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Using structured laser illumination planar imaging (SLIPI) as a new technique to monitor the degradation of biodegradable oils in electrical power transformers

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Abstract

The aging process of the insulating oils of an electrical transformer is initiated as soon as the transformer is put into service. The quality of these oils must therefore be rigorously evaluated to have reliable and exploitable data for decision-making. In general, the decision is to continue monitoring, reclaiming/regenerating, or replacing the oil in extreme cases. Thus, early diagnosis of power transformer oils helps prevent potential breakdowns that could considerably impact the electrical energy transmission and distribution network. This research used an imaging technique called SLIPI (Structured Laser Illumination Planar Imaging) to accurately determine the extinction coefficient in different samples of optically dense biodegradable oils (natural and synthetic esters). The variation in the extinction coefficient as a function of the aging of these biodegradable oils under test has been investigated. The results indicate that the SLIPI is reliable as a diagnostic tool for biodegradable oils in power transformers. This technique could therefore be an alternative solution to the conventional monitoring methods.

1 | INTRODUCTION

In any electrical energy transmission and distribution substation, there are several electrical devices. Among all these devices, power transformers represent a vital part of the substation. Transformers ensure the transition from one voltage level to another (either from very high voltage to high voltage or from high voltage to low voltage).

In terms of investment, transformers represent about 60% of the cost of a transformer station [1]. These essential devices must therefore function optimally and efficiently. Indeed, any breakdown or malfunction could cause electricity supply to be stopped in several cities and even an entire country. It is therefore essential to make an early diagnosis of transformers to anticipate incipient failures. Regardless of its excellent design and operation (insulation and cooling), the transformer has an Achilles' heel: The insulation system. Oils are used in this

respect as insulating and cooling fluids. When a power transformer is in service, its insulation system degrades over time. The oils that are part of this isolation system also age. It is therefore essential to strictly assess their level of degradation. This assessment provides usable data for the management and monitoring of transformers. This assessment is done using several diagnostic techniques. These techniques are classified into three categories which are: Electrical tests, physical tests and chemical tests [2].

It should be noted that the measurements can be carried out both on new oils and aged oils. For over ten decades, the most widely used oils in the world have been mineral oils. These oils are products derived from crude oil, and they are non-biodegradable and toxic to the environment. In the event of a spill on the ground, the costs of decontamination operations are extremely high. Another disadvantage of these oils is that they have very low flash and fire points and high flammability risk.

Given the weaknesses of mineral oils, the current global trend is to shift towards biodegradable oils [17]. These oils, also called alternative oils, are also environmentally friendly, have very high flash and fire points. These oils are therefore ideally suited to environments where the risk of fire is very high. Biodegradable oils are widely used in distribution transformers around the world [3]. Even though Siemens delivered a natural ester filled 420 kV power unit, their uses at very high voltage levels still require fundamental studies. As such, several research works are being developed worldwide. These works generally use the traditional techniques mentioned above. These techniques, although widely used, have limitations [4]. This also involves the diversity of interpretation methods with results that sometimes lead to contradictory conclusions, as in the case of the analysis of dissolved gases [5].

In this article, an alternative technique called SLIPI (Structured Laser Illumination Planar Imaging) [6–8] was used as a diagnostic tool to monitor the aging of biodegradable oils (natural esters and synthetic esters). This technique has already proven its effectiveness in classifying the quality of mineral oils, according to Regnima et al. [9]. It was also used by Bagui et al. to classify the quality of coffee [10]. From this technique, we have recently developed image processing strategies for spectroscopic measurements in dense solutions based on Principal Component Analysis (PCA) [11]. This article applies the single-phase Structured Laser Illumination Planar Imaging (1p-SLIPI) technique to natural ester oils and synthetic esters.

The SLIPI technique has been developed to solve problems related to the multiple scattering of optically dense compounds [12–14]. Note that the classical law of photon absorptivity known as the Beer–Lambert law makes it possible to characterize liquid or gaseous compounds of low concentrations. Beyond a certain concentration value, conventional optical spectroscopy is unable to provide reliable results. This is due to the high density of the scattering or absorbing particles in a studied specimen. Thus, the structured illumination imaging technique can selectively encode the incident photons, then do frequency decoding in the acquired images. Thus, this structured illumination imaging technique allows selectively encoding the incident photons, then carrying out frequency decoding in the acquired images. This principle makes it possible to overcome the multiple scattering of photons and rigorously determine diffuse media's optical properties [9, 15, 16].

In practice, the SLIPI method consists in laterally imaging a laser sheet modulated by a Ronchi grating, interacting with the diffuse sample. The recorded raw image results from a modulated component and an unmodulated component emanating from the photons due to multiple scattering. These multiple scattering photons are then removed by post-processing of the raw image. The obtained ballistic light and that of single distribution decrease exponentially with the length of the cell. Hence, applying an exponential fit according to the Beer–Lambert law, we have the possibility of determining the extinction coefficient of the probed sample.

This 1p-SLIPI approach was used to measure biodegradable oils' extinction coefficient in electrical power transform-

TABLE 1 Transformer oil classification for IFT (interfacial tension) [18]

IFT (dynes/cm)	Oil condition
30.0–45.0	Good oils
27.1–29.9	Proposition a oils
24.0–27.0	Marginal oils
18.0–23.9	Bad oils
14.0–17.9	Very bad oils
9.0–13.9	Extremely bad oils

ers. From this determined optical property, a comparative study is then carried out, having regard to the results obtained via usual methods of monitoring transformer oils: Dissolved Decay Products (DDP), Interfacial Tension (IFT), and Turbidity (TUR).

A detailed description of the diagnostic equipment and associated techniques is given. Finally, the results and the ensuing discussion, then the conclusion, are also provided.

2 | APPROACHES FOR THE DIAGNOSIS OF TRANSFORMER OILS

The approach measures transformer oils' properties during their aging using different diagnostic techniques and compares the values found with reference values. These reference values, organized at intervals, constitute a classification for the quality of the oil. Early decision-making should keep the transformer in good condition and even increase its useful life. As indicated in the introduction (Section 1), several conventional diagnostic techniques are presented for classification.

2.1 | Interfacial tension (IFT)

The Interfacial Tension (IFT) measures the tension at the interface between two liquids (oil and water) which do not mix and is expressed in dynes/cm. The measurement is done according to ASTM D971 [4]. The test is sensitive to oil decay products and soluble polar contaminants from solid insulating materials. A good oil indicates an interfacial tension of between 40 and 50 dynes/cm. Oil oxidation products lower the interfacial tension and affinity for both water (hydrophilic) and oil. This affinity for both substances lower the IFT. The greater the concentration of contaminants, the lower the IFT, with a badly deteriorated oil having an IFT of 18 dynes/cm or less. Generally, it is recommended to regenerate the oil when the value of its IFT is less than 25 dynes/cm. However, due to the high hydrophilic nature of the oil, the interfacial tension test may not be susceptible to changes in fluid quality. Moreover, the IFT test requires a trained person, and also, some precautions have to be taken as indicated in the ASTM D971 to do measurements [18]. Some guidelines for IFT have been suggested by some commercial laboratories [18] and given in Table 1.

