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PRODUCTION TECHNOLOGY AND INITIAL RAW OIL IMPACT ON TRANSFORMER OIL OPTICAL FEATURES DURING POWER TRANSFORMER DIAGNOSIS

Garifullin M.Sh., Kozlov V.K.
FSBEI HE Kazan State Power Engineering University, Russian Federation, Kazan, Krasnoselskaya, 51.
Email: g_marsels@mail.ru

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Abstract:

They performed the study of optical transmission spectra for transformer mineral oils in the range of 300-1000 nm using the example of GK, VG, Nytro, T-1500 and TKp brands. It was shown that the optical properties of oils fully reflect the characteristics of their chemical composition, conditioned by production technology and original oil feedstock. The possibility of rapid analysis for the identification of oil poured into the equipment, as well as its quality control were demonstrated. They made the conclusion about the necessity of taking into account the peculiarities of oil chemical composition poured into a transformer in the process of transformer diagnosis.

Keywords: Diagnostics of oil-filled transformers, transformer mineral oil, optical spectroscopy.

1. Introduction

The process of technical condition diagnosing and monitoring concerning the state of oil-filled power transformer provides quality the research of transformer oil poured into the equipment. Mineral oil is used as the transformer oil. Based on the study of oil physical and chemical properties they develop various techniques to identify the defects in transformer equipment. At that they do not take into account that the obtained results of standardized oil research may be influenced by the features of its chemical composition. This can lead to the misinterpretation of analysis results.

Currently, the oil-filled electrical equipment of Russia uses a wide range of domestic and foreign mineral transformer oils. An appropriate oil fraction is the raw material for the production of these oils. According to RD 34.45-51.300-97, the normalized indicators of oil quality depend on oil brand [1]. The differentiated approach to mineral oils is conditioned by the fact that depending on oil origin (extraction place and year), as well as production technologies, the physical and chemical properties of oils can differ significantly, which will affect their performance properties.

In practice, there are the cases when oil grade in equipment is not known, or there is a mixture of oils in the equipment. At the same time, based on the standard (normalized) research it is quite difficult to make an objective assessment of oil quality, as well as to predict its performance properties. In these conditions you can focus on the structural-group composition studies of oil. An effective tool for the structural-group composition study is the spectral analysis within infrared region in combination with UV-fluorimetry, but the practical implementation of these methods involves the use of expensive laboratory spectrophotometers.

Nowadays, the spectral range of 300 - 1000 nm is used frequently during the study of various materials chemical properties, which include a close UV, a visible and a close infrared area of the spectrum. The main advantages of this range use is the low cost of equipment, the ease of rapid analysis, and the relative simplicity of on-line monitoring technical implementation. This paper provides the overview concerning the production technology of various mineral oil grades, as well as the comparison results concerning the optical properties in a specified spectral range with respect to the most widely used transformer oils in Russian power systems: TKp T-1500, VG and GK, as well as the Swedish oil Nytro.

2. Study Materials and Methods

Oils were taken at the branch of OJSC "Network Company" Kazan electrical networks (KEN) (Kazan).

The transmission spectra were obtained using SF-56 spectrophotometer. The optical path length (cell thickness) makes 50 mm. The comparison cell is empty. The spectral resolution makes 1 nm. The wavelength deviation makes ± 1,0 nm. The slit width makes 1.5 nm.

3. Optical Features of Gk and Vg Oils

GK oil is produced according to TP 38.101.1025-85 (formerly according to TP 38.401.358-84) mainly from the West Siberian sulfur waxy crude oils using hydrocracking process and catalytic dewaxing.

