of reactive parameters of the equivalent scheme in the expression for active component of output voltage *E*, and the presence of active parameters of the equivalent scheme in the expression for reactive component of output voltage. In simplified form (4) can be obtained under the assumption that the value of current which flows through the part of electrical circuit on Fig. 1 which consists of stray inductance $L_s$ feedback resistor *R* and impedance of tested object $Z_p$ depends only on the value of impedance of tested object $Z_p$. and independent on the value of stray inductance $L_s$. In this case (1) can be written in the following simplified form:

$$I_1 = \frac{U}{Z_p} = \frac{U(j\omega C_p R_p + 1)}{R_p}. \qquad (8)$$

Mentioned assumption allows to simplify the expression for output voltage of voltage to current convertor. In this case the output signal can de determined as:

$$E_1 = \frac{U(j\omega C_p R_p + 1)}{R_p} \cdot (R + j\omega L_s + \frac{R_p}{j\omega C_p R_p + 1}). \qquad (9)$$

where $E_1$ denotes the value of output signal obtained under the assumption that current which flows through the tested object is independent on the value of stray inductance $L_s$. From (10) the values of active and reactive components of voltage $E_1$ on the output of the phase detector can be extracted in the following form:

$$\mathrm{Re}(E_1) = \frac{UR}{R_p} + U - U\omega^2 C_p L_s, \qquad (10)$$

$$\mathrm{Im}(E_1) = U\omega C_p R + \frac{U\omega L_s}{R_p}. \qquad (11)$$

In case of negligible stray inductance of tested object the expressions for output voltage for the principle circuit on Fig. 1 can be easily reduced to the expressions that determine the value of output voltage which have been derived in [8]. In this case active component of voltage $E_2$ can be determined as:

$$\mathrm{Re}(E_1) = \frac{UR}{R_p} + U, \qquad (12)$$

where $E_2$ denotes the value of output voltage for the simplest case of negligible stray inductance. Reactive component of voltage $E_3$ can be determined as:

$$\mathrm{Im}(E_2) = U\omega C_p R \qquad (13)$$

Previously described loss of accuracy electrical capacitance measurements caused by the presence of stray inductance, obviously, also affects the obtained values of power loss factor. For the case of applying of parallel equivalent scheme the value of power loss factor can be determined as a ratio of active $I_a$ and reactive $I_r$ components of current which flows through the tested object:

$$tg\delta = \frac{I_a}{I_r}. \qquad (14)$$

The accuracy of applying (16) depends on the value of stray inductance of tested object. The presence of stray inductance changes active and reactive components of current through tested object. For the case of substantial stray inductance the value of active component of current which flows through the tested object can be determined as:

$$I_a = \frac{UR_p}{R_p^2 - 2\omega^2 L_s C_p R_p^2 + \omega^4 L_s^2 C_p^2 R_p^2 + \omega^2 L_s^2}. \qquad (15)$$

Reactive component of current which flows through the tested object can be found by using the following expression:

$$I_r = -\frac{U\omega(-C_p R_p^2 + C_p^2 R_p^2 \omega^2 L_s + L_s)}{R_p^2 - 2\omega^2 L_s C_p R_p^2 + \omega^4 L^2 C_p^2 R_p^2 + \omega^2 L^2}. \qquad (16)$$

Consequently, the value of power loss factor, with taking into consideration the influence of stray inductance, can be determined according to:

$$tg\delta = -\frac{R_p}{\omega(-C_p R_p^2 + C_p^2 R_p^2 \omega^2 L_s + L_s)} \qquad (17)$$

As it can be seen for the case of negligible stray inductance $L_s$ (18) can be easily reduced to more spread case:

$$tg\delta = \frac{1}{\omega C_p R_p} \qquad (18)$$

Therefore, the influence of stray inductance of tested object on technical performance of measurement scheme with phase detector and voltage to current converter can be taken into consideration by determining the value of output voltage *E* according to (4) and by determining its real and imaginary components according to (5) and (7). Simplified form of mentioned expressions was obtained under the assumption that the value of current which flows through the part of electrical circuit on Fig. 1 which consists of stray inductance $L_s$ feedback resistor *R* and impedance of tested object $Z_p$ is independent on the value of stray inductance $L_s$. In this case the value of output voltage $E_1$ can be determined according to (9). Real and imaginary components of $E_1$ can be determined according to (10) and (11). In the simplest case of negligible stray inductance components of output voltage can be determined according to (12) and (13). It also should be noticed that for the case of negligible stray inductance $L_s = 0$ expressions (5) and (7) can be easily reduced to (12) and (13), which have been derived in previously mentioned research [8]. It is also necessary to mention, that even for the simplest case of negligible stray inductance the presence of additional resistance *R* which is used in order to provide feedback in voltage to current convertor affects the value of output signal of phase sensitive detector. This circumstance should be taken into consideration while determining the value of electrical capacitance. Therefore, for the case of negligible stray inductance which can be described by the expressions (12) and (13) the value of electrical capacitance can be determined as:

