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A Study for Examining Dissipation Factors of Various Insulations and Test Transformers in the Wide Range of Frequency

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Introduction

Many diagnosing techniques were introduced more than a decade ago and has been thoroughly evaluated in a number of research projects and field tests with good results [1, 2]. Recent attention has focused on measuring various dielectric response parameters, which characterize some known polarization phenomena. The three foremost techniques are: RVM (Recovery Voltage Method), PDC (Polarization and Depolarization Currents), FDS (Frequency Domain Spectroscopy) and measurements of electric capacitance *C* and loss factor (*tan* δ) in dependency of frequency [3]. Diagnosis of insulating systems requires non-destructive test methods. This may be accomplished by measuring partial discharge and/or dielectric dissipation factor and capacitance using conventional well-established laboratory techniques.

Tan delta, also called loss angle or dissipation factor testing, is a diagnostic method of dielectrics to determine the quality of the insulation. The tan delta results, along with other knowledge of the cables history, and possibly other test data like partial discharge, all help to give us some guidance. Measurements of capacitance and loss are classical methods and more and more attention is paid to measurements over a wide frequency range. Particularly low frequency measurements seem to yield much information about the state of the insulation. First, to test a dielectric (for example cable) with 60 Hz power requires a very high power supply. It is not practical, nearly impossible, to test a cable of several thousand feet with a 60 Hz supply. At a typical VLF frequency of 0.1 Hz, it takes 600 times less power to test the same cable compared to 60 Hz. Secondly, the magnitude of the tan delta numbers increase as the frequency decreases, making measurement easier. The values of tan δ, as well as other parameters of dielectrics, for given specimens of material are not strictly constant and depend on various factors as frequency, temperature, humidity and voltage. Here, the functions of frequency and voltage are analyzed [4, 5]. Using DC and AC high voltage test equipment has some disadvantages. The AC high voltage transformer is large, heavy and expensive even with resonant test sets. While testing by DC high voltage needs a very high voltage so it causes some damage on the insulation. Therefore, in this study, the very low frequency (VLF) transformer is represented to solve these problems.

Pancake model transformer

A so-called pancake model of transformer insulation is developed for a systematic study on factors that influenced the dielectric properties of a composite oil-paper insulation. It is seen the cross section of the pancake model transformer in Fig. 1. Experiments are performed by using this transformer.

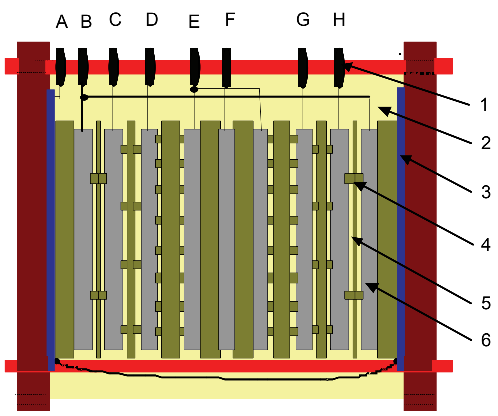

Fig. 1. Cross-section of the pancake model transformer. The marked elements are: 1 – connection (bushing); 2 – oil; 3 – copper plate; 4 – bakelite rod; 5 – spacer; 6 – pressboard

The oil-paper insulation system is a composite of two different dielectric media, where an insulating liquid with ionic conduction is mixed with a lower conducting impregnated solid (pressboard or paper). It is important to realize that each has its own dielectric response and, when putting them together, the total response will not only reflect properties of each material, but also the way they are combined. When these two media are put into contact (forming interfaces), charge accumulation occurs at the interfaces due to the differences between their electrical properties. This kind of polarization is called the Maxwell-Wagner or interfacial polarization [6]. The values of the transformer connections are shown in table 1. The model contained 8 pancake shaped coils (A-H) with ducts containing different amount of oil and pressboard between them (from 17/83 to 100/0). The four different type connections according to pressboard oil ratio are shown in table 1.

Table 1. Pressboard oil ratio at pancake transformer

Connection	CH-B	DG-CH	E-DG	F-E
Barriers/Oil	17/83	28/72	50/50	100/0
Spacers/Oil	15/85	28/72	55/45	100/0

Application and Test Results of four different insulations

Experiments are carried out using IDA 200 (Insulation Diagnostics Systems). The system measures the impedance of a specimen at a variable voltage and frequency. A Digital Signal Processing (DSP) unit generates a test signal with the desired frequency for the experiments.