It is believed that according to the technology GK oil produced by JSC "Angarsk petrochemical company" has a higher degree of undesirable component removal in comparison with VG oil [2]. VG oil, as well as the Swedish oils discussed below are obtained by hydrogenation processes at lower hydrogen pressures than during GK production. Thus, VG oil is inferior to GK by stability against oxidation, but it is considered to be more universal one in application. The scope of GK and VG oil application is the electrical equipment of higher voltage classes up to 1150 kV. The advantage of hydrogenation processes

- The development of isoparaffinic hydrocarbons from paraffinic ones as the result of saturation with hydrogen;
- The hydrogenation of unsaturated hydrocarbons;
- The decyclization of naphthenic hydrocarbons with the development of isoparaffins;

- The changes of aromatic hydrocarbons, resulting in naphthenic and paraffinic hydrocarbon concentration increase;

- The conversion of sulfur, oxygen and nitrogen compounds to hydrogen sulfide, ammonia and water.

Disadvantages of hydrotreatment technology

- The concentration of paraffinic hydrocarbons increases.

Fig. 1 shows the transmission spectra of VG and GK fresh oils. The absorption of emissions by petroleum products in the short-wave part of the presented spectrum (about 300 - 500 nm) is conditioned by the presence of aromatic (and polyaromatic) compounds [3]. The boundary of VG and GK oil transmission is within this range, which indicates the presence of the aromatic fraction in both grades of oil.

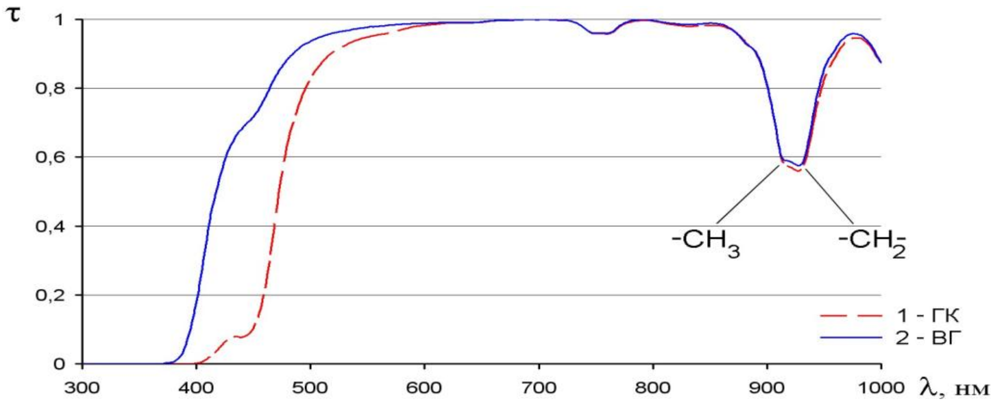

Fig. (1) – VG and GK oil transmission spectra.

While the transmission area of VG oil starts from shorter wavelengths, the concentration of aromatic hydrocarbons is lower therein. During UV studies of GK oil in a thin layer they showed that an aromatic fraction was represented primarily by mono and bicyclic compounds [3]. The concentration of polyaromatic hydrocarbons with three or more cycles in fresh oils is negligible. At the same time there is a clear absorption line on GK spectrum in the range of 420 - 440 nm, which can be attributed to perylene and its derivatives. Within the considered spectral range they also highlight the absorption band characteristic for all oils about 900 - 950 nm, which is formed by two separate but overlapping absorption bands of methyl ($-CH_3$, 913 nm) and methylene ($-CH_2-$, 930 nm) groups. Depending on the content of naphthenic and paraffinic hydrocarbons that form the basis of mineral oil, the ratio of methyl and methylene absorption band intensities changes. This is reflected in the form of the resulting absorption bands. Let's note that in GK and VG oils the methylene group in the range of 930 nm is highlighted more intensely. And this is explained by a sufficiently high content of paraffinic compounds in these oils.

4. Optic Features of NYTRO Oils: Let's consider then the Swedish transformer oils Nytro 11GX and Nytro 10X, which are produced from Venezuelan naphthenic oils containing a few sulfur compounds and waxes. By the virtue of the latter feature the oils have much better low temperature properties than GK and T-1500U oils produced from West Siberian waxy oils [4]. The production technology is the use of the hydrotreatment process. At that the oil Nytro 10X has a deep cleaning. According to the stability against oxidation in the presence of an electric field Nytro 10X oil exceeds the domestic GK oil with better stability, and Nytro 11GX is at GK level.

