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Mathematical Model and Practical Implementation of Transformer Oil Humidity Sensor

V. F. Hraniak, V. A. Matviychuk, and I. M. Kupchuk

Abstract — **The mathematical dependence of the integral dielectric constant of transformer oil on its humidity is obtained. It is shown that the increase in humidity in the range from 0% to 0.5%, which corresponds to its allowable change, is accompanied by a monotonic increase in the integral dielectric constant along the nonlinear dependence. The design of a high-frequency humidity sensor in the form of a band asym-metric waveguide is proposed, which transforms the latter into a phase shift of the information wave. The mathematical model is developed and the transformation equation is obtained. It has been experimentally established that the total relative error, which consists of the error of this model, the instrumental error of the hard-ware and the subjective error of removing the measured information does not exceed 2%. The article is devoted to solving the problem of reliability of technological equipment and is part of an interdisciplinary study on the development of a set of energy efficient equipment for feed preparation, which is performed on the basis of laboratories of Vinnytsia National Agrarian University.**

Index Terms—**transformer oil, humidity, measurement, relative dielectric constant, phase difference.**

Original Research Paper
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I. Introduction

Water makes part of the vast majority of organic and inorganic materials. Materials formed in natural conditions or generated as a result of manufacturing processes normally contain a certain amount of water, the mass fraction of which de-pends both on the material's ability to take up (absorb) or retain (adsorb) water on the surface and on the conditions, in which this phenomenon occurs [1].

Moisture content significantly affects physical and electrical properties of non-metallic materials, particularly that of transformer oil. More specifically, moisture content increase in the latter significantly reduces its dielectric strength, creating the conditions for a breakdown between transformers' live parts, oil circuit breakers and other equipment that involves its use [2].

Regular measurements of transformer oil humidity make an essential component of maintenance of electrical equipment's whole group. And so far as today transition from scheduled maintenance to on-demand maintenance is becoming increasingly widespread [3]-[4], we can conclude that development of transformer oil humidity sensors that would be suitable for high-precision express measurement or operation in conjunction with real-time control systems are an urgent scientific and applied task.

II. Setting the Task

Known means for transformer oil humidity measurement mainly work in manual mode, have unsatisfactory accuracy and measurement speed [5]-[7]. Therefore, the need for further research aimed at enhancement of known methods and development of new means characterized by high accuracy and speed of measurement control of these substances' humidity is obvious.

As regards the solution of this scientific and applied problem, promising are high-frequency methods of humidity measurement, characterized by high speed, zero inertia and volumetric measurement of sample humidity [8]-[9]. However, due to lack of research, their widespread use is significantly limited.

In view of the above, obvious is the feasibility of developing high-frequency humidity sensors suitable for both rapid control and real-time measurements of equipment operation.

III. Analyzing the Ways to Solve the Problem

One of control object's features is that both transformer oil and water belong to the same class of substances with relative magnetic permeability, the value of which is close to one [10]. Given that, magnetic parameters of sample, as its humidity in-creases, can be considered constant. Therefore, in further calculations it is advisable to only take into account the change in dielectric properties, which depend on hu-midity of control object (CO). Maximum allowable transformer oil humidity is 0.5%, which determines the required measurement range.

As shown above, when transformer oil humidity changes, its relative dielectric permittivity increases monotonically [11]. In addition, given the lack of chemical bonds between oil and moisture distributed therein [12], it can be considered as a spe-

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cial type of viscous emulsion, in which moisture impregnation in its essence is an insoluble dispersed phase [13]. The structure of such control object is shown in Fig. 1.

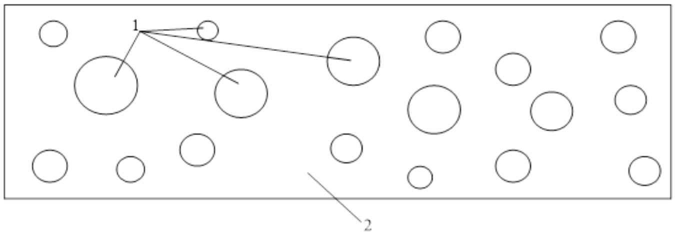

Fig. 1. Control object structure: 1 – moisture; 2 – transformer oil.