$$C_{p2} = \frac{\mathrm{Im}(E_2)}{U\omega R}. \quad (19)$$

As capacitance meters are usually build of applying of simplified schemes which don't contain stray inductance, in further analysis for more general expressions which take into consideration the presence of stray inductance the value of electrical capacitance will be determined by taking ratio of imaginary components of voltages $E_1$ and $E$ to the same parameter as in (19):

$$C_{p1} = \frac{\mathrm{Im}(E_1)}{U\omega R}. \quad (20)$$

$$C_p = \frac{\mathrm{Im}(E)}{U\omega R}. \quad (21)$$

**Illustration of impact of stray inductance on values of converted voltage, capacitance and power loss factor.** The influence of stray inductance on the accuracy of measurements can be illustrated by making calculations according to (14-16) and (7), (11), (13). Such calculations should be carried out with taking into consideration possible frequency dependence of $R_p$, $L_s$ and $C_p$. The dependence of $C_p$ on frequency of applied voltage can be negligible in case of considering tested object with polyethylene foam electrical insulation, as polyethylene belongs to the group of non-polar dielectric materials with types of polarization which predominantly can be characterized by an insignificant duration of set up time which is negligibly small in comparison with the half of the period of applied voltage. Therefore, under the assumption of usage of polyethylene foam as a dielectric material in case of carrying out calculations in a range of frequencies from 100 Hz to 20 kHz it is possible to neglect with the dependence of $C_p$ on frequency of applied voltage. The frequency dependence of power loss resistance $R_p$ is determined by power losses caused by polarization and electrical conductivity. Fig. 3 represents the equivalent scheme of tested object described in [11], complemented with the resistance $R$ of electrically conductive parts of tested object.

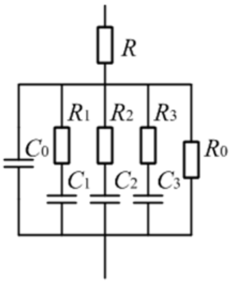


Fig. 3. Equivalent scheme of capacitive object with power losses and heterogeneous insulation. $C_0$ – geometrical capacitance, $C_1$, $C_2$, $C_3$ represent capacitance of "slow" polarization, $R_1$, $R_2$, $R_3$ represent power loss resistance caused by "slow" polarization, $R_0$ represents the value of electrical resistance determined through dc conductivity of tested object.

As under certain frequency of applied voltage each of $RC$ circuits on Fig. 3 can be partially or completely activated tested dielectric materials usually can exhibit pretty uneven frequency dependencies of power loss factor and, therefore, power loss resistance $R_0$. However, for the case of polyethylene foam electrical insulation $RC$ circuits caused by "slow" polarization can be negligible in a wide range of frequencies and changes of power loss factor with variation of frequency are insignificant. For all further calculations the value of power loss factor vas considered independent on frequency of applied field. Such assumption is pretty common in practice of making calculations of frequency dependence of electrical conductivity in telecommunication cables with electrical insulation made of previously chosen material even in case of applying in significantly higher range of frequencies. All calculations have been held for the case of $C_p$ equal to $53.3\cdot10^{-9}$ F and stray inductance of tested object $L_s$ equal to $3.08\cdot10^{-4}$ Hn under the previously accepted assumption of independent on frequency power loss factor. The value of feedback resistor $R$ was chosen equal 0.5 Ohm. The value of caused by power losses shunt resistance $R_p$ was determined according to:

$$R_p = \frac{1}{\omega C_p tg\delta} \quad (22)$$

The results of carried out calculations are represented on Fig. 4 – Fig. 7.

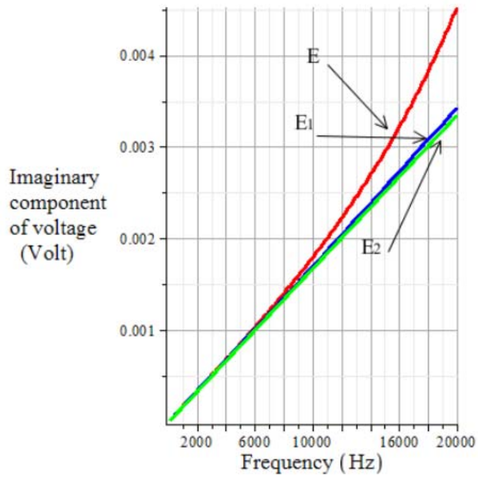


Fig. 4. Frequency dependence of imaginary component of voltage on the output of phase detector.

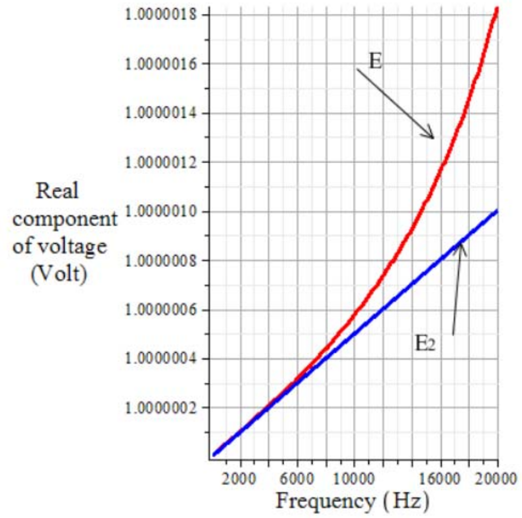


Fig. 5. Frequency dependence of real component of voltage on the output of phase detector.