Nytro 10X oil corresponds to TP 38.101.1025-85 requirements for GK oil, and Nytro 11GX corresponds to TP requirements 38.401.1033-95 for SA oil, and allows the mixing with domestic oils in all proportions. The oils of these brands can be used in the electric equipment of all classes, except for the inlets and measuring transformers.

Fig. 2 shows the transmission spectrum for Nytro oil, taken from the autotransformer 500/220 kV of the substation "Kindery" KES. The boundary of Nytro oil transmission spectrum begins in the same area as that the oils of VG and GK brand. At that component the integral absorption band has a pronounced difference in the range of 900 - 950 nm.

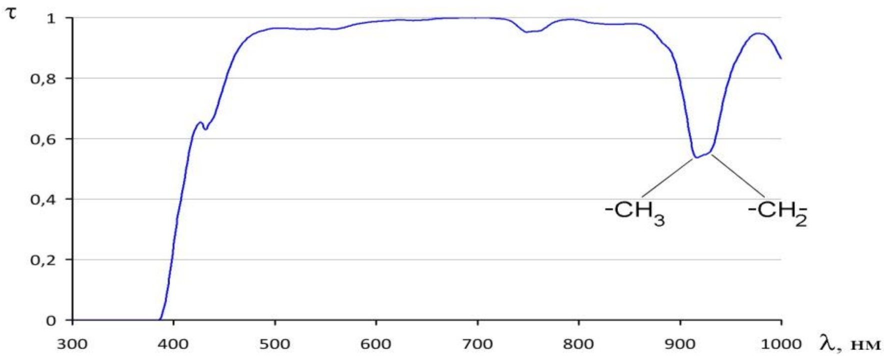

Fig. (2) – Nytro oil transmission spectrum (s/s «Kindery», AT-1).

According to the spectrum, the absorption band arm in the range of 930 nm is much weaker than at 913 nm, which is conditioned by the lower relative amounts of methylene groups $-CH_2-$ in Nytro oil molecules. This feature of the transmission spectrum is fully consistent with the data about the low content of paraffinic hydrocarbons in Nytro.

5. Optical Properties of T-1500 OIL

In addition to the oils obtained by hydrogenation processes mineral oils are produced at Russian refineries using the technologies of selective acid and alkali cleanings. A selective cleaning with the subsequent hydrogenation is applied during the production of T-1500 oil, issued at the beginning according to the GOST 982-80 by Baku Oil Refinery from Baku oils. Then the production of T-1500U oil started (TP 38.401.58107-94 and TP 38.401-58-107-97), and then the T-1500U TC oil production began (TP 0253-002-72868394-2013). T-1500 U oil is produced from sulfur waxy oils. The commodity oil is mixed with nitrogen containing anti-corrosion additive BETOL-1. This additive is produced by JSC "Ufaneftekhim", "Novoufimsky Refinery", OJSC "Nizhegorod-nefteorgsintez" and by JSC "OmskNPZ". The selective treatment is in selective extraction of unwanted components from a distillate by a solvent.

The action of selective solvents is based on different solubilities (in the mentioned solvents) of chemical compound individual groups composing a distillate. Phenol is used mainly as a solvent in order to obtain oil from sulphur oils. The components of transformer oil can be placed in the following order by the decreasing solubility in phenol:

- resins;
- sulfur and nitrogen compounds;
- polycyclic aromatic hydrocarbons and related sulfur compounds by structure;
- aromatic hydrocarbons;
- naphthenic and paraffinic hydrocarbons.

