The System of Transformer Oils Laser Control by the Method of Sounding Through a Cuvette

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***Abstract* — The paper represents system of transformer oils control by the method of environment laser sensing through a cuvette. Transformer oil acts as a dielectric active medium. Measurement of the indicators is based on the resonance examination of the laser beam. The method of constructing laser photometers for evaluation of transformer oils quality is considered. The use of photometers is tested on experimental stands in the production conditions of power plants (where the oils are used for heat transfer during cooling of transformers).**

Keywords* — *laser photometry, transformer pedals, measurement, expansion of a resonance laser beam.

I. Introduction

Powerful energy flows transmitted through transformers cause their heating. Overheating of transformers can lead to accidents and fires. For fast cooling of transformers, special oils are usually used.

Actuality. The stable mode of power supply systems and generating units depends on the technological state of the aggregates and electromechanical units (which are part of it). An important component of the stability of generating and distributing structures are powerful electro-transformers. They act as elements of the energy flows transfer(which is transformed into them). Electric transformers are a necessary component for the coordination of generators and networks by voltage and power.

Problem. To ensure an efficient thermodynamic regime, it is necessary to control the temperature of the transformers and their technological environment. Technological environment of transformers are high quality oils that act as a convection cooler. In the process of thermodynamic interactions increases the activity of chemical reactions of oils with the materials of a transformer (polymers, copper, iron case). This is due to the action of high voltage electromagnetic fields. Increasing the activity of chemical reactions leads to the diffusion of mechanical structure components (steel, copper, insulating materials). As a result of diffusion, the dielectric characteristics of the oil and its electrothermodynamic parameters are reduced. This can lead to an emergency.

Research methods. During research of the task of dielectric parameters monitoring (control) of transformer oils we used:

- theoretical foundations of laser physics, laser photochemistry, laser optics, theory of scattering of laser beam;
- methods and means of laser information-measuring systems creation.

II. Choosing of the Method for Solving the Problem of Transformer Oils Quality Control

Quality control of transformer oils at power plants is provided by the transformer oil supplier. During the operation transformer oil samples are taken and electrical tests are carried out with high voltage (which is a long-term procedure). For operational control of samples in the process of work, we proposed a method of laser sensing [8,10-13].

A. Laser measurements of environment parameters

Laser photochemistry (as a research tool) makes it possible to effectively study the following processes [1]:

- monomolecular decay;
- polymerization;
- bimolecular reactions under the action of laser radiation.

Important aspects of the study of technological environments using lasers are [2,14]:

- studying the processes of selective photojonization of atoms and molecules;
- studying the processes of selective photo dissociation of molecules under the action of a laser beam;
- study of the processes of forced laser beam scattering (and corresponding activation of energy levels).

In the process of technological environment measuring by laser it can occur selective stimulation of chemical reactions. The simulation of chemical reactions occurs by overcoming the activation threshold with the extra energy of the laser beam. This changes the molecular activity of the environment and reducing the intensity of the laser beam (1) [2-4]:

$$\left(I_{KR} \geq I_{K\Pi}\right), K = K_0 \exp\left(-\left(E_Q - \alpha E_K\right) / RT\right) \quad (1)$$

In (1): I_{KR}, $I_{K\Pi}$ – laser beam intensity, E_Q, E_K – activation energy, RT – thermodynamic coefficients.

B. Method of laser control of the transformer oils quality

Measurement of the technological parameters of the transformer environment (temperature, dielectric stability, ion and electrical conductivity), which is necessary for assessing the level of functional suitability, is a complex problem. This is due to the fact that the effect of high voltage distorts measurement results and makes direct measurements impossible. Measuring the level of dielectric stability is particularly difficult.

The influence of physical-chemical and electrodynamic factors on the structure of oils leads to a decrease in their electrical strength. This can cause a breakdown in the transformer. Control of the parameters of transformer oils in the area of the electrical substation (under high voltage conditions) makes it impossible to chemical analysis of impurities, which reduce their quality.

A possible solution to this problem is a photometric laser rapid analysis based on the effect of forced combinational scattering. [1,2,6-8].