It can be seen, that the presence of stray inductance leads to increment of real and imaginary components of voltage on the output of phase sensitive detector. Such increment becomes more significant with the increasing of frequency of applied voltage. It can be noticed, that according to (12) for the simplest case of negligible stray inductance real component of voltage on the output of phase sensitive detector doesn't exhibit any explicit frequency dependence, whereas real component of voltage which is determined according to (5) and (10), with taking into consideration the influence of stray inductance, exhibits a significant explicit frequency dependence.

Previously mentioned increment of voltage components obviously results in changes in obtained values of electrical capacitance displayed on Fig. 6. The influence of stray inductance on values of power loss factor is shown on Fig. 7.

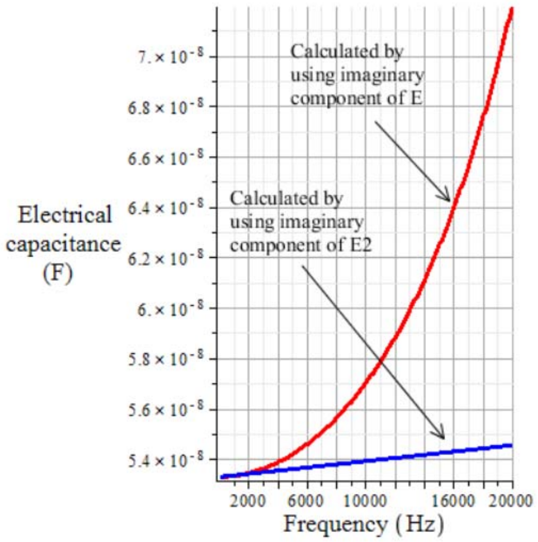


Fig. 6. Values of electrical capacitances calculated with taking into consideration the influence of stray inductance.

As it can be seen from Fig. 6, the presence of stray inductance causes increment of electrical capacitance, while the exact value of electrical capacitance is supposed to be constant and equal to 53.3 nF.

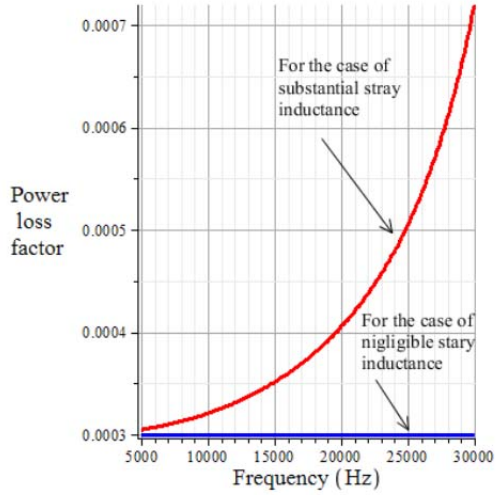


Fig. 7. Values of power loss factor calculated under the assumption of negligible stray inductance by using (1) and substantial stray inductance.

According to the results on Fig. 7 the influence of stray inductance on values of power loss factor is similar to the influence of stray inductance on values of electrical capacitance. Despite the previously made assumption of constant power loss factor, results of calculations carried out by using (7) exhibit an explicit frequency dependence and increased values of power loss factor.

**Conclusions.** The influence of stray inductance of tested object leads to the necessity of taking into consideration possible influence of resonant phenomena in measurement circuit which influence the accuracy of carried out measurements. Therefore, for tested objects with substantial stray inductance the increasing of electrical capacitance can be caused not only by the presence of humidity owing to the increasing of relative dielectric permittivity, but also by simple loss of accuracy due to the more substantial distinction in values of exact electrical capacitance and effective electrical capacitance caused by the impact of stray inductance.

Significant stray inductance of tested object leads to the explicit existence of frequency dependence of active component of voltage obtained on the output of phase sensitive detector, whereas for the ideal case of negligible stray inductance of active component of voltage doesn't exhibit such explicit frequency dependence.

The presence of stray inductance also leads to the existence of frequency dependence of measured electrical capacitance. Under the assumption that current which flows through the tested object is independent on the value of stray inductance $L_s$ the value of measured electrical capacitance doesn't exhibit substantial frequency dependence. However, such assumption is not valid for measurement schemes that can be applied in practice.

In case of substantial stray inductance the results of carried out measurements are dependent not only on the parameters of equivalent scheme of tested object $C_x$, $R_p$ and $L_s$ but also on the value of feedback resistor $R$.

The influence of stray inductance on obtained values of power loss factor results in increment of obtained results that causes additional difficulties and inaccuracy in assessment of technical state of tested capacitive object.

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