TABLE 2 Transformer oil classification for AN (acid number) [18]

AN (mgKOH/g)	Oil condition
0.00–0.10	Good Oil
0.05–0.10	Proposition A pils
0.11–0.15	Marginal oils
0.16–0.40	Bad oils
0.41–0.65	Very bad oils
0.66–1.50	Extremely bad oils

TABLE 3 Transformer oil classification for DDP (dissolved decay products) [19]

DDP (a.u.)	Oil condition
0–10	Good Oil
10–25	Proposition A oils
25–50	Bad oils
50–300	Very bad oils
>550	Extremely bad oils

TABLE 4 Transformer oil classification for TUR (turbidity) [19]

Turbidity (NTU)	Oil condition
0–1	Good oil
1–4	Proposition A oils
4–10	Marginal oils
10–30	Bad oils
30–150	Very bad oils
>150	Extremely bad oils

2.2 | Acid number (AN)

Acids in the oil originate from oil decomposition/oxidation products. Acids can also come from external sources such as atmospheric contamination. These organic acids are detrimental to the insulation system and can induce corrosion inside the transformer when water is present. The measure is made with Colour-Indicator Titration technique according to ASTM D974 [19]. The standard unit of measure is mgKOH/g. An increase in the acidity indicates the rate of deterioration of the oil with sludge as the inevitable by-product of an acid situation that is neglected. The acidity of oil in a transformer should never be allowed to exceed 0.25 mg KOH/g. This is the critical acid number, and deterioration increases rapidly once this level is exceeded. For this reason, utility professionals recommend reclaiming the oil when the acidity reaches 0.20 mg KOH/g [20]. The measurement procedure for this technique is very complex, with a high risk of error. Indeed, the operator must judge based on the change in colour of the solution. A very experienced operator is therefore required. Some guidelines for AN(Acid Number) have been suggested by some commercial laboratories [18] and given in Table 2.

2.3 | Dissolved decay products (DDP)

For this technique, an Ultra-Violet / Visible (UV/vis) spectrophotometer is used to assess the amount of degradation products dissolved in transformer oils. The dissolved products are generally: Peroxides, aldehydes, ketones, and organic acids. These degradation products can turn into sludge at some level of oil aging. This sludge can obstruct the passage of oil through the radial and axial channels within the transformer windings. The measurement is carried out following the standard ASTM D 6802 [21] in a range of 360–600 nm. This technique has a weakness, and the standard indicates that the oil under test should be filtered with a 50-μm thick paper filter to avoid interference. This filtering operation, similar to regeneration, denatures the oil under test and distorts the measurements. Some guidelines for DDP suggested by Issouf Fofana and Yazid Hadjadj [19] are given in Table 3.

2.4 | Turbidity (TUR)

This test method uses a ratio turbidimetric optical system to measure the turbidity of insulating according to ASTM D6181 [22]. Cloudiness or turbidity is attributed to matter whose diameter is approximately 20% of the wavelength of the incident light. Increasing turbidity signifies increasing transformer fluid contamination from external sources or internal chemical reactions (oxidation) that produce fine particulate matter. Other turbidity sources, such as water droplets or gas bubbles, are not of interest in this evaluation of insulating oils. The turbidity is expressed in NTU (Nephelometric Turbidity Unity). As an advantage, turbidimetry is accurate and helpful in measuring very low turbidity (less than 5 NTU). However, there are several limitations: the high cost, high power needed, and the fragility of the system [23]. Some guidelines for turbidity suggested by Issouf Fofana and Yazid Hadjadj [19] are given in Table 4.

2.5 | Colour (ASTM D 1500)

An oil's colour comes from the light-transmitting through it. Different colours are formed depending on the concentration and type of light-absorbing groups suspended in the oil. The colour of new oil is generally accepted as an index of the degree of refinement. For oils in service, an increasing or high colour number indicates contamination, deterioration, or both. Oxidation is a common cause of an overall darkening. An increase in acidity and reduction of IFT are followed by darker oil colour that indicates polar contaminant (Figure 1). This Figure is only

Good	Prop A	Marginal	Bad	Very Bad	Extremely Bad	Disastrous
Effect on transformer						
Proving these functions 1. Efficient cooling 2. Preserving insulation	Polar compounds (sludges) in solution (products of oil oxidation) causes the drop in IFT	Fatty acids coat the windings. Sludges in solution ready for initial fall out. Sludges in insulation voids highly probable.	In almost 100% of the transformers in this range sludges are deposited on core and coils. **Sludges are fisrt deposited in fin areas.**	Deposited sludges continue to oxidize and harden. **Insulation shrinkage is taking place.** Premature failure a good possibility.	Sludges insulate cooling fans, block vents causing higher operating temperatures.	Vast quantities of sludges may require other means than desludging procedures.

FIGURE 1 Effect of oil quality on transformer's condition [19]

TABLE 5 Some parameters of mineral, natural ester and synthetic ester oils [3, 25, 26]

Parameters	MO	NE	SE
Fire point (°C), ISO 2592	170	>350	>300
Flash point (°C), ISO 2592	160	>300	>250
Biodegradability (%) at 28 days, OECD 301	10	95	90
Water content (ppm), D1533	<20	<50	<50
Viscosity (mm^2/s @ 40 °C), ISO 3104	7.5	37	29
Acidity (mgKOH/g), D974	<0.01	<0.04	<0.03
Dissipation Factor (%) at 90 °C, IEC 60247	<0.002	<0.005	<0.006
Breakdown voltage (kV), IEC 60156	>70	>75	>75
Density (kg/m^3) at 20 °C, ISO 3675	885	920	970

TABLE 6 Description of transformer oil samples

Name of the samples	Oils samples description
MO-0h	New mineral oil
NE-0h	New natural ester oil
SE-0h	New synthetic ester oil
MO-250h	Mineral oil aged for 250 h
NE-250h	Natural ester oil aged for 250 h
SE-250h	Synthetic ester oil aged for 250 h
MO-500h	Mineral oil aged for 500 h
NE-500h	Natural ester oil aged for 500 h
SE-500h	Synthetic ester oil aged for 500 h
MO-750h	Mineral oil aged for 750 h
NE-750h	Natural ester oil aged for 750 h
SE-750h	Synthetic ester oil aged for 750 h
MO-1000h	Mineral oil aged for 1000 h
NE-1000h	Natural ester oil aged for 1000 h
SE-1000h	Synthetic ester oil aged for 1000 h
MO-1250h	Mineral oil aged for 1250 h
NE-1250h	Natural ester oil aged for 1250 h
SE-1250h	Synthetic ester oil aged for 1250 h
MO-1500h	Mineral oil aged for 1500 h
NE-1500h	Natural ester oil aged for 1500 h
SE-1500h	Synthetic ester oil aged for 1500 h
MO-2000h	Mineral oil aged for 2000 h
NE-2000h	Natural ester oil aged for 2000 h
SE-2000h	Synthetic ester oil aged for 2000 h
MO-2500h	Mineral oil aged for 2500 h
NE-2500h	Natural ester oil aged for 2500 h
SE-2500h	Synthetic ester oil aged for 2500 h

helpful as a guideline; the decision as to the eventual action to be taken on the oil must be based on the values of other properties.

