

## The effect of aging of transformer oil on the magnitude and temperature dependence of its Kerr constant

**Streszczenie.** Stwierdzono, że stała Kerra używanego oleju transformatorowego zmienia swoją wartość. Zaobserwowano także, że zmienia się jej zależność od temperatury. Otrzymane wyniki sugerują, że wyniki pomiarów stałej Kerra mogą być wykorzystane do bieżącej oceny stanu oleju transformatorowego.

**Abstract.** It is found that the Kerr constant of the aged transformer oil increases relative to that observed in the fresh one. Moreover, the temperature dependence of the Kerr constant of the aged oil is found to be stronger than in the fresh one. The results obtained allow to consider the use of Kerr effect measurements in monitoring of the conditions of transformer oils. (*Zmiany stałej Kerra wywołane zjawiskami starzenia oleju transformatorowego*).

**Słowa kluczowe:** Właściwości elektrooptyczne oleju transformatorowego, efekt Kerra, zależność temperaturowa efektu Kerra, ocena stanu oleju transformatorowego.

**Keywords:** Aged transformer oil, Kerr effect, temperature dependence of the Kerr effect, transformer oils condition monitoring.

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### Introduction

In last years transformer monitoring, controlling and diagnosis methods have been drawing constantly increasing attention and many efforts have been devoted to the investigations of the effect of aging on transformers oils properties (see, e.g. [1-11]).

In the previous years we have investigated both experimentally and theoretically the conditions of measurements of electro-optic effects in crystals (see, e.g. [12-15]). In our measurements of the quadratic electro-optic effect we have employed Nynas Nytro 10 GBN transformer oil as the immersion liquid. When considering measurements of quadratic electro-optic coefficients, where the modulating voltage applied to the crystal is of amplitude several kV, any immersion liquid can introduce an additional modulation of the light due to the fringing electric field in the neighbourhood of the crystal and the Kerr effect of the liquid. Therefore the electro-optic properties of the oil have been great interest to us. During our efforts to increase the accuracy of measurements and to separate the contributions of crystal sample and immersion oil we have observed that the Kerr effect of the oil in the test cell has been changing with time. This finding has motivated us to measure the Kerr constant of different oils, including the oil used previously in a real transformer. Up to now, numerous of experiments employing techniques based on the Kerr effect to determine the electric field distribution in the transformer oil (see, e.g. [16-18]) and on the surface of high voltage insulating systems (see, e.g. [19-21]) have been performed.

Previously the effect of aging on physical, chemical and electrical properties of the oils, including the breakdown voltage, total acidity, flash point, water content, ash content, viscosity, gases presence, volume resistivity, dielectric loss tangent and thermal conductivity has been considered. In some of the experiments the oil was mixed with different impurities and additives to simulate its practical degradation conditions [2]. However, to our best knowledge, the effect of aging of the oil on its Kerr constant has not been yet taken into consideration. The aim of this work is an experimental comparison of the magnitude of the Kerr constant and its temperature dependence observed in the fresh transformer oil and the one measured in the oil after a period of service in a real transformer.

### Experimental

Traditionally, the Kerr constant  $B$ , relates the birefringence  $\Delta n$  induced in the liquid with the square of the modulating electric field  $E$

$$(1) \quad \Delta n = B\lambda E^2,$$

where  $\lambda$  is the light wavelength. The birefringence originating from the Kerr effect makes the liquid optically uniaxial with the optic axis parallel to the electric field direction. Following from the Kerr effect symmetry, the intensity of a light beam passing through a cell with the liquid placed between a polarizer and an analyzer is given by [22]

$$(2) \quad I = I_0 \left\{ \cos^2(\alpha) - \sin(2\rho) \sin[2(\rho - \alpha)] \sin^2\left(\frac{\Gamma}{2}\right) \right\}.$$