As the analysis of literary sources shows, there are a number of different functional dependencies that describe the relationship between effective (integral) dielectric permeability and filler substance's volume fraction. In particular, functional dependences set forth in papers [11] have significant differences due to various as-sumptions introduced during their generation, such as a symmetric nature of dis-persed phase distribution in the sample (Bruggeman equation and Bruggeman-Hanoi equation obtained therefrom [14]), a small difference between the medium's and impregnations' dielectric permittivity (the dependence set forth in papers by Landau-Lifshitz), etc. However, since the dielectric permittivity of water and fat differs by about 40 times, the mass fraction of CO's moisture varies in the range of up to 0.5% and moisture impregnations are arranged arbitrarily, with their diameter varying in the range from 10 to 60 μm [8], which contradicts the parameters accepted in deriving the part of hypotheses' functional dependencies, to obtain the functional relationship between the integral dielectric permittivity and humidity for selected CO, it is advisable to use only those functional dependencies, in obtaining of which no assumptions that would contradict its physical properties were applied. The most common among such mathematical models is the Maxwell-Garnett equation,

$$\frac{\varepsilon_{eff}-\varepsilon_0}{\varepsilon_{eff}+2\varepsilon_0}=\sum_{i=1}^{n}\nu_i\frac{\varepsilon_i-\varepsilon_0}{\varepsilon_i+2\varepsilon_0}, \tag{1}$$

where ε_{eff} – the integral (effective) dielectric permittivity of the sample; ε_0 – the dielectric permittivity of the matrix substance; ε_i – the dielectric permittivity of the *i*-th filler; ν_i – the volume fraction of the *i*-th filler, which provides a fairly high precision of the results obtained for substances characterized by absence of molecular bonds between the matrix substance and the dispersed phase arranged in the form of impregnations in the shape close to a spherical one with the volu+me fraction of impregnations not exceeding 30% [15].

No less interesting is the dependence set forth in paper [15] and obtained on the basis of equation (1), by way of its solution with respect to ε_{eff}:

$$\varepsilon_{eff}=\frac{\varepsilon_0+2\sum_{i=1}^{n}\nu_i\left(\frac{\varepsilon_i-\varepsilon_0}{\varepsilon_i+2\varepsilon_0}\right)}{1-\sum_{i=1}^{n}\nu_i\left(\frac{\varepsilon_i-\varepsilon_0}{\varepsilon_i+2\varepsilon_0}\right)}, \tag{2}$$

Therefore, CO's dielectric permittivity will be calculated as follows:

$$\varepsilon_{з}=\frac{\varepsilon_{м}+2\nu\left(\frac{\varepsilon_{в}-\varepsilon_{м}}{\varepsilon_{в}+2\varepsilon_{м}}\right)}{1-\nu\left(\frac{\varepsilon_{в}-\varepsilon_{м}}{\varepsilon_{в}+2\varepsilon_{м}}\right)}, \tag{3}$$

where ε_{B} – relative dielectric permittivity of water; ε_{M} – relative dielectric permittivity of transformer oil; ν – the volume fraction of moisture in the sample.

That said, the volume fraction of water can be determined from known relation:

$$\nu=\frac{V_{в}}{V_{в}+V_{м}}, \tag{4}$$

where V_B, V_M – the volume occupied by water and, respectively, transformer oil.

Since the sample's moisture content is determined by known relation between masses of moisture and oil, which in turn can be presented through density and volume of the fractions, control object's humidity can be found from the following functional dependence:

$$W=\frac{V_{В}\cdot\rho_{в}}{V_{В}\cdot\rho_{в}+V_{Ж}\cdot\rho_{м}}\cdot 100\ \%, \tag{5}$$

where $\rho_{в}$, $\rho_{м}$ – the density of water and, respectively, milk transformer oil.