The similarities and the differences between the traditional methods presented above can be found in the scientific literature [23].

3 | THERMAL AGING PROCEDURE AND OILS QUALITY ANALYSIS

3.1 | Thermal aging procedure

Three (3) types of transformer oils were used to conduct this study: Mineral oils (MO), natural ester oils (NE), and synthetic ester oils (SE). Generally speaking, manufacturers measure the main characteristics of their new oils before delivering them to customers. Some of these characteristics concerning our three (3) study oils are given in Table 5. It can be seen from Table 5 that NE and SE oils have very high fire and flash points compared to MO.

Therefore, from new oils, as delivered by the manufacturer: Mineral oil (MO), natural ester oil (NE), and synthetic ester oil (SE), accelerated thermal aging in the laboratory was carried out according to the standard ASTM-D 1934 [24]. The preparation of oil samples of the transformer has been made at the University of Quebec at Chicoutimi, in Canada. The principle of this thermal aging consists for each of the three oils to be placed in a mechanical convection oven set at 115 °C, a stainless-steel beaker containing one litre of oil and pieces of copper whose dimensions are given by: 3 cm × 5 cm for 400 millilitres of oil.

These pieces of copper act as metal catalysts, thus accelerating reactions within the molecular chains of oils. The beakers are closed to simulate breathing through silica gel cartridges of an actual transformer in operation. The total duration of aging is 2500 h. During aging, oil samples were taken for aging times of 0, 250, 500, 750, 1000, 1250, 1500, 2000, and 2500 h. These oils samples are presented in Table 6.
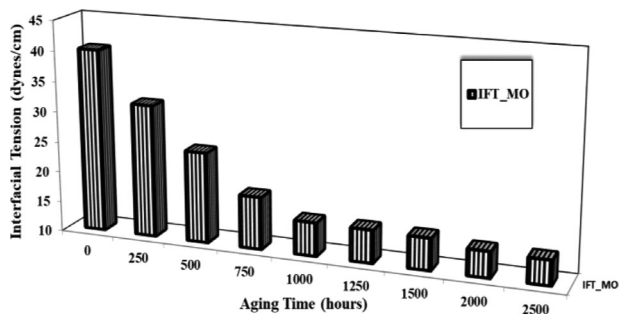
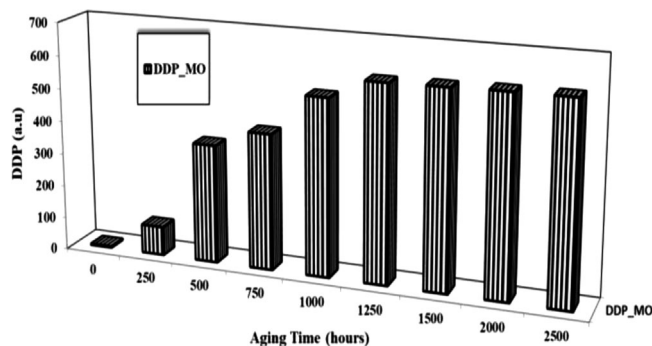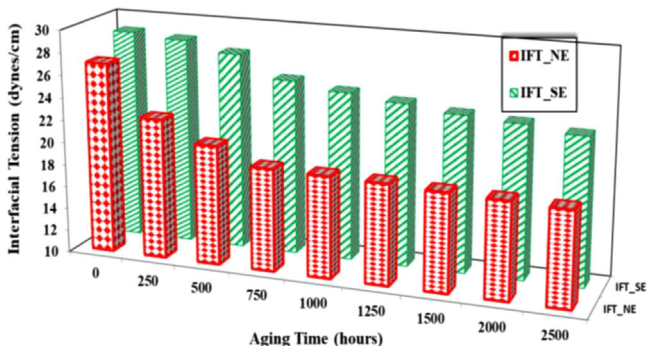**FIGURE 2** Interfacial tension of mineral oil as a function of aging time
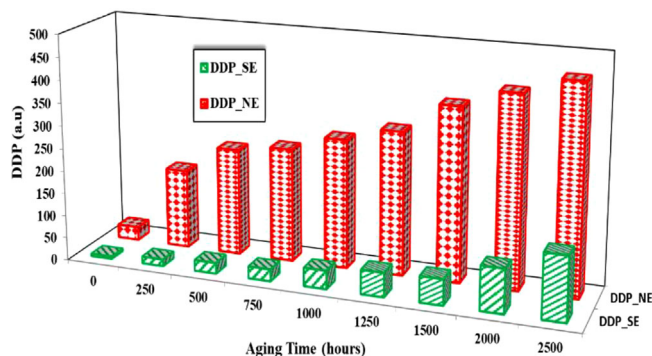

FIGURE 3 Interfacial tension for the oils NE and SE as a function of aging time

Conventional Techniques (DDP, TUR, and IFT) and SLIPI technique will be applied to these twenty-seven (27) oils samples presented in Table 6.

3.2 | Oils quality analysis using interfacial tension (IFT)

The interfacial tension measurements for the oil MO, carried out according to the duration of accelerated aging are grouped in Figure 2.

The interfacial tension measurements for the oils NE and SE carried out according to the duration of accelerated aging are grouped in Figure 3.

Figures 2 and 3 show that the IFT's value decreases for all three oils as the aging time increases. Indeed, for insulating oil in a transformer in service, the decrease of the IFT indicates a degradation of the quality of the oil due to an accumulation of contaminants and oxidation products [23]. The following analysis can be made only for mineral oil according to Section 2 and the classification given in Table 4 (Section 2.1). New mineral oil (MO) is classified as "good oil", but from 1000 h of ageing, it is classified as "very bad oils".

3.3 | Oils quality analysis using DDP

The DDP measurements for MO, carried out as a function of accelerated aging times are grouped in Figure 4.