The voltage over and the current through the specimen are measured with high accuracy. This procedure is repeated at different frequencies in the specified frequency range. As a result, the complex impedance, from which capacitance and dissipation factor or power factor is calculated, is obtained as a function of frequency.

With IDA 200, it is possible to diagnose insulation material in most objects in a high voltage installation (e.g. power transformers, measuring transformers, bushings, paper insulated cables etc.) The diagnostic measurement is done by applying a relatively low voltage – up to 140 V. IDA 200™ measures the capacitance and dielectric losses at discrete frequencies both above and below mains frequency (output signals with frequencies from 0.1 mHz to 1 kHz are available). By avoiding the mains frequency and its harmonics, an efficient filtering of their corruptive effects is enabled. The measurements showed that voltage dependence is fairly insignificant up to around 0.01 Hz for plywood as can be seen in Fig. 2.

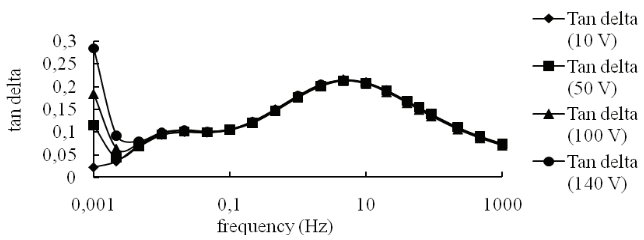

Fig. 2. Variation of dissipation factor of Plywood sample with frequency in different voltages

In many cases, tan δ does not practically depend on voltage so that, all other conditions being equal (Fig. 2, Fig. 3) the dielectric losses increase in proportion to the square of the voltage applied to the insulation. The value of tan δ is almost invariable with some values of voltage, but the curve of tan δ (U) abruptly rises when voltage grows a definite limit $U_{ion,}$, where begins the ionization. After passing the maximum point the curve slightly descends [7, 8].

C-tan δ values in the frequency domain should be preferred to obtain a "dielectric response function" which offers much more information to judge the actual state of an insulation or system [9].

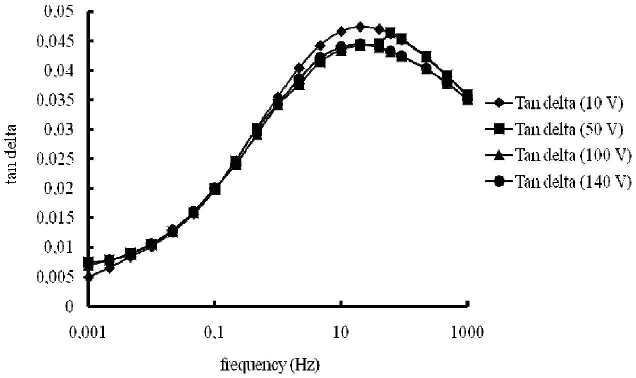

Fig. 3. Variation of dissipation factor of Plexiglas sample with frequency in different voltages

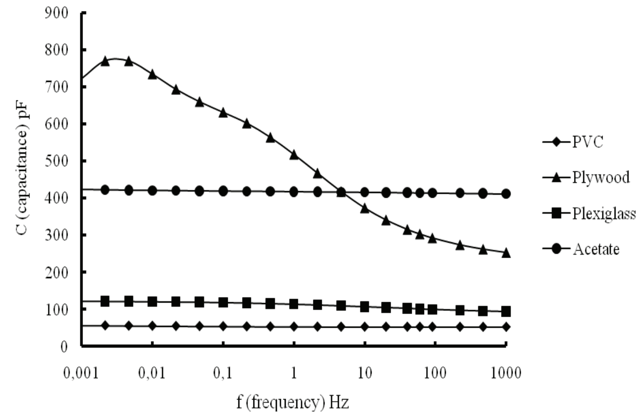

Fig. 4. Variation of capacitances of various dielectric samples with frequency at 50 V

Frequency dependence of measured dielectric losses for various dielectrics is depicted at 50 V in Fig. 4 and Fig. 5. Measurements are performed at temperatures 18-22 ^{0}C. At all frequency range, the measured capacitances do not vary with frequency except plywood, however the capacitance values of plywood increase with decreasing frequency. At this study, the frequency range of 0.001-1000 Hz is performed because, around of 1000, 60, 0.001-Hz are important for radio frequency, power frequency and test frequency respectively. The values of tan δ of four different dielectrics only for low frequency depending on voltage are displayed in Fig. 6.