Hence, by substituting (5) into (4), we obtain the functional dependence that unequivocally connects the volume fraction of water with sample humidity:

$$\nu=\frac{\rho_{М}\cdot W}{100\cdot\rho_{в}-W\cdot(\rho_{в}-\rho_{м})}. \tag{6}$$

Accordingly, by substituting (6) into (3) and performing simple mathematical transformations, we obtain:

$$\varepsilon_{з}=\frac{100\rho_{в}\varepsilon_{в}\varepsilon_{м}+200\rho_{в}\varepsilon_{м}^2+W(\rho_{м}\varepsilon_{в}\varepsilon_{м}+2\rho_{м}\varepsilon_{м}^2+2\rho_{м}\varepsilon_{в}-2\rho_{м}\varepsilon_{м}-\rho_{в}\varepsilon_{в}\varepsilon_{м}-2\rho_{в}\varepsilon_{м}^2)}{100\rho_{в}\varepsilon_{в}+200\rho_{в}\varepsilon_{м}-W(\rho_{в}\varepsilon_{в}+2\rho_{в}\varepsilon_{м}-3\rho_{м}\varepsilon_{м})}. \tag{7}$$

Let us introduce the following replacements:

$$F_1=100\rho_{в}\varepsilon_{в}\varepsilon_{м}+200\rho_{в}\varepsilon_{м}^2, \tag{8}$$

$$F_2=\rho_{м}\varepsilon_{в}\varepsilon_{м}+2\rho_{м}\varepsilon_{м}^2+2\rho_{м}\varepsilon_{в}-2\rho_{м}\varepsilon_{м}-\rho_{в}\varepsilon_{в}\varepsilon_{м}-2\rho_{в}\varepsilon_{м}^2, \tag{9}$$

$$F_3=100\rho_{в}\varepsilon_{в}+200\rho_{в}\varepsilon_{м}, \tag{10}$$

$$F_4=\rho_{в}\varepsilon_{в}+2\rho_{в}\varepsilon_{м}-3\rho_{м}\varepsilon_{м}. \tag{11}$$

Then, the functional dependence between effective dielectric permittivity and CO humidity can be represented as follows:

$$\varepsilon_3 = \frac{F_1 + WF_2}{F_3 - WF_4}. \tag{12}$$

To establish the nature of dependence between sample's dielectric permittivity and mass fraction of moisture arranged therein in the range of control object's humidity variation from 0% to 0.5%, let us simulate mathematical dependence (12). In this simulation, it is assumed that ambient temperature is 20°C. Simulation results are presented in Fig. 2.

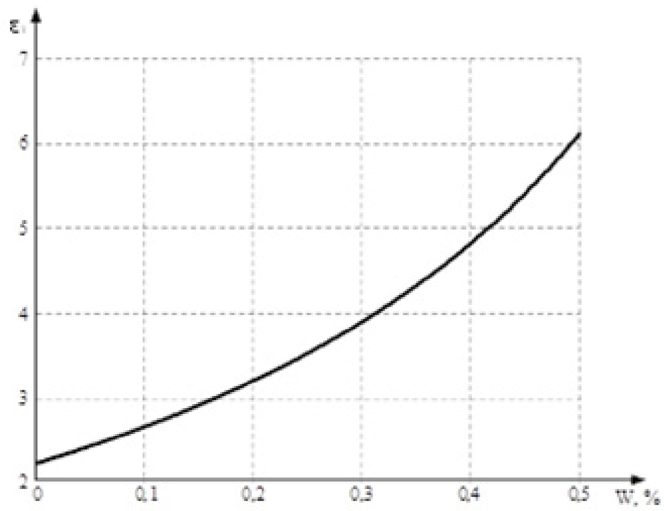

Fig. 2. Theoretical dependence between integral dielectric permittivity and sample's moisture content

As can be seen from Fig. 2, with humidity increase, sample's relative dielectric permittivity monotonically increases in a quasi-linear manner. This is due to in-crease in moisture portion in the sample, which is characterized by a higher value of dielectric permittivity in comparison with that of transformer oil.