FIGURE 4 DDP of mineral oil as a function of aging time

FIGURE 5 Interfacial tension for the oils NE and SE as a function of aging time
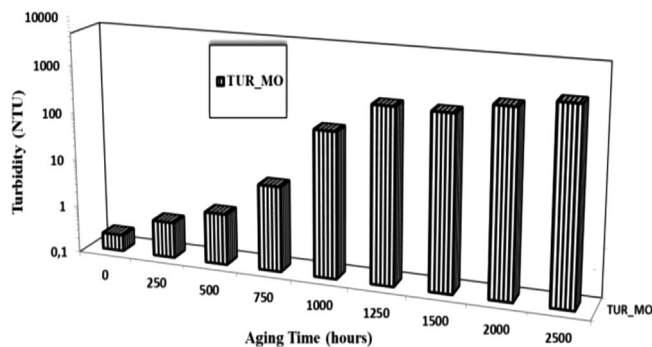

FIGURE 6 Turbidity of mineral oil as a function of aging time

The DDP measurements for the oils NE and SE carried out according to the duration of accelerated aging are grouped in Figure 5.

The results in Figures 4 and 5 indicate a general increase in DDP values for the three oils from 0 to 2500 h. This increase of DDP values reflects the aging of the power transformer oils.

3.4 | Oils quality analysis using turbidity

Turbidity measurements for MO, carried out as a function of accelerated aging times are grouped in Figure 6.
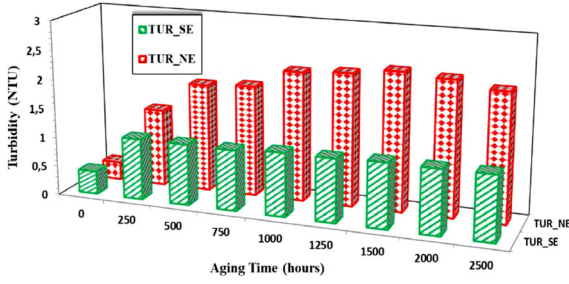
FIGURE 7 Turbidity for the oils NE and SE as a function of aging time

The turbidity measurements for the oils NE and SE carried out according to the duration of accelerated aging are grouped in Figure 7.

Figures 6 and 7 show that as the aging time increases, the turbidity value increases for all three oils. The turbidity values for MO oil are much higher than those for biodegradable oils. This increase indicates the degradation of the quality of the oils [23]. Following the classification for mineral oil given in Table 4 (Section 2.4), the analysis of the results of Figure 6 was made. When new (0 h), MO oil is classified as "good oils". From 1000 h, MO oil is classified as "very bad oils".

Analysis of the results of physicochemical techniques (DDP, TUR, IFT) showed that the longer the aging time increases, the more pronounced degradation of transformer oils is observed. Therefore, an aged oil at 2500 h is more degraded than aged oil at 1500 h, which is more degraded than new oil.

4 | SLIPI TECHNIQUE

4.1 | SLIPI measurements

The used SLIPI optical device configuration in this manuscript is shown in Figure 8. In addition to being fast and cost-effective, it has a simplified optical setup. It consists of continuous-wave (CW) laser beams of 450 nm source. The irradiation light is directed to a system of optical components using a dichroic mirror. A neutral density wheel is then used to adjust the incident irradiance. This allows optimizing the signal-to-noise ratio (SNR) while avoiding saturation. The laser beam is expanded and collimated through two spherical lenses. Finally, the laser sheet created by a cylindrical lens and modulated using a 5 lp/mm Ronchi grating is then completely reflected through a plane mirror on the cuvette containing an oil sample. The image of the decay of the luminous flux in the probed oil is recorded using a 14-bit electron-multiplying (EM) CCD camera, Luca (r) from Andor, located at 90° to the propagation direction of the laser light sheet.

4.2 | Single-phase SLIPI post-processing technique

An image acquired with the SLIPI device is the result of single scattering and multiple scattering photon intensities. The structuring of the incident flux by the Ronchi grating imposes a modulated component and a DC component. The amplitude of the modulated component reflects the absorption of the probed medium. It represents the contribution of photons having kept the memory of structuring pattern, unlike the DC component constituting the background noise. The photons from the latter component have different frequencies from that of the structuring system. The processing thus consists in extracting the intensities due to single scattering along each line pixel of probed transformer oil image and then, delete the additional intensity noise. The strategy for isolating these unwanted frequencies is done via 1D Fourier transform by implementing the lock-in detection algorithm [27]. This is based on single-phase scattering detection using Fourier transform.

Assume a 1D signal, $I(x)$ with a superimposed periodic variation of amplitude I_S in space according to Equation (1):

$$I(x) = I_S \sin(2\pi\nu x + \phi) + I_{MS}(x) \tag{1}$$

In this relationship, ν is the grating modulation frequency. I_S and I_{MS} are respectively the modulated signal amplitude and a non-modulated background. ϕ represents the unknown spatial phase of the superimposed modulation. Extract I_S and reject I_{MS} is the primary goal of the lock-in algorithm. To this end, the signal I is multiplied with two reference signals R_1 and R_2, created computationally, that have a relative phase shift of $\pi/2$. These two reference signals with an identical period (ν) which is equal to those of the modulated spectrum (expressed on the flowchart of the algorithm presented in Figure 9), are successively multiplied by the signal $I(x)$. This then results in two signals denoted $I_1(x)$ and $I_2(x)$, each composed of three components: a DC component, one modulated with 2ν, and one with ν. The two modulated components can be suppressed using a low-pass filter (LPF) in the Fourier domain, with a cutoff frequency less than ν. The resulting signals from this low pass filtering are noted with the tilde assignment on the diagram. From there, $\widetilde{I_S}$ can finally be extracted thanks to the following formula (2):

$$\widetilde{I_S} = 2\sqrt{\left(\widetilde{I_1}\right)^2 + \left(\widetilde{I_2}\right)^2} \tag{2}$$

From a recorded image via a single-phase SLIPI device, the modulated component I_S is related to the exponential decay of the photons resulting from the single scattered light during light-sample interaction. It is then necessary to apply an exponential fit to I_S, according to the Beer–Lambert absorption law, for the extinction coefficient μ_e extracting.