III. Laser Sensing of Transformer Oils

The dispersion of light in a cuvette with an oil sample (when laser beam passing through the sample) is described by the Rayleigh Law (2) [6]:

$$I_R = AI_0 / \lambda^4 \qquad (2)$$

In (2): I_R – the intensity of the scattered light, I_0 – the intensity of the incident beam A – integral characteristic of the environment.

At high power of a laser beam, forced scattering occurs due to energy balance imbalance. In this case occurs spontaneous transitions of electrons from orbits (direct and inverse) and their breakaway, which causes conductivity (electric and polarization).

The spontaneous transition describes the relationship (3):

$$n_c = N_2 A_{12} \Delta t \qquad (3)$$

The induced transition describes the relationship (4):

$$n_n = N_1 B_{21} U\left(V_1 T\right) \Delta t \qquad (4)$$

The induced transition with radiation describes the relationship (5):

$$n_\mathrm{I} = N_2 B_{12} U\left(V_1 T\right) \Delta t \qquad (5)$$

In (3)-(5): $N_1 = N_0 \exp\left(-E_i / kT\right)$, $N_2 = N_0 \exp\left(-E_2 / kT\right)$ – the number of molecules in the energy states $\left(Z_1 ' Z_2\right)$; B_{12} – transition probability of radiation induced light; B_{21} – probability of absorption; $\left(A_{12} / B_{12}\right) = 8\Pi \eta \lambda^3 / C^3$ – y equilibrium condition of Rayleigh-Jeans Law.

Equation (6) describes the situation under the influence of a laser beam on an environment in which there is a number of molecules N (at room temperature T) in a forced oscillatory state with energy $h\omega_k$. This, accordingly, can lead to active resonant amplification of the photon flux, the breakaway of electrons from the orbits of the components of the oils molecules and their impurities (copper, steel) and the emergence of electronic conductivity.

$$N = N_0 \exp\left(-h\omega_k\right) / RT \qquad (6)$$

A. System of Remote Laser Sensing of Transformer Oil Samples in Cuvettes

Let's consider the system of remote laser sensing of transformer oil samples in cuvettes. The method was verified by a series of experimental tests [4,7-13]. Fig. 1 shows a scheme of laser impact on the environment.

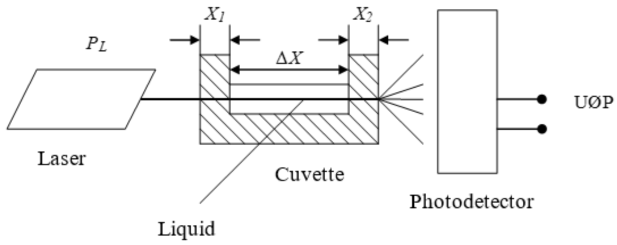

Fig. 1. A simplified scheme for investigating the influence of a laser on the environment

At the same time (in an experiment with oils) it is necessary to consider:

- Effect of impurities concentration changes in the oil (the state of oil waste).
- Effect of power change on oil parameters.

When laser beam passing with intensity I through the layer of environment and walls of the cuvette there is an increase the level of activity of impurities components [4].

Photon laser activation causes photonic synchronization at which $\mathrm{I}_{1c} = A\exp\left(g\mathrm{I}_0 L\right)$, $\Delta I_k = qII_{12}\Delta\mathrm{X}$. This leads to an increase of the laser beam energy at the exit of the cuvette. In the absence of the synchronic effect, the laser beam is weakened when it passes through the cuvette in the direction of sounding (in the direction of the corporal angle [1,7]):

$$\ln\frac{I_0}{I_n} = \int_0^\pi \left(K_1 \cos^2\theta + \frac{K_2 + K_3}{2}\sin^2\theta \right) \times \\ \times f\left(\theta\right) \mathrm{Sin}\,\theta d\theta + S_n + S \qquad (7)$$

In (7): $\left(K_1, K_2, K_3\right)$ – indicators of dispersion weakening along the axes (XYZ) in the direction of corporal angle θ.