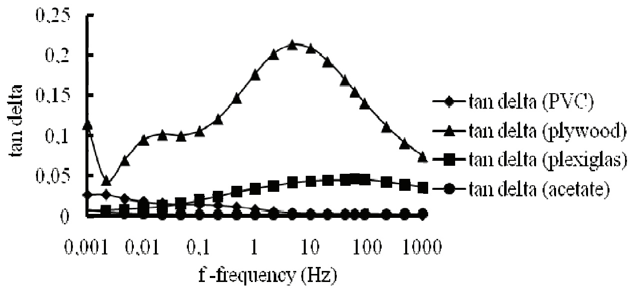

Fig. 5. Variation of tan delta depending on frequency for various dielectric materials

As the below (1) shows, the lower the frequency (f), the higher the tan delta number [4]:

$$\begin{cases} lim_{w \to 0} \tan \delta = \infty, \\ lim_{w \to \infty} \tan \delta = 0. \end{cases} \quad (1)$$

This equation shows the dependence of tan δ (w), by differentiating with respect to w and equating the derivative to zero, it is possible to get the value of w' of the frequency corresponding to the maximum tan δ_{max} as illustrated in Fig. 2–Fig. 5. For these materials tan δ_{max} is around about 10 Hz. This phenomenon depends on different polarization mechanisms. At low frequency range interfacial relaxation mechanism is effective [10].

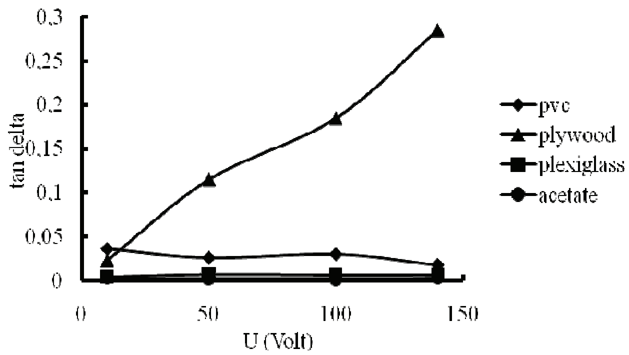

Fig. 6. Variation of tan delta depending on voltage for various dielectric materials (f=0.001 Hz constant)

Dissipation factor is not affected from variation of voltage except at low frequency for plywood (Fig. 6). The results confirm that voltage affects the tan δ values at low frequency much more than those at power and high frequencies. The increase is caused by the increasing capacitance depending on permittivity and interfacial corona breakdown inside the plywood. As seen from Fig. 6, tan delta at very low frequencies is too much rather than that at very high frequencies. Moreover, the measurements on materials inside wood (for example paper, crepe paper, pertinax and pressboard) which are not shown here are similar to plywood as in Fig. 6. The values of tan δ of these wooden materials are about constant for high frequency ranges with various voltages however at low frequency range tan δ has increasing slope with higher voltages. It seems to differ from materials inside plastics by the fact that they have no voltage dependence within the whole frequency range. $U_{ion,}$ value is not shown here for materials inside plastics like pvc, plexiglass and acetate. $U_{ion,}$ can be larger than 140 V for plastics materials.

Experimental results for pancake transformer

The most suitable waveform for using in voltage withstands tests is the very low frequency (VLF) test method. The VLF method proof that it is helpful and simple method which gets a good indication in global condition and gets a loss value as the leakage current measurement in conjunction. The most commonly used commercially available VLF test frequency is 0.1 Hz. It has simple measurement circuit, better sensitivity and less charging power in relationship to 50 Hz measurement and also less measurement time compared with RVM and PDC. In this part of our studies, the insulation diagnostic system IDA 200 is used to measure the dielectric losses tan δ(f) and capacitance(f) at discrete frequencies. So far a significant rise of the 0.1 Hz loss factor compared with 50 Hz has been expected because of the capacitive current through the test object decreasing with frequency [11]. The previous works show that the same breakdown mechanisms are operative at both frequencies. The 0.1 Hz and 50 Hz breakdown voltage stresses are not significantly different for the aging times. There is no fixed correlation between the losses at 0.1 Hz and 50 Hz. Nevertheless, there is some correlation that could be useful in translating diagnostic criteria from one frequency to the other. Both are much lower than the DC breakdown voltage stresses. Because of better sensitivity of 0.1 Hz, the dissipation factor measurements are compared to 50 Hz.