As mentioned above, in terms of improving the accuracy of measuring humidity control, promising is the use of high-frequency waveguide measurement methods. Therefore, as a primary measuring transducer (sensor) we offer a band-type asymmetric sensor designed based on the principle of band asymmetric waveguide, which must be characterized by invariance to influencing values of environment, have a high speed of response and simple design [16] (Fig. 3).

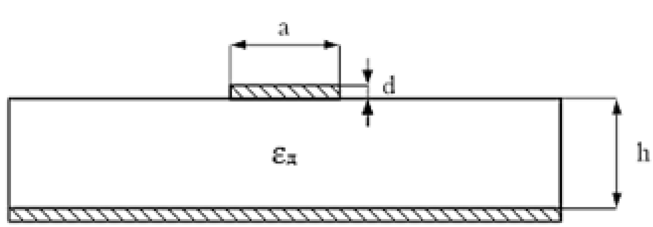

Fig. 3. Cross section of band asymmetric waveguide

The peculiarity of band asymmetric humidity sensor lies in the fact that the structure of the line's electromagnetic field is quite complex. For practical tasks, a simplified presentation of electromagnetic wave propagating in such a waveguide in the form of TEM wave is used [17]. That said, at relatively low frequencies (of HF band), such accepted simplification does not add a significant error to calculations [17]. Hence, having introduced restrictions on informative wave's frequency, in future we will assume that the informative wave is a TEM-type wave.

As has been proved in [18], magnetic field's power lines are concentrated in the central conductor's edge zone. Therefore, given the belonging of transformer oil's, water's and dielectric's located between the central conductor and the grounding to one class of substances with relative magnetic permeability, the value of which is close to one, magnetic parameters of such a wave can be considered constant [10]. Therefore, only the change in dielectric parameters is taken into ac-count in further calculations.

Since the electromagnetic wave propagating in the band-type asymmetric humidity sensor is overlapped by both the sensor's structural elements and the control object, in the process of generating the sensor's mathematical model comprehensively studied was "sensor-sample" system, the block diagram of which is shown in Fig. 4.

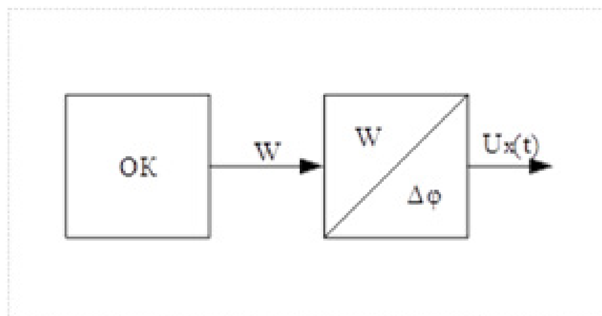

Fig. 4. Block diagram of "sensor-sample" system

As shown in [17, 18], the equivalent (effective) dielectric permittivity of such system can be determined by the following expression:

$$\varepsilon_{eff} = \frac{\varepsilon_\partial + \varepsilon_3}{2} + \frac{\varepsilon_\partial - \varepsilon_3}{2H}, \tag{13}$$

where ε_3 - the sample's relative dielectric permittivity; ε_∂ - the dielectric substrate's relative dielectric permittivity.

In expression (13), parameter H takes into account the relationship between substrate thickness h and central conductor width a and is determined using the formula [19]:

$$H = \sqrt{1 + 10\frac{h}{a}}. \tag{14}$$

where h is the dielectric substrate thickness; a is central conductor width.

As shown in (13), the equivalent dielectric permittivity of band asymmetric humidity sensor is functionally related to the dielectric permittivity of sample and substrate material. Since the phase shift of the informative wave is defined as the phase difference between the informative channel and the reference channel, the phase of which corresponds to the phase of unloaded sensor (with no control object), let us consider the processes occurring in the band asymmetric waveguide with no sample. Accordingly, given the absence of sample on the surface of the waveguide (presence of air with the dielectric permittivity of about 1 in its place), the effective dielectric permittivity is defined as [19]:

$$\varepsilon_{efon} = \frac{\varepsilon_{\partial}+1}{2} + \frac{\varepsilon_{\partial}-1}{2H}. \quad (15)$$

Taking into account the connection between dielectric permittivity with electromagnetic wave's phase velocity for both cases, let us write down the relationship:

$$V = \frac{c}{\sqrt{\varepsilon_{eff}}}, \quad (16)$$

$$V_{\text{оп}} = \frac{c}{\sqrt{\varepsilon_{efon}}}, \quad (17)$$

where c is the speed of electromagnetic wave's propagation in vacuum.