For a given sample, the optical depth (OD) and the transmittance (T) are related by the following relation (3):

$$A = OD/ln(10) = -log_{10} T \tag{3}$$

The absorbance (A) in this relationship gives a quick indication of how much light has crossed the sample. A is related to the extinction coefficient μ_e by the relation (4), as
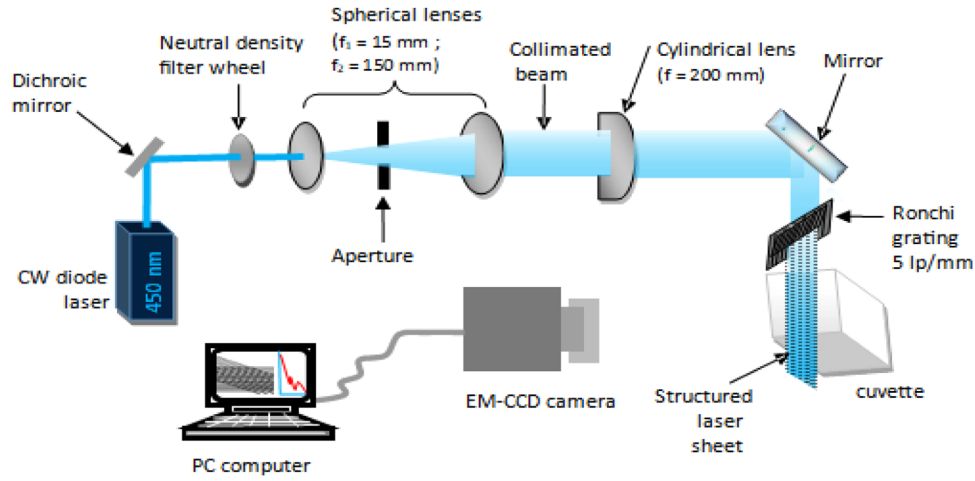
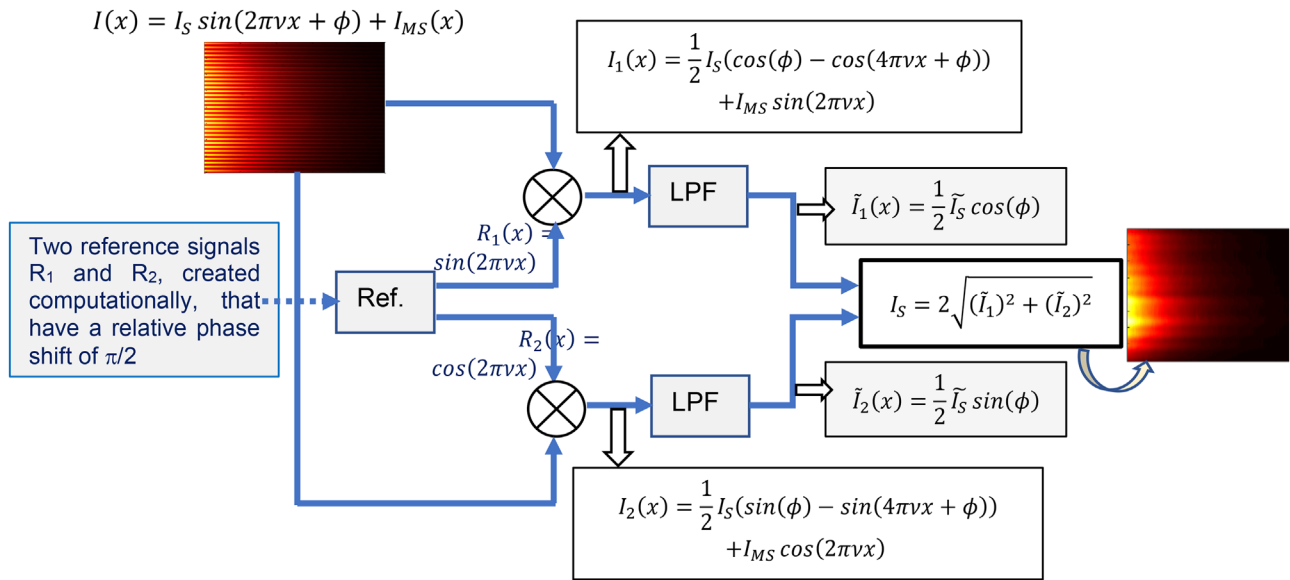**FIGURE 8** 1p-SLIPI optical arrangement detailed schematic

FIGURE 9 Diagram of extraction process of photons due to single scattering in images acquired via SLIPI optical device. This so-called lock-in detection process allows reconstruction of SLIPI images, plots the corresponding exponential decay graphs, and calculates the optical properties of oils

a function of the length L of the cuvette used in the SLIPI measurements.

$$\mu_e = \frac{ln10}{L} A \qquad (4)$$

Calculating the extinction coefficient of each sample takes into account the fact that the extinction coefficient is related to the concentration N of molecules/particles contained within the studied oil sample, according to Equation (5):

$$\mu_e = N \cdot (\sigma_a + \sigma_s) \qquad (5)$$

where σ_a and σ_s are the absorption and scattering cross-sections, respectively.

5 | STRUCTURED ILLUMINATION ANALYSIS RESULTS AND DISCUSSION

5.1 | 1p-SLIPI results

The single-phase SLIPI recorded images for some samples of each type of oil are shown in Figure 10.

Some observations should be noted from these images:

- At 00 h (unaged oils), the modulation is quite noticeable in the image corresponding to mineral oil. This would mean that the signal is optimal there, unlike ester oils, where the modulations are less noticeable. Indeed, the near transparency of these ester oils does not optimize the lateral detection of single scattering through the SLIPI device. The associated SLIPI
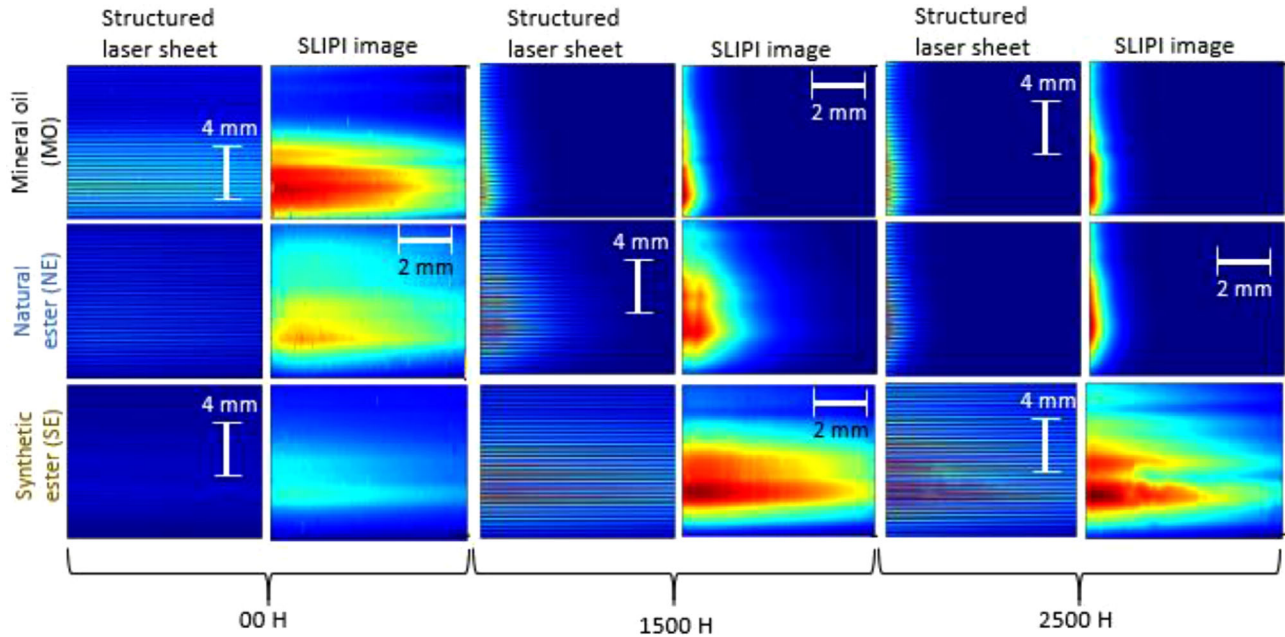
FIGURE 10 Images of the structured light sheet crossing the cuvette containing the oil samples. The corresponding SLIPI images are given on the right-hand side. The first line is for the images obtained with mineral oils (MO). The second line shows the photos from natural ester oils (NE). The last line corresponds to those of synthetic ester oils (SE). For each of these three types of oils, images of new oils (00 h), oils aged at 1500 h and at 2500 h are presented