Here  $\alpha$  is the angle between the planes of polarization in the polarizer and analyzer,  $I_0$  is the maximum emerging light intensity,  $\rho$  is the angle between the plane of polarization and the direction of the applied electric field, and  $\Gamma$  is the phase difference between the ordinary and extraordinary beams, namely

$$(3) \quad \Gamma = \Gamma_0 + kLAL.$$

In the above,  $\Gamma_0$  is that part of  $\Gamma$  which is independent of the electric field, where  $k=2\pi/\lambda$  and  $L$  denotes the path length of the light beam in the liquid subjected to the electric field. If the polarizers are crossed (i.e.  $\alpha=\pi/2$ ), oriented in such way that  $\rho=\pi/4$ , and the optical bias  $\Gamma_0=(2n+1)\pi/2$  (where  $n=0,1,2,\dots$ ) is provided by a retardation plate, Eq. (2) may be rewritten in the form

$$(4) \quad I = \frac{I_0}{2} [1 + \sin(k\Delta nL)].$$

The intensity of the emerging light may be easily converted into an electric signal, e.g. voltage. For a sinusoidal modulating voltage the Kerr constant is given by

$$(5) \quad B = \frac{U_{2\omega} d^2}{\sqrt{2} U_c U_m^2 L},$$

where  $U_{2\omega}$  is the rms voltage measured at the second harmonic of the modulated emerging light intensity,  $d$  is the distance between electrodes,  $U_m$  is the rms modulating voltage, and  $U_c$  is the voltage proportional to the constant component of the light intensity transmitted by the system.

The experimental setup used in our measurements is shown in Fig. 1.

The electro-optical properties of the fresh Nynas Nytro 10 GBN mineral oil and the one after 6 months of service period in a distribution transformer, were compared. In our measurements the length of the aluminium parallel-plane electrodes immersed in the oil was 150 mm while the distance between them 5 mm. The modulating voltage of frequency

417 Hz, for which we found relatively low noise in our experimental system, was applied to the electrodes with  $U_m$  up to 1 kV, and the He-Ne laser ( $\lambda=0.633 \mu\text{m}$ ) was employed as the light source. The measurements were performed within the temperature range 20-50 °C.

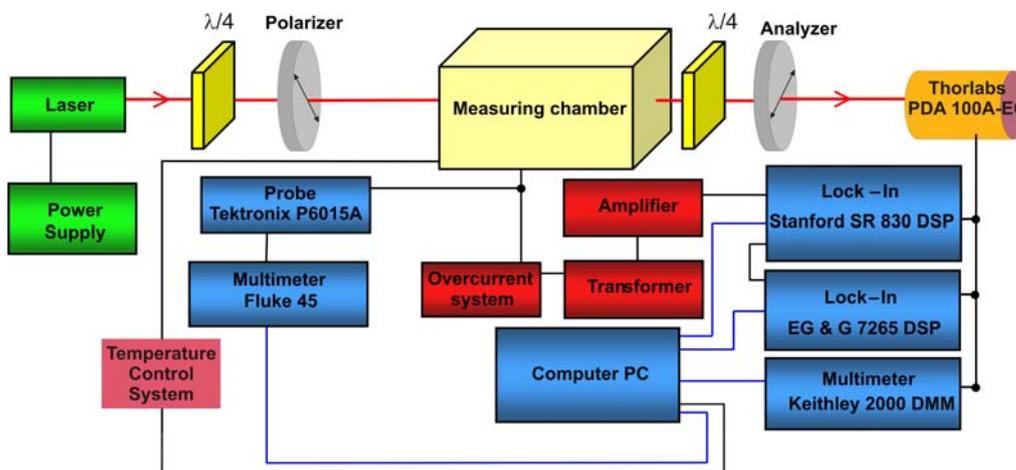


Fig.1. The experimental setup of the optical and electronic components used in the polarimetric method

## Results

The results obtained for the Kerr constant and its temperature dependence presented in Table 1 and illustrated in Fig. 2 indicate that the electro-optic properties of the fresh and aged transformer oil are significantly different. The Kerr constant obtained in our measurements for the used oil is nearly twice as high as the one observed in the fresh oil. The changes in the Kerr constant with temperature, as described by  $(1/B)(\partial B/\partial T)$ , are four times stronger for the used oil in comparison to the fresh one.