The energy irradiance of the laser beam in the section of the Gaussian beam is determined according to (8) (with direct sounding of the prototype), where P_L – laser power

$$E_L = \left(2P_L / \pi r^2\right) \exp\left(-2r_d^2 / r\right) \qquad (8)$$

The maximum intensity of the laser beam along the beam axis in the direction of sounding is determined on the basis of

(9). where r – the radius of the rings of intensity relative to the axis of the beam, PL – laser power.

$$E_{i\max} = 2P_L / \pi r^2 \tag{9}$$

When passing a laser beam through an active environment, we have, respectively, a transmittance, which depends on the structure of the molecules of oils and the concentration of impurities (10), where r_μ – molecular scattering factor ($r_\mu = (r_o + r_d)$), where r_o – oil, and r_d – impurities.

$$\alpha_n = \exp\left[-\int r_\mu(\lambda,k)\,dl\right] \tag{10}$$

The total normalized power of the laser beam to the input of the cuvette is determined from (11).

$$P_n = \int_0^r \int_0^{2\pi} p_L^2(r,\phi)\, r dr d\phi \tag{11}$$

In (10): $P_l(r,t_0) = \frac{P_0}{S}\exp\left(-r^2 / a_0^2\right)$ – power distribution density in the cut-off S laser beam.

At the output of the cuvettes we get a partially scattered signal with an overlay active resonant component (which depends on the quality of the oil and the concentration of pollution):

$$\begin{aligned} I_X(\theta,L,t) &= (1-R_0)\, I_0^t \exp\left(\pm\alpha_X(\theta)L\right) = \\ &= I_X(C_K,L,t) + I_{XR} \end{aligned} \tag{12}$$

In (11): θ – environment parameter, $R(\theta)$ – coefficient of scattering on inhomogeneities, L – length of the cuvette, $\alpha_X(\theta)$ – coefficient of activity of the environment $\left(\alpha_X[\theta] = F\left(\theta, \vec{P}(r,t)\right)\right)$.

If expressing the absorption coefficient due to the absorption of parts, then the ratio for power at the output of the cuvette will be (13):

$$I_R = I_0 10^{-\varepsilon C d} \tag{13}$$

In (13): I_0– the intensity (or power) of the laser, C_0 – concentration of absorption of parts, d – thickness of the absorbing layer, ε – decimal molar absorption coefficient.

According to the Lambert-Beer law, the photon loss rate is proportional to the number of bimolecular shocks (photon-molecule). Then, respectively, losses can be estimated depending on the concentration level of impurities C_K (14):

$$I_R(\alpha_X, C_X) = I_0 \exp\left(-\alpha_X C_X(\theta_R) L_R\right) \tag{14}$$

In (14): I_R, I_o – the integral laser beam intensity in mW.

On the basis of (14) we obtain (15):

$$\ln \Delta I_R = \left[\ln I_R - \ln I_0\right] = \pm\alpha_X C_X(\theta_R) L_K \tag{15}$$

Equation (15) determines the loss (or activation) of the laser beam, depending on the quality of the transformer oils and the level of impurity of the components of metals (copper, iron, steel body).

B. *The influence of glass cuvette quality on the result of laser measurement*

Equation (16) defines the consideration of the design of the cuvette and the losses it gives (for the intensity of the laser beam). The sign (+) in (16) – determines the active medium that amplifies the laser signal – pure oil; the sign (-) is a loss due to impurities.

$$\pm \ln \Delta I_R^K + \ln \Delta I_R(\theta) = \pm\alpha_X C_X(\theta_X) L_K \tag{16}$$

The optical density of the glass is determined in accordance with (17), where K_λ – the transmittance at the frequency λ (it should be minimal to not affect the transfer of power of the laser beam).

$$D_X = -\lg T_\lambda = 0,434 K_\lambda d_s \tag{17}$$

The optical transparency of the glass (transmission coefficient) can be determined according to [4] (18):

$$I_\lambda = \frac{I_R}{I_0} e^{-K_\lambda d_s} = 10^{-Ki_{\bar{\lambda}} d} \tag{18}$$

In (18): K, Ki – are the natural and decay coefficients of transmission of glass in thickness d. The relative absorption is defined as ($A=1-T$), and is the result of interaction in the structure of glass.

IV. Testing of the System for Estimating the Concentration of Impurities in Transformer Oils

Two-channel photometer of a difference type was developed for conducting experimental studies of determination of parameters of quality of transformer oils (oils) and other chemical solutions.