images reflect this because we can notice a high amplitude of the modulated signal with mineral oils. On the other hand, low amplitude of the modulated component is recorded for ester oils. However, the comparison between NE and SE shows that the signal is optimal for NE oil compared to SE.

- At 1500 h, the modulation depth of mineral oil is very low, and the SLIPI image gives the amplitude of the modulated component. This highlights the fact that this sample induces a strong photon absorption. The high density of this oil thus causes a more excellent value of the extinction coefficient than that of the ester oils. The resulting natural ester oil structured image has an intermediate modulation depth. For SE, the modulation depth is optimal, as well as the modulated amplitude. SE oil is, therefore, less dense than NE, itself less dense than mineral oil, at 1500 h.

- For 2500 h, the mineral and natural ester oils are very dense, with a very low modulation depth. Indeed, these samples have a very high optical density, and light transmission is almost impossible. On the other hand, SE allows photon propagation and optimal detection of single scattering.

The light intensity decay graphs for each probed oil are shown in: Figures 11–13.

The type of oil classifies these spectra in graphs noted: (Figure 11) for MO, (Figure 12) for NE, and (Figure 13) for SE. The value of the extinction coefficient determined for each sample is given in the legend. The graphs are almost straight for a given type of new oil (00 h), and the aging time is short. Then they have a slight curvature when the aging time is low. For these samples, the radiation is very weakly absorbed. But the more aging time increases, the more the graphs have an exponential
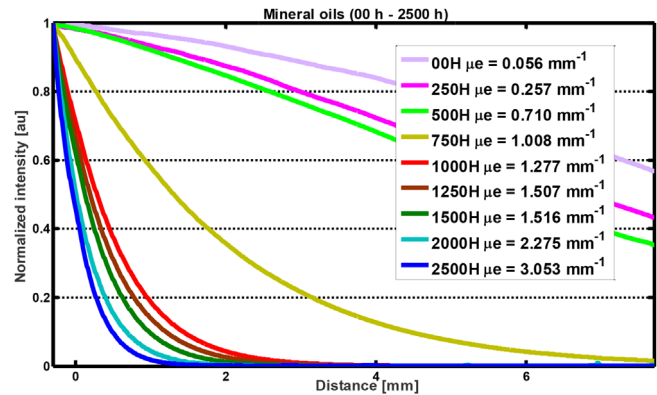

FIGURE 11 Graphs resulting from the exponential decay of light intensity obtained using lock-in detection algorithm for each sample of MO probed with laser light at $\lambda = 450$ nm. The corresponding extinction coefficient values are posted on each illustration

decay form. For these samples, there is a strong absorption of laser radiation. This curvature is even more accentuated for mineral oils (MO). Note also that the synthetic ester oil exception to this common observation with two other oils. The graphs obtained from SE are not strongly curved, even when aged at 2500 h. So the optical density of this oil is low, varying slightly from one aging time to another.

5.2 | Discussion of 1p-SLIPI results

The 1p-SLIPI technique allows an excellent classification of the aging state of mineral oils and biodegradable oils
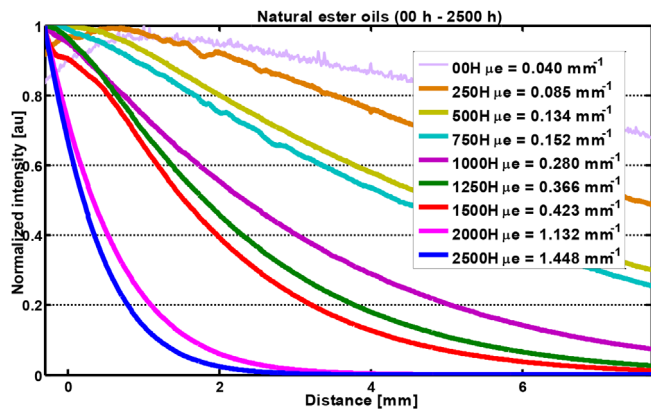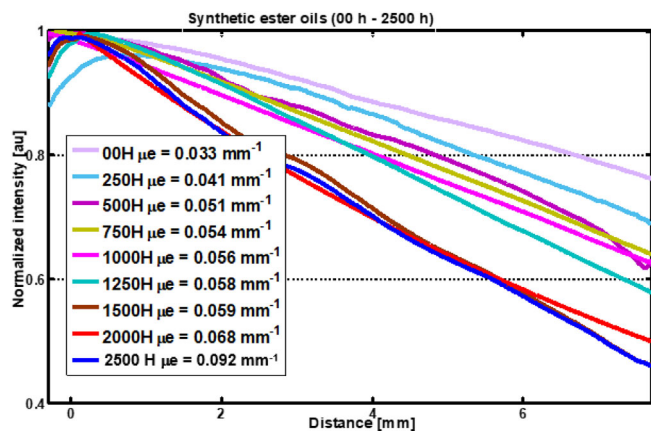
FIGURE 12 Graphs resulting from the exponential decay of light intensity obtained using lock-in detection algorithm for each sample of NE probed with laser light at $\lambda = 450$ nm. The corresponding extinction coefficient values are posted on each illustration