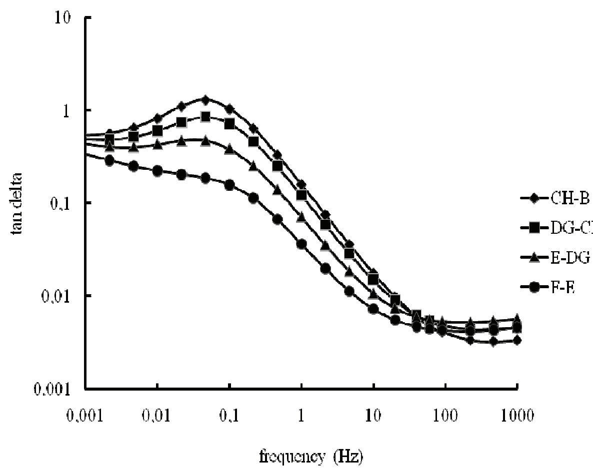

Fig. 7. Variation of tan delta depending on frequency for various connections of pancake transformer

In Fig. 7, the variation of dissipation factor for different connections of pancake transformer can be seen for the frequency range of 0.001 Hz and 1000 Hz. Measurements, at a low voltage (100 V) usually show a leakage current response, the losses increase with decreasing frequency. A pure dc conductance is characterized by a frequency dependence of the loss. The real permittivity shows nonlinear response. The presence of dispersed or water trees causes a general increase of the loss factor. Furthermore it is observed that the dielectric properties at very low frequencies are especially sensitive to the changes induced by aging. The character of frequency and tan delta can be seen more clearly in Fig. 8. This character depends on moisture, oil conductivity and temperature. The dissipation factor plotted against frequency shows a typical inverted S-shaped curve. With increasing temperature the curve shifts towards higher frequencies. Moisture influences mainly the low and the high frequency areas. The middle section of the curve with the steep gradient reflects oil conductivity. Fig. 8 describes parameter influence on the master curve. Using DFR (Dielectric Frequency Response) for moisture determination is based on a comparison of the transformers dielectric response to a modeled dielectric response (master curve). A matching algorithm rearranges the modeled dielectric response and delivers a new master curve that reflects the measured transformer.

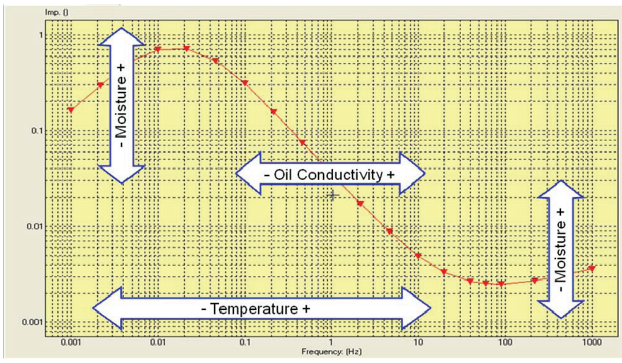

Fig. 8. Parameters that effects the dissipation factor at various frequencies

At the second part of the experimental study, the dissipation factors are obtained by using phase angle difference of the signals. The phase angle difference is mathematically evaluated with signal processing system in Matlab. Additionally, Fast Fourier Transformation is used for frequency selective information which gives the opportunity of measuring the harmonics of the signals. The sinusoidal VLF test voltage with 0.1 Hz frequency is generated with a commercial mobile (VLF BAUR) generator and an experimental VLF source designed for test voltage levels up to 20 kV_{ef} alternatively.

Loss angle is a measure of the resistive loss of the insulation which ideally would be purely capacitive. For example, in the event where there has been water ingress into paper insulation, the resistive losses would increase identifying that there is a problem with the insulation. For a pure (reference) capacitor there is a 90" phase difference. Any shift in this phase difference can be measured producing an indication of the loss angle. At here, the dissipation factor is obtained by calculating the phase difference of the base wave and the current through the reference capacitor. A new XLPE cable has 35 kV nominal voltage is used as a reference capacitor. As seen equation (2), Ipr and Ipc represent the current of the resistive and pancake transformer respectively. Also, Δt shows the phase time difference between pancake transformer and cable. Ts is the one period time (10 s)