The method of projection laser sensing is used to create a photometer. In the work of a two-channel photometer of a difference type, the difference comparison procedure is used (differential method) (19).

$$\begin{aligned} \Delta\alpha(C_K,\theta) &= \left|\alpha_e(C_K,\theta) - \alpha_i(C_{Ki},\theta_i)\right| \cdot K_i \\ \Delta\alpha(C_K,\theta) &= K_F\left(P_{Si}, P_{Se} / P_L\right) \end{aligned} \tag{19}$$

In (19): α_e – coefficient of scattering of the reference sample, α_i – coefficient of scattering of the controlled sample, K_F – photometric coefficient.

In fig. 2: LPS – laser power supply; SL –semiconductor laser; Cuvette$_e$ – cuvette with reference samlpe; Cuvette$_w$ – cuvette with the sample to be studied, PD_1, PD_2 – photodetectors; SPU –signal processing unit; OPEU –unit of oil parameters evaluation, A/D –analog/digital converter.

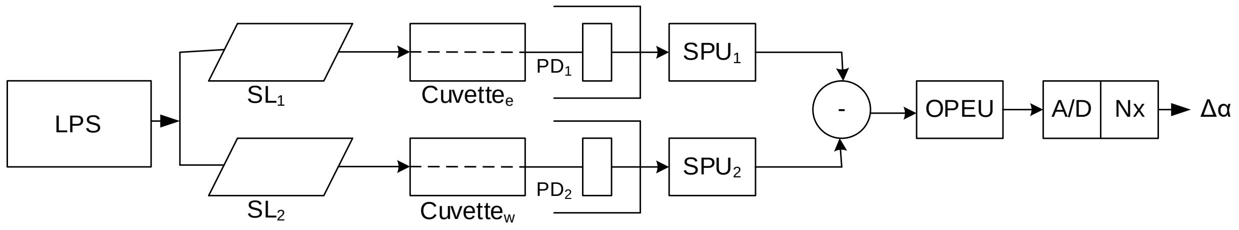

Fig. 2. Laser dual channel photometer

A. Results of Research of Transformer Oils Quality by a Method of Laser Sensing

Stage I. Calibration by a laser method of remote sensing of optically pure glass plates from standard photometric models (using a two-channel differential photometer).

Stage II After calibrating the cuvette, fill them with transformer oil: reference, spent (from AT-2A to AT-7). After calibrating the photometer on two channels with reference oils, measurements are made by replacing the waste oils from AT-2A to AT-7 in one of the channels. The results of the experiments carried out are presented in Table 1 (data processed on the basis of the averaging process of each reference). To obtain a stable assessment, was given time for the transient process of setting the cuvette sensing regime. Parameters of the experimental cuvette: L_n = 25mm (width of the cuvette), Ld = 24mm (length of the cuvette), L0 = 3,3mm (the thickness of the cuvette walls), H = 40mm (the height of the cuvette). In Table 1: $K\alpha_0$ – coefficient of refraction of glass (walls of the cuvette), $\Delta\alpha(L_x)$, $\Delta\alpha(C_k)$ – transmission coefficient (pure oil L_x) and (oil with impurities C_k).

TABLE I. RESULTS OF RESEARCH OF TRANSFORMER OILS IN CUVETTES WITH THE BASIC DIRECTION OF SENSING

Exp. №	Type of transformer oil	$K\alpha_0$	$\Delta\alpha(L_x)$	$\Delta\alpha(C\kappa)$
1	2А/Б-nolmal	+0,30	+0,55	+0,25
2	2A-worked out	+0,30	+0,05	-0,25
3	AT-3A	+0,30	+0,20	-0,10
4	AT-3Б	+0,30	+0,25	-0,05
5	AT-5	+0,30	+0,28	-0,02
6	AT-6	+0,30	+0,28	-0,02
7	AT-7	+0,30	+0,15	-0,15

V. CONCLUSION

According to the results of the measured measurements of the oils for transparency, it can be concluded that the pure oils have active characteristics of the interaction with the laser beam (that is, it intensifies its intensity). Contaminated and partially contaminated oils are characterized by loss of characteristics due to the penetration into their chemical structure of the extra components (materials of the internal environment of the transformer (Cu, Al, Fe, Fe)) and the dissolution of the isolating substances (paper, film, shellac and other components). From the information point of view, we have a sufficient interval of the laser scattering index as the basis for creating a laser control system for the quality of transformer oil. Such a laser controller can function in operating mode.

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