T-1500 U oil has a small amount of sulfur (0.3%) and a relatively high stability against oxidation as compared to the oil T-1500. An elevated level of aromatics hydrocarbons in T-1500 oil causes a higher water solubility as compared to most mineral oils and oil oxidation products that are the polar hydrocarbons like aromatic compounds. Therefore, T-1500 oil was used during the "washing off" from oxidation products, and paper insulation drying as the base of detergent composition [5].

Selective treatment advantage

- Selective extraction of unwanted components from distillate by a solvent.

Technology disadvantages

- It requires a mandatory dewaxing because oil freezing temperature after purification makes about -20 °C (instead of -45 °C).

Fig. 3 shows the spectra of T-1500 oils from KES power transformers (substation "Optics" and "Savinovo"). The presence of aromatic compounds large content in comparison with the above considered oils leads to a more intense light absorption in the range of 300 - 450 nm. Thus, the transmission border moves into long-wave range.

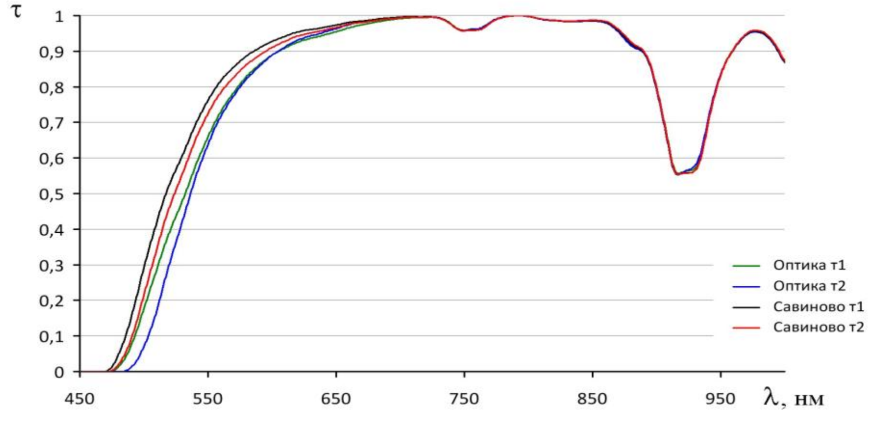

Fig. (3) – Oil transmission spectra of T-1500 type (s/s "Optics" and "Savinovo" KES).

It should also be noted that the shape of an absorption band curve makes about 900 - 950 nm closer to Nytro oil than to GK oil, indicating a smaller content of paraffin compounds in T-1500 oil as compared with GK oil.

6. Optical Properties of TKp Oils

Acid-alkaline cleaning is used in the production of TKp oil, which was produced from Baku oils by Baku refinery according to TP 38.101890-81. In the future they launched the production at the Yaroslavl refinery according to TP 38.401.5849-92. In 2010 it was out of production as an obsolete one. Currently, the production was resumed according to TP 0253-002-72868394-2013 (TKp TC TP 0253-002-72868394-2013) in Yaroslavl at "Slavneft-YANOS".

Anastasievskaya low sulphur naphthenic oil was used mainly for the production. The basis of technological process is the acid-alkaline treatment and contact additional treatment. The purpose of a contact additional treatment is the improvement of oil color, its stability, viscosity index by selective removal of raw material polar components (tar compounds, acid containing compounds, sulphonic acids and selective solvent residues) using adsorbents. Natural clays (bleaching soils) and synthetic aluminosilicates are used as the adsorbents.

Advantages of used production technology

- Unsaturated compounds formed during the distillation of oil are polymerized and are removed by acid tar;
- They are dissolved partially in acid without any changes and they are condensed partially through the condensation reaction and asphalt-resinous substance polymerization and are precipitated by an acid tar;
- Nitrogen compounds are transformed into the acid tar almost completely in the form of sulfates;
- Sulfur compounds are extracted in small amounts;
- Naphthenic acids are dissolveв and sulfonated;
- Polycyclic aromatic hydrocarbons are removed with short side chains.