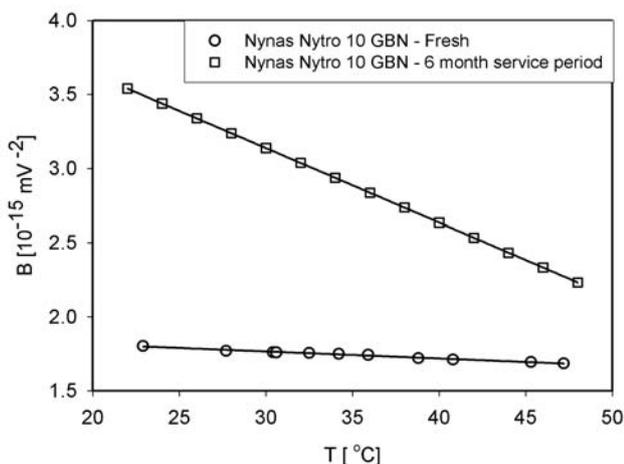


Fig.2. The temperature dependencies of the fresh Nynas Nytro 10 GBN transformer oil and the same oil after 6 months service period

Table 1. The comparison of the Kerr constant  $B$  (at 23 °C) and its temperature dependence  $(1/B)(\partial B/\partial T)$  in the fresh transformer oil Nynas Nytro 10 GBN and the same oil after 6 months service period

Oil	$B [10^{-15} \text{ mV}^{-2}]$	$(1/B)(\partial B/\partial T) [10^{-3} \text{ }^\circ\text{C}^{-1}]$
Fresh	$1.8 \pm 0.1$	$-2.6 \pm 0.2$
Aged	$3.5 \pm 0.2$	$-14.2 \pm 0.8$

## Discussion

It is known, that because of sustained application of electric and thermal stresses and various chemical reactions the properties and composition of the transformer oils change with their age. In fresh oils, only a minority of their compounds is polar. In the aged transformer oils the amount of polar fractions increases. For example, the adsorption of polar fractions of fresh and aged oils has been previously investigated by using silica gel [2]. The adsorbed amount of polar fractions was found to be higher for aged oils in comparison to new ones. It is commonly accepted that the presence of polar compounds causes degradation of transformer oils properties. The Kerr constant of most non-polar liquids, including transformer oils, is the order of magnitude  $\sim 10^{-15} \text{ m/V}^2$ . This is two-three orders of magnitude lower from the Kerr constant observed in polar liquids, for example the Kerr constant of pure water is  $5 \cdot 10^{-13} \text{ m/V}^2$ . The temperature dependence of  $B$  in polar and non-polar liquids is also different. In non-polar liquids the Kerr constant varies inversely with temperature and in the polar ones decreases more strongly, changing inversely with the square of temperature. The fact that the Kerr constant of the aged transformer oil is noticeably higher and its decrease with temperature is stronger than that of the fresh oil is in agreement with the previously reported findings indicating the increase in the amount of polar species in aged oils.

## Concluding remarks

Monitoring of oil properties may prevent future failure of transformers. One of possible methods of such monitoring may be measurements of electro-optic properties of the transformer oil, namely; the changes in the magnitude of the Kerr constant with time and the range of its changes with temperature, during the transformer service. We propose to join our experience in electro-optic measurements with the experience of specialists in the field of electric power apparatus. In our opinion, efforts are needed to relate the changes in electro-optic response of the transformer oil used in real transformers to their other physical, chemical and electrical properties.