Operating with phase velocity values, the phase difference between the informative and the reference channels can be determined by the following relationship:

$$\Delta\phi = \phi_{in} - \phi_{on} = 2\pi f \cdot \left(\frac{l}{V} - \frac{l}{V_{\text{оп}}}\right), \quad (18)$$

where ϕ_{in} - the informative wave phase; ϕ_{in} - the reference wave phase; f–the electromagnetic wave frequency; l – the wavelength.

By substituting (16) and (17) into (18) we obtain:

$$\Delta\phi = 2\pi fl \cdot \left(\frac{\sqrt{\varepsilon_{eff}}}{c} - \frac{\sqrt{\varepsilon_{efon}}}{c}\right). \quad (19)$$

Then, taking into account relations (13) and (15), expression (19) can be written as follows:

$$\Delta\phi = 2\pi fl \cdot \left(\frac{\sqrt{\frac{\varepsilon_{\partial}+\varepsilon_{3}}{2} + \frac{\varepsilon_{\partial}-\varepsilon_{3}}{2H}}}{c} - \frac{\sqrt{\frac{\varepsilon_{\partial}+1}{2} + \frac{\varepsilon_{\partial}-1}{2H}}}{c}\right). \quad (20)$$

Since other parameters for particular waveguide are constant (20), the phase difference between the informative wave and the reference wave functionally depends only on the sample's relative dielectric permittivity.

By substituting (12) into (20) and by introducing the replacements, we obtain:

$$\Delta\phi = \sqrt{\frac{D_1}{A_4 - W \cdot A_5} + \frac{WD_2}{A_4 - W \cdot A_5}} - D_3, \quad (21)$$

where D1 – D3 and A4, A5 are constant coefficients calculated as follows:

$$D_1 = 4\pi^2 f^2 l^2 \cdot \left\{ \left[H\left(\varepsilon_{\partial} + \varepsilon_{жс}\right) + \left(\varepsilon_{\partial} - \varepsilon_{жс}\right) \right] \cdot F_3 \right\}, \quad (22)$$

$$D_2 = -4\pi^2 f^2 l^2 \cdot \left\{ \left[H\left(\varepsilon_{\partial} + \varepsilon_{жс}\right) + \left(\varepsilon_{\partial} - \varepsilon_{жс}\right) \right] \cdot F_4 \right\} - \\ - HF_2 + \rho_{в}\varepsilon_{жс}(\varepsilon_{в} + 1 - \varepsilon_{жс}H), \quad (23)$$

$$D_3 = \frac{2\pi flF_1}{c} \sqrt{\frac{(\varepsilon_{\partial}+1)}{2} + \frac{(\varepsilon_{\partial}-1)}{2H}}, \quad (24)$$

$$A_4 = 2c^2 H \cdot F_3, \quad (25)$$

$$A_5 = 2c^2 H \cdot F_4. \quad (26)$$

Expression (21) establishes an unambiguous relationship between sample humidity and phase difference between the informative and the reference waves, which in its essence is the conversion equation of band-type humidity sensor that converts humidity into phase shift of the informative wave.

To confirm the adequacy of this mathematical model, experimental studies were conducted using asymmetric band waveguide with gytenax substrate with the length of 2000 mm, the substrate thickness of 2 mm and the central conductor width of 2.5 mm. The following hardware was used in the experiment: "FK2 – 12" phase difference meter and "G4 – 107" high frequency signal generator. The room temperature was $20^0 \pm 2^0$ *C* The block diagram and photo of the experimental unit are shown in Fig.5. and Fig. 6.