FIGURE 13 Graphs resulting from the exponential decay of light intensity obtained using lock-in detection algorithm for each sample of SE probed with laser light at $\lambda = 450$ nm. The corresponding extinction coefficient values are posted on each illustration
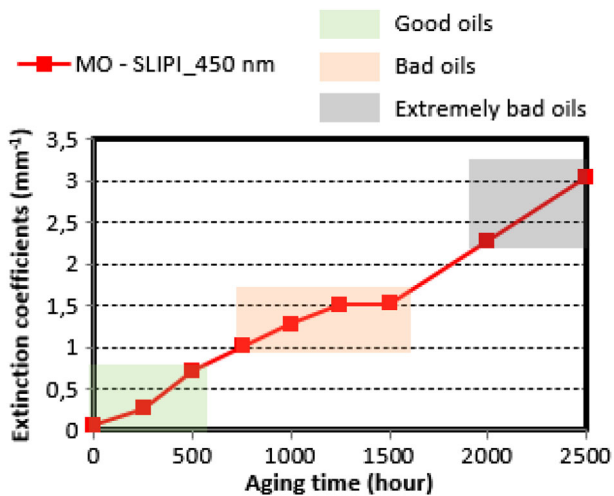
FIGURE 14 Evolution of the extinction coefficient as a function of the aging time of mineral oil (MO) samples probed with 1p-SLIPI at $\lambda = 450$ nm
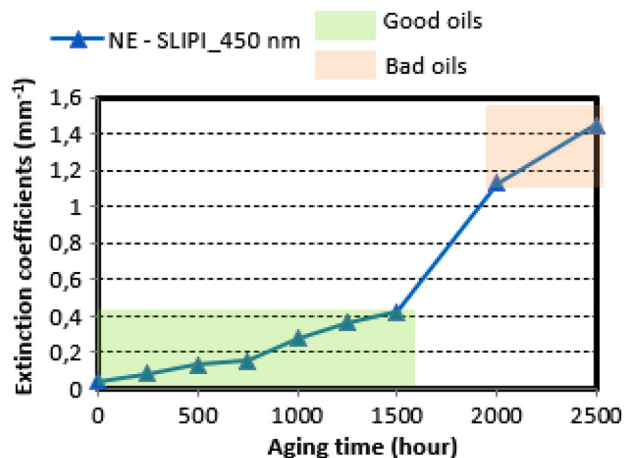
FIGURE 15 Evolution of the extinction coefficient as a function of the aging time of natural ester (NE) oil samples probed with 1p-SLIPI at $\lambda = 450$ nm
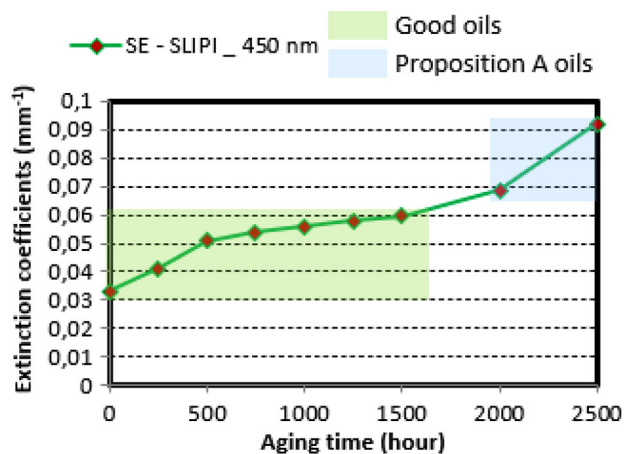

FIGURE 16 Evolution of the extinction coefficient as a function of the aging time of synthetic ester (SE) oil samples probed with 1p-SLIPI at $\lambda = 450$ nm

(natural ester (NE) and synthetic ester (SE)). This classification is based on the extinction coefficient values of oil samples. This optical property calculated using this approach is an essential indicator in monitoring the deterioration of studied oils. A high value of the extinction coefficient of an oil, indicates that this one is strongly degraded. In this case the radiation is absorbed there much more. This also highlights the evolution of the various physicochemical parameters. Note that the SLIPI technique made it possible to determine in details, minor variations in the states of consecutive degradation from one oil sample to another. However, the discoloration of these samples appears almost identical. Thus, the minimum deviations are around $1/100$ mm^{-1}.

Mineral oil samples show three states overall in their aging. These oils stay good between 00 and 500 h. Then, they are in a bad state (bad oil) between 750 and 1500 h. Finally, these mineral oils become extremely bad, beyond 1500 h. This is
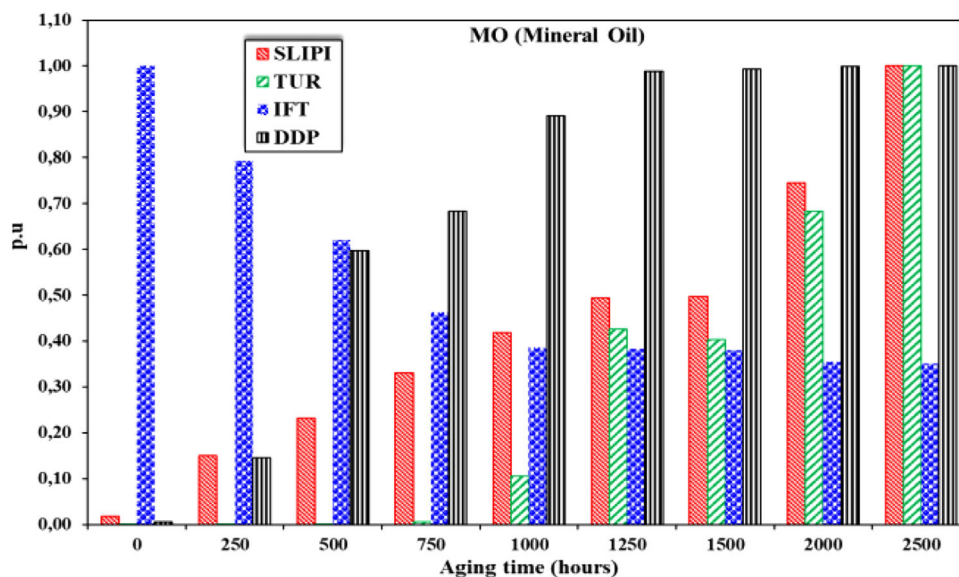
FIGURE 17 Comparison between conventional techniques (DDP, IFT and TUR) and the SLIPI for mineral oil (MO)
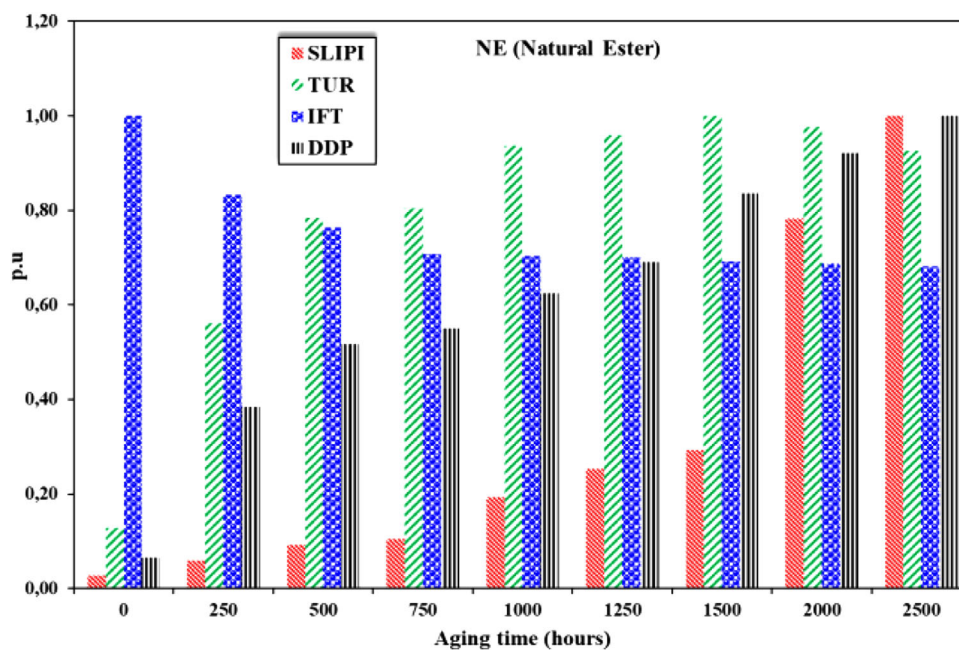