Technology disadvantages

- The removal of oil valuable components in acid tar takes place, and some sulfur compounds and naphthene-aromatic hydrocarbons are not completely removed;
- The development of acid tar, not applied in production, complicating it and making it more expensive.

Figure 4 shows the transmission spectrum of fresh transformer oil TKp obtained from the refinery. The disadvantages of the obsolete production technology have a distinct reflection on the represented spectrum. First of all, the oil transmission boundary begins from the wavelength of 470 nm, which indicates a high content of aromatics in oil.

Moreover, as compared with T-1500 oil spectra, shown on Fig. 3, in a short-wave area the transmission curve has a more gentle rise (spectrum "shift").

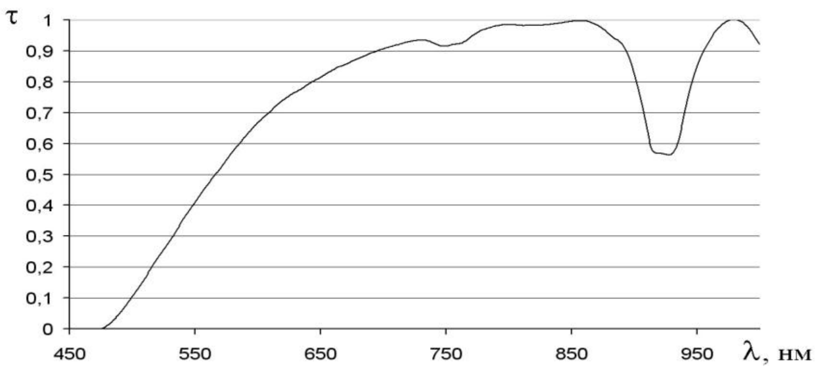

Fig. (4) – TKp fresh oil transmission spectrum.

The transmission reduction in considered spectral range is conditioned first of all by the molecular absorption of polyaromatic compounds with four or more condensed aromatic rings.

Another factor influencing the transmission reduction is the radiation scattering during the dispersed phase, which is formed in fresh oil by the associates from asphaltene molecules [6]. The influence of this factor will be increased during oil aging growth, as the developed oxidation products of hydrocarbon molecules are polar in nature and tend to be associated with the development of colloidal particles [3, 7-8].

Thus, the characteristics of the TKp oil transmission spectrum in a short wave region is conditioned by the increased content of polyaromatic and resin-asphaltene molecules, which is the consequence of the acid-alkaline cleaning low efficiency. According to the shape of the absorption band in the range of 900 - 950 nm TKp oil is located between GK and T-1500. Thus, the content of paraffinic compounds in this oil is lower than in GK, but is higher than in T-1500.

Fig. 5 shows TKp oil transmission spectra selected from KES power transformers.

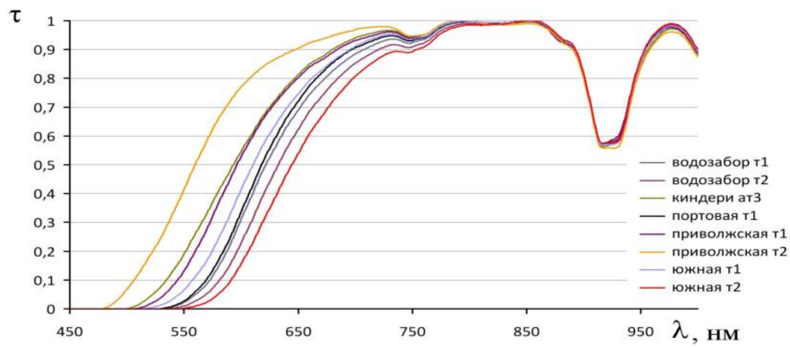

Fig. (5) – TKp oil transmission spectra, obtained from KES transformers.