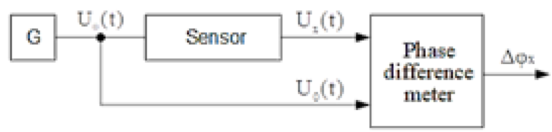

Fig. 5. Block diagram of the laboratory unit

Fig. 6. Photo of the laboratory unit

In the proposed laboratory unit, a signal from the output of the high-frequency generator is fed to the input of the band asymmetric sensor, where it undergoes a phase shift according to the conversion equations (20). From the output of the sensor the signal is fed to the input "A" of the phase difference meter, the input of "B" which receives a signal directly from the output of the high-frequency generator. In the phase difference meter, the phase difference between the information and reference signals is converted into the appropriate DC voltage level, which is fed to the input of the normalizing converter. The signal amplified in the normalizing converter is fed to the ADC input, where it is converted into a proportional serial binary code N, which is read by the server. Further numerical processing and visualization of measurement results takes place in the server.

The measurement procedure using the proposed measuring instrument (Fig. 6) involves the sampling of a small volume of the studied transformer oil with subsequent measurement of the mass fraction of moisture in it. An industrial sample of such a measuring instrument, which will be equipped with a miniature high-frequency generator and a microprocessor numerical converter, can be used for rapid measurements during the scheduled technical inspection of the relevant electrical equipment.

The results of simulation of theoretical transformation function (21) and experimental static characteristic Δφ (W) are shown in Fig. 7.

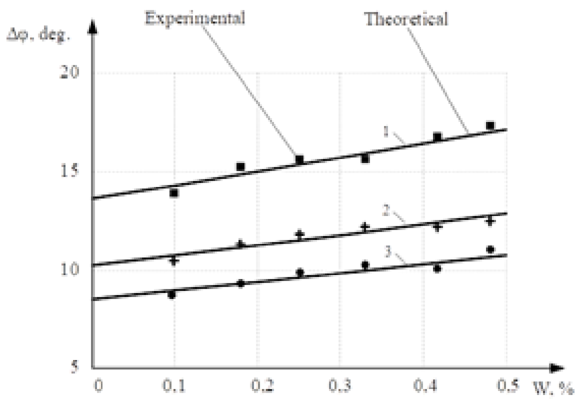

Fig. 7. Theoretical and experimental static characteristics of band-type asymmetric humidity sensor, for some values of informative waves' frequency: 1 –400 MHz; 2 – 300 MHz; 3 –250 MHz

The comparison between experimental data and theoretical values shows that given the above restrictions, the total relative error, which consists of this model's error, the hardware's instrumental error and the subjective error of measured in-formation retrieval does not exceed 2% [20], with static characteristic of band-type asymmetric sensor during humidity transformation into difference being clearly nonlinear in its nature (Fig. 7). The obtained error is significantly lower in comparison with measuring instruments that implement conductometric and dielcometric measurement methods, but is inferior to the thermogravimetric measurement method [21]. However, given the speed of measurement (thermogravimetric measurement typically takes about an hour), the use of this approach is technologically justified.

IV. Conclusions

1. The mathematical model of the dependence between transformer oil's inte-gral relative dielectric permittivity and its humidity has been developed. It has been shown that, within the allowable range of transformer oil humidity variations, humidity increase will lead to a monotonic increase in the integral dielectric perme-ability with nonlinear dependence.

2. Proposed was transformer oil humidity sensor's design in the form of a band-type asymmetric waveguide, which is suitable both for construction of ex-press humidity measurement tools and for operation in conjunction with computer-ized real-time control systems. Its mathematical model has been developed and transformation equation has been obtained, which unambiguously connects the in-formative wave's phase shift with the humidity of studied sample.

3. In order to confirm the adequacy of proposed mathematics, conducted were a number of experimental studies, the results of which allowed establishing that the total relative error, which consists of this model's error, the hardware's instrumen-tal error and the subjective error of measured information retrieval does not exceed 2%.

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