FIGURE 18 Comparison between conventional techniques (DDP, IFT and TUR) and the SLIPI for natural ester (NE)

illustrated in Figure 14, which shows the extinction coefficient evolution as a function of aging time.

The detailed analysis of extinction coefficients different values calculated at 450 nm using the 1p-SLIPI approach, allows the establishment of decision Table 7 for mineral oils.

Two classes emerged for ester oils, on the other hand, during their aging from 00 h (new oils) to 2500 h. NE oils are in good condition between 00 h and 1500 h, for μ_e values between 0 and 0.423 mm^{-1}, then they become bad between 2000 and 2500 h when the value of μ_e is between 1.132 and 1.448 mm^{-1} (Figure 15).

TABLE 7 Guidelines for extinction coefficient values at 450 nm for mineral oils (MO)

Oil condition	Extinction coefficient (mm^{-1})
Good oils	0–0.056 ± 0.005
Proposition A oils	0.056 ± 0.005–0.257 ± 0.016
Marginal oils	0.257 ± 0.016–0.710 ± 0.023
Bad oils	0.710 ± 0.023–1.516 ± 0.058
Very bad oils	1.516 ± 0.058–2.275 ± 0.015
Extremely bad oils	> 2.275 ± 0.015

FIGURE 19 Comparison between conventional techniques (DDP, IFT and TUR) and the SLIPI for synthetic ester (SE)
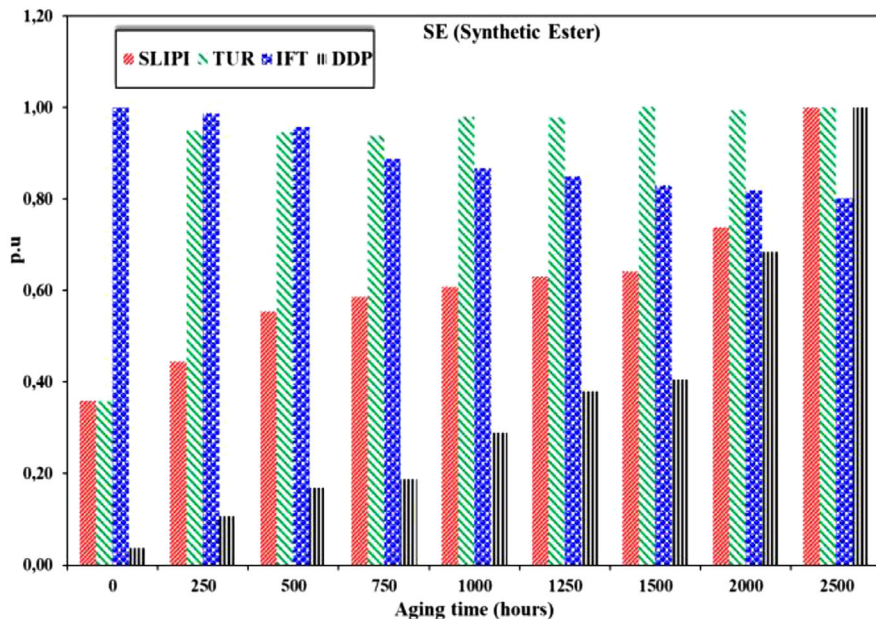
Synthetic ester (SE) oils remained good until aging beyond 1500 h, before being in a poor degradation state, starting at 2000 h. For good oils, the value of μ_e is between 0 and 0.425 mm^{-1}. For Proposition A oils, the value of μ_e range from 0.068 to 0.092 mm^{-1} (Figure 16).

Considering the above, it is clear that the SLIPI technique is well suited to monitoring the deterioration and aging of oils in electrical power transformers

5.3 | Comparison between conventional techniques and the SLIPI

This section presents the comparison between conventional techniques (DDP, IFT and TUR) and the SLIPI according to their capability to monitor the aging of transformer insulating oils. Indeed, it has been showed in Figures 2–7 that, from a certain aging time, the parameters (DDP, TUR and IFT) vary very little. This comparison has been done in p.u (per unit). In the case of the SLIPI technique, the calculation has been carried out by using the extinction coefficient. The results obtained are presented in Figures 17 to 19. It can be clearly observed that the SLIPI parameters vary significantly according to aging time whatever the type of oil, unlike the others (DDP, TUR and IFT) which sometimes saturate from aging time. Thus, the SLIPI technique represents a great improvement to study the impact of aging (diagnosis) of transformer insulating oils. It could be considered for future development in monitoring the aging of oils effectively.

6 | CONCLUSION

Biodegradable oils and/or oils with a high fire point are the candidate oils for replacing mineral oils in the decades to come. The effective diagnosis of service aged oil is necessary to monitor their physicochemical and dielectric behaviour.

This article investigates an alternative technique called SLIPI (Structured Laser Illumination Planar Imaging). Since the SLIPI technique, a non-destructive technique, gives excellent results, it could serve as a tool for diagnosing the conditions (deterioration and aging) of biodegradable oils suitable for power transformers. The obtained results have been compared to existing physicochemical techniques and were found very satisfactory.

In fact, we obtained the following results:

- The extinction coefficient determined with the SLIPI technique increases with the aging of the oils (in other words the SLIPI can therefore follow the aging of the oils)
- Unlike traditional techniques (IFT, TUR and DDP) which saturate after a certain aging time, the extinction coefficient determined with the SLIPI technique increases without saturating (better monitoring of oils aging).
- A classification of the quality of oils based on the extinction coefficient has been proposed. This classification gives the state of the oils, namely: Good oils; proposition a oils; marginal oils; bad oils; very bad oils; extremely bad oils.

The technique of SLIPI seems to offer an interesting alternative technique for diagnosing biodegradable oils than other time-consuming and expensive methods. However, additional interlaboratory studies and for transformers in service on the electrical network are necessary to further consolidate these results.

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