$$\tan\delta = Ipr/Ipc = \tan((360^* \Delta t)/Ts). \quad (2)$$

The results that obtained by using the phase difference technique are shown in Fig. 9. As seen Fig. 9, at this voltage range, there is no correlation between dissipation factor and voltage. Initially, at low voltage levels, the transition to leakage current response is similar to the voltage dependent permittivity response. At higher voltages the response changes and a leakage current behavior is added to the response. The specific voltage level can not be seen at this voltage range. Leakage current through water trees are present already at low voltage levels. The frequency and voltage dependence of the response reveals the type of response and gives an estimate of the degree of water tree deterioration. Secondly, if the response in the case of field measurements, does not fit any of the below shown response types then it is most probably due to the influence of some artifact such as creep current at terminations. These types of effects usually increase the loss but do not change the capacitance. Earlier studies, presented in [12, 13] have shown that the dielectric response, obtained by high voltage dielectric spectroscopy measurements, is correlated to water tree content and breakdown voltage. Higher losses and increasing non-linear response are associated with lower breakdown voltage. The values of dissipation factor related to CH-B connection have the maximum values since this connection has maximum oil ratio. Measurement results show that estimated relative moisture content and paper degradation are influenced by additional parameters like construction of insulation system.

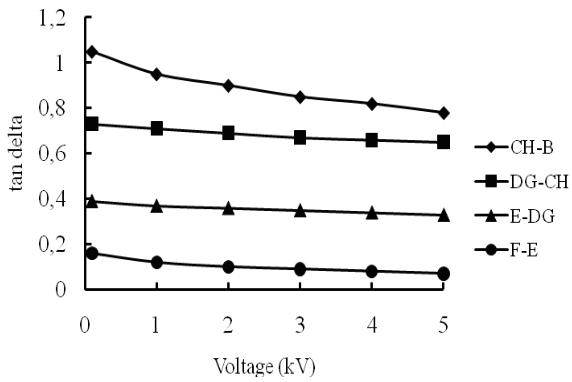

Fig. 9. Variation of tan delta depending on voltage for various connections of pancake transformer

The previous results confirm that voltage affects the tan δ values at low frequency much more than those at power and high frequencies [14]. The increase is caused by the increasing capacitance depending on permittivity and interfacial corona breakdown inside the pertinax and paper. The power factor of the wooden materials like paper and pertinax are affected from the voltage very much. Good dielectrics such as pressboard, when perfectly dry, show no change of dielectric constant with applied voltage. Dielectrics which are damp, however, or impregnated with a substance containing ionic impurities, show a slight dependence of dielectric constant upon stress, due to space charge formation by the ions. The increase of loss angle due to moisture in paper is known with greater precision than pressboard. The values of tan δ of wooden materials are about constant for high frequency ranges with various voltages however at low frequency range tan δ has increasing slope with higher voltages [15]. Wooden insulations are sensitive to variation of voltage especially at low frequency.

The nonlinearity also is studied by analyzing the harmonics in the measured integrated current. The aging produces a significant increase especially in the third harmonic.

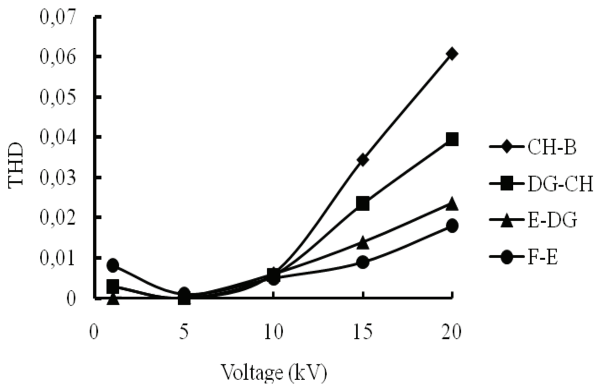

Fig. 10. Variation of total harmonic distortion (THD) depending on voltage for various connections of pancake transformer

As seen in Fig. 10, the variation of total harmonic analysis of pancake transformer shows the same relationship with dissipation factor. Previous results show that the harmonic content in the integrated current relates to the breakdown strength of insulation [16, 17]. The different types of response also could be recognized in the harmonic content. Cables with low loss linear permittivity response have low levels of both odd and even harmonic distortion. Cables with voltage dependent permittivity response have an increased harmonic distortion but the increase is larger in the odd distortion compared with the even distortion. In cables with leakage current response, the harmonic distortion increases even more and the odd and even distortion are within the same range. The applied voltage level may influence the measurements in low frequency region; make sure record applied voltage level for future reference. In a later stage of ageing, water trees contribute with a leakage current, either already at low voltage or arising at a certain voltage level. Although tan δ values does not depend on voltage for plastics materials, tan δ of plywood varies with increasing voltage value at low frequency range. It is affected from interfacial polarization at low frequencies. 140 V cannot be enough high voltage to observe the increasing point of voltage value for materials inside plastics.