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## REFERENCES

- [1] Wahab M.A.A., Hamada M.M., Zeitoun A.G., Ismail G., Novel modelling for the prediction of aged transformer oil characteristics, *Electric Power Systems Res.* 51 (1999) 61-70.
- [2] Jada A., Chaou A.A., Bertrand Y., Moreau O., Adsorption and surface properties of silica with transformer insulating oils, *Fuel* 81 (2002) 1227-1232.
- [3] Inyang H.I., Kaanagbara L., Estimation of electric transformer service life from oil degradation kinetics, *J. Energy Engineering* 133 (2007) 19-25.
- [4] Mijailovic V., Method for effects evaluation of some forms of power transformers preventive maintenance, *Electric Power Systems Res.* 78 (2008) 765-776.
- [5] Mohammad R. M., Aging Study and Lifetime Estimation of Transformer Mineral Oil, *American Journal of Engineering and Applied Sciences* 1 (2008) 384-388.
- [6] Kohtoh, M., Kaneko, S., Okabe, S., Amimoto, T., Aging effect on electrical characteristics of insulating oil in field transformer, *IEEE Tran. Power Deliv.* 16 (2009) 1698-1706.
- [7] Tenbohlen T., Koch M., Aging performance and moisture solubility of vegetable oils for power transformers, *IEEE Tran. Power Deliv.* 25 (2010) 825-830.
- [8] Kohtoh M., Ueta G., Okabe S., Amimoto T., Transformer insulating oil characteristic changes observed using accelerated degradation in consideration of field transformer conditions, *IEEE Tran. Power Deliv.* 17 (2010) 808 – 818.
- [9] Abdi S., Boubakeur A., Haddad A., Harid N. Influence of Artificial Thermal Aging on Transformer Oil Properties, *Electric Power Components and Systems* 39 (2011) 1701-1711.
- [10] Parvin P., Shoursheini S.Z., Khalilnejad F., Bavali A., Gosha M.M., Mansouri B., Simultaneous fluorescence and breakdown spectroscopy of fresh and aging transformer oil immersed in paper using ArF excimer laser, *Optics and Lasers in Engineering.* 50 (2012) 1672–1676.
- [11] Różga P., Wytrzymałość elektryczna transformatorowych płynów izolacyjnych na bazie estrów syntetycznych i naturalnych, *Przegląd Elektrotechniczny (Electrical Rev.)*, 90 (2014) 245-247.
- [12] Gunning M.J., Raab R.E., Kucharczyk W., Magnitude and nature of the quadratic electro-optic effect in potassium dihydrogen phosphate and ammonium dihydrogen phosphate crystals, *J. Opt. Soc. Am. B* 18, (2001) 1092-1098.
- [13] Kucharczyk W., Nowicz R., Some aspects of applications of electrooptic effects, *Zeszyty Naukowe Politechniki Łódzkiej, Elektryka* 107 (2006) 5-12.
- [14] Ledzion R., Górski P., Kucharczyk W., Does the contribution of PO<sub>4</sub> group is exclusively responsible for the quadratic electro-optic effect in KDP-type crystals? *J. Phys. Chem. Solids* 68 (2007) 1965-1968.
- [15] Izdebski M., Kucharczyk W., Systematic approach for finding configurations for measuring quadratic electro-optic coefficients in noncentrosymmetric crystals, *J. Opt. Soc. Am. B* 25 (2008) 149-152.
- [16] Zahn M., Hanaoka R., Kerr electro-optic measurements of transformer oil in point-plane geometry, *IEEE Proceedings of the 4 th Int. Conf. on Properties and Application of Dielectric materials*, 1994, Brisbane Australia.
- [17] T. Maeno, Y. Nonaka, T. Takada, Determination of electric field distribution in oil using the Kerr-effect technique after application of dc voltage, *IEEE Trans. Electric Insul.* 25 (1990) 475-480.
- [18] Okubo H., Wakamatsu M., Inoue N., Kato K., Koine H., Charge behaviour in flowing oil in oil/pressboard insulation system by electro-optic field measurement, *IEEE Trans. Dielectr. Insul.* 10 (2003) 956-962.
- [19] Kasprzak W., Nadolny A., Kaczmarek M.S., Woźniak Z., Pochylski M., Efekt Kerra w cieczach o różnych właściwościach elektrooptycznych, *Przegląd Elektrotechniczny (Electrical Rev.)* 84 (2008) 166-169.
- [20] Kasprzak W., Nadolny Z., Wyznaczanie kierunku i wartości wektora natężenia pola elektrycznego za pomocą metod wykorzystujących elektrooptyczny efekt Kerra, *Przegląd Elektrotechniczny (Electrical Rev.)* 88 (2012) 47-50.
- [21] Kasprzak W., Nadolny Z., Dobór cieczy optycznie aktywnej w celu wykorzystania jej w metodzie pomiaru natężenia pola elektrycznego bazującej na elektrooptycznym efekcie Kerra, *Przegląd Elektrotechniczny (Electrical Rev.)* 88 (2012) 248-250.
- [22] M. Born, E. Wolf, *Principles of Optics*, Cambridge Univ. Press, Cambridge, 2005, p. 825.

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