During the operation of electrical equipment the simultaneous increase of aromatic and polyaromatic compound content as well as of oxidation products takes place in mineral oils. As we noted above, both of these factors lead to the transmission decrease in the short wavelength region of the spectrum due to the molecular absorption by complex aromatics and the scattering on the oxidation products. The consequence of this is the displacement of oil transmission border in the range of 550 - 600 nm. The oils, the transmission spectra of which are shown on Fig. 5, were selected from the power transformers, provided by thermal syphon filters with silica gel. Silica gel absorbs most part of oxidation products. Taking this into account, we can conclude that the characteristic displacement of the transmission spectra curve to a long wavelengths is conditioned mainly by the increase of complex polyaromatic hydrocarbons in oils.

7. Analysis of Physical-Chemical Properties of Various Transformer Oils

Let us compare the qualitative analysis obtained results concerning the chemical composition features of considered transformer oils with the known data of their typical structural-group composition shown in Table 1 [9].

Table 1: Chemical composition features of some of the transformer oils [9].

The amount of carbon atoms ASTMD-3238-80,%, in:	GK	T-1500У (Ufa)	T-1500У (N-N)	T-1500 Bak.	TKp Bak.	TKп Yaros.	Nytro 11GX	Nytro 10X
aromatic nuclei, C_A	1,6	10,0	4,9	14,2	12	18,9	4,46	0,85
naphthenic cycles, C_H	40,2	34	41,3	40,6	35,4	40,1	56,04	61,25
paraffinic hydrocarbons and alkyl chains, $C_П$	58,2	56	53,8	45,2	52,6	41	39,5	37,9
$C_H/C_П$ ratio	0,69	0,61	0,77	0,90	0,67	0,99	1,42	1,6

The table analysis leads to the conclusion that the highest content of paraffinic hydrocarbons is contained in GK oils, and the smallest content of corresponding hydrocarbons is contained in Nytro oils that is fully consistent with the above results of the spectral analysis. The content of wax fraction in T-1500 and TKp oils strongly depends on the place of their production - Baku, Nizhny Novgorod, Ufa and Yaroslavl. Based on the obtained results of spectral analysis, we can conclude that the studied oils of T-1500 and TKp brands are produced at Baku refinery. In order to represent the behavior of different brand oils in the operating conditions they use various laboratory methods. However, the results of a particular oil sample studies cannot have a general character due to the differences in the chemical composition of different crude oil batches. Besides, during the production of oils at various plants there can be differences in manufacturing processes. At that such factors as the changes in the chemical composition of oil at the used in different conditions are not taken into account, as well as the mixture of different oils during refilling in electrical equipment - Table 2 [9].

Table 2: Oil brands, recommended for change and (or) refill into high voltage inputs [9].

Item №	Oil brand, poured into an inlet	Oil brand, recommended for a change or topping
1	GK	GK
		SA
		VG
		Nytro 10X
		Nytro 11GX
		Technol 2000
2	T-750	T-750
		T-1500 У
		T-1500
		Technol 2000
3	T-1500	T-1500
		T-1500 У
		Technol 2000
4	TKp	T-750
		T-1500 У
		T-1500
		Technol 2000

8. Conclusions

1. All mineral transformer oils, used in Russia, have a unique chemical composition, conditioned by original raw material and production technology.

2. Using mineral oil transmission spectra in the range of 300-1000 nm one can reveal characteristic features of their chemical composition and to identify the brand of oils.

3. The offset of oil transmittance spectrum boundary operated in transformers equipped with adsorption filters, is conditioned primarily by complex polyaromatics increase in oil.

4. During the complex diagnostics of power transformers it is necessary to consider the chemical composition features of a transformer oil poured into it.

9. Summary

Thus, the prediction of mineral oil brand properties on the basis of preliminary laboratory studies is a conditional one. An objective quality control and the prediction of oil operational properties requires an idea about its real chemical composition. It was demonstrated that the optical studies in the spectral range of 300 - 1000 nm is an effective way of express-analysis concerning the features of structural-group composition for mineral transformer oils.

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