Conclusions

To summarize the results, one may say that dielectric response measurements on oil-paper insulation are sensitive not only to the state of the paper, but also the oil conductivity, moisture content and the geometry of the test object. High dielectric loss is normally ascribed to the presence or water trees or high quantities of water within the insulation.

Both frequency and time domain measuring techniques are considered and resulted in the development of a HV frequency domain measuring system for the diagnosing of insulations. Since the power factors of some insulation are dependant to frequency and master curve is dependant to frequency, it is important to choose frequency domain techniques. By measuring the capacitance and tan δ over a frequency spectrum rather than at a fixed frequency, information about the status of the insulating material can be obtained. An analysis of the measured dissipation factor frequency characteristic allows for a more complete diagnostics of the examined insulation. Tan delta measurement should be regarded as a diagnostic tool to evaluate condition of insulation. In this paper, dissipation factor (tan δ) of various dielectric materials at variable frequency are studied. Among these materials, acetate has the lowest tan δ values for 0.001-1000 Hz frequency range. Moreover it is relatively insensitive to electrical interference at low frequency in fieldwork. Especially the responses at low frequency range are more important for testing the insulation system. The harmonic and frequency response analysis are proven and effective means of detecting in transformers.

A discharge free VLF test is recommended to enable partial discharge measurements to be carried out in addition to loss angle and straight withstand testing, because some dissipation factor tests can be flexible. Results from low frequency dielectric loss measurements indicate that degree of non-linearity may become a valuable parameter, even at test voltages far below the service stress.

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Modern technology and developments in signal acquisition and analysis techniques have provided new tools for insulation diagnostics. There is still today a need for improved non-destructive diagnostic methods for electrical equipment. Measurements of capacitance and loss are classical methods and more and more attention is paid to measurements over a wide frequency range. Particularly low frequency measurements seem to yield much information about the state of the insulation. Tan delta, also called loss angle or dissipation factor testing, is a diagnostic method of testing insulations to determine the quality of the insulation. In this paper, dissipation factor and capacitance of various dielectric materials at variable frequency are studied. When measured at a fixed frequency only, the property changes in the different materials cannot be discerned. In this paper, results show that of measurements done on the insulation between different various four types dielectrics materials. And finally these results are compared each other to select the best dielectrics. Acetate is the best dielectric material among our experimented materials. Moreover, dissipation factor measurement at very low frequency 0.1 Hz is one of the diagnostic methods for condition assessment of isolation systems of power transformers. This paper gives a background to frequency domain spectroscopy, correlation between dissipation factor and aging condition of insulation. 0.1 Hz measurements in combination with Fast Fourier Transform theory modeling can be used to calculate dissipation factor and harmonic analysis. Among the electrical methods, dielectric spectroscopy measurements in frequency (0.1 mHz - 1 kHz) domain have gained the reputation of allowing to estimate moisture content in paper and pressboard insulation. Ill. 10, bibl. 17, tabl. 1 (in English; abstracts in English and Lithuanian).

E. Onal. Įvairių izoliacijų ir testinių transformatorių sklaidos koeficiento tyrimas plačiame dažnių diapazone // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 27–32.

Tirti įvairių dielektrinių medžiagų sklaidos koeficientai ir talpa esant kintamam dažniui. Pateikti matavimų, atliktų su keturiomis skirtingomis dielektrinėmis medžiagomis, rezultatai. Atliktas šių rezultatų palyginimas pasirenkant tinkamiausią dielektriką – acetatą. Be to, tirta sklaidos koeficiento ir izoliacijos senėjimo tarpusavio koreliacija. 0,1 Hz matavimų kombinuojant juos su greitos Furjė transformacijos teorija, modeliavimas gali būti panaudotas skaičiuojant sklaidos koeficientą ir atliekant harmoninę analizę. Il. 10, bibl. 17, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).